KINEMATIC ANALYSIS OF LOWER LIP-JAW AND TONGUE-JAW INTERACTIONS DURING SYLLABLE REPETITIONS: SOME ASPECTS OF MOTOR EQUIVALENCE

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ABSTRACT

A rate-controlled syllable repetition task (/pa/, /pi/, /ta/, /ti/; 3 and 5 syllables per second) was used to study the effects of jaw - lower lip and jaw - tongue tip coordination on differential movement amplitudes. In some cases, significant negative covariation across repetitions emerged, but the opposite constellation was observed as well. Considering the systematic effects of vowel context and syllable rate, the jaw showed some independency from the lower lip and the tongue. However, the differential functional role of jaw contribution to the compound gestures varied across speakers and conditions. These findings are at variance with the suggestion of a speaker-independent gestural organization of speech units at the stage of phonological processing.

1. INTRODUCTION

The gesture has been considered a basic phonological unit [1, 2] in terms of a more or less abstract articulatory trajectory, represented in the motor system as a coordinative structure [see 3]. According to this model, inter-articulator coordination may directly reflect phonological processing. However, a study on the articulation of American English vowels [4] has shown that the 'translation' of a phonetic target, in terms of a perceptually relevant goal, into a pattern of inter-articulator coordination seems to be speaker- rather than language-specific. These findings weaken the concept of the gesture as a supramodal unit of speech processing [see 5]. Furthermore, the phenomenon of motor equivalence implies articulatory trajectories or activities to be quite variable, whereas the phonetic targets, for example in terms of acoustic properties, remain relatively invariant [6, 7, 8, 9, 10]. Whereas the gesture model postulates a more direct relation between phonological categories and motor programs, the motor equivalence point of view assumes that motor organization is the result of additional processing at a later stage.

The present study considered the influence of jaw - lower lip and jaw - tongue tip coordination on differential movement amplitude. Within this context, the word 'articulator' refers to the lower lip and the tongue tip as opposed to the mandible. For example, the compound lower lip - jaw trajectory is modeled as a jaw plus an additive articulator (ie., lower lip) movement [see 11]. Some authors suggest differential roles of jaw and articulators during speech production: Whereas the latter are primarily involved in relatively fast consonant gestures, the jaw trajectory has been supposed to represent a correlate of the syllabic sonority profile [12] and to be associated with the slower vowel gestures [11, 13, 14]. Furthermore, vowels, as compared to consonants, tend to be closer associated with opening than closing gestures (Gracco, 1994), are more sensitive to changes in speech rate, and exhibit more undershoot [15, 16, 17, 18, 19]. Obviously, two aspects of speech motor control compete with each other: The differential roles of jaw and articulators with respect to vowel and consonant production require mechanisms of independent control whereas the mechanism underlying motor equivalence requires a close integration of both subsystems. Using a syllable repetition task under controlled speech rate conditions, the present study investigated these aspects of lip - jaw and tongue - jaw coordination by means of electromagnetic articulography. In order to account for speaker variability, a group of nine subjects was analyzed.

Negative covariation between lip and jaw displacement has been reported as an aspect of motor equivalence although experimental results of the various studies are inconsistent in this respect [20, 7, 21, 22]. When considering covariation among subsystems, the most important factor is the nature of the source of variability underlying the data. For example, if a speaker varies on a global dimension such as the hyper-hypoarticulation scale, two subsystems may exhibit positive covariation [23]. In contrast, if the source of variability is a kind of perturbation or imprecision within one subsystem, the other might show a compensatory behavior, resulting in negative covariation. For example, lip adjustments for jaw imprecision have been assumed to underly negative lip - jaw covariaion [21, 7]. In the present study, various analyses were performed in order to assess jaw - articulator covariation in movement amplitude a) across repetitions, b) across subjects, c) across vowel categories, and d) across speech rate conditions.

