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Electromagnetic articulography as a tool in the study of lingual coarticulation *

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ABSTRACT

An electromagnetic system was used to study tongue and jaw movements for a large corpus of German VCV nonsense words. The aims were: 1) to determine whether this system is suitable for large-scale acquisition of phonetically varied data, 2) to describe the overall ranges of variability for the sounds of German, 3) to investigate vocalic influences on the intervening consonant, 4) to investigate compensatory articulation in tongue - jaw coordination.

The results showed that overall variability was higher for those consonants assumed to impose fewer constraints on precise tongue positioning, while for both consonants and vowels there was more variability at locations on the tongue remote from the area of maximum constriction. The investigation of vocalic effects on the intervening consonant gave rather equivocal results: more anticipatory influence for the non-lingual consonants and more carryover influence for the lingual ones. More significant was the necessity for separate consideration of the different locations on the tongue and the different vowels. Thus /i/ strongly constrained the overall VCV movement pattern. Taken with the overall small range of variability for /i/ and clear differences in tongue position found for /i/ and /y/ this raised the question of the influence of the specific sound system on patterns of variability. The negative correlation between tongue- and jaw height observed in alveolar and palatal fricatives suggested that jaw and dorsal positions coordinate each other to form an exact constriction and that the open-close jaw gesture does not directly correspond with tongue height.

1. INTRODUCTION

The overall aim of this work was to achieve a better understanding of contextually induced variability in speech sounds. Two questions relevant to coarticulatory processes were addressed: firstly, the relative magnitude of anticipatory and carryover effects in VCV sequences were examined since previous investigations have given a rather equivocal picture (1,2,3,4,5,6); secondly the issue of compensatory adjustments between articulators (here tongue and jaw) was considered in the light of the hypothesis that coarticulatory effects represent a form of naturally-induced perturbation (cf. Edwards (7)). As a precursor to these questions the overall range of variability for most of the consonants of German as well as the point vowels was determined with the intention of determining whether differences could be interpreted in terms of required articulatory precision. Specifically it was hypothesized that for both consonants and vowels a location on the tongue close to the area of maximum constriction will show less variation than one more remote from it. In addition we wanted to check Perkell's observation that in the case of point vowels the remaining variation will be parallel to the main axis of the vocal tract, rather than perpendicular to it (8,9,10).

2. METHOD

An electromagnetic transduction system (Articulograph AG 100, Carstens Medizinelektronik, Göttingen, Germany) was used to monitor movements of jaw and tongue with 5 receivers, 3 on the tongue and one each on the upper and lower incisors. To simplify examination of the effects of interest the intermediate coil on the tongue will be left out of further consideration. The sample rate used for the articulatory data was 193.5 Hz. Audio and synchronization signals were recorded on a DAT recorder. After completion of the experiment the audio and synch signals were aligned on a laboratory computer with the articulatory data. Figure 1 gives a schematic overview of the experimental setup.

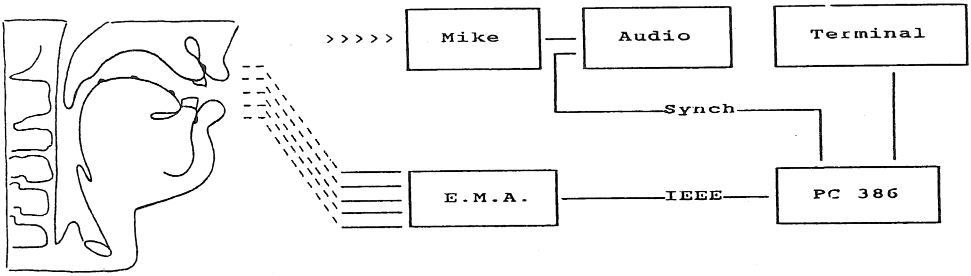

Figure 1: The experimental set-up

3. MATERIAL

The speech material consisted of nonsense words of the form bV1CV2 embedded in the sentence frame 'Ich sage ——— bitte'. The consonants were /p,b,m,f,v,t,d,n,s,l,ʃ,k,g,h/, the vowels were /i,a,u/ giving a basic corpus of 126 forms (3V1 × 14C × 3V2). In addition all consonants were produced in two contexts with the front rounded vowel /y/, namely /yCa/ and /aCy/ giving another 28 forms. The nonsense words were spoken with the equivalent of lexical stress on the first syllable (as in 'niemals' = /ˈni:mals/). These 154 stimuli were given five separate randomizations and were presented to the subject, a male speaker of German, on a computer screen.
In the analysis the coordinates of the reference coil at the upper incisors were subtracted from those of the others and the data was rotated so that the principal component of jaw movement was vertical. A waveform editor was used to locate the positions of V1, C, and V2. The analyses are based on articulatory configurations determined at the mid-point of these three segments.

