

Chapter 5

IMPLICATIONS OF THE CONCEPTS UNDERLYING TASK-DYNAMIC MODELING ON KINEMATIC STUDIES OF STUTTERING

Peter J. Alfonso

The assigned task is to demonstrate how the concepts underlying task-dynamic modeling can improve our understanding of speech motor organization in those who stutter. The discussion focuses on the principles underlying, and the results of experiments that have centered upon, certain organizational principles of skill motor behavior. Based on the results of experiments of this type, the following assumptions are drawn: (1) the stutterers' speech motor system exhibits generalized spatio-temporal dysfunction and (2) the dysfunction occurs at a level of motor control that is generally responsible for spatio-temporal organization of all skilled motor activities. This implies that the disorder of stuttering is associated with, in addition to the linguistic factors that are encoded in speech movements and the behavioral influences which might mediate them, irregularities at a rudimentary and pre-linguistic level of motor control. An example of how these assumptions can be tested by task-dynamic modeling is given.

This paper will discuss how the concepts underlying task-dynamic modeling can help us understand better speech motor control in those who stutter. To this end, I discuss the results of a select body of research that explores the motor organization of speech by stutterers, and conclude that the research suggests that perceptually fluent speech gestures produced by stutterers do not follow certain general principles of motor organization in human behavior. The discussion will be limited to stutterers' speech that is perceived to be fluent, partly because of time constraints, but more importantly because it is not clear whether stutterers' speech movements during their perceptually fluent speech, and by inference their control of the speech mechanism, are different, in some way, from nonstutterers. First, some experimenters have concluded that stutterers' perceptually fluent speech is not different than control subjects' fluent speech, while other experimenters think that it is (see, for example, Van Riper, 1982, Chapter 16; Bloodstein, 1987, Chapter 1).

Although there are a number of reasons why the results of experiments on stutterers' perceptually fluent speech are in conflict, the conflicting results are undoubtedly confounded by the general lack of adequate definitions and criteria

for distinguishing among certain essential characteristics of stuttering, for example, involuntary dysfluency and perceptual fluency. This issue is discussed recently in considerable detail in "Research needs in stuttering: Roadblocks and future directions" (Cooper, 1990) and need not be elaborated here.

A second reason for the conflict in the results is that most of these experiments are based on perceptual and speech acoustic data, and few include kinematic and neuromuscular data in parallel with perceptual and acoustic, although it is generally the case that perceptual and acoustic data in the absence of simultaneously gathered physiological data are not sufficient to answer questions about speech motor control. This is a significant problem with regard to the fluency issue because while a segment of stutrer's speech may appear normal or "fluent" at the perceptual level, it may appear abnormal or "dysfluent" at the acoustic, and/or movement and muscular levels (Alfonso et al., 1984; Baer & Alfonso, 1984; Shapiro, 1980).

A third reason for the conflict in the results of the reported literature is that the routinely posed form of the question, "Is stutterers' fluent speech similar to the fluent speech of adults who do not stutter," is too broad. It is likely that certain aspects of speech do not differentiate the groups while other aspects do differentiate the groups. Using respiratory comparisons as an example, Baken et al., (1983) found no differences between stutterers and control subjects in chest wall preposturing maneuvers immediately preceding fluent speech. Yet, significant group differences in subglottic pressure (e.g. Lewis, 1975; Peters & Boves, 1988), flow rates (e.g. Hutchinson, 1975), and lung volume change and deflation for speech (e.g. Watson & Alfonso, 1987; Story, 1990) have been observed. Thus, it might be that stutterers and normal speakers perform certain speech respiratory gestures in a similar fashion, for example, respiratory preposturing, but that other aspects of speech respiration, for example, the magnitude of the inspiratory charge, are performed differentially. With respect to task-dynamic modeling, the concepts underlying the current version of the model would be appropriate for addressing specific questions about supralaryngeal articulation, but not speech production in general.

A fourth reason for the conflict in the results of these types of experiments, and the one most pertinent to the main focus of this paper, is that group comparisons are frequently based on physiological data that reflect relatively variant phonetic level speech gestures. Group data based on phonetic level contrasts are inherently unstable since spatial and temporal control of the speech structures to mark phonetic distinctions varies as a function of phonetic context, stress and rate, dialect, and individual speaker preferences. Rather, we need to make group comparisons based on relatively stable spatial and temporal characteristics of normal speech dynamics, for example, those that best reflect organizational principles of speech motor control (Alfonso et al., 1986, 1987a,b; Caruso et al., 1988).

Dynamic parameters that are relatively invariant across multiple productions of an utterance are thought to be good representatives of speech motor control

parameters (e.g. Gracco & Abbs, 1986) and form the bases for the notion of coordinative structures, from which task-dynamic, and other models of speech production, are empirically formed. Implicit in this notion is that the individual articulator components comprising a multiarticulate gesture are functionally linked into coordinative systems. These relatively stable spatial and temporal characteristics could also serve as criteria for distinguishing between a normal or fluent motor system and an abnormal or dysfluent motor system. Examples of stable dynamic parameters that could serve as criteria are; (1) displacement/velocity ratios and peak velocity profiles, (2) motor equivalence covariability, and (3) interarticulator relative-timing and sequence patterns.

As an example of the first criterion, the kinematics associated with the individual articulator components that comprise, for example, an alveolar closure gesture, the tongue tip and tongue blade, and the jaw in this example, as well as the alveolar gesture itself, that is, the additive contribution of the anterior tongue and the jaw, should demonstrate smooth and single peaked velocity profiles. On the other hand, group comparisons based solely on the amplitudes of the individual articulator displacements, particularly in the absence of other related movement data, should be treated with some degree of caution since speakers achieve alveolar closure gestures with distinctly different contributions of individual tongue and individual jaw displacement, thus reflecting idiosyncratic speaker preference rather than a general speech motor characteristic common to all speakers within the group.

A second criterion would focus upon the organization of the relative tongue-jaw displacement, that is, to determine whether the gesture demonstrates motor equivalence covariability, which reflects the way in which the motor system reorganizes itself enroute to a task goal when faced with either internal or external perturbations. In normal fluent motor systems, when one structure in coordinated movement is perturbed, a response will be observed in all structures to which the perturbed structure is linked by a common task. The two ways in which motor equivalence is generally assessed reflects the motor systems response to internal or external perturbations. With respect to the motor system response to internal perturbations, in repeated-trial tasks, the magnitude of the variability associated with the displacement of the vocal-tract gesture, the alveolar closure in this example, should not be greater than either of the magnitudes of the variabilities associated with the individual articulator displacements comprising the gesture, the tongue and the jaw in this example. A second way that is often used to test motor equivalence is the traditional perturbation paradigm, where an unexpected external force is applied to a speech structure. In the example of the alveolar closure gesture, an external perturbation applied to the jaw should elicit a compensatory response to the anterior portion of the tongue but not in the lower lip.

The third criterion focuses primarily on certain temporal characteristics of speech, specifically, on inter-articulator relative-timing and sequencing, since in normal systems consistent latencies among and ordering of articulator movements are observed in specific phonetic contexts.