2. METHODS

Nine subjects produced multiple repetitions of the consonant-vowel sequences /pa/, /pi/, /ta/, and /ti/. Speech rates of 3 and 5 syllables per second were elicited by presentation of synthetic syllables over headphones during the recordings. Lower lip, tongue tip, and jaw movements were measured by use of electromagnetic articulography (AG100, Carstens, Göttingen; sampling rate 400 Hz). Prior to analysis, the trajectories were low-pass filtered at 25 Hz. For each trajectory, the predominant direction of movement was determined by means of principle component analysis [see 24]. Amplitude was defined as the displacement in the direction of the first principal component of the respective gesture. Jaw amplitude was subtracted from the compound lower lip - jaw and the compound tongue tip - jaw gestures, respectively, in order to obtain the differential articulator amplitudes.

The effects of vowel type, syllable rate, and place of articulation on jaw and articulator amplitudes were tested by means of ANOVAs. Partial correlation analysis was used in order to address the various aspects of motor equivalence between jaw and articulator movements. The advantage of this technique is that data can be pooled across several subconditions after the particular statistical effects of these subconditions have been removed from the data set.

3. RESULTS

3.1. Analysis of variance

Two repeated measures ANOVAs were performed considering the subject means of jaw and articulator amplitude, respectively, as the dependent variables. Place of articulation (/p/, /t/) and vowel type (/a/, /i/), both referring to phonetic context, were entered as between-factors and rate (3 Hz, 5 Hz) as a repeated-factor. Vowel type had a highly significant effect on jaw excursion ($F[1,30] = 54.46$; $p < .01$). In contrast, articulator amplitude did not show a significant vowel main effect, but the vowel × place of articulation interaction was significant ($F[1,30] = 11.59$; $p < .01$). The influence of speech rate was stronger on articulator ($F[1,30] = 41.27$; $p < .01$) than on jaw amplitude ($F[1,30] = 9.43$; $p < .01$). As shown in Figure 1, vowel type consistently influenced jaw amplitude (/a/ > /i/). A similar tendency (/ta/ > /ti/) was observed in /t/-utterances with respect to tongue tip amplitudes whereas the lower lip showed the opposite tendency (/pi/ > /pa/).

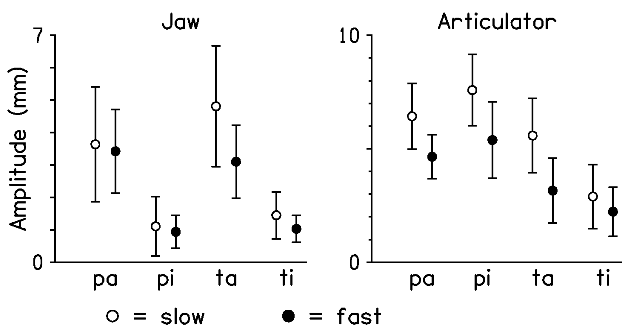

Figure 1. Group means and standard deviations of differential jaw and articulator amplitude depending on the factors vowel type, syllable rate, and place of articulation.

3.2. Jaw - articulator correlation across repetitions

The jaw - articulator correlations were computed for each subject separately after the effects of speech rate and vowel as well as their interaction had been removed statistically (partial correlation analysis). This was done by, first, performing a linear regression analysis of the three dummy variables VOW (/a/ = 0; /i/ = 1), RATE (slow = 0; fast = 1), and VOW × RATE on jaw and articulator amplitude, respectively and, second, computing Pearson correlation coefficients from the residuals of this regression. Six of the 17 correlations shown in the upper part of Table 1 were significant at $p < (0.05/17)$ which is well above chance. With respect to sign, the correlation coefficients varied across subjects and place of articulation. Speaker N8, for example, had positive correlations in /p/, and negative ones in /t/ utterances whereas N9 showed the reverse tendency. Examples of jaw - articulator scatterplots are shown in Figure 2.