4. RESULTS

4.1. OVERALL VARIABILITY

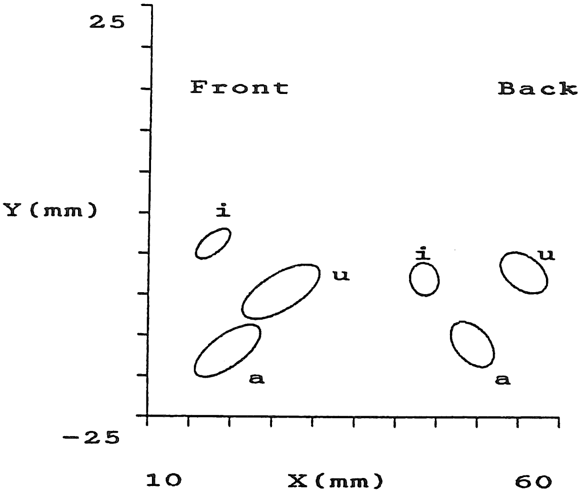

Figure 2: Two-sigma ellipses for V1 in all V2-contexts and in all consonantal contexts except the grooved fricatives. N = 144 (front), N = 108 (back).

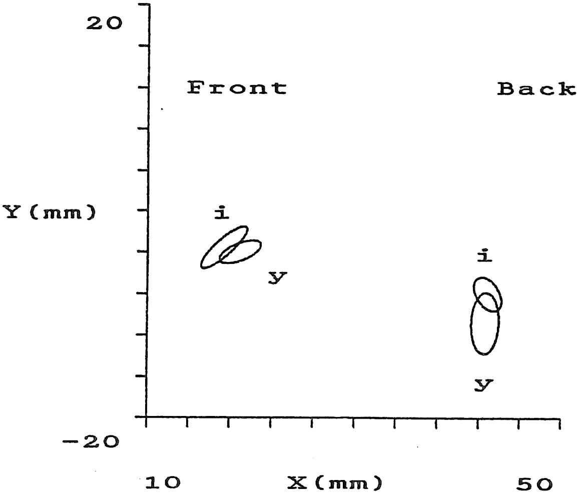

Figure 3: Two-sigma ellipses for /i/ and /y/ in preconsonantal position. V2 = /a/, C = /p, b, m, f, v/. N = 20 (front), N = 15 (back).

4.1.1. VOWELS

Figure 2 presents results for the three vowels /i/, /u/ and /a/ in the stressed preconsonantal position for the two tongue coils.
The expectation of smaller variability at the coil nearest the assumed site of maximum constriction is generally confirmed. /u/ has more variability at the front coil, while /i/, with the least overall variability, has slightly more variability at the back coil. The status of /a/ is ambiguous. It has more variation at the front coil in V1 but at the back in V2. Not really being a back vowel it does not perhaps require very precise control of the pharyngeal constriction.

The orientation of the ellipses appears rather unspecific, i.e. not obviously related to the proximity of a vocal tract wall.
The clear difference between /i/ and /y/ shown in Figure 3 can be characterized as a lowering of the tongue body for /y/. This is not due to a simple difference in jaw height. The data confirm for German the differences between front rounded and unrounded vowels observed by Wood (11) in a variety of languages with this phonological contrast.

Table 1 shows the two-sigma ellipse areas and the coordinates of the ellipse centres for V1 and V2. The most obvious difference between V1 and V2 is the increased variability for the more weakly stressed V2.

