LANGUAGE AND SPEECH, 1993, 36(2, 3), 235–260


# A COMPARATIVE INVESTIGATION OF COARTICULATION IN FRICATIVES: ELECTROPALATOGRAPHIC, ELECTROMAGNETIC, AND ACOUSTIC DATA*

PHILIP HOOLE
*Ludwig-Maximilians-Universität, Munich, FRG*
NOEL NGUYEN-TRONG
*CNRS, Aix-en-Provence, France*
and
WILLIAM HARDCASTLE
*Reading University, U.K.*

The principal aim of this investigation was to compare coarticulatory effects at different levels of the speech production system, in order to gain insight into the relations between the different levels. To this end, the relative magnitudes of carryover and anticipatory coarticulation with adjacent vowels were measured at the midpoints of the two lingual fricatives /s/ and /ʃ/ in two speakers each of English, French, and German. Linguopalatal contact patterns derived from electropalatographic recordings were compared with an analysis of the acoustic output. The results indicated, firstly, that mismatches between articulatory and acoustic results are not uncommon. Secondly, and more surprisingly, while there was no difference in the overall magnitude of coarticulatory effects for /s/ and /ʃ/, not all speakers showed a predominance of the same coarticulatory direction on both fricatives; this complicated the observed tendency for the predominance of carryover coarticulation to be greater in German and English than in French. Two speakers were retested using comparative analyses of electropalatography and electromagnetic articulography. These two procedures gave a closely parallel picture of lingual coarticulatory regularities (while complementing each other in terms of characterizing articulation). The implications of these results for identifying language-specific coarticulatory regularities are discussed.

*Key words:* coarticulation, fricatives, electropalatography, electromagnetic articulography, French, German

* This work was supported by ESPRIT/BRA 3279 ACCOR. The authors are grateful to Bruno Repp for comments on an earlier version of this paper, and are also indebted to Barbara Kühnert and Christian Ledl for numerous discussions of this work as well as for help with the figures.

Address correspondence to: Philip Hoole, Institut für Phonetik und sprachliche Kommunikation, Ludwig-Maximilians-Universität München, Schellingstraße 3, D–80799 München.

## INTRODUCTION

The aim of the present study is to compare coarticulatory effects at different levels of the speech production system. The overall context of the work is provided by the continuing efforts of many investigators to arrive at a better understanding of coarticulatory regularities in different languages. One influential approach has been to focus on the relative magnitude and respective nature of anticipatory and carryover effects. Thus Parush, Ostry, and Munhall (1983) noted that previous investigations had given a rather equivocal answer to the question of whether one coarticulation direction predominates (see also the recent discussion in Recasens, 1989). This then provided the impetus for these authors to perform a particularly detailed kinematic analysis of tongue dorsum movement in VCV sequences (using velar consonants and back vowels). The results gave support to the concept of qualitative differences between anticipatory and carryover effects, the former being manifested more in durational measurements (of the VC transition) and the latter more in spatial measurements (of the CV transition). Further support for qualitative differences is found in Recasens' (1989) detailed study of the extent of lingual coarticulation as a function of the gestural antagonism of different consonants and vowels. Anticipatory effects proved somewhat less extensive but also less variable in temporal terms than carryover coarticulation, thus indicating that the former may more closely reflect pre-planning than the latter.

Studies of this kind represent one important approach towards resolving unclear aspects of lingual movement patterns. However, a further implication of the discussion by Parush *et al.* is that one reason for the conflicting results in the literature could very well reside in the wide variety of procedures that have been used to investigate coarticulation. Different techniques tap into the speech production process at different levels and with different degrees of completeness. The particular motivation for the present study was therefore to gain a better understanding of the implications of this fact by examining coarticulation at a number of distinct levels.

Clearly, a comparison of coarticulatory regularities at the acoustic and articulatory levels is particularly important. Improvements in acoustic models of speech production require improved understanding of the acoustic consequences of articulatory behaviour. Models of speech perception would benefit from better knowledge of the articulatory regularities that are recoverable by the listener from the speech signal. The latter point can also be seen from a more technological perspective, since – as discussed by Schmidbauer, Casacuberta, Castro, Hegerl, Höge, Sanchez, and Zlokarnik (1993) – an articulatory level of representation may well become increasingly important in the development of more robust speech rocognition systems.

However, despite its obvious interest there have been comparatively few attempts to compare coarticulation in the acoustic and articulatory domains. There are exceptions, of course: Recasens (1984, 1991) has examined electropalatographic (EPG) contact patterns in parallel with the second formant of vowels; Recasens and Farnetani (1990) have conducted a palatographic and formant analysis of laterals. But a substantial increase in systematic knowledge would be highly desirable.

For the purposes of this study it was decided to focus on lingual fricatives. Compared with plosives, for example, fricatives have the advantage of showing no major acoustic discontinuities during their time course and are thus somewhat more amenable to parallel articulatory and acoustic analysis (*cf.* Hoole, Ziegler, Hartmann, and Hardcastle, 1989). In addition, the languages available to us had two reasonably comparable lingual fricatives, /s/ and /ʃ/.

The study was divided into two parts. The first part consisted of an investigation conducted both at the acoustic level, representing the output of all articulatory activity, and at the lingual articulatory level, representing the activity of just one articulatory component as seen in the light of one specific instrumental technique, in this case dynamic palatography. The second part adopted a different perspective, but again based on the suggestion that conflicting views of coarticulatory regularities could be due to the different techniques used. For a complex articulator such as the tongue there is currently no technique that gives a complete assessment of articulation for a wide range of utterances. Thus EPG can only reveal those aspects of lingual activity involving palatal contact, while the ultrasound method of Parush *et al.* (1983) essentially registers vertical movement of a single point on the tongue dorsum. Accordingly, we attempted to address the open question of whether different methods of lingual transduction applied to the same speaker would give comparable results. Thus one subject was re-examined using simultaneous electropalatography and electromagnetic articulography (EMA), the latter technique allowing the investigation of patterns of lingual *movement* as opposed to patterns of linguopalatal *contact*. In addition, the palatographic data of a second subject were compared with a separately conducted EMA investigation.

There are three further issues to which this study can contribute. First of all, there is the issue of cross-language differences in coarticulatory behaviour. Analysis of the relative magnitude of anticipatory and carryover effects, as well as of the overall magnitude of contextually induced effects, provides a succinct means of characterizing such differences. A better knowledge of language-specific aspects of articulatory regularities is, of course, crucial to a better understanding of speech motor control in general, since it should ultimately be possible to separate articulatory regularities dependent on the structure of a given phonological system from those dependent on the more universal neurological and biomechanical constraints of the speech motor system. This is a large issue, to which we will have only a very modest contribution to make, simply because the number of subjects (two per language) precludes generalizations. However, even studies of restricted (cross-language) scope such as this one still help to provide the essential empirical foundation on which more general conclusions can later be based. Two of the languages investigated here (English, French) are common to a recent investigation of lingual coarticulation by Farnetani, Hardcastle, and Marchal (1989), and agreement of results would give mutual reinforcement to the confidence that can be placed in them.

The second topic relates to the question of gestural antagonism as a factor determining the magnitude of coarticulatory effects. On the basis of several investigations, Recasens (1984, 1989, 1991) has developed a model for the spreading of coarticulatory effects. Thus, for example, "the degree of transconsonantal V-to-V coarticulation is related inversely and monotonically to the degree of tongue-dorsum contact, for more palatal-like *vs.* more alveolar-like consonants" (Recasens, 1989, p. 294). However, these well-documented regularities in terms of place and closeness of constriction may well need supplementing by separate consideration of the influence of manner of articulation. Recasens (1989) refers to this possibility in comparing the behaviour of /ʃ/ and /t/. Other work on coarticulatory resistance (e.g., Bladon and Nolan, 1977) has shown that the fricative /s/ is very resistant to coarticulation. It is thus conceivable that the constraints of fricative production on tongue dorsum positioning could make the more alveolar /s/ just as resistant to coarticulatory effects as the more palatal /ʃ/.

Thirdly, and finally, virtually nothing is known about the extent to which speakers' articulatory strategies are stable over time. The speakers re-examined in Part II provided some relevant data.

In conclusion, it should be pointed out that there is a shift in emphasis in this study, compared with most of the studies of coarticulation cited above. The aim is less to throw light on the nature of coarticulation itself; rather, we take coarticulation as given, viewing it as the expression of the temporal organisation of speech. We then attempt to capture coarticulatory regularities in a single measure (specifically the relative magnitude of carryover and anticipatory effects) and use this measure as an index of the extent to which a comparable picture of the temporal organisation emerges at different levels of the speech production system. In order to be able to apply this approach to a reasonably large number of subjects (six) and vowel contexts (nine), we use rather global articulatory and acoustic measures of coarticulation. An equally valid but complementary approach would be to look in detail at the acoustic and articulatory expression of coarticulation in just one or two speakers in a very restricted range of vowel contexts.

