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Articulatory strategies for vowel production in stressed and unstressed syllables

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Abstract
Articulatory data of two German speakers have been analysed within the gestural framework. They indicate that the distance of neutral to gestural target position increases for the lower lip movements of vocalic gestures in stressed vs. unstressed syllables (i.e. extremalization of target position for these gestures) while gestural stiffness increases for one speaker but decreases for the other for these gestures. Since a high stress level is linked with high articulatory effort it can be shown that a lowering of stiffness for stressed versus unstressed gestures must be compensated for by *extremalization of target position.* We conclude that stiffness changes alone cannot lead to a proper description of stress-induced variations of articulation without taking into account variations of other articulatory parameters.

1. Introduction

The problem of stress-induced variation of articulation has been focused within many studies using physiological, kinematic, and dynamic parmeters. While stress controls many parameters in the acoustic domain (i.e. fundamental frequency, overall intensity, spectral composition, segment duration), it has been hypothesized that stress is linked with mainly one feature in the articulatory domain: articulatory effort or physiological energy (Öhman 1967, Gay 1978). Measurements confirmed this hypothesis; thus, the electromyographic activity for stressed gestures increases in duration and peak amplitude in comparison to unstressed gestures (Harris 1971, Tuller et al. 1982). A quantitative definition of articulatory effort is given by Nelson (1983, p. 141): Effort equals the impulse cost of an articulatory gesture which leads to the integral of force per mass acting on the articulator over time (ibid., p. 136) and can be estimated from gestural peak velocity (Nelson 1983, p. 141, Nelson et al. 1984). A phonetic interpretation of effort is given by Lindblom (1983 and 1990). Lindblom (1983, p. 230) introduced "vocal effort" as an underlying phonetic factor which together with duration controls the degree of undershoot: Speakers have the choice to undershoot articulatory targets or not. According to a raise in effort or in the "level of performance of the system" (Lindblom 1983, p. 231) less or no undershoot can occur even if duration of gestural activation is very short: The speaker hyperarticulates in this case (Lindblom 1990). But the normal or preferred mode of articulation (hypospeech mode, which leads to phonetic reductions) is left only if demanded by the situation of communication, i.e. by the listener. Since stressed syllables indicate semantically important parts of the utterance, it is assumed that stressed syllables are produced in the mode of hyperarticulation and therefore with increased effort in comparison to unstressed syllables.

2. The gestural theory

The gestural theory provides an excellent framework for a quantitative interpretation of articulatory measurements (Kelso et al. 1985 and 1986). A gesture can be defined as a goal-directed articulator movement defining a discrete category like "labial closure" or "glottal opening" (Browman and Goldstein 1990 and 1992). The dynamics of gestures can be described by a critically damped linear second order dynamic system, i.e. by a critically damped harmonic oscillator (Hawkins 1992, Saltzman and Munhall 1989). The gestural parameters can be divided into kinematic and dynamic parameters. The kinematic gestural parameters (figure 1a) are (1) peak velocity v_{max} indicating the maximum velocity in the temporal center of the gesture, (2) displacement at the end of the gesture (end displacement) y_{end} indicating the maximum displacement reached by the gestural articulator movement, (3) peak-to-peak displacement dy_{pp} indicating the gestural displacement amplitude, and (4) peak-to-peak time dt_{pp} indicating the duration of the gestural movement. The dynamic gestural parameters (figure 1b) are target position y_{tg}, eigenperiod T_0, phase value of peak velocity pha_{vp} and end phase value (phase value at end of gesture) pha_{end}. The dynamic parameters are directly related to our quantitative dynamic concept of gestures (Kröger 1993 and Kröger et al. 1995). These parameters can be compared to dynamic gestural parameters defined by other authors. It must be remarked that eigenperiod is a measure of gestural stiffness, but quantitatively reciprocally proportional to stiffness (Kröger 1993).