REVIEW OF RESEARCH FINDINGS

There are relatively few, but all recent studies, that have examined these types of parameters in stutterers' perceptually fluent speech. Of course, we need to ascertain what the values of these parameters are before we can implement task-dynamic modeling, or any other physiological based model for that matter, to improve our understanding of stutterers' speech motor control. In what follows, I will first discuss the results of some of these experiments, primarily to demonstrate examples of data that could be used as certain dynamic parameters of the model. Because of the significant differences in various aspects of these experiments, for example, in the methodology, speech tasks such as phonetic context and rate, numbers and severity of stutterers and their therapeutic histories, and to a lesser extent the instrumentation, a comparison of the results is not, in all cases, straightforward. Because of this, I will begin each topic by first discussing the differences in the experiments reported by Caruso, Abbs and Gracco (1988) and Alfonso, Story, Watson (1987a,b). I do this primarily because they were among the first experiments specifically designed to examine the motor control parameters referred to above, and because they represent, in some cases, the extreme differences in the results, they serve as a good point of departure in regards to the ubiquitous intersubject variability issue that is generally observed in stutterers, and in some cases, control subjects' data. Lastly, I will demonstrate some of our early attempts to use task-dynamic modeling by modifying certain dynamic parameters of the model to conform with data obtained from our experiments that

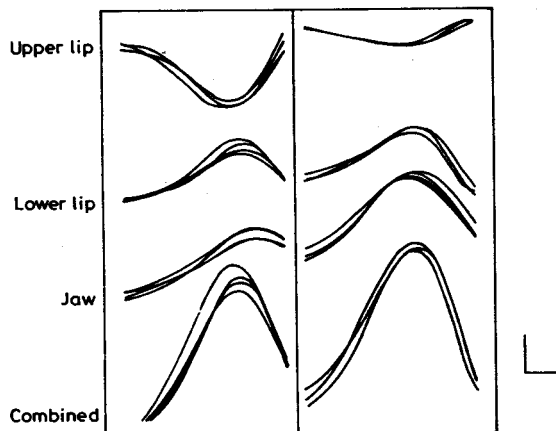


Figure 1. Taken from Caruso, Abbs & Gracco (1988). Superimposed velocity profiles for upper lip, lower lip, jaw, and combined closing movements (4 trials) for the first "p" in "sapapple" for 1 normal speaker (left) and 1 stutterer (right). Individual movements and the combined signal for both the stutterer and the normal speaker manifested single-peaked velocity patterns. Horizontal and vertical calibrations represent 20 ms and 70 mm.s, respectively.

investigated adult stutterers' tongue and jaw movements in perceptually fluent speech (Alfonso et al., 1987a,b).

Turning to the first criterion, where single-peaked velocity profiles serve as an index of coordinated multiarticulator systems, Figure 1 shows velocity profiles for upper lip, lower lip, jaw, and combined movements for the closing gesture in the first /p/ in "sapapple" taken from Caruso, Abbs and Gracco (1988). In this experiment, the movements of the lips and jaw were transduced by means of strain-gauges attached to light-weight head-mounted cantilever beams. The trajectories on the left are from a normal speaker and the trajectories on the right are from a stutterer. Note that the velocity profiles for each of the articulators and the combined signal, which represents a labial closing gesture here, is characterized by smooth and singled-peaked velocity profiles indicating that stutterers are capable of organizing, in the spatial and temporal domains, the movements of the individual articulators to yield well-coordinated labial closure and release gestures.

Figure 2 shows a different view of peak velocity and is taken from Alfonso, Story, Watson (1987a). The figure shows peak vertical displacement amplitude by derived peak velocity for lower lip, tongueblade, and jaw movements during

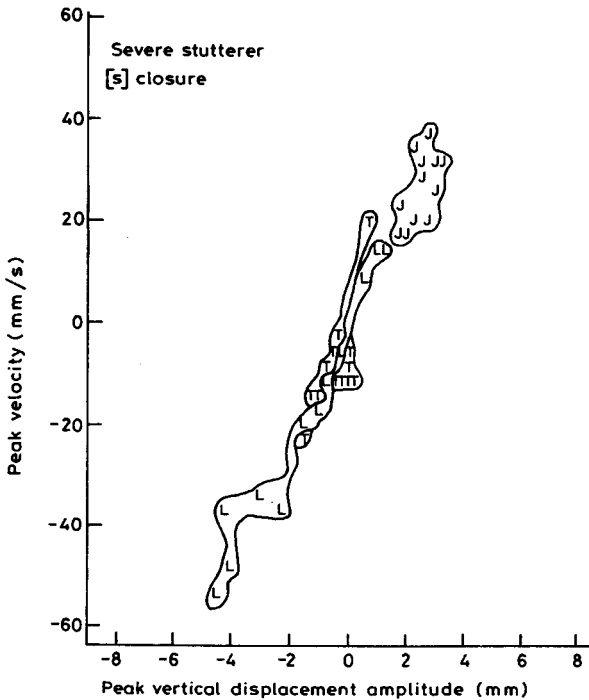


Figure 2. Taken from Alfonso, Story & Watson (1987). Peak vertical displacement amplitude by derived peak velocity for lower lip (L), tongue blade (T), and jaw (J).

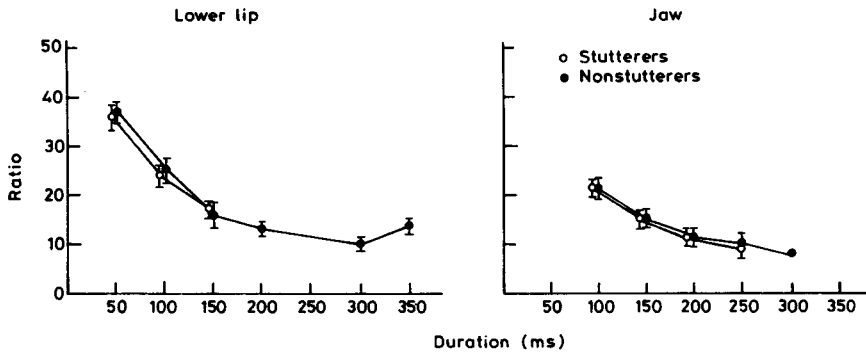


Figure 3. Taken from De Nil and Abbs (1989a). Ratio of peak velocity/displacement by closure duration.

initial /s/ closure in multiple productions of /esese/ for a single severe stutterer. Articulator displacement was derived by the x-ray microbeam pellet tracking system at the University of Tokyo. Small lead-pellets were glued to the lips, tongue, and jaw for this purpose. For the sake of clarity, the data points associated with the movement of each structure have been enclosed within solid lines. Note that the same general relationship between displacement amplitude and peak velocity previously reported for limb movements and lip-jaw movements holds for these data as well (Kelso et al., 1985). That is, peak velocity varies directly with displacement amplitude; for example, peak velocity increases as displacement amplitude increases. The correlations for peak displacement amplitude and peak velocity for stutterers and controls in this experiment varied from .89 to .95. Table 1, taken from De Nil & Abbs (1989a), shows similar results for lip and jaw movements, which were transduced by a strain-gauge system similar to that in the Caruso experiment. The figure shows velocity/displacement ratios across variable speech rates and demonstrates that both stutterers and control subjects scale peak velocity as a function of the intended displacement amplitude.