## PART I: ELECTROPALATOGRAPHIC AND ACOUSTIC INVESTIGATION

### *Methods*

*Materials.* The fricatives /s/ and /ʃ/ were uttered in nonsense words of the form V1CV2, V1 and V2 being all combinations of /i/, /u/, and /a/. These VCV sequences were spoken with as nearly equal stress on the two syllables as was compatible with the accentuation patterns of the different languages. Thus English and German had stress on the first syllable but an unreduced vowel in the second syllable, with the exception that in the English corpus /a/ in V2-position was replaced by a schwa, as in the suffix "er". French has stronger stress on the second syllable but an unreduced first syllable, as in words such as "cassa" uttered phrase-finally. It should also be pointed out that German /s/ in syllable-initial position, as here, is voiced in standard pronunciation, but devoices freely, especially in the south; our two speakers tended on the whole towards a partly voiced variant. The words were spoken in isolation five times (seven times for one German speaker) in randomized order, together with other material not relevant here. Two speakers each of English (ENG1: male, age 48, from Australia but resident for many years in the UK; ENG2: female, age 35, from Southern England), French (FRE1 and FRE2: both female, aged 25–30 and from South-Eastern France), and German (GER1: male, age 38, from Southern Germany; GER2: male, age

55, from the Rhineland) were analyzed. All speakers spoke standard forms of the language with slight regional influence.

The recordings were made at the University of Reading, the EPG signal being sampled at 200 Hz, and the audio signal at 20 kHz (microphone Sennheiser MKH40).

*Analysis procedures.* A waveform editor was used to locate the onset and offset of frication in the consonants. Acoustic analysis was then performed over a frame centered at the mid-point of the noise portion. An FFT was made of this frame (512 point Hamming window), and the spectral values were collapsed into 1 Bark wide bins. The spectral information below 8 Bark was ignored in the subsequent stages. On the one hand, this choice of cutoff frequency is high enough to help eliminate analysis problems that might be caused by low-frequency energy from residual voicing, as in the German /s/. On the other hand, it is low enough to retain information from spectral peaks related to the second formant of the flanking vowels, which have been shown to be consistently present as long as the constriction is not so close as to completely decouple the rear cavity (*cf.* Soli, 1981; McGowan and Nittrouer, 1988). Over the remaining critical bands (from eight to 22) the spectral centre of gravity and the spectral dispersion were then calculated, corresponding to the mean and the standard deviation of the spectra considered as probability density functions. Parameters based on spectral moments have proved to distinguish fricatives very reliably (*cf.* Tomiak, 1990; Forrest, Weismer, Milenkovic and Dougall, 1988). The centre of gravity and dispersion measures have the advantage that they do not require hand-picking and labelling of specific peaks in the spectrum. However, used on their own they may give rather misleading results if multiple well-defined peaks do indeed exist in the spectrum. They are thus usually supplemented by additional measures. For example, Tomiak (1990) also calculated higher order spectral moments (skewness, kurtosis). The approach followed here was to recalculate centre of gravity and dispersion after (a) boosting the high-frequency end of the 8–22 Bark range by 2 dB/Bark (roughly 6 dB/octave), and (b) boosting the low-frequency end of this range by the same amount. The effect of these manipulations can be considered in the high-frequency case as emphasizing the spectral region in which the main concentration of energy for /s/ is to be expected, and in the low-frequency case of emphasizing the region in which residual second-formant information is to be expected. We thus model the spectral shape by means of a total of six parameters (three pairs of centre of gravity and dispersion values).

The initial stage in the EPG analysis involved extraction of the frame corresponding to the spectral analysis at the centre of the frication. The EPG contact pattern of eight rows (front–back) and eight columns (lateral–medial) was then converted to a vector of eight values by summing the number of contacts per row.

## Results

The results will be presented in two main sections: first an overall consideration of the articulatory and acoustic characteristics of the two fricatives, and secondly a detailed consideration of coarticulatory effects.

*Overview of the fricatives.* In Figure 1 profiles of tongue contact for /s/ and /ʃ/, based

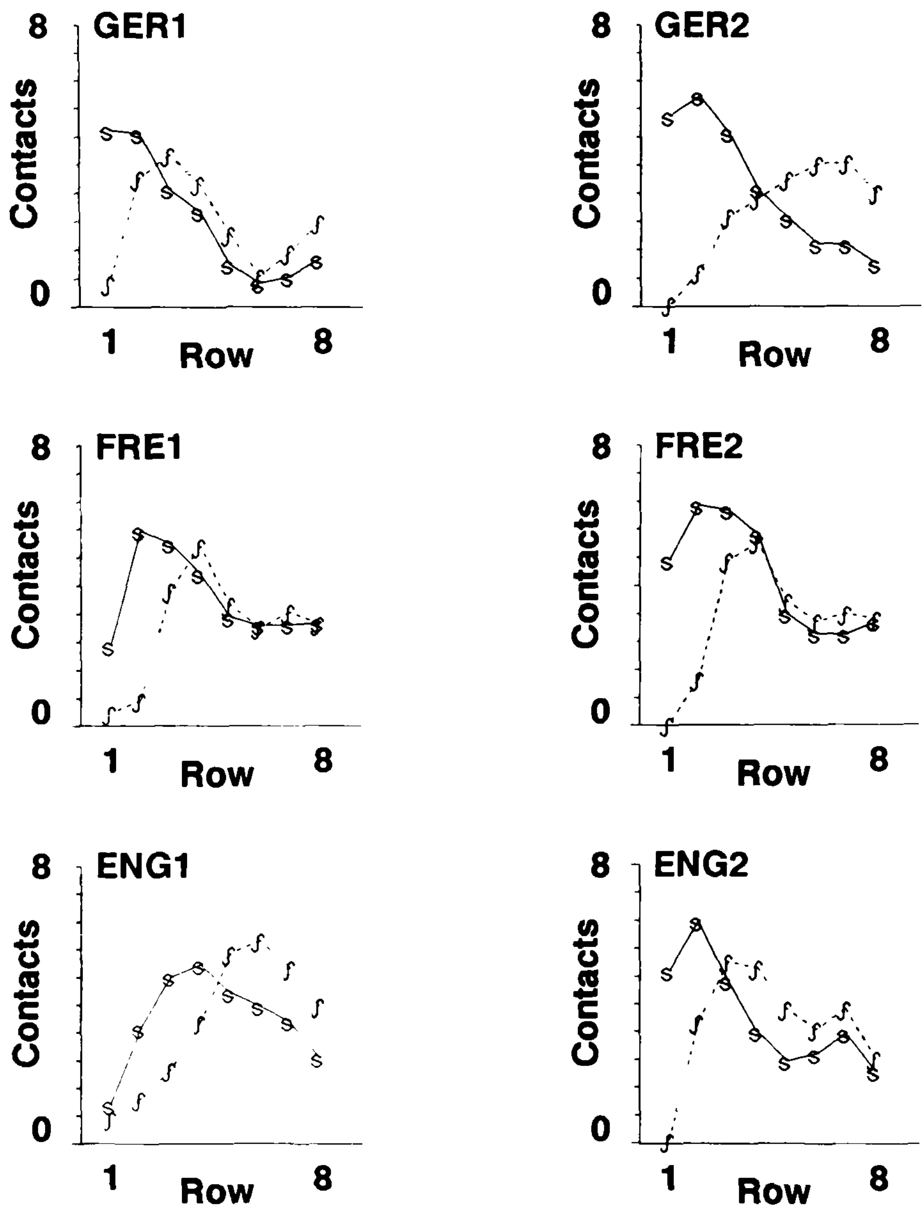


Fig. 1. Average linguopalatal contact per row at the acoustic midpoints of the fricatives /s/ (solid lines) and /ʃ/ (dashed lines) for the six speakers (row 1 at front; row 8 at back).

on the sums per row and averaged over all repetitions and vowel contexts, are given for each speaker (N = 45, except for speaker GER2 where N = 63). The location of the maximum contact for /s/ is in one of the front two rows in every case except for ENG1, where it is in row 4. For /ʃ/ the row with most constriction varies more widely, from Row 3 (GER1, ENG2) to Row 7 (GER2). Consequently, the details of the /s/–/ʃ/ contrast are rather different over the speakers. Nonetheless, all speakers show overall more contact in the back 4 rows for /ʃ/ than for /s/, although the effect is not very striking for the two French speakers. This was confirmed by performing three-way ANOVAs (two fricatives X three first vowels X three second vowels) separately for each speaker and EPG row. For all speakers and all rows the main effect of consonant was significant at the 1% level except in the following cases: FRE1, Rows 6 and 8 both not significant; FRE2 rows 4 and 8 both not significant; GER2, row 4 only significant at the 5% level.

Turning now to the acoustic measurements, Figure 2 shows results for four of the six parameters used to model the spectral shape. At the top are the means and standard deviations for each speaker and fricative for the centre of gravity (left) and dispersion (right) in the high-frequency emphasis condition. At the bottom are the corresponding centre of gravity and dispersion values with low-frequency emphasis. The general picture is completely consistent over all subjects. With regard to the high frequency emphasis parameters all subjects not surprisingly have a higher centre of gravity and lower dispersion for /s/ than for /ʃ/, reflecting a well-defined concentration of high-frequency energy related to the shorter front cavity in /s/. For the low emphasis parameters precisely the opposite pattern obtains, with lower centre of gravity and greater dispersion for /s/. This consistent result probably has two reasons: On the one hand, /ʃ/ has the major concentration of energy in the mid-frequency region, but still close enough to the low-frequency region to drag up the frequency of the low-emphasis centre of gravity. On the other hand, it has been found elsewhere (Soli, 1981; McGowan and Nittrouer, 1988) that the spectral peaks related to the second formant are lower in frequency for /s/ than for /ʃ/. Finally, the low-frequency emphasis results in a much flatter spectrum for /s/, increasing the dispersion.