(1a)

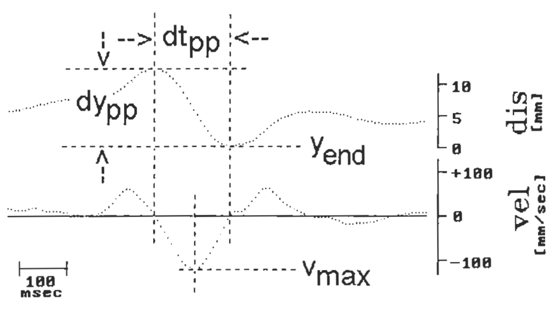
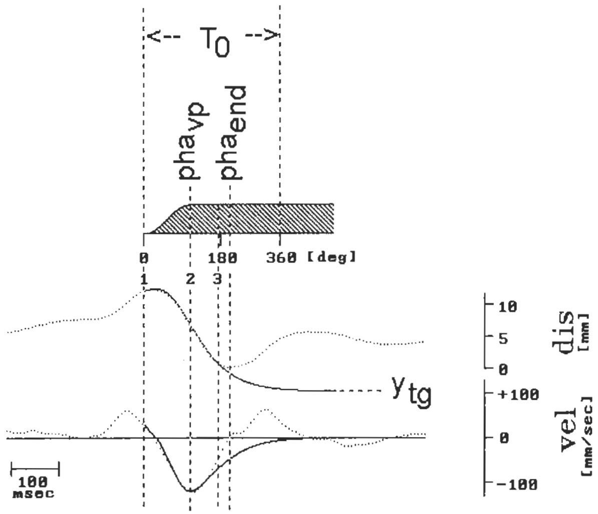


Figure 1 (a) Measurement data (articulatory displacement and velocity as functions of time) and for an opening gesture. The kinematic extrema of this gesture are indicated by dashed lines. **(b)** (next page) Gestural model fit for the same opening gesture. The shaded area indicates gestural activation. Gestural phase values are given in degrees. Mark 1 (3) indicates beginning (end) of fit interval; mark 1 (2) indicates beginning (end) of gestural onset interval.

(1b)



It should be noted that y_{end} is a kinematic parameter indicating the articulator displacement which is *effectively reached* by the gesture-executing articulator, while target position y_{tg} is a parameter stemming from our quantitative dynamic gestural model indicating an *ideal or "virtual"* target position, which is never reached by gestures occuring in fluent or casual speech (Kröger 1993 and Kröger et al. 1995, see also Browman and Goldstein 1990 and 1992 and Hawkins 1992).

Articulatory effort as defined by Nelson (1983) is proportional to gestural peak velocity and equals the total (physical) impulse transferred on the articulator by the gesture (Kelso et al. 1985, p. 273). This definition describes the effort stemming from accelerating the articulator from an initial position (i.e. a position near the target of the preceding gesture) towards its (new) gestural target postion. Beside this *dynamic* component of effort, we assume that *static* effort should be introduced within an overall gestural-linguistic concept to account for the effort of holding a characteristic vocal tract constriction. Static effort differentiates types of vocal tract constrictions: For example the effort of holding a near closure (for a fricative) is likely to be higher than the effort of holding a full closure (for a plosive or nasal). But in this paper we will focus on the dynamic component of effort. A quantitative expression for articulatory effort, which is closely related to the definition of articulatory effort given by Nelson (1983), has been developed for our quantitative gestural model (Kröger 1997). This expression for effort indicates that effort increases with increasing stiffness and with extremalization of target position.

3. The kinematics and dynamics of articulation for the stressed-unstressed-contrast

The articulatory effects of stress on kinematic parameters are well known. Articulatory measurements indicate an increase in displacement magnitude, duration, and peak velocity for stressed in comparison to unstressed gestures (Kent and Netsell 1971, Stone 1981, Ostry et al. 1983, Kelso et al. 1985). But the analysis of the influence of stress on articulation using dynamic parameters leads to different results. On the one hand, it has been found that unstressed gestures are characterized by higher stiffness values than stressed gestures (Ostry et al. 1983, Kelso et al. 1985, Smith et al. 1993) while the relative timing of gestures (gestural phasing) remains unchanged (Tuller and Kelso 1984, Kelso et al. 1986). On the other hand, the assumption of stable phase relations was rejected since it has been found that gestural overlap decreases in stressed syllables in comparison to unstressed syllables, resulting in an enhancement of the hold portion of gestures for stressed syllables (Nittrouer et al. 1988, Beckman 1991, Beckman et al. 1992, Harrington et al. 1995).

4. Material and method

Our data corpus was collected from two adult speakers (CO, female, 29 years old; DM, female, 26 years old; both native speakers of German with no known speech anomalies). The speakers produced four repetitions of the sentence "Ich habe [CV:CəCV:] betont" ("I have stressed [CV:CəCV:]") with [V:] = [a:], [E:], [e:], [i:] and [C] = [b], [p], [m]. Each vowel was combined with each consonant (only identical vowels and identical consonants per logatome: 12 cases) and sentence stress was varied (['CV:CəCV:] and [CV:Cə'CV:]). We analysed the articulatory traces of the lower lip movement of the first and the last vocalic gesture of the logatomes for each speaker (N=192 per speaker: 4 vowels × 3 consonants × 2 stresses × 2 positions × 4 repetitions).