		Place of articulation /p/		/t/	
Source of variance		d.f.	*r*	d.f.	*r*
Repetitions,	N1	80	-.24	70	-.08
	N2	80	.10	120	-.45*
	N3	-	-	110	-.07
	N4	70	.08	70	.24
	N5	120	.55*	120	-.29*
	N6	110	-.31*	90	-.15
	N7	80	.27	70	-.17
	N8	110	.55*	120	-.41*
	N9	70	-.17	70	.24
Subjects		32	-.19	24	-.51
Rate condition		32	-.23	36	.20
Vowel category		32	-.71	36	.54

Table 1. Correlation between jaw and articulator amplitude in dependency of various sources of variance. All systematic sources of variance not specified in the left column have been partialled out prior to computation of Pearson *r*. Significance (*) for repetitions: $p < (0.05 / 17)$, for the remaining sources $p < (0.05 / 2)$

3.3. Jaw - articulator correlation across subjects

A similar correlation analysis as reported in the previous section was performed with the subject means across repetitions. Again, the main effects and interaction of speech rate and vowel category were partialled out, leaving subject variability as the residual source of variance. If all subjects organized their articulation in a similar way, but differed in a global size factor, we would expect strong positive correlations between jaw and articulator amplitude. As shown in the second part of Table 1, correlations tended to be negative rather than positive, in spite of considerable amplitude differences across subjects (see Figure 2).

3.4. Correlations across rate condition and vowel context

Two further correlation analyses of jaw and articulator amplitude were performed with a) the rate condition and b) the vowel context as sources of variability. In these analyses, subject variability, vowel or rate, and the subject × vowel or subject × rate interaction, respectively, were parialled out. As a rule, movement amplitude is smaller in fast as compared to slow speech. If rate, in terms of a global scaling parameter, affected both the jaw and the articulators consistently across speakers, positive jaw - articulator correlations would be expected in case of speech rate as the predominant source of variability. As shown in the third section of Table 1, neither for /p/ nor for /t/ the correlation differed significantly from zero. This indicates that fast speech rate does not consistently reduce jaw and articulator amplitudes across subjects.

In case of vowel context as the source of variability, jaw - articulator correlations were significantly negative for bilabial articulation, but positive for /t/ items (Table 1, bottom line). This indicates that the relative contribution of the jaw and the articulators is organized in a complex vowel- and consonant-specific way, confirming the above findings with respect to the interaction between vowel type and place of articulation.

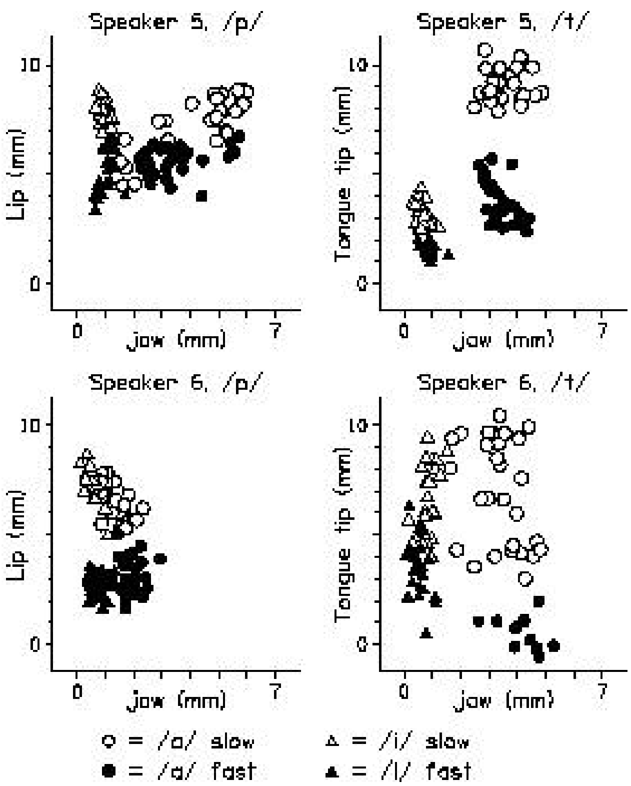

Figure 2. Scattergram of articulator amplitude plotted against jaw amplitude. Each symbol refers to a single syllable.