The parameters with no frequency weighting are not shown here as they are largely redundant, at least in terms of a distinction between /s/ and /ʃ/: For all subjects centre of gravity and dispersion were both higher for /s/.

While the general trends are very clear, there are some notable features in individual speakers that require comment. Firstly, it was seen in the EPG data that ENG1 has a very retracted EPG pattern for /s/. Accordingly, in the acoustic data the high-emphasis centre of gravity is lowered (and the low-emphasis one is raised). However, the acoustic separation of the two fricatives remains quite clear-cut in the high-emphasis condition. In contrast, the two French speakers are noteworthy because the acoustic separation between /s/ and /ʃ/ is surprisingly unclear for every parameter in Figure 2, either because the respective means are close together or because the standard deviations are comparatively large. As with the EPG data, separate three-way ANOVAs were carried out for each of the six spectral parameters. The French speakers provided the only instances where the main effect of fricative did not reach the 1% level of significance,

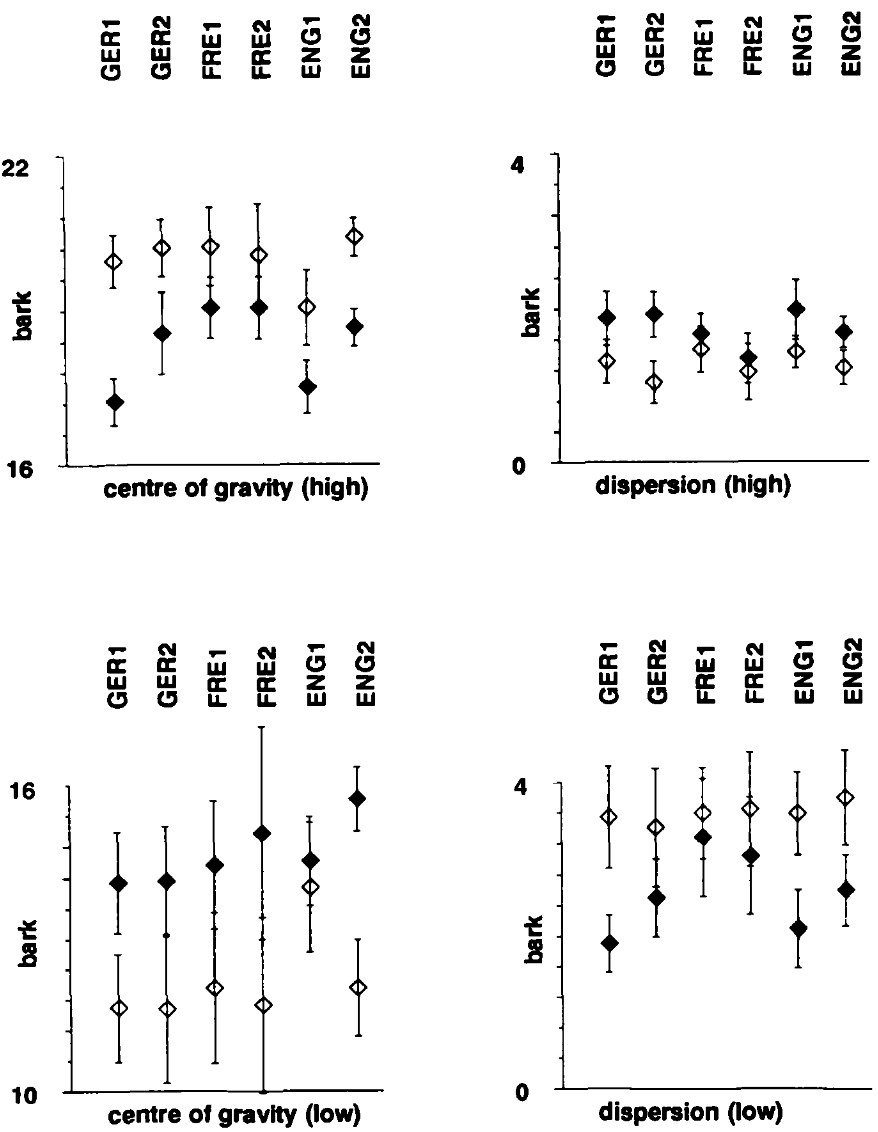


Fig. 2. Mean values and standard deviations of spectral parameters at the acoustic midpoints of /s/ (empty diamonds) and /ʃ/ (filled diamonds) for each speaker. Top: High-frequency emphasized spectral centre of gravity and dispersion (in Bark). Bottom: Low-frequency emphasized spectral centre of gravity and dispersion (in Bark).

namely for low-frequency dispersion in FRE1 and high-frequency dispersion in FRE2. There is thus a certain degree of parallelism between the acoustic and EPG results for these two speakers; nonetheless, it still remains a little difficult to reconcile the acoustic findings with the palatographic patterns in Figure 1. At front locations on the palate the French speakers do not appear atypical. At the rear four rows, they do, as noted above, show less difference between /s/ and /ʃ/ than the other speakers. This seems mainly due to a particularly large amount of contact for /s/. This could be consistent with Dart's (1991) conclusion from a comparative palatographic, linguagraphic, and acoustic study of English and French alveolars and dentals that for /s/ there is a stronger tendency to find a high tongue-body position behind the major constriction in French than in English. Unfortunately, our acoustic data suggest that /ʃ/ approaches /s/, rather than the other way round.

Contrasting with the French speakers is GER2, the final subject to be commented on briefly here. This was the subject showing a very retracted /ʃ/ configuration, and who accordingly has the largest articulatory distance between the two fricatives. This is not reflected in an obvious way in the acoustic parameters. With the exception of the high-emphasis dispersion parameter, the distinction is not more pronounced than in the other speakers.[1]

*Analysis of coarticulatory effects.* In this section EPG and acoustic results will be presented in parallel, as far as possible, with the focus on the relative magnitudes of anticipatory and carryover effects.

In view of the range of different levels at which coarticulatory effects were to be assessed, it seemed important to use a measure that could be applied in a homogeneous fashion to the different levels. The coarticulation index devised by Farnetani (1990) seemed a promising candidate. It can essentially be regarded as a distance measure and, while originally developed for use with EPG data, it can thus be applied in a simple way to acoustic data as well (and also to EMA data, see Part II). It consists of a series of comparisons between patterns derived from different contexts, in our case between pairs of symmetric and asymmetric VCV contexts. The symmetric context serves as a baseline against which an anticipatory or carryover effect can be measured. Thus, by way of example, the difference between the palatal patterns at the midpoint of the fricative noises in the sequences /isa/ and /isi/ can be regarded as the anticipatory influence of /a/ on /s/ in the context of /i/, or that between /usa/ and /asa/ as the

[1] The most promising avenues towards resolution of problems of this kind, as well as for interpreting the unexpectedly wide range of constriction locations for /ʃ/, are firstly more complete articulatory data (combination with EMA will be treated in Part II) and secondly taking into account the three-dimensional nature of the palatal anatomy of the speakers. While this should considerably enhance our understanding of the relationship between individual palatal patterns and the related acoustic results, it should be noted that the analyses to be presented in the next section should be more independent of such considerations, since they are based on a series of *within*-parameter comparisons.

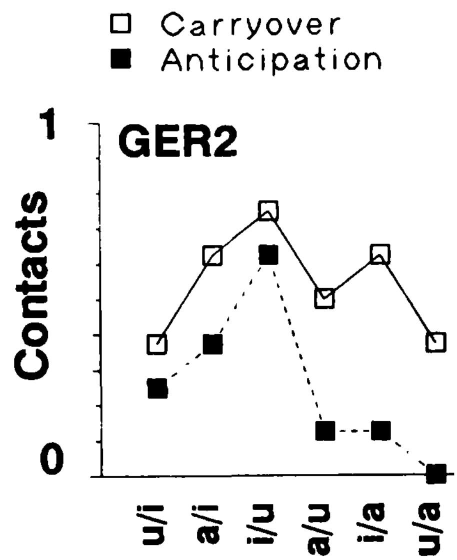


Fig. 3. Carryover (empty squares, solid line) and anticipatory (filled squares, dashed line) coarticulatory vowel influences on the palatal contact patterns of /ʃ/ for speaker GER2. The labels on the abscissa, e.g., u/i, should be read "coarticulatory effect of /u/ in the context of /i/", etc. See text for further explanation.

carryover effect of /u/ on /s/ in the context of /a/. In the present experiment the stages, in detail, were, firstly, to compute the number of contacts in each of the eight rows for each item. Regarding the eight row totals as eight parameters, the medians for each of the eight parameters were, secondly, calculated over the five repetitions of each VCV combination. The absolute difference between two VCV items was then calculated separately in each row, and the difference was finally averaged over the eight rows. With the three vowels in the corpus (all combinations of V1 and V2) a total of six "carryover" and six "anticipatory" comparisons can be made (i.e., /i/ in the context of /u/, /i/ in the context of /a/, /u/ in the context of /i/, /u/ in the context of /a/, /a/ in the context of /i/, and /a/ in the context of /u/).