The articulator movements were tracked by an alternating magnetic field device, the Articulograph AG-100 (Carstens Medizinelektronik GmbH, Lenglern, Germany; for a description and evaluation of the device see Schönle et al. 1987, Tuller et al. 1990 and Perkell et al. 1992, p. 3093f, Hoole 1993). Receiver coil placement and the analysis procedure for parameter estimation is described by Kröger et al. (1995). The acoustic signal was recorded simultaneously (16bits, 16kHz). The kinematic and dynamic gestural parameters described above were measured for each gesture. The kinematic parameters are taken from the main movement component of the (cubic-spline-smoothed) receiver coil displacement-over-time curves (see Kröger et al. 1995, p. 1884f). The dynamic parameters were estimated by our gestural fitting procedure (procedure I, see Kröger et al. 1995, p. 1883).

5. Results

Analyses of variance were performed for all parameters in order to evaluate the effects of vowel (df=3,191), consonant (df=2,191), stress (df=1,191) and position (df=1,191) for each speaker. A four-way-ANOVA has been executed for each speaker (table 1). Since we are interested especially in stress-induced parameter variation, one-way-ANOVAs have been executed for the factor stress in the case of significant interactions which include this factor (table 2).

The main results for the factor stress are as follows: (1) For both speakers the main effects of stress are significant for all kinematic parameters and for the dynamic parameter target position (table 1). In the case of eigenperiod and end phase significance is lost for the factor stress for speaker DM and for the phase value of peak velocity for both speakers. For most parameters some of the main effects of the other factors (vowel, position, consonant) are also significant. (2) The two-way-interactions without the factor stress (vowel × position, vovel × consonant, position × consonant) reach significance in some cases while two-way-interactions including the factor stress (stress × vowel, stress × position, stress × consonant) reach significance only for peak-to-peak displacement for speaker DM and for peak velocity and eigenperiod for both speakers (table 1). Three-way and four-way-interactions reach significance only in few cases. (3) Interactions have been analysed in detail only for the cases including the factor stress. These results are summarized in table 2 for all kinematic and dynamic parameters reaching significant effects for stress for the whole or part of the corpus. These main effects (table 2, column 3) indicate the direction of change for a parameter in the case of the stressed-unstressed-contrast: higher peak-to-peak time, higher peak-to-peak displacement, higher peak velocity, lower end displacement, lower target position for both speakers for stressed than for unstressed gestures; higher eigenperiod for speaker CO and lower eigenperiod for speaker DM for stressed than for unstressed gestures. The effect of eigenperiod for speaker DM reaches significance only for consonant /b/ (i.e. one third of the corpus). All interactions reaching significance and including the factor stress are listed in column 4. The examination of all subcases defined by these interactions (critical subcases) indicates that only for the parameter peak velocity for speaker DM a significant subcase (/CV:/=/pe:/ in the third syllable of the logatome, see table 2, column 7) occurs, which does not reproduce the tendency of the main effect. This subcase comprises 8 out of 192 analysed gestures. Thus for nearly all parameters and all speakers the main effects are reproduced by all subcases reaching significance for the stressed-unstressed-contrast (see table 2, column 7). Subcases and the appertaining levels of significance are listed for two-way interactions including the factor stress in detail (table 2, column 5). For all significant subcases defined by these two-way interactions the tendency of the main effect is reproduced.

table 1a

parameter	dt_{pp}		dy_{pp}		v_{max}		y_{end}	
speaker	CO	DM	CO	DM	CO	DM	CO	DM
st	***	***	***	***	***	***	***	***
vo	***	***	***	***	***	***	***	***
po	....	....	....	***	**	....	....	***
co	***	....	....	***	***	***	....	**
st×vo	....	....	....	*	....	....	....	....
st×po	....	....	....	....	....	....	....	....
st×co	....	....	....	....	**	*	....	....
vo×po	*	**	....	***	....	***	....	*
vo×co	*	*	*	....	**	....	*	....
po×co	***	....	....	*	***	*	....	....
st×vo×po	....	....	**	....	....	....	*	....
st×vo×co	....	....	....	....	....	....	....	....
st×po×co	....	....	....	....	....	....	....	....
vo×po×co	....	....	....	....	....	....	....	....
st×vo×po×co	....	....	....	....	....	*	....	....