TABLE 1:

		FRONT COIL N = 144			BACK COIL N = 108		
		area mm2	xc mm	yc mm	area mm2	xc mm	yc mm
	/i/	9.3	17.8	-3.8	10.9	43.5	-8.0
V1	/u/	36.5	26.2	-9.6	20.0	55.6	-7.3
	/a/	29.0	19.8	-16.9	20.6	49.5	-18.0
	/i/	15.3	18.6	-4.2	20.7	43.9	-8.5
V2	/u/	42.7	26.4	-10.4	30.4	55.0	-7.4
	/a/	31.9	21.0	-16.1	34.7	49.5	-17.4

4.1.2. CONSONANTS

Figure 4 shows, analogously to the vowels in Figs. 2 and 3, the areas of the two-sigma ellipses for both coils and each consonant averaged over all vocalic contexts. The relationship expected in the hypothesis that a location close to the constriction will vary less than one further away was confirmed. Consider, e.g., front vs. back for /t/, /d/, /n/ on the one hand and /k/, /g/ on the other, with /ʃ/ occupying, as might be expected, an intermediate position. The rear coil for /k/ showed a clear influence of the preceeding vowel, but the constraint of forming a constriction resulted in the variability taking the form of a very elongated ellipse, while at the front coil the pattern of variation was more circular; this is reflected in a ratio of major to minor axes of the ellipses of 3.41 at the back and 1.04 at the front. In the alveolar group the 'constrained' front coil shows differences in variability that tie in neatly with intuitive notions of required articulatory precision, the order being /s/, /t/, /d/, /n/, /l/. This could be regarded as an ordering with respect to the extent that target undershoot results in unacceptable acoustic deviations. Thus the proximity to a vocal tract wall is not the only factor reducing variability; reduced variability also appears to reflect active articulatory control. This becomes quite clear if the supposedly unrestrained back coil for the alveolars is considered: in the case of /s/ the variability is less than at the front coil for /d/ and /n/. The enormous difference between the non- linguals (i.e. bilabials and /h/) and the rest was of course to be expected. Nevertheless this group of sounds continues the trend for the voiceless plosive to show less variability than the voiced cognate and the nasal.

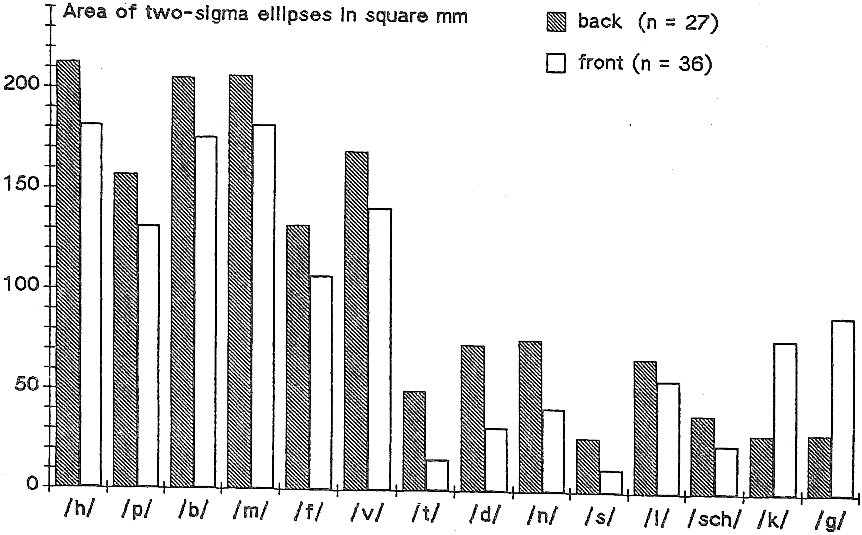

Figure 4: Area of two-sigma ellipses for each consonant at both tongue positions. Averaged over all vocalic contexts. Shaded columns for back measurement position (N = 27). Unshaded columns for front position (N = 36)

4.2. COARTICULATORY EFFECTS ON THE INTERVOCALIC CONSONANTS

The spatial magnitude of carryover and anticipatory effects on the consonant was assessed using a variant of a measure suggested by Kiritani and Sawashima (5). Our method consisted in holding one vowel, e.g. V1, in a VCV sequence constant and calculating at each coil the area of the two-sigma ellipses for a given consonant combined with all V2. Averaging over all V1 for a given consonant gives a measure of anticipatory effects for that sound. The analagous procedure is applied to V2 to estimate carryover effects.
The measures displayed in the following figures represent averages over specific combinations of these areas.

