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TONGUE-JAW INTERACTIONS IN LINGUAL CONSONANTS

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1. INTRODUCTION

In several speech production studies the concept of motor equivalence has been discussed as a potential central principle of articulatory coordination. The concept suggests that a goal may be relatively invariant while the contributions of the individual articulators achieving that goal may vary in a reciprocal relationship. In addition to a number of perturbation experiments, the most influential study supporting the notion of motor equivalence is probably the one by Hughes and Abbs (1976). Investigating the relative contributions of upper-lip, lower-lip and jaw during multiple vowel productions they reported mutual covariations between the three articulators. Thus, in tokens in which the upper lip moved a little less downwards the jaw or both lower lip and jaw moved a little further upwards to produce relatively invariant spatial positions for each vowel.

Edwards (1985) introduced a new aspect to the study of inter-articulatory coordination by associating it with the phenomenon of coarticulation. Her reasoning was that the coarticulatory context is one of the major influences on positions of articulators for particular sounds and, therefore, effects on the displacement of one articulator might be compensated for by the appropriate adjustment of another articulator in order to keep contextual influences within the allowed limits.

The major purpose of the present experiment was to further explore the assumption put forward by Edwards (1985) with respect to tongue-jaw interactions and to examine to what extent her findings can be generalized or, alternatively, to what extent inter-articulatory coordination capabilities might be speaker- and/or sound-specific. Accordingly, a broad inventory of German lingual consonants was studied.

2. EXPERIMENT

Tongue-jaw coordination of one female and two male German speakers in VCV-sequences was investigated. The consonants were either /t,d,n,s,l/ or /$/, the vowels /i/, /u/ or /a/. Each consonant was repeated 30 to 40 times and the sequences were embedded in the carrier phrase "sage b___ bitte".

Kinematic signals were recorded with the help of an electromagnetic transduction system (Articulograph AG 100, Carstens Medizinelektronik). The receiver coils were placed on the lower teeth to register jaw movements; 1 cm posterior to the tongue-tip to track tongue movement most crucial for alveolar production; and at the upper teeth to serve as reference coil. Audio signals were recorded simultaneously. After normalization procedures of the kinematic data (tilt correction of the receiver coils, subtraction of head movements, rotation to the axis of the principal component of jaw movement) the articulatory configurations at the acoustic mid-point of the consonant were used for the analyses discussed below.

Since the tongue is anatomically coupled to the jaw, observed *total tongue* (TT) positions always contain a jaw-related (J) component. However, *intrinsic tongue* (IT) values were needed to study the fine coordination of the lingual-mandibular system. The horizontal intrinsic tongue values were obtained by simply subtracting the x-values of the jaw from the measured x-values of the tongue for the horizontal dimension. For the vertical intrinsic tongue values, however, subject-specific weighting factors of relative jaw influence have been applied before subtraction analogously to the procedure proposed by Edwards (1985).

Statistical analyses were performed in two steps. Firstly, total tongue variability was calculated in order to determine the magnitude of vowel coarticulation of the different consonants. Secondly, Pearson correlation coefficients were computed to detect possible compensatory adjustments between intrinsic tongue and jaw. Theoretically, it is assumed that high negative correlations - i.e. little articulatory contribution of one articulator and high contribution of the other, or vice versa - are indicators of inter-articulatory adjustment. However, we are well aware of the fact that we are dealing with part-whole correlations since the jaw values are inherently reflected in the intrinsic tongue values as a consequence of the applied subtraction procedure. As has been pointed out by Benoit (1986), such part-whole correlations might give a bias towards negative correlations. For these reasons, only correlations significant at the 1% level were interpreted as demonstrating articulatory reciprocity. Moreover, as an additional judgement method, a comparison between constituent and overall variabilities (Hughes & Abbs 1976) was carried out which generally confirmed the results obtained by the correlation analyses.

3. RESULTS

In the following presentation, vertical and horizontal results will be discussed separately.

3.1. Vertical analysis

Table 1 shows the overall vertical variability of total tongue positions for each consonant and speaker. Here and henceforth the data of the consonants have been calculated across all vocalic contexts. It will be observed that the three speakers differ in their *absolute* values of TT variability. However, the *relative* influence of the vocalic environment is consistent across the three subjects. For all speakers, the vertical TT variability of /s/- or /t/-productions is far less affected by the phonetic context than the TT variability of /l/-productions. More specifically, the variation within the alveolar group gradually increases in the order of fricative, voiceless plosive, voiced plosive and nasal and/or lateral. The productions of the fricative /$/ take an intermediate position, their variabilities being fairly constrained but not as constrained as those of the alveolar counterparts.

vertical	t	d	n	s	l	$
(A)	0.96	1.48	2.08	0.90	2.33	1.29
(B)	1.39	1.41	1.58	0.81	2.12	1.57
(C)	1.89	2.10	2.37	1.78	2.15	3.76

Table 1: Standard deviations (mm) of total tongue (TT) measurements in the vertical dimension across vocalic contexts for all subjects.

The results of the vertical correlation calculations, i.e. the correlation coefficients between intrinsic tongue and jaw height, are summarized in table 2. It becomes apparent that for subject (A) significant correlations occur for those sounds for which the coarticulatory influences described above were relatively low. The strongest IT-J interactions can be found for the fricative /s/, followed by the productions of /t/ and the alveo-palatal /$/. The correlation of the front coil for /d/-productions almost reached the defined significance level whereas no significant values can be observed for /n/ and /l/.