In the present study the index will be applied at the mid-point of the frication since at this location a comparison with the acoustic analysis is most straightforward.

By way of example, in Figure 3 the result of a complete set of comparisons of this kind is represented graphically for the EPG data for /ʃ/ of subject GER2. The six carryover comparisons are joined by a solid line and the corresponding anticipatory comparisons by a dashed line. In this particular case the magnitude of the effects in both directions varies over quite a wide range, yet for any given comparison of the effect of one vowel on another the carryover effect is always larger. The scaling of this figure

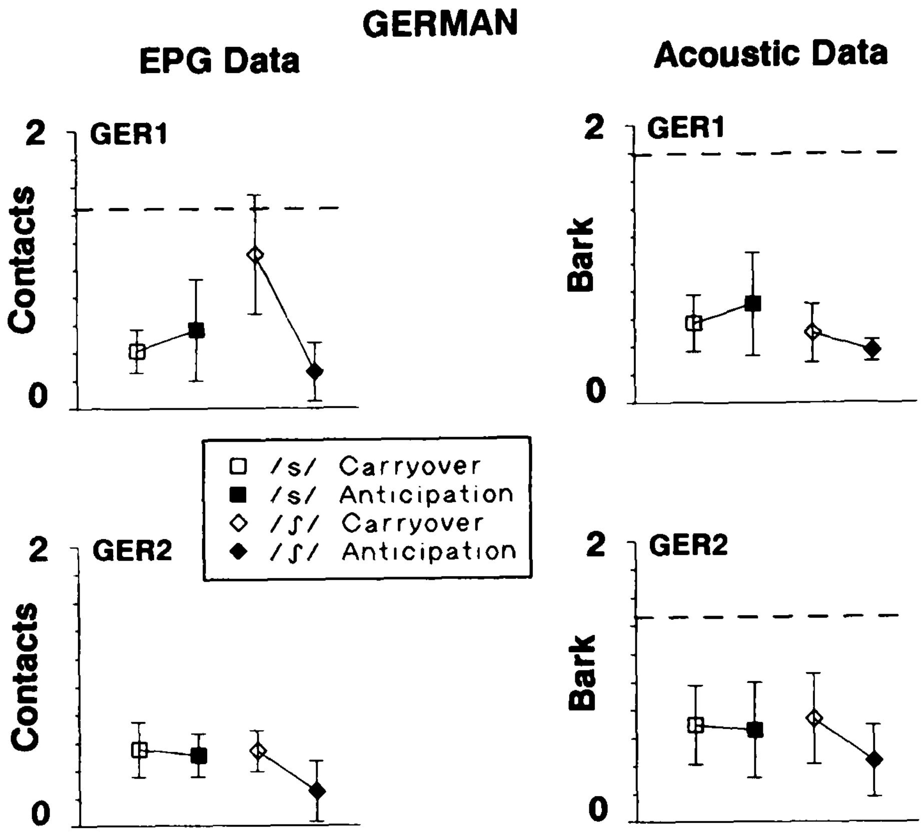


Fig. 4. Averaged coarticulatory indices with standard deviations of EPG and acoustic data for /s/ and /ʃ/ for the two speakers of German. Effects shown in each panel are (from left to right): carryover /s/ (empty squares); anticipation /s/ (filled squares); carryover /ʃ/ (empty diamonds); anticipation /ʃ/ (filled diamonds). The horizontal dashed lines indicate the magnitude of the difference between /s/ and /ʃ/ (the line for EPG data of GER2 is not shown: It would be located at 2.64). Precise values are given in Table 2 (p. 249).

is such that for a particular comparison a value of 1.0 would mean an average difference of one contact in all eight rows. Since the values are here all less than 1.0, it is more illuminating to say that a value of 0.5 means that the two EPG patterns involved in a comparison differ at four electrode locations (= eight rows X 0.5) on the average.

In order to give a better appreciation of overall trends, however, the results will now be presented for each subject individually by averaging over all six comparisons in each direction, giving an overall value for each coarticulation direction and each fricative. In other words, the data fot GER2's /ʃ/ in Figure 3 can be reduced to two values, one for each coarticulatory direction. Repeating this for /s/ gives two more values.

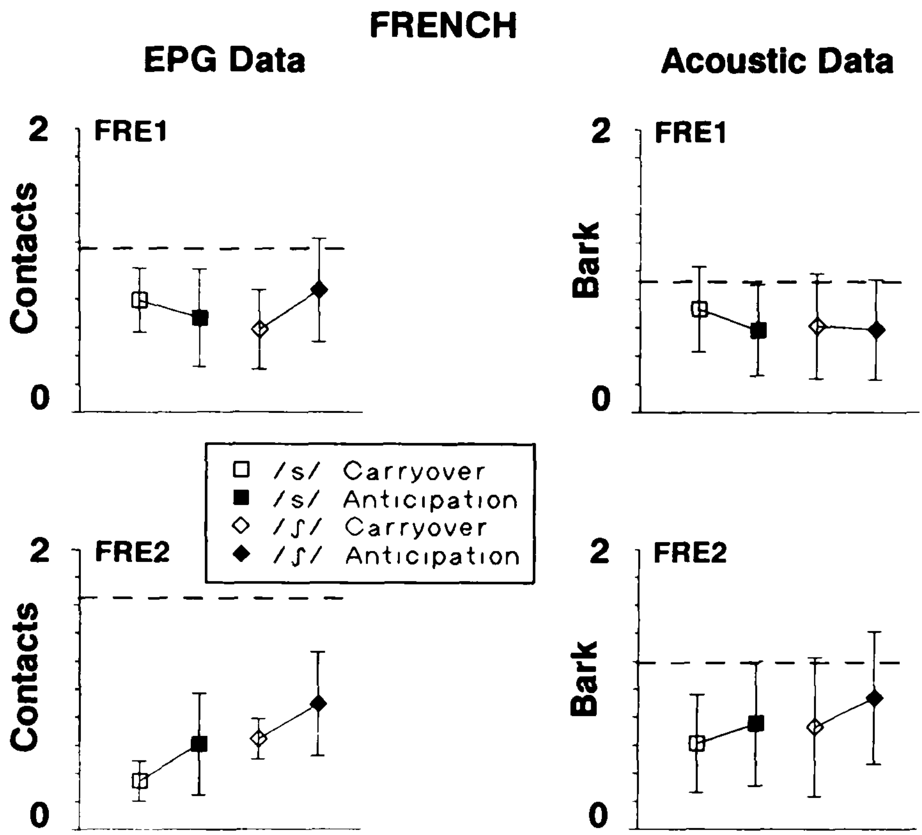


Fig. 5. Coarticulatory indices for the two French speakers. Arrangement of the data as in Figure 4.

The EPG results derived in this way are presented in Figures 4, 5, and 6 for German, French, and English, respectively, each individual panel in the figures thus consisting of four values. In the same figures the results of a comparable analysis of the acoustic data are presented in parallel. Specifically, the acoustic comparisons were made by considering the set of three centre of gravity and dispersion pairs as a vector of six values (all in Bark) and then (as with the EPG Row vector) computing the average of the absolute differences between the members of the vector in pairs of VCV conditions (as with the EPG data, medians for each VCV condition were computed first).

At this point, it should be recalled that coarticulatory lip-rounding from flanking /u/-vowels is, of course, a major element in the spectral contrasts for which no corresponding articulatory information is available here. However, as discussed in the introduction, the intention of this study was to examine overall coarticulatory effects at different component levels of the speech production process, accepting that the relationships at any given level are only a small part of the total picture.

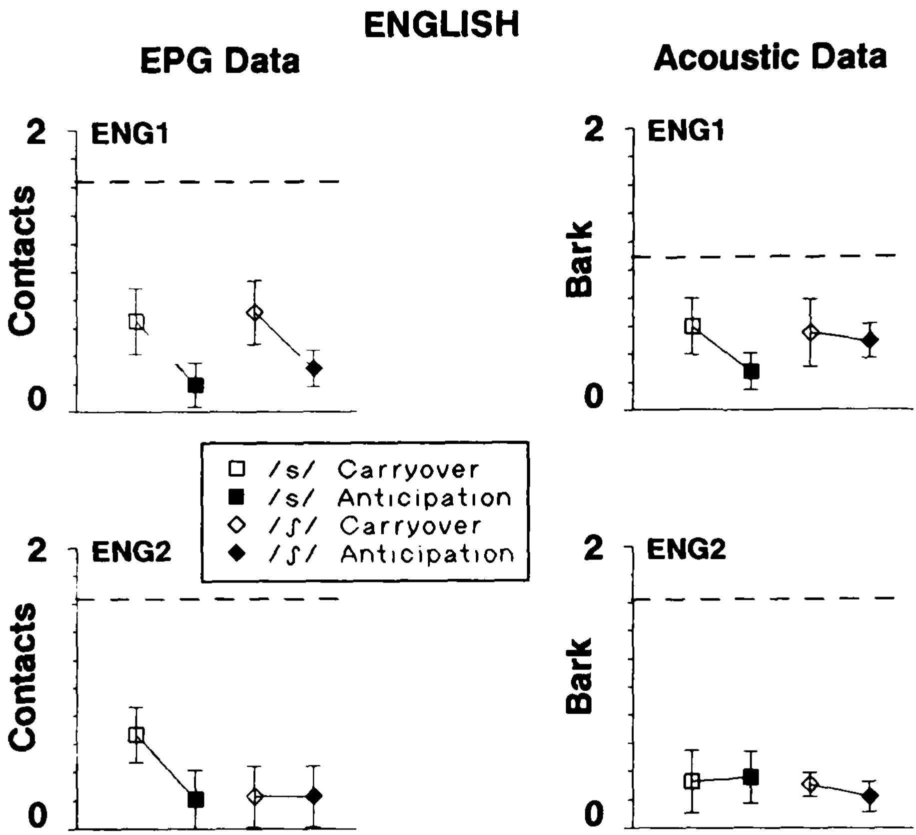


Fig. 6. Coarticulatory indices for the two English speakers. Arrangement of the data as in Figure 4.