Figure 5 gives a breakdown of anticipatory and carryover effects according to consonant, obtained by averaging over the three vowels and two coils for the two coarticulation directions. The standard deviation is large everywhere because of the systematic effects of the individual vowels and coils, which are examined in detail below.
In the non-lingual group a clear tendency towards greater anticipatory effects is seen. The velars as expected show the opposite effect (e.g. 2). (We could also note here that the characteristic elliptical trajectory of the tongue body with forward movement during closure occurred consistently in the velar stops, confirming previous investigations (e.g. 2,12).) The alveolars and /ʃ/ also show a tendency towards greater carryover effects. The absolute size of the coarticulatory effects is greater for the non-linguals, being closely related to the overall range of variability detailed in Figure 4.

To prevent the next set of comparisons being unduly influenced by the substantial range in variability for the different consonants we decided to normalize the ellipses on which the coarticulation measures are based by dividing their areas by the area of the corresponding overall ellipse from Figure 4. Using this normalized measure it was possible to consider the coarticulatory effects separately for the different coils and vowels. To avoid averaging over less than two items the consonants were collated into three groups, namely the non-linguals (n = 6), the alveolars (n = 6, /ʃ/ was included here too), and the velars (n = 2). The results for the three groups are given in Figures 6-8.

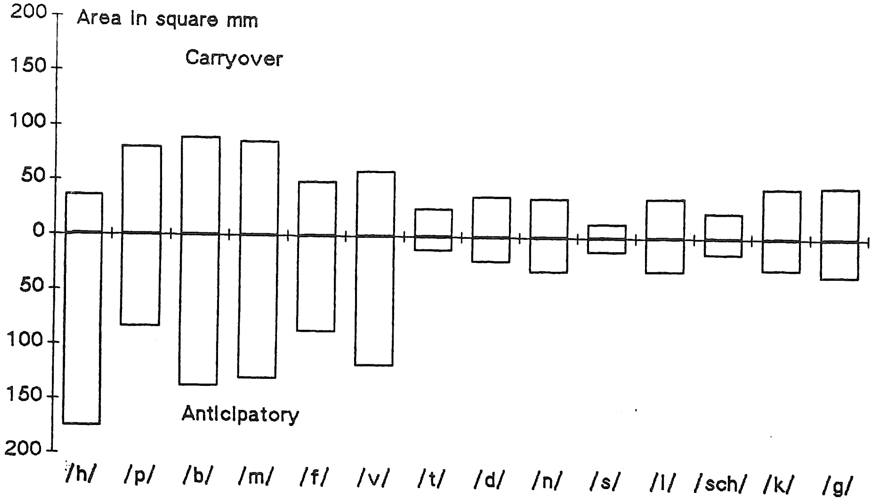

Figure 5: Mean carryover effects (upwards) and anticipatory effects (downwards) for each consonant. Each bar represents the average (N = 6) over the areas of two-sigma ellipses determined for each combination of three vowels and two tongue measurement positions.

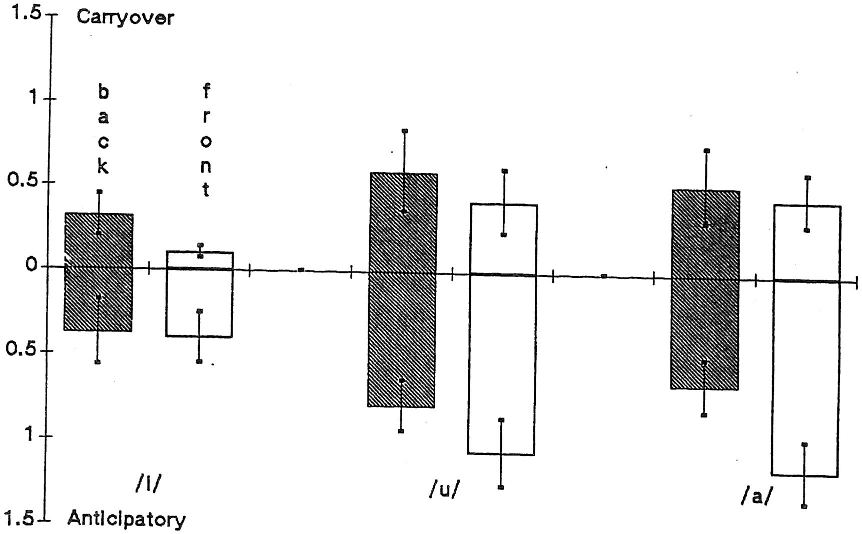

Figure 6: Mean normalized carryover effects (upwards) and anticipatory effects (downwards), broken down according to vowel and tongue measurement position (shaded for back position, unshaded for front) for the non-lingual consonant group (/p, b, m, f, v, h/, N = 6). Error bars indicate +/- 1 s.d.