All of these data support the notion that certain displacement and velocity characteristics of stutterers' perceptually fluent speech, particularly with respect to individual articulator movements, are not distinguishable from the same characteristics of non-stutterers' fluent speech. However, intersubject variability is very high, particularly for stutterers, and seems to be related primarily to stuttering severity, therapy influence, and speech rate. I will return to the influence of these variables on stutterers' speech movements later.

The second criterion centers on the demonstration of motor equivalence covariability. The coefficient of variation (CV), the ratio of the standard deviation and the mean, is often used here because it permits a comparison of displacement variability among different speech structures despite differences in absolute displacement for each of the structures. Table 1 is taken from the Caruso et al.

(1988) experiment and shows the CV's for the closing gesture associated with the first /p/ in "sapapple". Recall that a well-coordinated multi-articulate system would demonstrate less variability for the vocal-tract gesture, the combined signal here, relative to the variability associated with each of the articulator members of the gesture, the upper and lower lip, and the jaw in this example. The figure shows that the CV for the combined signal (C) is smaller or equivalent to any of the CV's for the individual articulators (UL, LL, J) for both the stutterers and the controls and suggests that both stutterers and controls demonstrate comparable levels of motor equivalence covariability.

Table 1. Taken from Caruso, Abbs & Gracco (1988). Coefficients of variation of the peak closing displacement for ear speech structure and the combined signal.
 n= number of movements; UL= upper lip movement; LL= lower lip movement; J= jaw movements; C= combined signal.

CONTROLS						
	N1 n=176	N2 n=173	N3 n=175	N4 n=168	N5 n=71	N6 n=119
UL	0.204	0.303	0.149	0.125	0.095	0.251
LL	0.160	0.159	0.116	0.181	0.103	0.210
J	0.255	0.154	0.214	0.167	0.266	0.262
C	0.136	0.138	0.113	0.104	0.092	0.186
STUTTERERS						
	S1 n=153	S2 n=172	S3 n=175	S4 n=124	S5 n=137	S6 n=172
UL	0.113	0.185	0.129	0.259	0.327	0.225
LL	0.067	0.123	0.149	0.132	0.078	0.124
J	0.197	0.172	0.114	0.206	0.139	0.138
C	0.069	0.123	0.090	0.105	0.083	0.086

Figure 4 shows a different result. These data are taken from the Alfonso et al. (1987a) experiment and represent the weighted average CV's for closure and release alveolar gestures, namely the alveolar obstruents /t,s,n/. The control subject demonstrates motor equivalence. The magnitude and the relative patterns of the control subject's data for alveolar obstruent closure and release gestures are equivalent to the lip-jaw CV's for the first /p/ in sapapple by a large group of control subjects reported by Gracco and Abbs (1986). Notice, however, that the stutterers' data are quite different. The combined CV is greater than the CV associated with jaw movements, and the CV associated with tongue movements is the largest of all. These data do not support the idea that stutterers control functionally linked articulators in such a way that would result in invariant gestural goals.

What can account for the differences in the results observed in these two

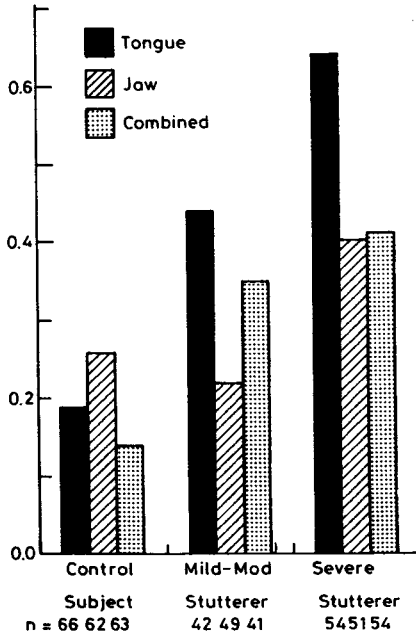


Figure 4. Taken from Alfonso, Story & Watson (1987). Weighted average coefficients of variation for tongueblade, jaw, and combined tongue-jaw peak vertical displacement amplitude.

experiments? Some possibilities are rather obvious. For example, the subjects in the Caruso et al. (1988) experiment, which included five stutterers, repeated the word "sapapple" at a normal rate while the subjects in the Alfonso et al. (1987a) experiment, which included only two stutterers, produced the nonsense words /etete, esese, enene/ in a reaction-time task. The difference may be due to the relatively fast speech rate, the task, and the small number of stutterers in the Alfonso et al. (1987a) experiment, as well as other parameters that I will mention later. However, differences in the relative displacement of the individual articulators

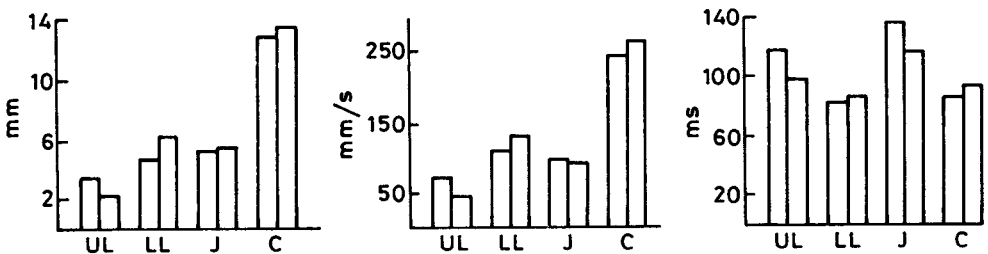


Figure 5. Taken from Caruso, Abbs & Gracco (1988). Bar diagrams of UL, LL, J and C movement characteristics (displacement (left), peak velocity (middle) and duration (right) for the 6 stutterers and 6 normal subjects. The vertical lines represent + 1 SEM. Normal subjects (leftmost bar): stutterers (rightmost bar).

between the two groups of stutterers would seem to represent a significant contribution to the disparity in the results. Figure 5 shows that both controls and stutterers in the Caruso et al. (1988) experiment enlisted comparable amounts of displacement for both the lips and the jaw and the combined signal. While several of the group differences, including the combined signal for displacement and velocity, reached statistical significance ($p = .443$), the actual group differences were small. Recently, McClean, Kroll, and Loftus (in press), who also measured lip and jaw movements for /p/ closure in "sapapple", found no significant differences in the same displacement and velocity characteristics between controls and stutterers who had no history of speech therapy. However, significant group differences were found in stutterers who had recently completed therapy, although the differences were in articulator latency and in the duration of jaw movements and were most likely related to slower posttherapy speech rate. Contrary to these results, however, Figure 6 shows that the spatial organization of obstruent closure and release gestures (for simplicity, only /t/ and /s/ closure are shown here) is clearly different