table 1b

parameter	dt_{pp}		dy_{pp}		v_{max}		y_{end}	
speaker	CO	DM	CO	DM	CO	DM	CO	DM
st	***	***	***	....	....	....	*	....
vo	***	***	**	**	*	**	....	....
po	***	**	....	*	....	....	....	....
co	***	***	*	***	**	....	*	....
st×vo	....	....	....	....	....	....	....	....
st×po	....	....	....	....	....	....	....	....
st×co	....	....	**	*	....	....	....	....
vo×po	....	*	*	....	....	....	....	....
vo×co	*	....	*	....	....	....	....	....
po×co	....	....	**	...	**	....	....	....
st×vo×po	*	....	....	....	....	....	....	....
st×vo×co	....	....	....	....	....	....	....	....
st×po×co	....	....	....	....	....	*	....	....
vo×po×co	....	....	....	....	....	....	**	....
st×vo×po×co	....	....	....	**	....	....	....	....

Table 1 Levels of significance (four-way-ANOVA) for factors stress, vowel, position and consonant (st, vo, po, co) for all kinematic and dynamic parameters for each speaker. (***: $p<0.001$, **: $p<0.01$, *: $p<0.05$, ...: not significant).

parameter	speaker	main effect	interactions	cases of TWI	level	negative cases	level
dt_{pp}	CO	>	none				
	DM	>	none				
dy_{pp}	CO	>	st×vo×po			none	
	DM	>	st×vo	/a:/, /ε:/	***	none	
				/e:/, /i:/	***		
v_{max}	CO	>	st×co	/b/, /m/	*	none	
				/p/	....		
	DM	>	st×co	/b/	***	none	
				/p/, /m/	*		
			st×vo×po×co			/pe:/(syll3)	*
y_{end}	CO	<	st×vo×po			none	
	DM	<	none				
y_{tg}	CO	<	st×vo×po			none	
	DM	<	none				
T_0	CO	>	st×co	/b/	....	none	
				/p/	***		
				/m/	*		
	DM	(<)	st×co	/b/	*	none	
				/p/,/m/	....		
			st×vo×po×co			none	
pha_{end}	CO	<	none				

Table 2 Analysis of interactions for four kinematic parameters and the dynamic parameters target position and eigenperiod for both speakers. Column 3: The main effect indicates the direction of the change of parameter values (< (>): decrease (increase) in values for stressed versus unstressed gestures); Column 4: Significant interactions including the factor stress; Column 5 and 6: All cases for two-way interactions and levels of significance; Column 7 and 8: Cases not reproducing the tendency of main effect and levels of significance. Levels of significance: ****: $p<0.0001$, ***: $p<0.001$, **: $p<0.01$, *: $p<0.05$, ...: not significant.

Since the main effects of stress are widely reproduced also for the critical subcases indicated by significant interactions, mean values for each speaker and each vowel for stressed and unstressed gestures can be interpreted for the four kinematic parameters and for the dynamic parameters target position and eigenperiod (figure 2): (1) For both speakers, peak-to-peak displacement, peak-to-peak time, and peak velocity is higher for stressed versus unstressed gestures. (2) End displacement and target position are lower for stressed versus unstressed gestures. Hence the distance between these positions and the lip closure position is enlarged for stressed in comparison to unstressed gestures and hence target position and displacement maximum are further away from the closure position (i.e. are located in a lower position) in a stressed than in an unstressed gesture. (3) Eigenperiod exhibits different tendencies for both speakers. There is an increase in eigenperiod for speaker CO and a decrease for speaker DM for stressed versus unstressed gestures. (4) The mean values for the phase value of peak velocity are 102^0 for speaker CO and 88^0 for speaker DM and those for the end phase are 204^0 for speaker CO and 162^0 for speaker DM. In the case of speaker CO significiant differences occur for the factor stress for the end phase value. The mean values are 196^0 for the stressed and 212^0 for the unstressed gestures.