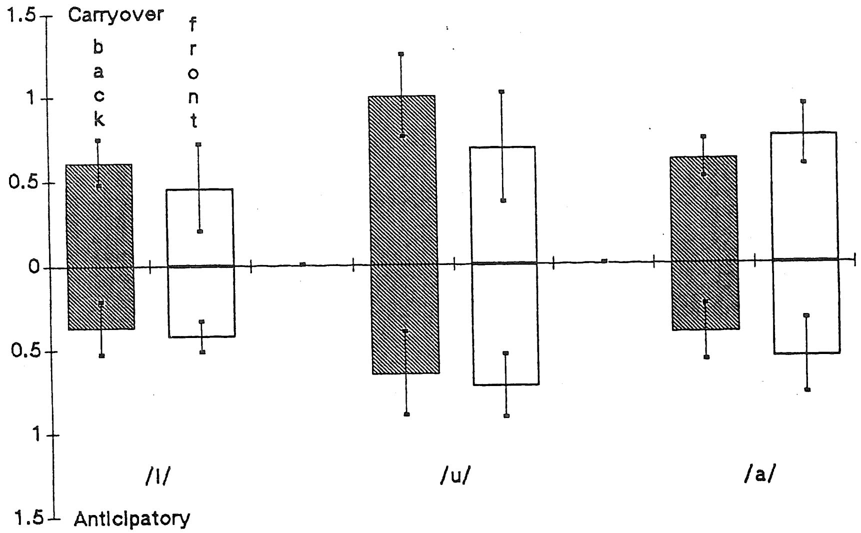

Figure 7: Alveolar consonant group (/t, d, n, s, l, ʃ/, N = 6), other details as in Fig. 6.

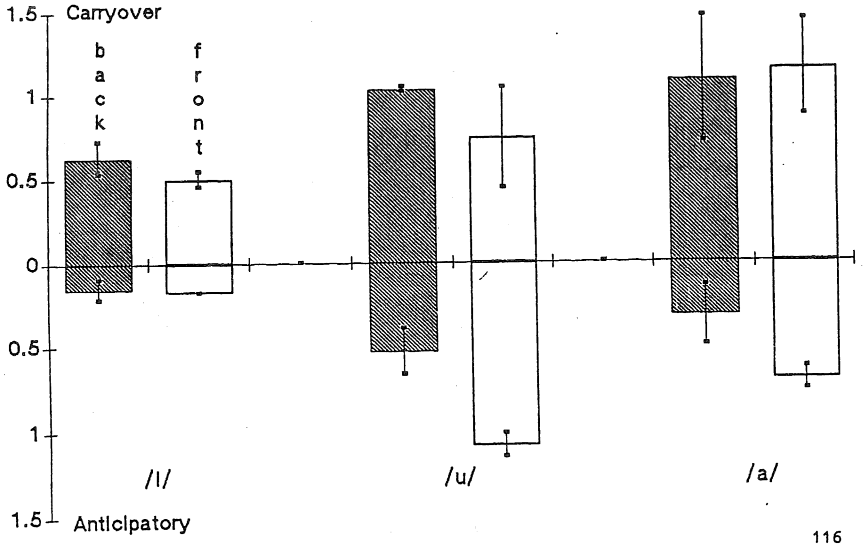

Figure 8: Velar consonant group (/k, g/, N = 2), other details as in Fig. 6.

The most salient trend evident over all groups is that both pre- and post- consonantal /i/ clearly excercises a constraining influence with regard to the extent of coarticulatory variation that can occur (5,6).

A further trend visible in all three figures is that there is a shift in the relative weight of anticipatory and carryover effects from the front coil to the back coil, there being either less carryover or more anticipation or both at the front location. This trend is most evident for the non-lingual group in Figure 6 and it also reveals that the overall predominance of anticipatory coarticulation for this group seen in Figure 5 is due to the front coil alone. For the lingually unconstrained group of consonants it is possible that this reflects a lesser degree of inertia in the tongue-blade, allowing anticipatory influences to become apparent earlier.