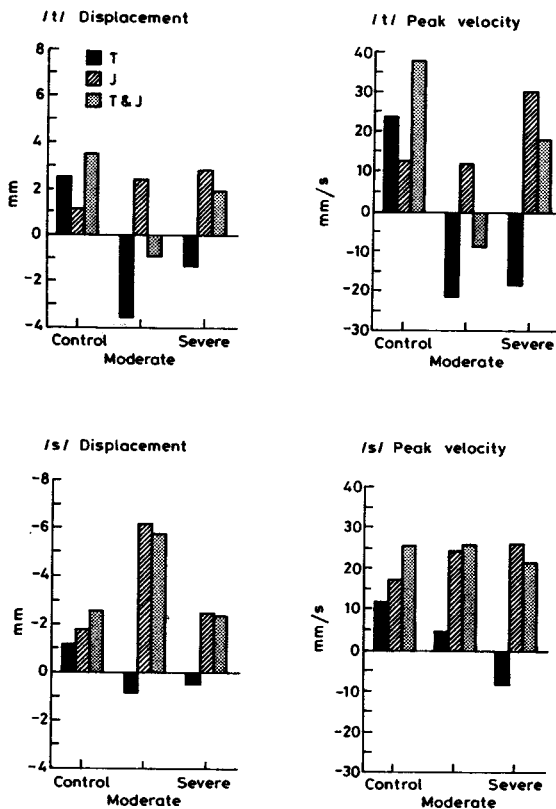


Figure 6. Taken from Alfonso, Story & Watson (1987).

for the two stutterers compared to the one control subject in the Alfonso et al. (1987a) experiment. The figure shows the vertical displacement and associated peak velocity of a lead pellet attached to the tongue blade and demonstrates that the control subject, like all of the subjects in the Caruso experiment, achieves closure by complimentary activity of the individual articulators (the jaw and tongue blade) that comprise the gesture. However, the stutterers achieve closure primarily by jaw displacement with little, and occasionally paradoxical, tongue displacement. Thus, the control subject behaves like non-stuttering subjects in other experiments by demonstrating complementary movements of the speech structures while the stutterers behave in a qualitatively different fashion, notably by demonstrating paradoxical displacement of the tongue blade and jaw. The trial-to-trial variability in peak displacement amplitude and peak velocity, which is not shown in Figure 6, is much greater for the stutterers than the control subject. All of these differences were statistically significant. It could be that the stutterers' lack of movement covariability demonstrated in Figure 4 is related to their dominance of a single member of a supralaryngeal complex to achieve closure and release gestures.

More recent experiments shed some light on two other possible influences on the differences observed between the Caruso and Alfonso experiments, namely therapy influences and speech rate control. A recently completed doctoral dissertation by Story (1990) examined the kinematics of stutterers' perceptually fluent speech as a function of therapeutic intervention and speech rate. Considering therapy influences first, Table 2 shows within-subject differences in mm between pre- and post-treatment conditions for UL, LL, J movements for /p/ closure (Table 2a) and release (Table 2b) in /pit/ and /pet/ produced in the carrier phrase "he see CVC again" for two controls and three stutterers. The stutterers were classified as severe pre-therapy and then mild post-therapy. Negative values indicate smaller post-therapy displacements relative to the corresponding pre-therapy values. Note that the pre- and post-treatment comparisons for both stutterers and controls reveal subject differences in the relative organization of the gestures. For example, control ES produced session 2 /p/ closure with much less J displacement and more UL displacement compared to his session 1 /p/ closure. Control DW, on the other hand, decreased J displacement but increased LL displacement. Most importantly, note that on average the combined displacement for closure and release gestures shows only about a one half mm pre- and post-therapy difference for the control subjects. On the other hand, the stutterers significantly decreased displacement amplitude post-therapy, note that the combined displacement pre- and post-therapy differences range from -1 to -4 mm. Similar results were obtained for /t/ closure and release in /fit/ and /fet/. All of the stutterers pre- and post-treatment difference values were statistically significant in all phonetic contexts, whereas a much smaller percentage of the control subjects' difference scores were significant.

Turning next to the influence of speech rate of stutterers displacement and velocity characteristics, Figure 7a, taken from Story (1990), shows /p/ closure

Table 2a. Taken from Story (1990). Displacement amplitude difference values (in mm) for /p/ closure in the words /pit/ and /pet/ at normal speech rate.

		CONTROLS ES	DW	STUTTERERS KH	PC	AB
J	/pit/	-.93	-.66	-.19	-1.19	-.84
	/pet/	-.78	-.48	-.31	-1.15	-.96
LL	/pit/	-.06	1.18	-.17	-.50	-1.58
	/pet/	-.40	1.19	-1.02	-.55	-1.54
UL	/pit/	.72	.25	-.11	-.64	-.03
	/pet/	.76	.02	.18	-.87	.16
Combined	/pit/	-.15	.78	-1.06	-2.32	-2.44
	/pet/	-.42	.73	-1.20	-2.57	-2.35

Table 2b. Taken from Story (1990). Displacement amplitude difference values (in mm) for /p/ release in the words /pit/ and /pet/ at normal speech rate.

		CONTROLS ES	DW	STUTTERERS KH	PC	AB
J	/pit/	.15	-.49	-.82	-2.48	-2.20
	/pet/	-.10	-.49	-.64	-2.75	-2.30
LL	/pit/	-.99	.52	-.20	-1.02	-1.31
	/pet/	-.93	1.14	-.35	-.76	-1.32
UL	/pit/	.22	-.51	-.18	-.37	-.29
	/pet/	.73	-1.27	-.12	-.75	
Combined	/pit/	-.62	-.48	-1.19	-3.86	-3.80
	/pet/	-.32	-.61	-1.10	-4.25	-3.62

displacement values for /pit/ and /pet/ for control subject ES at normal, fast, and slow speech rates. The acoustic duration of the phrase "he see pete (or pate) again" ranged from a mean of 750 ms at fast rates to a mean of 3500 ms at slow rates for the control subjects. Note that the session 1 (shown on top) and 2 (shown on the bottom) patterns are very similar. The normal and fast rates generate similar displacements while the slow rate generates relatively smaller displacements. Figure 7b shows the same conditions for stutterer KH. Phrase duration for the stuttering subjects ranged from a mean of 675 ms at fast rates to a mean of 5200 ms at slow rates. Note, first, that for all speech rates during the post-therapy condition (shown as session 2 at the bottom) displacements are less than their comparable pre-therapy displacements (shown as session 1 at the top) for all articulators and the combined signal, and second, that within the post-therapy condition, each articulator and the combined signal show less displacement at slow rates compared to normal and fast. This latter pattern is not

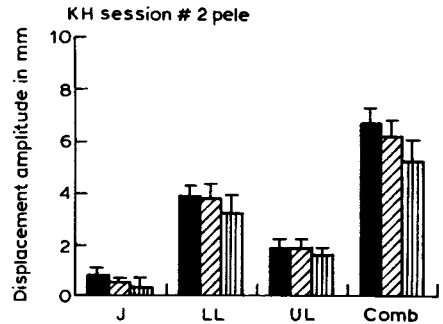
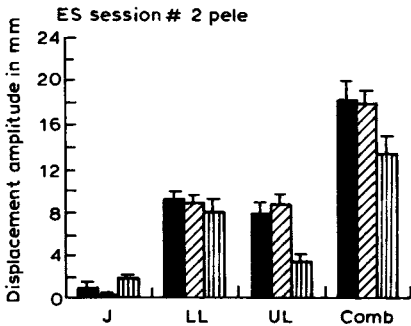
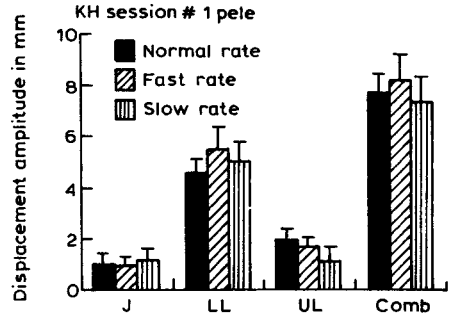
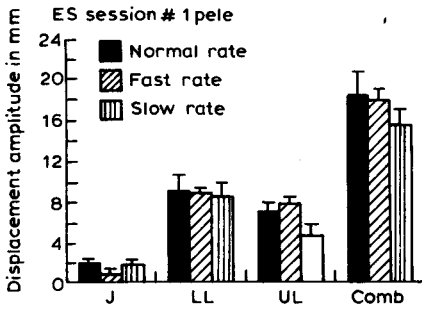


Figure 7a. Taken from Story (1990).
Control subject.