Regarding the interpretation of Figures 4–6 it should be pointed out that the standard deviations displayed tend to lead one to underestimate the possible robustness of differences between carryover and anticipatory effects, since a consistent difference between the two directions was often associated with wide variation in the absolute magnitude of the coarticulatory effects. This can perhaps be better appreciated by comparing the full information in Figure 3 with the corresponding "reduced" version of GER2's EPG data in Figure 4. A summary of statistical testing of the relationships shown in Figures 4–6 is given in Table 1: For each panel in the figures, i.e., each subject and measurement technique, a two-by-two ANOVA was run (two consonants X two directions of coarticulation) with repeated measurements on direction of coarticulation. The simple effects of direction were tested separately for each fricative using paired $t$-tests and cross-checked using the nonparametric Wilcoxon test in view of the small value of n (*cf.* the paired arrangement of the anticipatory and carryover effects in Fig. 3).

TABLE 1

Summary of significant effects at $p < 0.05$ (*) and $p < 0.01$ (**); EPG results on left, acoustic results on right. The columns correspond (from left to right) to main effect of Direction of Coarticulation (DIR), main effect of Consonant (CONS), Consonant by Direction interaction (CONS by DIR), simple effects of Direction of Coarticulation separately for /s/ and /ʃ/

| | EPG | | | | | ACOUSTICS | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | DIR | CONS | CONS by DIR | s | ʃ | DIR | CONS | CONS by DIR | s | ʃ |
| GER1 | * | | * | | * | | | | | |
| GER2 | * | | | | * | | | | | * |
| FRE1 | | | * | | | | | | | |
| FRE2 | * | * | | | | | | | | |
| ENG1 | ** | | | * | * | ** | | | * | |
| ENG2 | * | * | * | * | | | | | | |

It transpired that there are no drastic differences in the magnitude of the coarticulatory effects for the different subjects, so the articulatory and acoustic results could be plotted with the same scaling for all subjects. However, as an additional aid to interpretation, the magnitude of the distance between /s/ and /ʃ/ is indicated by a horizontal dashed line across the figure for each subject. The distance was calculated in exactly the same way as the actual coarticulatory comparisons, with the exception that the average /s/ configuration was compared with the average /ʃ/ configuration (effectively the data in Figs. 1 and 2) rather than one asymmetric VCV context with a symmetric one. This enables the sub-phonemic comparisons forming the substance of the figure to be related to the (presumably) nearest phonemic distinction and should thus facilitate comparisons across subjects and also permit comparison of the magnitude of the articulatory and acoustic effects within subjects (see Maeda, 1991, for a recent more formal proposal for comparing magnitude of variability in the acoustic and articulatory domains).

The precise figures for the /s/–/ʃ/ distance are given in Table 2. The values given in the table reflect the discussion above of the overall magnitude of the /s/–/ʃ/ distinction in articulation and acoustics. Thus GER2 has far and away the greatest EPG distance, while FRE1 has the lowest distances for both EPG and acoustics.

TABLE 2

Indices for the phonemic /s/–/ʃ/ distinction with respect to acoustic and electropalatographic parameters for the six speakers

| | EPG (contacts/row) | ACOUSTICS (Bark) |
|---|---|---|
| GER1 | 1.45 | 1.80 |
| GER2 | 2.64 | 1.47 |
| FRE1 | 1.16 | 0.93 |
| FRE2 | 1.66 | 1.20 |
| ENG1 | 1.65 | 1.10 |
| ENG2 | 1.65 | 1.63 |

Regarding the more global aspects, there are in both articulation and acoustics no consistent differences in the magnitude of the coarticulatory effects between /s/ and /ʃ/. In only two cases was the main effect of consonant significant (EPG data for FRE2 and ENG2), and in the case of ENG2 the situation is rendered less clear-cut by a significant consonant by direction interaction. As for the subjects, while broadly comparable in the magnitude of their effects, there are some differences between them, particularly in relation to the "phonemic" metric. In the EPG data, speaker GER2's coarticulatory effects are very small in relation to the /s/–/ʃ/ distance while speaker FRE1's are large. In the acoustics, both French speakers show coarticulatory effects that approach the magnitude of the /s/–/ʃ/ distance, while the opposite extreme in this case is represented by ENG2. Comparing the magnitudes of the articulatory and the acoustic effects across speakers in relation to the phonemic metric, no common pattern emerges. GER1 has greater magnitude of coarticulatory effects in the EPG data, FRE1 and ENG2 have comparable magnitude in EPG and acoustics, while GER2, FRE2, and ENG1 have greater magnitude in the acoustics.

Turning to the more detailed aspects of the pattern within each speaker, and looking first at the articulatory data, we can identify three speakers with a preferred coarticulatory direction common to both fricatives, namely ENG1 and GER2 (carryover) and FRE2 (anticipation). The preference is strongest in ENG1, who is the only subject in whom the main effect of direction is significant at $p < 0.01$. In the other three subjects no clear preference emerges; unexpectedly, in fact, they all show a significant consonant by direction interaction. This is particularly notable for GER1, with predominance of anticipation on /s/ and very clear predominance of carryover on /ʃ/, while FRE1 shows the reverse pattern, albeit less obviously.

With regard to the acoustic data the first point to make is that, compared with the articulatory data, far fewer effects reach significance. This could indicate that articulatory adjustments posterior to the main constriction are having only a relatively weak effect on the acoustic output. For three subjects (GER2, FRE2, and ENG1) the overall *pattern* of the acoustics certainly follows that of the EPG results closely, the relationships simply being less clear-cut. For GER1 the pattern is also broadly the same, but the very large articulatory carryover effect on /ʃ/ is much less obvious acoustically. On the other hand, for the remaining two subjects, FRE1 and ENG2, a trend in the articulatory data (e.g., greater, though non-significant anticipation for /ʃ/ in FRE1's EPG data) is actually absent in the acoustic data. For ENG2, the acoustic effects are overall very small, so that the clear articulatory effect for her /s/-productions (predominance of carryover) simply does not have any correspondingly clear acoustic manifestation. This is thus a similar situation to GER1's /ʃ/-productions.

## PART II: COMPARATIVE ELECTROMAGNETIC INVESTIGATION

In this section, EMA data will be presented for two subjects, GER2 and ENG2. As discussed in the Introduction, these investigations continue the theme underlying Part I of tapping into the speech production process at different levels. Since EMA and EPG give rather different pictures of lingual activity, it is of interest to compare these different representations of the same speech phenomena.

In addition, it should be noted that EMA allows many further comparisons between coarticulatory regularities at different levels of the speech production system, e.g., lingual *vs.* mandibular coarticulation, an issue about which currently very little is known, and which we will not be able to pursue further here (but see Kühnert, Ledl, Hoole, and Tillmann, 1991, in which the relationship between coarticulation and compensatory articulation proposed by Edwards, 1985, is followed up for three speakers of German using EMA data on tongue and jaw movement).

A further motivation for the present comparison of EMA and EPG data was more methodological in nature, forming part of our ongoing efforts to assess the utility of EMA in articulatory research. (For a general discussion of design considerations in electromagnetic systems see Perkell and Cohen, 1986.) In the electromagnetic system at our disposal (AG100, Carstens Medizinelektronik, Göttingen) we have made a number of essential modifications to the distributed software to allow more precise calibration and more effective identification of unreliable data. This is the subject of a separate report currently in preparation. Our own bench tests indicate the absolute accuracy attainable to be of the order of 0.3 to 0.5 mm (for further tests of the same system see Schönle, Müller, and Wenig, 1989; Tuller, Shao, and Kelso, 1990). However, despite these enhancements, it would still be extremely desirable to compare, for example, data derived from three positions on the tongue using EMA and some alternative technique simultaneously. In practice it is not obvious how this might be achieved.

Given this situation, we considered that even a more indirect comparison of EMA with an additional technique could prove beneficial. As mentioned above, EMA and EPG clearly do not give an identical picture of lingual articulation. On the other hand, for the sounds forming the substance of this paper, which involve a close constriction in the front part of the mouth, it would be rather disturbing if the two techniques did not give a similar picture of phonetic regularities, such as the relative strength of anticipatory and carryover coarticulation.

*Methods*

The procedures followed for the two subjects will now be outlined separately, as there were some substantial differences.