Figures 7 and 8 confirm the overall impression of greater saliency of carryover effects for the alveolars and especially for the velars. However, there is one clear instance in Figure 8 where this pattern for the velars is reversed, namely for the front coil with the vowel /u/. This is precisely where such a reversal might be considered most likely, since the velars and /u/ both constrain the front coil only loosely (see Figure 2 and Figure 4), thus leaving it free to swim against the predominant carryover current.

The trend for the so-called alveolar group is only consistent at the rear coil, suggesting that the front coil is so tightly constrained by the consonant production itself that neither the preceeding nor the following vowel succeed in exercising a predominant effect.

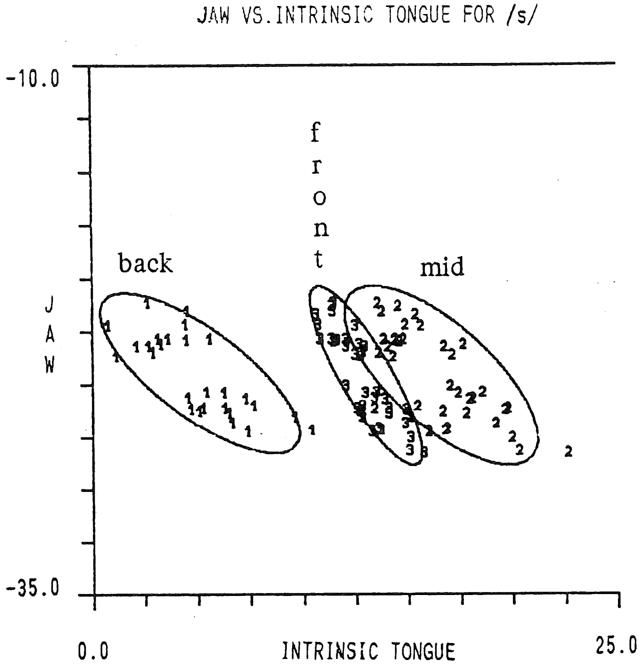

Figure 10: Relationship between jaw height and intrinsic tongue height for all 3 tongue coils for /s/.

With regard to the question of compensatory adjustments between tongue and jaw, the first step was to determine the intrinsic tongue contribution for each of the 3 tongue coils by subtracting the estimated jaw contribution assuming pure rotation at the temporomandibular joint (cf. Edwards (7)). We then looked for cases of large negative correlations between jaw and intrinsic tongue position. The strongest correlations were found for /s/. This is shown for the 3 tongue coils in Figure 10. A complete breakdown for all lingual consonants is given in Table 2.

Lingual Consonants

Coil	/t/	/d/	/n/	/s/	/l/	/ʃ/	/k/	/g/
back	-.06	.39	.39	-.75××	.30	-.34×	-.27	-.34×
mid	-.42×	-.10	.33	-.71××	.15	-.69××	-.26	.06
front	-.64××	-.36×	.14	-.85××	-.06	-.50×	.02	.14

TABLE 2 :

Correlation coefficients between jaw- and intrinsic tongue height over all vocalic contexts ($p < .05$ ×; $p < .01$ ××).

It will be observed for the alveolars that the correlations become weaker and increasingly confined to the front-most coil in the order /s/-/t/-/d/-/l/-/n/. As might be expected /ʃ/ shows the strongest correlation for the mid coil rather than for the front coil. The fact that for /ʃ/ correlations are weaker than for /s/ is probably implies that jaw position is already so highly constrained (see Fig. 9) that there is less necessity for jaw-tongue trade offs. The low correlations for /k/ and /g/ at the back coil need not mean that no compensatory adjustments are occurring. If mandibular movement involves some translation as well as rotation then the correlations at the back coil will have been underestimated. The considerable horizontal variation in closure location for /k/ and /g/ may also tend to obscure vertical jaw-tongue interactions.

4.3. TONGUE - JAW INTERACTIONS

Figure 9 presents the data for jaw height at the mid-point of the consonants. The fricative /ʃ/ is distinguished by its high jaw position and the small amount of variability. Probably this reflects the fact that this dorsal fricative constrains the activity of the whole articulatory system more strongly than blade articulations do, as Recasens (6) has shown. Thus /s/, too, has a high jaw position but considerably more variability. At the other end of the scale is /l/, where jaw position is almost as low as for /h/, which of course lacks a constriction altogether. This probably represents a mechanism to aid the contrast between concave tongue shape for /l/ and convex for /s/ and /ʃ/ (cf. Stone (13)).