Figure 7b. Taken from Story (1990).
Stutterer.

consistently observed in the pre-therapy condition. The data for the remaining subjects are similar to those demonstrated in Figures 7a and 7b. The pre- and post-therapy comparison shown in Figure 7b could be the basis for the often cited observation made by Zimmerman (1980a,b) that stutterers' supra-laryngeal displacements are slower and smaller in amplitude compared to normal speakers if the stutterers in his experiment were using therapy induced control strategies to maintain fluency.

Figure 8 is taken from De Nil and Abbs (1989a) and shows the relationship between jaw displacement (the left panel) and jaw peak velocity (the right panel) with /b/ closure duration in repeated utterances of /bae/. The differences between the groups become more distinct as speech rate decreases, that is, as closure durations increase. The group differences were significant at 150 ms and beyond. Once again, large intersubject variability for both groups was observed. The observation here that stutterers and controls increase displacement amplitude at slower rates is contrary to the Story (1990) observation of decreasing displacement at slow speech rates and may be attributable to a therapy effect on the Story (1990) stuttering subjects, and to speech utterance and/or the absolute rate differences between the experiments, since both the controls and stutterers

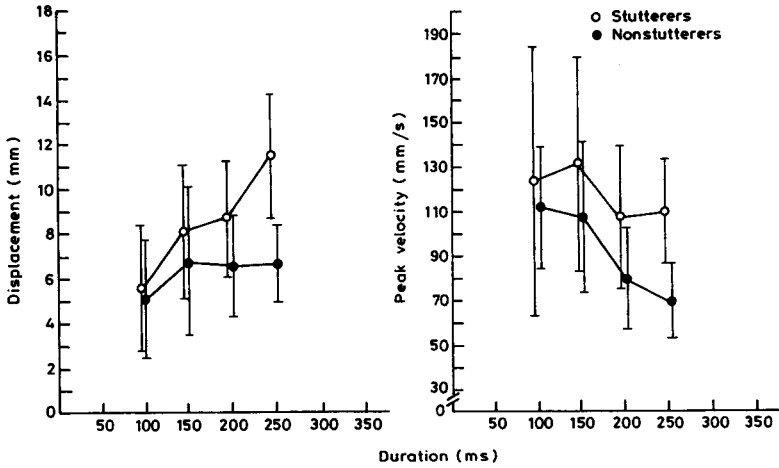


Figure 8. Taken from De Nil and Abbs (1989a). Jaw displacement and peak velocity by closure duration.

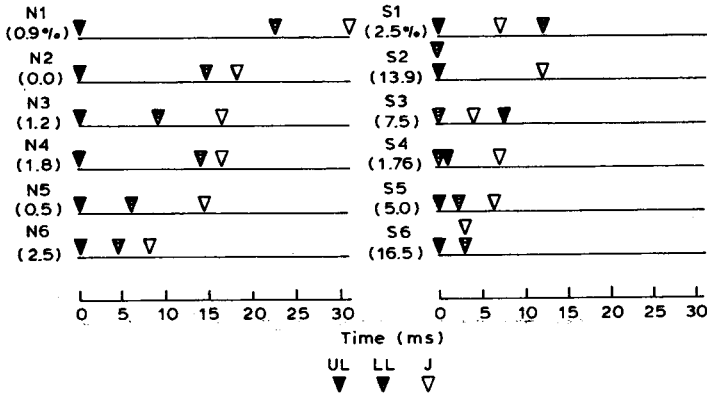


Figure 9. Taken from Caruso, Abbs & Gracco (1988). Schematic representation of the temporal ordering of UL, LL and J peak velocities for each of 6 stutterers (S) and 6 normal (N) speakers. Percentage of sequencing reversals are shown in parentheses for each subject.

decreased displacement amplitude at slow rates in the Story (1990) experiment. It should be noted that in the Story experiment the departure from normal to slow rates was much greater than the difference between normal and fast rates. Turning to the last criterion, interarticulator relative-timing and sequencing, the results, at first blush, appear less contradictory than those discussed above. Figure 9, taken from the Caruso et al. (1988) experiment, shows interarticulator relative-timing and the temporal ordering of the upper lip, lower lip, and jaw for the first /p/ closure in "sapapple". Note that in the control subjects' data, shown on the left, consistent order of movement is upper lip first, followed by the lower lip, and

finally the jaw. This same sequence has been observed in larger groups of control subjects for the same task (e.g. Gracco & Abbs, 1986). However, only one of the six stutterers, shown on the right, showed this same sequencing pattern. In addition, the stutterers were found to be more variable in their sequencing patterns compared to the controls. The UL-LL-J temporal pattern in the "sapapple" context is most likely related to neural and biomechanical interactions and thus reflects differences in both neural control and biomechanical processes between stutterers and controls (Gracco, 1988).

Figure 10 shows the percent occurrence of context dependant tongue-jaw sequence patterns and demonstrates that similar results were observed for tongue and jaw movements in the Alfonso et al. (1987b) experiment. These data are pooled across the /t,s,n/ contexts and, like the Caruso data, represent temporal order relative to the peak in the velocity profiles associated with the displacement of each of the articulators. Figure 10 is of interest here because for the control subject different temporal patterns were observed for different phonetic contexts. For example, the tongue leads in /t/ closure but the jaw leads in /s/ and /n/ closure. For the stutterers, the tongue leads regardless of the phonetic context. The figure shows that the control subject demonstrates a consistent context dependant sequence in about 95 percent of the utterances while the stutterers showed the same sequence in about 60 percent of the utterances. As in the Caruso data, the stutterers' sequencing patterns were more variable relative to the control subject. Figure 11 shows the variability associated with tongue-jaw relative-timing. Here, the CV for interarticulator latency is plotted, which normalizes for intersubject differences in speech rate. The figure demonstrates that the two stutterers' show much more token-to-token variability in tongue-jaw relative-timing compared to the control subject, and supports the conclusions drawn from other experiments that stutterers demonstrate different temporal organization of the speech structures even during their perceptually fluent speech production. The group difference is statistically significant and is consistent with the relative

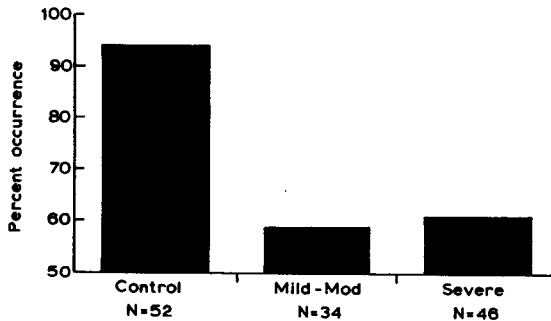


Figure 10. Taken from Alfonso, Story & Watson (1987). Stutterers' tongue-jaw sequence compared to control by utterance type re velocity peaks.