*Subject GER2.* For this German subject, the EMA data were recorded separately from the EPG data. The fricatives analyzed here come from a more extensive recording with a corpus similar to that used in the EPG recordings of Part I. In contrast to the EPG data for this subject, the EMA recording was made with a carrier phrase 'Ich sage bV1CV2 bitte'. The EMA movement transduction system was used to monitor the position of three coils attached to the midline of the tongue, ranging from roughly 1 to 5 cm from the tip. One coil was attached to the lower incisors (= 'jaw' coil) and one was attached to the upper incisors as reference. The articulatory data were recorded at a sample rate of 193.5 Hz. Synchronized audio data were also recorded and were used for identification of fricative segments; however, as the sample rate available at the time of this recording was rather low, no acoustic analysis of the fricatives was carried out. Four repetitions of the material were completed.

*Subject ENG2.* In this recording we employed EMA and EPG simultaneously for the first time. A previous pilot recording with a different subject had not revealed noticeable electromagnetic interference between the two pieces of equipment. The present subject was highly experienced in the use of the artificial palate and was thus considered particularly suitable for a first experiment of this kind in which admittedly a considerable amount of paraphernalia in the oral region had to be contended with. Possible remaining disturbance of articulation will be discussed further below. The receiver coils were applied in essentially the same way as for the first subject, with three on the tongue and one on the lower incisors. However, the reference coil was applied to the bridge of the nose. The articulatory data (EMA and EPG) were sampled at 200 Hz. The audio data were recorded on DAT tape and then digitially transferred to a laboratory computer and down-sampled to 16 kHz. The software controlling the EMA system generated a synchronization signal that was recorded on the second channel of the DAT tape as well as being connected to one of the four A/D input channels included in the EPG unit (Reading EPG system). After completion of the experiment this synchronization information was used to align the data on a laboratory computer.

The subject recorded five repetitions of a corpus consisting of words of the form bV1CV2 with V1, V2, and C as in the corpus used in Part I (plus a small amount of additional material). The words were spoken in a carrier phrase 'It's a ____ please'.

*Pre-processing of the EMA data.* The EMA data were smoothed by low-pass filtering at 40 Hz. The position of the reference coil was subtracted from that of the other coils to compensate for slight shifts in the position of the helmet to which the transmitter coils were attached. In addition, the data for ENG2 were normalized by locating the origin of the system of coordinates at the average jaw position in each block of repetitions. (For comparative purposes, in Fig. 7 below the data of GER2 are also plotted relative to his average jaw position.) The articulatory data for both subjects were also rotated within the two-dimensional coordinate system in such a way that the first principal component extracted from a principal component analysis of the jaw movement data was oriented in a vertical direction (*cf.* Edwards, 1985). Inspection of a set of control tasks embedded in the experimental session (e.g., adoption of a reproducible neutral articulatory position for several seconds) indicated in the last repetition that the rear coil for GER2 and the front coil for ENG2 were behaving erratically (probably coming loose), so these data were excluded from further analysis.[2]

*Results*

Analogously to the procedure followed in Part I, we first discuss the lingual configuration for /s/ and /ʃ/ in the two speakers and then go on to an analysis of the coarticulatory effects, again using the coarticulatory index procedure. Applied to the EMA data, this means that the difference between two VCV contexts is based on the distance between a given coil in the two different contexts, averaging over the three tongue coils. The EMA results are compared with the relevant EPG and acoustic results.

*Lingual configuration.* Figure 7 shows two-sigma ellipses for /s/ and /ʃ/ at the three tongue locations in the two speakers. Compare these configurations with the respective EPG patterns for these two speakers given in Figure 1. The new synchronously acquired EPG pattern for ENG2 was similar to that seen in the earlier recording (shown in Fig. 1) except that there was less contact at maximum constriction for /s/, there being an average of 4.8 contacts compared with 6.4 in the EPG-only recording (as seen below, the /s/–/ʃ/ contrast was acoustically also somewhat reduced in the combined recording).

Looked at in combination, the EMA and EPG data give a plausible and quite consistent picture of fricative articulation, as far as it is possible to judge without having additional anatomical information. At the front two coils, ENG2 simply shows a slight shift of similar magnitude and direction at both coils when moving from /s/ to /ʃ/. In accordance with this, the EPG pattern for /ʃ/ looks like /s/ shifted backwards. For GER2, however, the front coil shifts considerably more back and up than in ENG2, while the mid coil shifts backwards but only slightly. Thus the extension of the front part of the

---

[2] In the case of speaker ENG2 this identification of unreliable data was supported by a recently completed set of more rigorous procedures involving consideration of the estimated angle of tilt of the receiver coils. (Electromagnetic transduction systems need to compensate for errors caused by inclination of the receiver coils away from the main measurement plane; see Perkell and Cohen, 1986. However, at large angles of tilt the compensation algorithm is less accurate and, in addition, the signal to noise ratio deteriorates.)

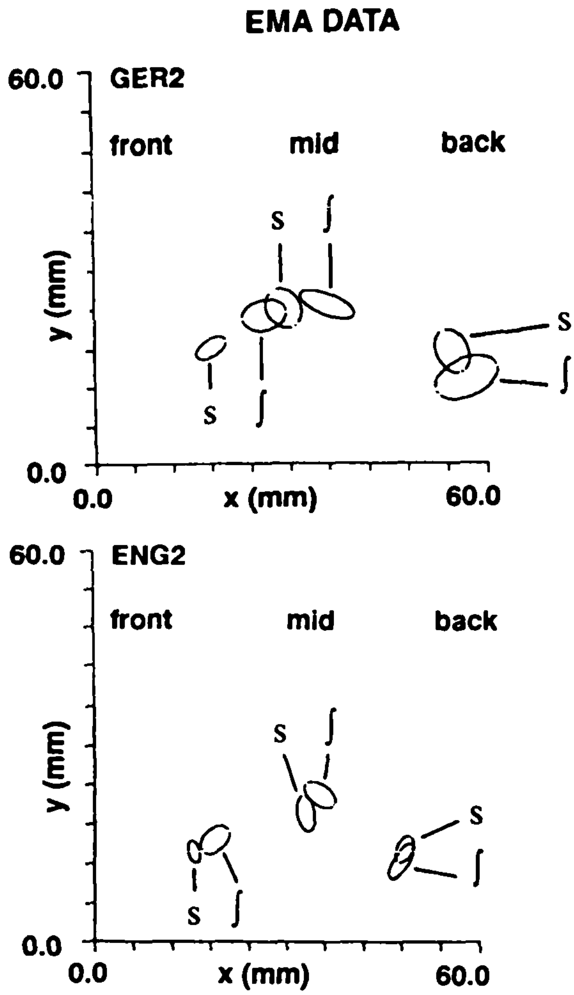


Fig. 7. Two-sigma ranges of variation for three fleshpoints on the tongue transduced by EMA.

tongue changes appreciably going from /s/ to /ʃ/. Correspondingly, in the EPG data this speaker shows a much more sizeable shift rearward than ENG2, accompanied by a change in the overall shape of the contact pattern. It can also be observed that for both speakers /ʃ/ has more contact than /s/ at the rear of the EPG pattern, but shows a lower tongue position than /s/ at the rear EMA coil. Measurements made on the dental impressions of the two speakers indicate that the rearmost EMA coil would in fact have been located roughly below the rearmost row of EPG electrodes. Consequently, the data would be consistent with deep grooving of the /ʃ/ in this location, a fact that has been observed in radiographic studies. The combined techniques presented here thus also confirm Stone's (1991) recent emphasis on the importance of combining sagittal and coronal views of lingual function.

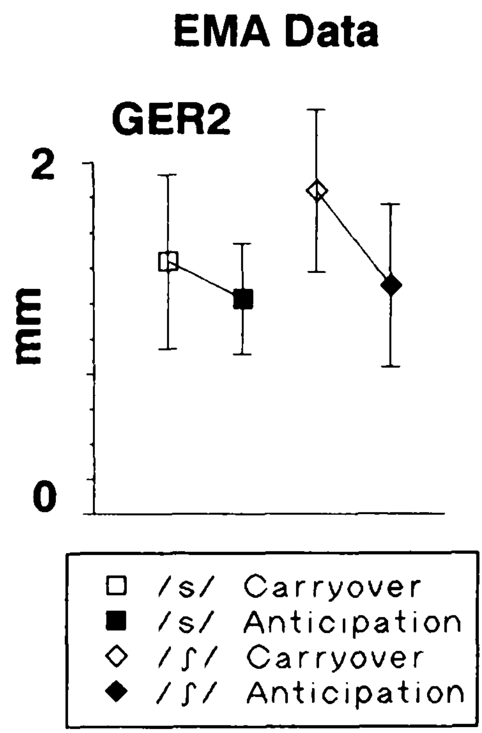


Fig. 8. Coarticulation analysis of lingual EMA data for subject GER2. A horizontal line indicating the /s/–/ʃ/ distance is not shown: It would be located at 4.4 mm. Arrangement of data as in Figure 4 (p. 245).

*Coarticulation analysis.* As in Part I, most of the figures in this section indicate the magnitude of the /s/–/ʃ/ distance in addition to the coarticulatory effects themselves. In the new combined recording for ENG2 the /s/–/ʃ/ distance was reduced compared with the earlier recording. This was particularly true for the acoustics, viz., a decline from 1.63 to 0.88 Bark. For the EPG data there was a somewhat smaller decline from 1.65 to 1.26 contacts. Presumably the acoustic distinctiveness was particularly sensitive to the change in the size of the maximum constriction noted above. In view of these remarks, as well as the above discussion of lingual configuration for the two speakers, it comes as no surprise that the /s/–/ʃ/ distance in the EMA data is substantially larger for GER2, namely 4.4 mm compared with 2.1 mm for ENG2.