4. COMMENTS

Assuming that the jaw is associated with vowel rather than consonant gestures, the open vowel /a/ might be characterized predominantly by an increased opening amplitude of jaw movements as compared to /i/ whereas the particular contribution of the articulators to the compound trajectory may show minor /a/ - /i/ differences only. This suggestion was confirmed by the present results with respect to /pa/ and /pi/ articulation, but not for /ta/ and /ti/. Obviously, the lower lip is controlled more independently from the jaw as compared to the tongue tip.

As concerns correlation analysis, highly significant negative jaw - articulator correlations were obtained in some cases when random variability across repetitions was the underlying source of variance, although the results varied across speakers and places of articulation. These inconsistencies suggest that motor equivalence, in terms of negative covariation between subsystems across repetitions of the same item, may indeed occur under some conditions, but does not represent a general principle of speech motor organization. However, negative covariation might reflect the result of simple biomechanical phonomena as well: Assuming, for example, a passive lower lip, then the jaw performs the entire movement, and the compound lower lip - jaw trajectory, due to lip inertia, loose coupling, and dampening, might have a smaller amplitude than the underlying jaw movement, that is, the lower lip would show a pseudo-compensatory behavior. For example, the negative tongue tip amplitudes of the fast /ta/ productions of speaker 6 (see Figure 2) might be caused by this mechanism. Reconsideration of the present data with repect to differential movement amplitudes, however, revealed that the majority of significant correlations as listed in the upper part of Table 1 cannot be explained in this way. Therefore, the presence of motor equivalence, at least with respect to tongue tip and jaw articulation in some subjects, cannot be ruled out. However, considering the inhomogeneous picture across subjects and place-of-articulation conditions, the present results argue against rather than confirm the generalizations made in [21] with respect to lower lip and jaw coordination.

A previous study [22] measured correlations across repetitions in 24 subjects under 12 different conditions and obtained a wide range of - in most cases non-significant - positive as well as negative correlation coefficients. Regarding the distribution of correlation values, the present results show a similar pattern. The lower percentage of significant cases reported in [22] can be explained by the small number (only 8 or 5) of repetitions underlying the computed correlation coefficients. Actually, the histogram of these data as shown in [22] gives the impression of a bimodal distribution. Thus, although the average correlation may not significantly differ from zero, this can be the result of two competing mechanisms, one being motor equivalence and the other representing variability on a superordinate factor affecting both subsystems in the same direction.

In a broader sense, the term motor equivalence may also be used to describe subject-specific strategies. Therefore, jaw-articulator correlations were considered across speaker variability. Assuming that all speakers organize their articulatory behavior in a similar way, but differ in anatomical size in terms of a general size factor, positive correlations between jaw and articulator amplitude must be expected. In spite of considerable subject variability in amplitudes, the present study showed negative correlations across subjects, indicating individual differences with respect to the relation of jaw and articulator amplitudes. Thus, at least to some degree, the differential use of jaw and articulators is organized in a speaker-specific way.

Considering jaw and articulator amplitudes across variation of external control variables such as vowel type or speech rate, correlations are expected to be positive if the amplitude modification affects both subsystems to a comparable degree. Negative values, in contrast, may indicate systematic factor-induced reorganization, and zero values can be observed when the factor-induced reorganization is inconsistent. When speech rate was the source of variability, correlations did not significantly differ from zero, arguing against a global scaling factor influencing both subsystems. As indicated by the above ANOVA results, rate seems to affect articulator rather than jaw amplitudes, but the rate effects were largely inconsistent.

With respect to vowel category as the source of variability, correlations differed in sign across places of articulation: In bilabial gestures, jaw - lower lip correlations were negative, indicating vowel-induced reorganization, whereas in apical gestures jaw - tongue tip correlations were positive indicating a common, vowel-induced scaling factor, confirming Lindblom and Sundberg (1971) in that jaw and tongue constitute a synergism for the production of vowel height.

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