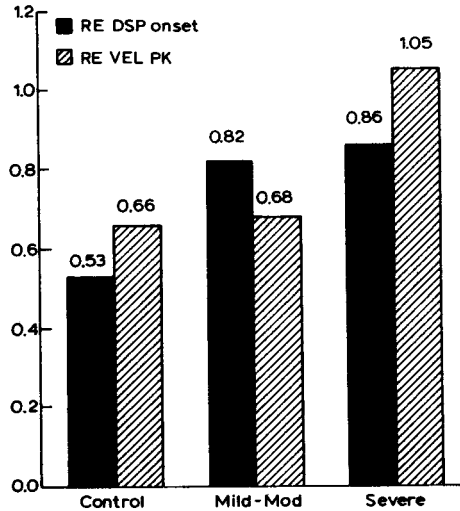


Figure 11. Taken from Alfonso, Story & Watson (1987). Weighted average coefficients of variation for tongue-jaw relative timing re displacement onset and peak velocity.

displacement variability for these same subjects (see Figure 4) where the control subject shows the least variability and the severe stutterer shows the most.

More recent experiments have shown that interarticulator relative-timing and sequence patterns for stutterers can vary as a function of stuttering severity and program specific fluency-enhancing techniques, and in the case of both stutterers and control subjects, can also vary as a function of speaking rate and phonetic context. Figure 12, taken from Story and Alfonso (1989), shows an example of severity and therapy influences on lip and jaw relative-timing and sequence patterns during /p/ closure for perceptually fluent productions of "he see pete again". The data for two controls, shown on the left, represent two different sessions about six weeks apart and are consistent with the results of the Caruso et al. (1988) experiment with respect to both interarticulator relative-timing and sequence patterns. The stutterers data, shown on the right, are quite different. Recall that these stutterers were classified as severe pre-therapy and mild post-therapy. Considering inter-articulator latencies first, note that pre-therapy latencies for stutterer AB (specifically lower lip lag of the upper lip) and for stutterer PC (specifically jaw and upper lip lag of lower lip) are much greater than the corresponding control subject latencies. For both of these subjects, post-therapy latencies are significantly reduced relative to their pre-therapy latencies, even though their post-therapy speech rate was significantly reduced compared to their pre-therapy rate. Turning next to sequential order, note that two of the stutterers, KH and PC, do not show the expected sequence in either the pre- or post-treatment condition. Also note that for stutterer KH, the pre- and post-treatment

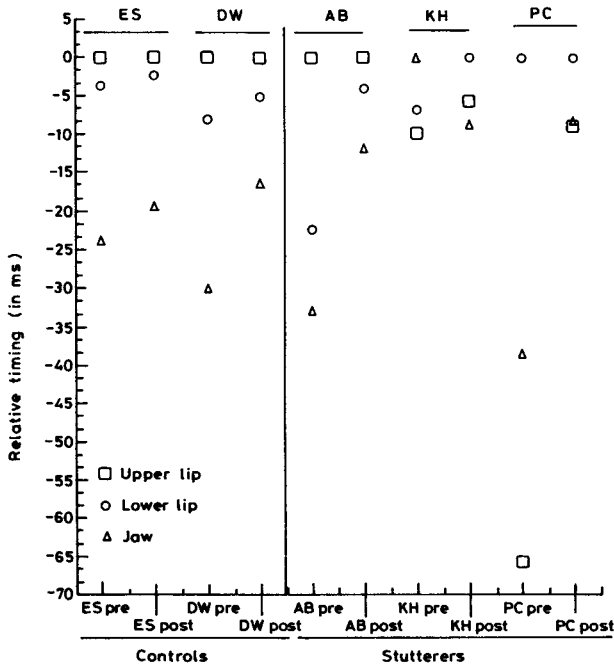


Figure 12. Taken from Story & Alfonso (1989). Temporal organization of upper lip, lower lip, and jaw for /pit/.

comparison shows a complete sequence reversal. Similar results were obtained for /pet, fit, and fet/ and indicate that post-therapy fluently enhanced speech can be marked by improved interarticulator relative-timing and, less frequently, by alteration of the sequence patterns, although the altered sequence may not be like that of the controls.

Turning next to the influences of phonetic context and speaking rate on the UL-LL-J sequence observed in /p/ closure, Figure 13, taken from De Nil and Abbs (1989b), shows the frequency of this sequence for repeated productions of /bae/. Speech rate varied from two to seven syllables per second over three second intervals. Note first that the UL-LL-J sequence for /b/ occurred in only 36 percent of the control subjects' utterances and in 25 percent of the stutterers' utterances, which is a much lower percentage than the /p/ closure sequence reported by Gracco and Abbs (1986) and Caruso et al. (1988) for control subjects. Figure 14 shows that, for both controls and stutterers, the expected sequence occurred most often at fast rates and least often at slower rates. Similar results were reported by Story, Alfonso and Munhall (1987) for two normal talkers. The prevalent sequence, the UL-LL-J, occurred 84 and 89 percent of trials at normal and fast rates respectively for /p/ closure in /pit/ and /pet/ tokens. However, the prevalent sequence at slow rates was LL-UL-J, which occurred 69 percent of the time.

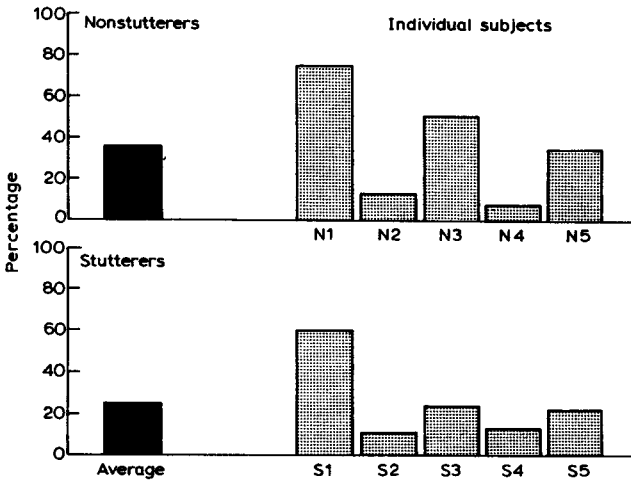


Figure 13. Taken from De Nil and Abbs (1986b). Frequency (%) of UL-LL-J sequence.