The results of the coarticulation analysis for GER2 are given in Figure 8. They show a very weak predominance of carryover articulation for /s/ and a rather clearer predominance of carryover for /ʃ/. Although the effect of coarticulation direction did not reach statistical significance, this corresponds quite closely to the pattern found in the earlier EPG recording (*cf.* Fig. 4), and thus appears to be a consistent feature of the

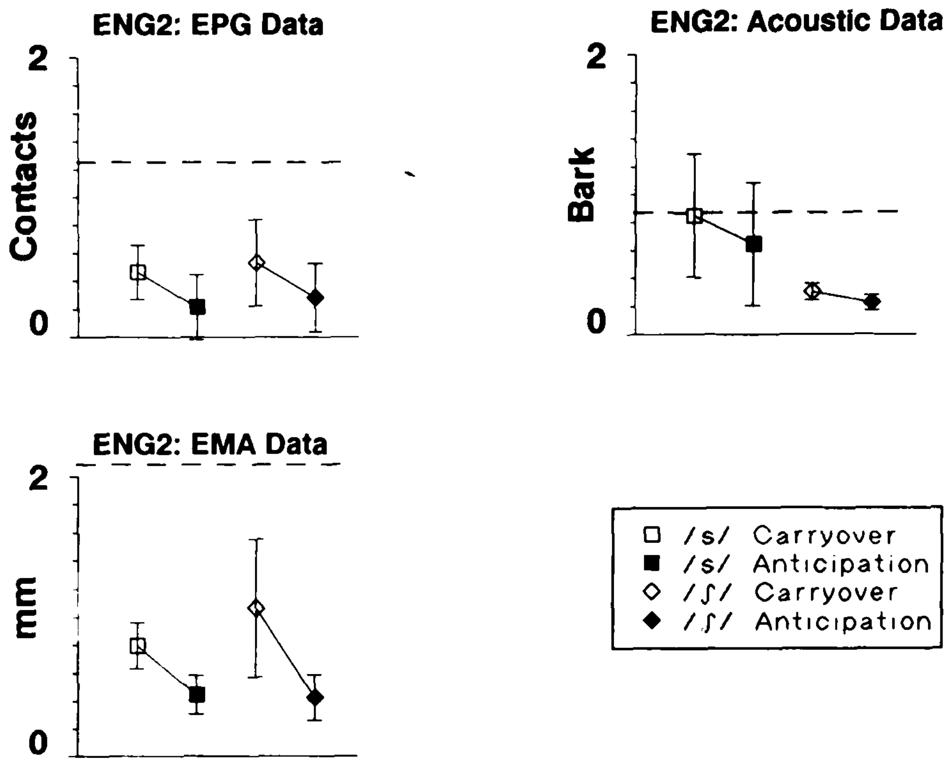


Fig. 9. Coarticulation analysis of synchronously acquired lingual EMA data (bottom left), EPG data (top left) and acoustic data (top right), for subject ENG2. Arrangement of data as in Figure 4.

speaker's behaviour. On the other hand, the overall magnitude of the coarticulatory effects is now somewhat larger for /ʃ/ than for /s/ while in the EPG recording the reverse was the case. (Also, when the magnitude of the coarticulatory effects is related to the size of the /s/–/ʃ/ distance, the effects appear larger overall in the EMA than in the EPG recording, possibly due to a less deliberate style of delivery related to use of carrier phrase in the EMA recording.)

Turning to ENG2, we first compare the synchronously acquired EMA, EPG, and acoustic data. This is done in Figure 9. First of all it will be noticed that the EMA and EPG data parallel each other very closely indeed. Statistical analysis was complicated by the fact that one vowel context with /ʃ/ was unfortunately omitted from the corpus, so that while the effect of coarticulation direction was significant for /s/ in both the EMA and EPG data, it just missed reaching significance for /ʃ/. A further similarity between the EMA and EPG data was that the absolute magnitudes of the coarticulatory effects obtained with the two techniques also appear very similar when seen relative to the /s/–/ʃ/ distance indicated in Figure 9. The acoustic data parallel the articulatory data at least as far as the predominant coarticulatory direction is concerned; however, the effect of direction was not actually significant. Moreover, there is some discrepancy in the magnitude of the effects, since the acoustic effects for /ʃ/ were significantly smaller than for /s/, which was certainly not the case in the articulatory data. Comparison with the earlier EPG and acoustic results (*cf.* Fig. 6) gives a rather confusing picture. For /s/ the earlier weak and rather puzzling predominance of anticipation in the acoustics has changed to a weak predominance of carryover, while the clear predominance of carryover in the EPG data is common to both sessions. /ʃ/ shows exactly the reverse picture. The acoustic relationships are very similar in the two recordings (weak predominance of carryover), while the EPG results have changed from no predominant coarticulation direction in the earlier recording to fairly clear carryover predominance in the later one. It is unclear what could be responsible for these differences. Speaker ENG2's fricatives were shorter in the newer recording, averaging 144 msec compared with 189 msec in the earlier one. (Speaker GER2 had almost identical values in both: 145 msec and 147 msec respectively.) It may be that clear coarticulation effects tend to disappear at the midpoint of very long consonants.

## DISCUSSION

The simplest pattern of results that could be expected from Part I was that each speaker would show a well-defined coarticulatory strategy that was equally apparent in both fricatives and in both the articulatory and acoustic domains. Only three of the six speakers showed such straightforward patterns. Such a large proportion of less easily characterized patterns can be seen as one of the main points of interest of these results.

The departure from the simple pattern took two forms. One subject (GER1) favoured different coarticulatory directions on the different fricatives. This result was not anticipated. In a preliminary EMA study of most of the German consonants (Hoole, Gfroerer, and Tillmann, 1990) we did find some evidence that non-lingual consonants have much more obvious anticipatory effects than lingual ones, presumably because the tongue is then simply much freer to anticipate upcoming vowel articulations. However, it was unexpected to find such differences between the two quite closely related articulations examined here. Clearly, behaviour of this kind will cut across attempts to make language-specific generalisations about coarticulation. We return to this issue briefly below.

The second 'deviant' pattern occurred where there was a mismatch between articulatory and acoustic results. This could indicate that some lingual adjustments have no very salient acoustic consequences, or that the time-course of events for other articulators such as the lips is different from that of the tongue. These represent cases that would benefit from investigation with separate more detailed techniques designed to look at the precise nature of the correlation between articulation and acoustics. Such an approach is exemplified in a study by Nguyen-Trong, Hoole, and Marchal (1991). The more globally oriented methods proposed in the present study were in fact intended as a complement to such a more detailed approach. Since they are fairly straightforward to apply, they could indeed by used to sift out interesting cases for further analysis.

The second issue to which we turn is that of whether /s/ would prove more variable than the more dorsal /ʃ/. In this case the results were straightforward. Neither fricative showed consistently greater variability. In other words, /s/ places just as severe constraints on overall tongue position as does /ʃ/ with its greater primary tongue-dorsum involvement. This is not to deny that /s/ may allow the tongue dorsum more freedom to vary than the more critically involved tongue tip (as in fact is the case for both EMA speakers in Fig. 7). However, additional data on GER2, discussed elsewhere (Hoole *et al.*, 1990) and generally confirmed in other more recent EMA recordings, show quite clearly that variability at mid and rear coils is substantially less for /s/ than for other alveolar consonants. This tight control is not surprising in the light of the tentative interpretation of the French speakers' data that the shape of the vocal tract behind the major constriction can have a relevant impact on the acoustic salience of the /s/–/ʃ/ distinction.

The present results in no way contradict the Recasens model that the degree of tongue dorsum involvement is a primary determinant of the extent to which coarticulatory effects can spread. On the contrary, they simply indicate that the basic constraint formed by tongue dorsum involvement (as reflected in place of articulation and closeness of constriction) is further modulated by manner of articulation.

Comparison of the views of lingual activity given by EPG and EMA suggested that, for the class of sounds investigated here, these techniques give an interestingly complementary view of articulation while at the same time giving a highly similar view of coarticulation. Thus, for the elucidation of the details of articulation these two techniques could prove a fruitful combination. On the other hand, this investigation suggests that reliable information on coarticulatory patterns can be derived even when, as is generally the case, only partial information on lingual activity is available. In short, this reinforces the confidence that can be placed in electropalatographic and electromagnetic results. This is of particular importance for the latter, much younger, technique and confirms the results of an analysis of high front vowels, also using subject GER2 (Hoole and Tillmann, 1991), in which the EMA and EPG data gave a coherent picture of the lingual articulatory differences between the German vowels /i/ and /y/.

The most puzzling aspect of the present results was the shift in coarticulatory patterns for ENG2 between the earlier (EPG) and later (combined) recording. It must be admitted that this study does not provide a very stringent test of stability in articulatory behaviour over time; as already mentioned, the sessions had several differences, e.g., regarding carrier phrase and speech rate, so say nothing of overall experimental setup. Nonetheless, the result still serves to underline the fact that a number of carefully controlled 'longitudinal' studies of the articulatory strategies of individual speakers might be one way of partially compensating for the chronically small number of subjects in instrumental phonetic investigations.