On the contrary, subject (B)'s results for the vertical correlation analysis show significant negative values for the two highly variable sounds /n/ and /l/. Thus surprisingly, there seems to be no relation between small variability and observable inter-articulatory adjustment and no compensatory mechanisms seem to operate for the articulation of the positionally highly constrained alveolar fricative /s/. However, the latter might be explained by this speaker's rather small range of jaw movement (sd=0.92 mm) together with a very accurate positioning of the tongue tip for this consonant leaving little scope or necessity for tongue-jaw trade-offs. A similar

vertical	t	d	n	s	l	$
speaker (A)	-.64	-.36	.15	-.85	-.06	-.50
p	.000**	.015	.193	.000**	.354	.001**
speaker (B)	-.19	.04	-.72	-.06	-.55	.14
p	.147	.415	.000**	.369	.001**	.224
speaker (C)	-.27	-.56	-.31	-.58	-.59	-.27
p	.047	.000**	.027	.000**	.000**	.044

Table 2: Pearson correlation coefficients between intrinsic tongue and jaw in the vertical dimension for all speakers.

speaker-specific articulatory strategy within the labial-mandibular system has been reported by Sussman et al. (1973).

For speaker (C), significant vertical correlations between IT and J are found for productions of /s,d,l/, not for /t,n,/.

3.2. Horizontal analysis

The horizontal data of TT variation are illustrated in table 3. In general, horizontal variabilities are higher than the vertically measured ones; however, the relative contextual influence on the different alveolars increases once more from /s,t,d,n/ to /l/ for speaker (A) and (B). Subject (C)'s data, by contrast, deviates slightly from this order. The /s/-productions again show the most restricted range of positional variation, but /l/ is less variable than /d/, /n/ and /t/, respectively.

horizontal	t	d	n	s	l	$
(A) TT	1.32	1.81	1.91	1.22	2.23	1.52
(B) TT	1.32	1.74	1.65	1.27	1.90	2.50
(C) TT	2.86	2.50	2.66	1.21	2.03	1.88

Table 3: Standard deviations (mm) of total tongue (TT) measurements in the horizontal dimension across vocalic contexts for all subjects.

The results of the horizontal correlation analyses are summarized in table 4. Here, for speaker (A) highly significant negative correlations could only be found for /s/, the data of /l/-productions narrowly failed to meet the defined significance level. Hence, in the case of /s/ the restricted range of horizontal variability might again be reflected in the active compensatory cooperation of the two articulators whereas this relation does not hold true for any other of the consonants.

Significant negative correlations between IT and J in subject's (B) data can be observed for almost all sounds (/d/ just failed to reach the one percent significance level) except for the the alveo-palatal fricative /$/. Unlike the first speaker, therefore, subject (B) shows more instances of horizontal than of vertical articulatory adjustments.

The same seems to be valid for speaker (C) who shows highly significant horizontal correlation coefficients for all consonants woth the exception of /s/.

4. DISCUSSION

The main purpose of the study was to explore the relationship between coarticulatory influences on, and articulatory coordination of, the lingual-mandibular system for German alveolars.

The results of the variability analyses were consistent for all three speakers and suggest that there is a specific pattern of coarticulatory variation in German alveolar sounds. Vertically as

horizontal	t	d	n	s	l	$
(A)	-.05	.17	.02	-.77	-.35	.15
p	.376	.158	.465	.000**	.018	.194
(B)	-.46	-.39	-.63	-.49	-.47	.01
p	.003*	.014	.000**	.003*	.004*	.479
(C)	-.60	-.80	-.69	-.27	-.65	-.64
p	.000**	.000**	.000**	.048	.000**	.000**

Table 4: Pearson correlation coefficients between intrinsic tongue and jaw in the horizontal dimension for all speakers.

well as horizontally - with slight deviations for speaker (C) in the horizontal dimension - total tongue variability increases in the order of fricatives, voiceless plosives, voiced plosives, nasals and/or laterals. As such the results fit nicely with findings that have been reported for other languages such as English (Bladon & Nolan 1977), Swedish (Engstrand 1989) or Italian (Farnetani 1990) suggesting, therefore, some cross-language validity of articulatory precision for which, however, a compelling phonetic explanation still remains to be elaborated.

The speakers' fine coordination between intrinsic tongue and jaw accompanying this pattern of overall tongue variability, on the other hand, gave a rather complex picture. Direct support for the theoretical position taken by Edwards (1985), namely that coarticulation seems to be limited by compensatory responses of individual articulators, could only be found in the data of one speaker. This subject displayed reciprocal interactions between the two articulators precisely for those sounds for which the contextually induced variability was found to be small. Thus, some speakers do indeed seem to apply tongue-jaw trade-offs flexibly and selectively in cases in which articulatory precision is required.

Yet, in addition to being sound-specific this kind of motor strategy also appears to be speaker-specific since the results of the two other subjects did not necessarily support a relationship between inter-articulatory adjustments and small variability of total tongue displacement. Rather, there is evidence in the data of the second speaker that a different articulatory strategy is used to achieve the necessary limitation of variability simply by such exact placements of the component articulators that there remains no further need for complementary adjustments.

A further factor which should be considered relates to the articulatory coordination in the horizontal dimension. Although not yet extensively investigated the importance of this component should not be discounted since we are studying, after all, complex gestures in three-dimensional space. Indeed, for two of the speakers, 83 percent of the correlation coefficients calculated for the alveolars showed evidence of horizontal inter-articulatory coordination between tongue tip and jaw. Considering the ubiquitous presence of variation in most speech production studies such a large percentage indicates a fairly strong tendency. One reason for the different importance attached by speakers to the horizontal and vertical domain might simply lie in the individual anatomical structures as the palate of every speaker differs in length and steepness of the area between alveolar ridge and palatal vault. Thus, ultimately, the speaker-specific anatomical forms of the palate should be integrated into articulatory investigations.

In conclusion, our results suggest that, although we found some evidence of compensatory articulations, we still should be cautious in extending the concept of motor equivalence to a general principle of speech motor control.

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