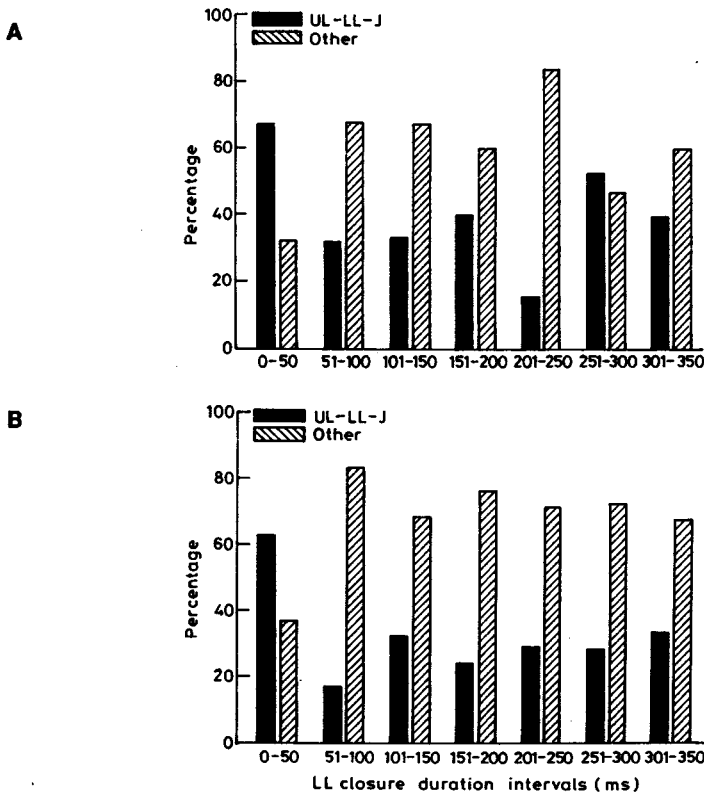


Figure 14. Taken from De Nil & Abbs (1989b). Peak velocity sequencing for each LL closure duration in nonstutterers (A) and peak velocity sequencing for each LL closure duration in stutterers (B).

Token-to-token variability for inter-articulator relative-timing, particularly when involving jaw latency, was also much greater at slow rates compared to normal and fast. Similar rate dependant results were obtained for stutterers by Story (1990), even in the post-therapy condition when the stutterers successfully increased the frequency of their perceptually fluent speech.

CONCLUDING REMARKS

This review suggests that stutterers' speech motor performance can significantly depend upon: (1) speech rate, (2) phonetic context, (3) stuttering severity and (4) therapeutic history. These dependencies result in large variability in virtually all types of data collected from stutterers, and in certain cases, from control subjects as well. Obviously, we need to increase our data base, particularly with regard to speech motor control, before we can conclude with some degree of certainty whether velocity profiles, indices of motor equivalence, or just about any other measure of stutterers' perceptually fluent speech movements are normal, or alternatively, aberrant in some way. It would be to our advantage to begin a study of the feasibility of establishing a central store of physiological data with international access.

Because of the four dependencies listed above and the resultant variability problem, we should take care to adequately describe the essential methodological details of our experiments so that appropriate inferences can be made across different experiments, particularly because different protocols might reflect different dependencies. For example, it might be appropriate to limit the phonetic context, as in the example of the well studied initial /p/ in "sapapple" to address certain research questions, or it might be appropriate in a different experiment to compare one kinematic parameter across a variety of phonetic contexts. Similarly, it might be appropriate to gather data from limited recording sites from a large number of subjects, or it might be appropriate to gather a large amount of data from multiple recording sites from a limited number of subjects depending on the specific question the experiment seeks to resolve. We need to continue to weigh the advantages and disadvantages of these protocols with regard to the hypotheses under test, and to clearly describe all of the essential details related to these four dependencies.

In conclusion, the experiments reviewed here are particularly significant for the following two reasons. First, the results of these experiments, which examined speech motor organization during stutterers' perceptually fluent productions, indicate that the stutterers' speech motor system exhibits generalized spatio-temporal dysfunction rather than functioning normally except during moments of overt dysfluency. Second, the results of these experiments support the notion that the disorder of stuttering, as interpreted by McClean (1990) and Prins (1991), is associated with a relatively rudimentary form of motor control that is generally responsible for, and follows certain general principles of, spatio-temporal organization of all skilled motor activities, for example, handwriting and typing. This

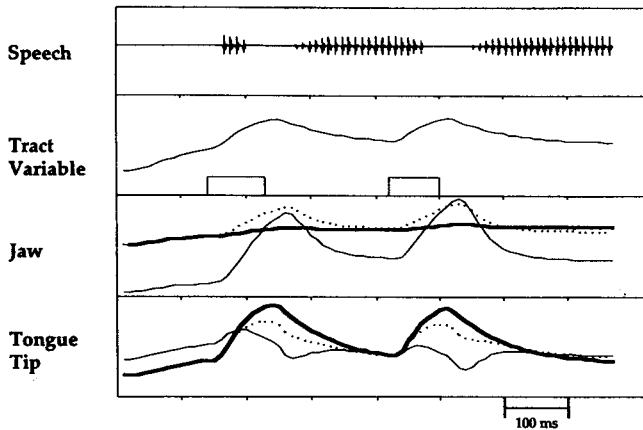


Figure 15. Jaw and tonguetip trajectories for various modifications of the articulator weights associated with jaw movements. Thick lines represent trajectories generated in the normal condition. Dashed and thin lines represent increasing jaw contribution to alveolar closure and release, and the compensatory action of tongue tip displacement. See text for further details.

implies that the disorder of stuttering is associated with, in addition to the linguistic factors that are encoded in speech movements and the behavioral influences which might mediate them, (e.g. Zimmerman, 1980c; Smith & Weber, 1988) irregularities at a rudimentary and pre-linguistic level of motor control.

TASK-DYNAMIC MODELING OF STUTTERERS' PERCEPTUALLY FLUENT UTTERANCES

The complexity of stutterers' speech motor control requires the synthesis of data stemming from new approaches and different disciplines. In this light, I conclude with a brief description of our first attempts to use the computational gestural model, and importantly, the dynamic component of the model, to test the assumptions about stutterers' perceptually fluent speech drawn from our tongue-jaw x-ray microbeam study (Alfonso et al., 1987a,b). Recall that we observed that the two stutterers produced alveolar gestures primarily by jaw displacement with relatively little tonguetip or tongueblade elevation. To model this behavior, the articulator weights associated with movements of the jaw were modified so that minimal anterior tongue displacement (with respect to the jaw) is produced during execution of alveolar closure and release gestures; virtually all of the net motion is achieved by jaw displacement. Under these constraints, multiple repetitions of normal rate alveolar stop-vowel-stop sequences are generated to determine if the acoustic output is perceived as normally fluent speech. Keep in mind that we have not modified other kinematic parameters. Rather, these

utterances were generated by the model with normal spatial and temporal coordination between the tongue and the jaw, only the relative magnitudes of the individual displacements have been modified. Figure 15 shows the results of these modifications and illustrates that the current version of the model allows us to begin this work. The top record of Figure 15 shows the acoustic signal associated with /etete/, one of the utterances used in the Alfonso et al. (1987a,b) experiment. The second record shows the tract variable movement, the boxes indicating the period during which the alveolar gesture is activated. The two lower records show the trajectories associated with jaw and independent tongue tip vertical displacement. The thick line in the jaw record represents the trajectory generated by the default articulator weights referred to as the normal condition, and shows that the model produces this utterance with jaw elevation that is appropriate for the vowel context and with only slight vertical assist for /t/ closure and release. The thick line in the tongue tip record shows that alveolar closure and release, in the normal condition, is achieved primarily by large displacements of the tongue tip. The dashed lines in the jaw and tongue tip records show the results of decreasing the articulator weights for the jaw and the resultant compensation of the tongue tip. Under this condition, the jaw component continues to assist the tongue body in vowel production but also clearly assists the tongue tip in /t/ closure and release. The acoustic output is indistinguishable from the normal condition. Finally, thin lines show the consequences of decreasing the articulator weights to obtain maximal vertical displacement of the jaw, and the compensatory adjustments to the tongue tip and body, until acoustic output is no longer possible. This condition corresponds most closely to the stutterers' tongue-jaw relative displacements observed in the Alfonso et al (1987a,b) experiment. Note that the jaw contributes even further in alveolar closure and release, however, as mentioned above, this extreme jaw displacement does not result in an acoustic output, presumably because of the jaw's effect on other articulator movements, for example, the lips and tongue body. Our modeling of stutterers' speech is just beginning, but we are encouraged by our first attempts. We hope to be able to demonstrate the benefits of modeling five years from now at the third Nijmegen conference on speech motor control.