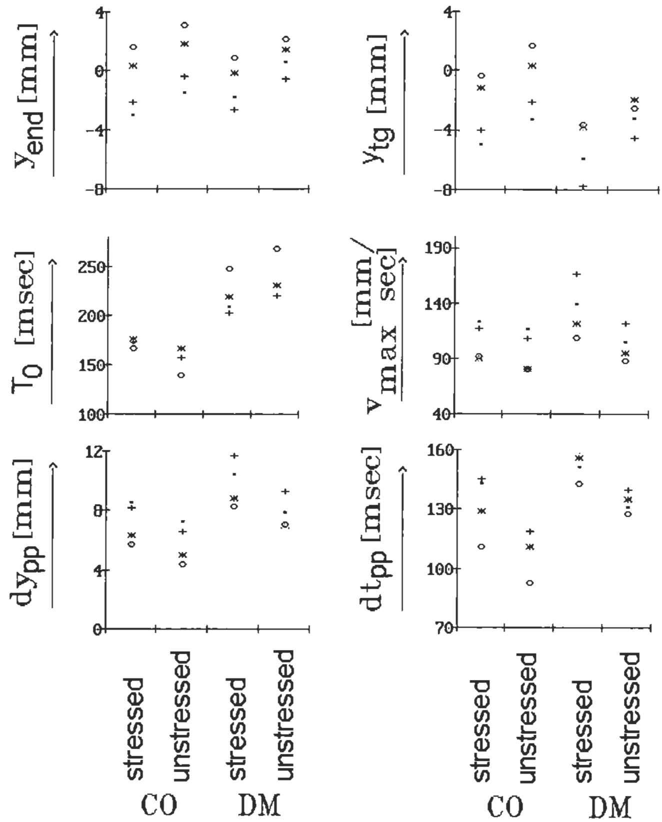


Figure 2 Mean values for end displacement y_{end}, target position y_{tg}, eigenperiod T_0, peak velocity v_{max}, peak-to-peak displacement dy_{pp} and peak-to-peak time dt_{pp} for each speaker (CO and DM) and for each vowel (. = /i:/, * = /e:/, + = /ɛ:/, o = /a:/) in the stressed and unstressed case. The direction towards negative values for y_{ex} and y_{tg} indicates lip opening.

Articulatory effort (Kröger 1997) has been calculated for all measured gestures within this corpus. The correlation of gestural peak velocity and articulatory effort is high for the whole corpus over both speakers (k=0.86, p<0.001). A scatter plot of effort and peak velocity (figure 3) and mean values for peak velocity and articulatory effort for each speaker and each vowel for the stressed and the unstressed case are given (table 3).

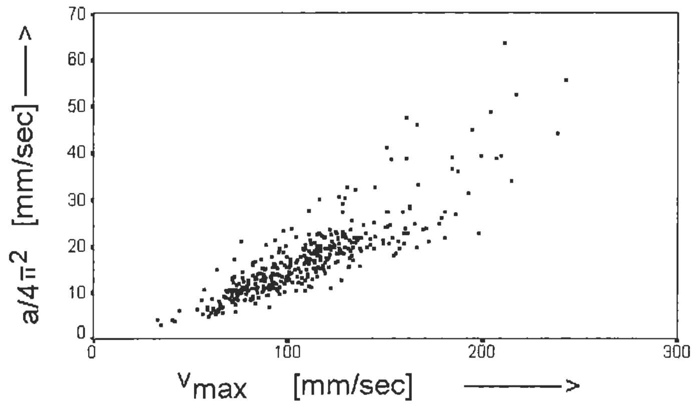


Figure 3 Articulatory effort a as a function of peak velocity v_{max} for each gesture analysed within the corpus for both speakers.

para-meter	$a/4\pi^2$ [mm/s]				v_{max} [mm/s]			
stress	stressed		unstressed		stressed		unstressed	
speaker	CO	DM	CO	DM	CO	DM	CO	DM
/a:/	20.8	23.2	18.7	14.4	123	139	117	105
/ɛ:/	20.2	30.6	16.7	18.0	118	166	108	122
/e:/	13.7	20.7	11.4	15.6	90	119	81	97
/i:/	13.4	15.8	12.4	10.9	92	109	81	88

Table 3 Mean values of articulatory effort a and mean values of peak velocity v_{max} for speaker CO and DM for the corpus separated by factors vowel and stress.