Within the labial group of sounds it may be observed that the labiodental fricatives have a higher jaw position than the bilabial occlusives, and also less variation. This most likely also reflects the constraining influence of fricative production, with less scope for compensatory adjustments between lower lip and jaw. In general, the relative jaw heights agree quite well with data presented and discussed in, for example, Kent and Moll (12).

An analysis of carryover and anticipatory effects analogous to that carried out for tongue configurations (Fig. 6-8) provided no clear cut trends except for predominantly anticipatory coarticulation in /h/, while the vowel /a/ had less of a constraining influence than /i/ or /u/.

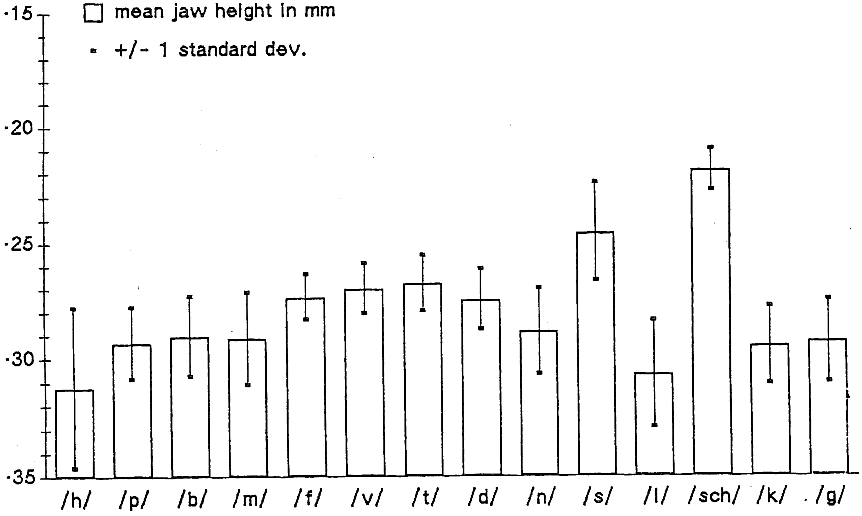

Figure 9: Mean jaw height for each consonant averaged over all vocalic contexts. Error bars indicate +/- 1 s.d. N = 36

5. DISCUSSION

This investigation consisted of three general themes: 1. the question of the overall range of variability for a substantial proportion of the German sound inventory, 2. the nature of contextual variation as observed at the mid-point of intervocalic consonants, 3. the question of compensatory adjustments between jaw and tongue.
With regard to the first theme, if the observed differences in tongue position for /i/ and /y/ generalize to all four front rounded vowels in German then the front vowel space of German appears very crowded indeed. This leads to the question of whether the small articulatory variability in /i/ (Fig. 2) and its constraining influence on articulatory processes (Figs. 6-8) are two sides of the same coin, and whether this represents a language- specific adjustment to maintain phonetic distinctions reliably. With regard to the consonants, too, the patterns of variability appear to be controlled very flexibly and precisely by the articulatory system for the different speech sounds and the different articulators. This is essentially the conclusion also pointed to by the examination of tongue-jaw trade- offs. More significant than the confirmation that such trade-offs exist is the finding that this principle of motor organization is used flexibly and selectively depending on the precision with which specific vocal tract configurations must be attained. Concerning the second theme the examination of the relative preponderance of carryover and anticipatory effects in spatial terms again produced rather equivocal results. It would appear that the question is very sensitive to the particular experimental and analysis technique used, i.e. to the precise location in space and time where the analysis is performed.

6. CONCLUSION

If coarticulation is regarded as an expression of the dynamic nature of speech sounds then the more fundamental task is to identify those processes that would allow a complete specification of the sounds of a language in dynamic terms. Relevant ingredients are apparent in the articulatory processes examined in this experiment, namely the inherent ranges of variability for different speech sounds, inherent constraints on independent movement of different articulators imposed by different speech sounds, inherent differences in the dynamics of different parts of the tongue, and flexible trade-off between different articulators. These processes may additionally be modified by the exigencies of specific sound systems.

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