Regarding language-specific effects, we have already mentioned a number of interesting features in the results that complicate simple statements in this area. However, it is still possible to compare the present results with further results available elsewhere and consider what language-specific tendencies could be followed up.

The German and English speakers showed a predominantly carryover pattern. For English, there may have been a bias in favour of carryover effects since /a/ as V2 was reduced to schwa. Nonetheless, the findings agree, for example, with the recent cross-language results of Farnetani *et al.* (1989) showing carryover effects to be more consistently present than anticipatory ones. It is interesting to note that this consistency in the results occurs even though the Farnetani *et al.* study used a different stress pattern, namely stress on the second syllable.

For German, where less information is available, the results appear at first sight to be at variance with those of Butcher and Weiher (1976). This study generally showed a stronger tendency towards anticipatory coarticulation in VCV syllables with /t/ and /k/. However, for the alveolar plosive (which presumably offers a better comparison with our data than the velar one) there are a lot of missing data and the picture is anything but clear-cut. For example, their Table IV could be interpreted as showing stronger *carryover* effects in syllables with combinations of /i/ and /a/.

Of our French speakers one clearly favoured anticipation, the other had an ambiguous pattern. This also agrees with Farnetani *et al.*, at least in the negative sense that in the latter study the predominance of carryover was less obvious in French.

The slight differences between the languages in the predominant coarticulatory pattern probably reflect the slight differences in stress pattern and vowel reduction pointed out in the "Methods" section. However, a more rigorous examination of this point was beyond the scope of this paper. It would require analysis of the target positions of the flanking vowels as well as of the kinematic characteristics of the VC and CV transitions (*cf.* Parush *et al.*, 1983). This analysis would have been extremely difficult to carry out in the present context of a parallel examination of articulatory and acoustic regularities because of the qualitative changes in the acoustic and EPG signals in passing from fricative to vowel (changing source characteristics in the acoustic domain; negligible information on low vowels in the EPG signal).

One issue relevant from a cross-language perspective that was not discussed in the Introduction is that of the influence of phonological organisation on coarticulatory patterns. Specifically, some evidence has been found for vowel systems that the density of the system is inversely related to the amount of contextually-induced variability (Manuel, 1990). To date, there have been few attempts to extend this hypothesis to consonant systems. For present purposes it is interesting to note that French has fewer voiceless fricatives than the other two languages (i.e., /θ/ in English, /ç, x/ in German) and that French does in fact show evidence of greater contextually-induced variability, especially in terms of the proposed phonemic metric. Unfortunately, the voiceless fricatives are not an ideal field for testing a consonantal version of the density hypothesis with respect to these languages; in German the distributional properties of /ç, x/ are very different from those of the other fricatives, while in English it is perhaps questionable whether the weak (non-strident) fricative /θ/ will result in noticeably stronger constraints on the variability of the strident fricatives /s/ and /ʃ/.

To conclude this discussion we would like to refer back to Dart's (1991) recent extensive study of English and French alveolar and dental consonants. Her investigation of the articulatory configurations of these sounds showed rather persuasively that language-specific tendencies can indeed be identified (French: more laminal and dental, higher tongue body; English: more apical and alveolar, lower tongue body). However, it also demonstrated how frequent departures from the 'core' articulatory configuration could be; a particular strength of this study was that a sufficient number of subjects was investigated (about 20 per language) for it to be possible to give some estimate of the probability of occurrence of the various categories of departure from the core pattern.

On the basis of the findings presented and discussed here, it appears very likely that the kind of picture uncovered by Dart for articulatory regularities also applies to coarticulatory regularities. In other words, language-specific trends undoubtedly exist, but much remains to be done before we will be in a position to accurately estimate the probability of occurrence of the less common patterns.

## REFERENCES


BLADON, A., and NOLAN, F. (1977). A video-fluorographic investigation of tip and blade alveolars in English. *Journal of Phonetics*, **5**, 185–193.

BUTCHER, A., and WEIHER, E. (1976). An electropalatographic investigation of coarticulation in VCV sequences. *Journal of Phonetics*, **4**, 59–74.

DART, S. (1991). Articulatory and acoustic properties of apical and laminal articulations. *UCLA Working Papers in Phonetics*, **79**, 1–155.

EDWARDS, J. (1985). Contextual effects on lingual-mandibular coordination. *Journal of the Acoustical Society of America*, **78**, 1944–1948.

FARNETANI, E. (1990). V-C-V lingual coarticulation and its spatiotemporal domain. In A. Marchal and W. Hardcastle (eds.), *Speech Production and Speech Modelling* (pp. 93–130). Dordrecht: Kluwer.

FARNETANI, E., HARDCASTLE, W., and MARCHAL, A. (1989). Cross-language investigation of lingual coarticulatory processes using EPG. *Proceedings of the European Conference on Speech Communication and Technology (Paris, 26–28 Sept. 1989)*, **2**, 429–432.

FORREST, K., WEISMER, G., MILENKOVIC, P., and DOUGALL, R. (1988). Statistical analysis of word-initial voiceless obstruents: Preliminary data. *Journal of the Acoustical Society of America*, **84**, 115–123.

HOOLE, P., GFROERER, S., and TILLMANN, H.G. (1990). Electromagnetic articulography as a tool in the study of lingual coarticulation. *Forschungsberichte des Instituts für Phonetik und sprachliche Kommunikation (München)*, **28**, 107–122.

HOOLE, P., and TILLMANN, H.G. (1991). An articulatory investigation of front rounded and unrounded vowels. *Proceedings of the 12th International Congress of Phonetic Sciences (Aix-en-Provence, 19–24 Aug. 1991)*, **2**, 362–365.

HOOLE, P., ZIEGLER, W., HARTMANN, E., and HARDCASTLE, W. (1989). Parallel electropalatographic and acoustic measures of fricatives. *Clinical Linguistics and Phonetics*, **3**, 59–69.

KÜHNERT, B., LEDL, C., HOOLE, P., and TILLMANN, H.G. (1991). Tongue-jaw interactions in lingual consonants. *PERILUS (Institute of Linguistics, University of Stockholm)*, **XIV**, 21–25.

MAEDA, S. (1991). On articulatory and acoustic variabilities. *Journal of Phonetics*, **19**, 321–331.

MANUEL, S. (1990). The role of contrast in limiting vowel-to-vowel coarticulation in different languages. *Journal of the Acoustical Society of America*, **53**, 1070–1082.

MCGOWAN, R., and NITTROUER, S. (1988). Differences in fricative production between children and adults: Evidence from an acoustic analysis of /ʃ/ and /s/. *Journal of the Acoustical Society of America*, **83**, 229–236.

NGUYEN-TRONG, N., HOOLE, P., and MARCHAL, A. (1991). Articulatory-acoustic correlations in the productions of fricatives. *Proceedings of the 12th International Congress of Phonetic Sciences (Aix-en-Provence, 19–24 Aug. 1991)*, **3**, 18–21.

PARUSH, A., OSTRY, D., and MUNHALL, K. (1983). A kinematic study of lingual coarticulation in VCV sequences. *Journal of the Acoustical Society of America*, **74**, 1115–1125.

PERKELL, J., and COHEN, M. (1986). An alternating magnetic field system for tracking multiple speech articulatory movements in the midsagittal plane. *MIT Technical Report*, Vol. 512.

RECASENS, D. (1984). V-to-V coarticulation in Catalan VCV sequences. *Journal of the Acoustical Society of America*, **76**, 1624–1635.

RECASENS, D. (1989). Long range coarticulation effects for tongue dorsum contact in VCVCV sequences. *Speech Communication*, **8**, 293–307.

RECASENS, D. (1991). An electropalatographic and acoustic study of consonant-to-vowel coarticulation. *Journal of Phonetics*, **19**, 177–192.

RECASENS, D., and FARNETANI, E. (1990). Articulatory and acoustic properties of different allophones of /l/ in American English, Catalan and Italian. *Proceedings of the International Congress on Speech and Language Processing (Kobe, 18–22 Nov. 1990)*, **2**, 961–963.

SCHMIDBAUER, O., CASACUBERTA, F., CASTRO, M.J., HEGERL, G., HÖGE, H., SANCHEZ, J.A., and ZLOKARNIK, I. (1993). Articulatory representation and speech technology. *Language and Speech*, this volume.

SCHÖNLE, P., MÜLLER, C., and WENIG, P. (1989). Echtzeitanalyse von orofacialen Bewegungen mit Hilfe der elektromagnetischen Artikulographie. *Biomedizinische Technik*, **34**, 26–130.

SOLI, S. (1981). Second formants in fricatives: Acoustic consequences of fricative-vowel coarticulation. *Journal of the Acoustical Society of America*, **70**, 976–984.

STONE, M. (1991). Toward a model of three-dimensional tongue control. *Journal of Phonetics*, **19**, 309–320.

TOMIAK, G. (1990). An evaluation of spectral moments metric with voiceless fricative obstruents. *Journal of the Acoustical Society of America*, **87**, Suppl. 1, S106–107.

TULLER, B., SHAO, S., and KELSO, J.A.S. (1990). An evaluation of an alternating magnetic field device for monitoring articulatory movements. *Journal of the Acoustical Society of America*, **88**, 674–679.