6. Discussion

Our results are widely in agreement with the experimental results given by other authors: The mean values for peak-to-peak displacement, peak-to-peak time and peak velocity estimated from our measurement data increase with increasing stress level (see also Ostry et al. 1983, Kelso et al. 1985). Increasing peak velocity indicates increasing articulatory effort for stressed versus unstessed gestures (see also Nelson 1983). End displacement and target positions are lower (more extremal, i.e. higher distance in comparison to the lip-closure position) in the stressed than in the unstressed case. Eigenperiod shows different tendencies for both speakers. The measured increase in eigenperiod (i.e. decrease in stiffness) for stressed versus unstressed gestures for speaker CO is in accordance with measurement data using alternative approaches for stiffness estimation (Ostry et al. 1983, Kelso et al. 1985, Smith et al. 1993). Since the end phase value decreases slightly for speaker CO for stressed versus unstressed gestures, the increase in peak-to-peak time is mainly achieved by an increase in eigenperiod (i.e. decrease in stiffness) for this speaker. The increase in kinematic peak-to-peak time for stressed versus unstressed gestures for speaker DM can be modeled in the gestural approach only by assuming that the decrease in eigenperiod is compensated by a decrease in the temporal overlap of gestures. This tendency for gestural phasing (i.e. for the relative timing of gestures) was postulated by Beckman (1991) and Beckman et al. (1992). But this hypothesized effect for the end phase values does not reach significance in our corpus.

In contrast to Smith et al. (1993) our findings do not support assumptions that one dynamic parameter (gestural stiffness or gestural phasing) alone is responsible for the articulatory processes accomplishing the stressed-unstressed-contrast. Moreover our results indicate that a further underlying gestural parameter and an appertaining gestural process - i.e. the extremalization of target postions - must be taken into account in order to understand the articulatory processes involved in stress level changes. The model of articulatory effort developed above indicates that it is the *target extremalization* that compensates the decrease in stiffness for stressed versus unstressed gestures in order to reach a higher effort level (speaker CO). Thus, stress is not related to a particular gestural parameter but strongly related to the level of articulatory effort: A decrease in stiffness (increase in eigenperiod) - leading to a decrease in effort if all the other gestural parameters are kept constant - only occurs for stressed versus unstressed gestures *if target extremalization is strong enough to compensate this effect*, i.e. to increase the effort of the gesture.

The effort values calculated by our quantitative approach for each gesture show high correlation with peak velocity for all gestures as postulated by Nelson (1983). This underlines the accuracy of the quantitative expression for articulatory effort developed by Kröger (1997). Our quantitative expression for effort indicates that effort is reciprocally proportional to eigenperiod squared and hence increases with decreasing eigenperiod (i.e. increases with increasing stiffness). Secondly, effort increases with increasing extremalization of target position since this extremalization increases the instantaneous articulator-target distance. The numerical values of effort are much higher than peak velocity values (table 3) for two reasons. Firstly, the losses of energy due to critical damping are not included; the calculated values for effort only indicate the energy transferred on the articulator by the gestural force field (Kröger et al. 1995, Kröger 1997). Secondly, only the energy transferred on the articulator by the gestural force field prior to the time instant of the velocity peak contributes to the amount of peak velocity.

As quoted above, mainly stiffness (Ostry et al. 1983, Kelso et al. 1985, Smith et al. 1993) and phasing (relative timing) of gestures (Tuller and Kelso 1984, Nittrouer et al. 1988, Beckman et al. 1992) have been focused in other approaches, while the gestural target position has not. Only Browman and Goldstein (1990, p. 372f) suggest that the measured increase in gestural peak-to-peak displacement may result from extremalization of target positions. We attribute this neglect of the gestural target values to two factors. Firstly, many measurement techniques cannot estimate gestural target positions since the dynamic models used for measuring gestural parameters are too simple (see Hawkins 1992, p. 14ff for a discussion of critical damping for gestural models, of modelling gestural target positions, and of phase value calculation). Within these approaches, the equilibrium position of the second order system indicates the rest position of the articulator and not the equilibrium position defined by the gesture. Secondly, traditional phonetic theory leads to the notion that target positions define the phonetic identity of gestures (place and manner of articulation) and therefore remain constant under prosodic or paralinguistic transformations. But since target extremalization does not change gestural movement direction and since gesture-induced end displacement is defined by clipping values rather than by (virtual) target positions (see Kröger 1993), target extremalization does not affect the phonetic identity of gestures.

Further measurements based on our quantitative gestural approach will be undertaken in order to investigate other prosodic and extralinguistic transformations (e.g. final lengthening and speech rate); target extremalization will be studied by analysing more types of gestures including tongue tip and tongue body gestures.

Acknowledgements
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