ACKNOWLEDGEMENT

Preparation of this paper supported in part by NIH Grant DC-00121 and BRS Grant RR-05596 awarded to Haskins Laboratories. Final version of this paper was completed during the author's tenure as Fulbright Research Scholar, The University of Nijmegen, The Netherlands. Grateful acknowledgement is extended to Dr. Wouter Hulstijn for his careful and constructive review of the final draft of this paper.

REFERENCES

- Alfonso, P.J., Watson, B.C. & Baer, T. (1984). Muscle, movement, and acoustic measurements of stutterers' laryngeal reaction times. In: M. Edwards (Ed.), *Proceedings of the 19th Congress of the International Association of Logopedics and Phoniatrics* (Vol. II, pp. 580-585). Perth, Scotland: Danscott Print Limited.
- Alfonso, P.J., Watson, B.C. & Seider, R.A. (1986). Tongue and jaw articulation in stutterers' fluent speech. *ASHA*, 28-10, 166. Paper presented at the Annual Convention of the American Speech-Language-Hearing Association.
- Alfonso, P.J., Watson, B.C. & Baer, T. (1987). Measuring stutterers' dynamical vocal tract characteristics by x-ray microbeam pellet tracking. In: H.F.M. Peters and W. Hulstijn (Eds.), *Speech motor dynamics in stuttering* (pp. 141-150). Wien: Springer-Verlag.
- Alfonso, P.J., Story, R.S. & Watson, B.C. (1987a). The organization of supralaryngeal articulation in stutterers' fluent speech production: A second report. *Annual Bulletin of the Research Institute of Logopedics and Phoniatrics*, 21, 117-129.
- Alfonso, P.J., Story, R.S. & Watson, B.C. (1987b). Spatial-temporal variability of tongue-jaw movements in stutterers' fluent speech. *ASHA*, 29-10, 159. Paper presented at the Annual Convention of the American Speech-Language-Hearing Association.
- Baer, T. & Alfonso, P.J. (1984). On simultaneous neuromuscular, movement, and acoustic measures of speech articulation. In: R.G. Daniloff (Ed.), *Articulation assessment and treatment issues*. San Diego: College Hill Press.
- Bloodstein, O. (1987). *A Handbook on Stuttering*. Chicago, Ill.:The National Easter Seal Society.
- Caruso, A.J., Abbs, J.H. & Gracco, V.L. (1988). Kinematic analysis of multiple movement coordination during speech in stutterers. *Brain*, 111, 439-455.
- Cooper, J.A. (1990). Research needs in stuttering: Roadblocks and future directions. *ASHA Reports 18*. Rockville, MD: ASHA Publications.
- De Nil, L.F. & Abbs, J.H. (1989a). Alterations in lower lip and jaw kinematics of stutterers and nonstutterers as a function of speech rate. *JASA*, 85-1, S148. Paper presented at the Spring Meeting of the Acoustical Society of America. Syracuse, New York.
- De Nil, L.F. & Abbs, J.H. (1989b). Influence of rate on stutterers' and nonstutterers speech movement timing. *ASHA*, 31-10, 65. Paper presented at the Annual Convention of the American Speech-Language-Hearing Association. St. Louis, Missouri.
- Gracco, V. (1988). Timing factors in the coordination of speech movements. *Journal of Neuroscience*, 8, 4628-4639.
- Gracco, V.L. and Abbs, J.H. (1986). Variant and invariant characteristics of speech movements. *Experimental Brain Research*, 65, 156-166.
- Hutchinson, J. (1975). Aerodynamic patterns of stuttered speech. In: L.M. Webster and L.C. First, (Eds.), *Vocal Tract Dynamics and Dysfluency*. New York: Speech and Hearing Institute.
- Kalinowski, J.S. (in progress). Kinematic strategies associated with enhanced fluency following completion of an intensive Van Riperian therapy program. Unpublished Ph. D. dissertation, University of Connecticut.
- Kelso, J.A.S., V. Bateson, E., Saltzman, E. & Kay, B. (1986). A quantitative analysis of reiterant speech production: Phase portraits, kinematics, and dynamic modeling. *Journal of the Acoustical Society of America*, 77, 266-280.
- Lewis, J.J. (1975). An aerodynamic study of 'artificial' fluency in stutterers. Unpublished doctoral dissertation, Purdue University.
- McClellan, M. (1990). Neuromotor aspects of stuttering: Levels of impairment and disability. In: J. Cooper (Ed.), *Research needs in stuttering: Roadblocks and future directions, ASHA Reports number 18*. Rockville, MD: ASHA.
- McClellan, M.D., Kroll, R.E. & Loftus, N.S. (in press). Kinematic analysis of lip closure in stutterers' fluent speech. *Journal of Speech and Hearing Research*.

- Peters, H.F.M. & Boves, L. (1988). Coordination of aerodynamic and phonatory processes in fluent speech utterances of stutterers. *Journal of Speech and Hearing Disorders*, 31, 352-361.
- Prins, D. (1991). Theories of stuttering as event and disorder: Implications for speech production processes. In: H.F.M. Peters, W. Hulstijn and C.W. Starkweather (Eds.), *Speech motor control and stuttering*. Amsterdam: Elsevier Science Publishers.
- Shapiro, A.I. (1980). An electromyographic analysis of the fluent and dysfluent utterances of several types of stutterers. *Journal of Fluency Disorders*, 5, 203-231.
- Smith, A. & Weber, C. (1988). The need for an intergrated perspective on stuttering. *ASHA*, 30-10, 32. Paper presented at the Annual Convention of the American Speech-Language-Hearing Association.
- Story, R.S. (1990). Articulatory, laryngeal, and respiratory movements in stutterers' fluent speech before and after therapy. Unpublished Ph. D. dissertation, University of Connecticut.
- Story, R.S. & Alfonso, P.J. (1989). Temporal reorganization of lip and jaw gestures following an intensive therapy program. *ASHA*, 31-10, 65. Paper presented at the Annual Convention of the American Speech-Language-Hearing Association. St. Louis, Missouri.
- Story, R.S., Alfonso, P.J. & Munhall, K. (1987). Lip and Jaw kinematics at various speaking rates. *ASHA*, 29-10, 123. Paper presented at the Annual Convention of the American Speech-Language-Hearing Association. New Orleans, Louisiana.
- Van Riper, C. (1982). *The Nature of Stuttering* (2nd ed.). Englewood Cliffs, NJ: Prentice-Hall.
- Watson, B.C. & Alfonso, P.J. (1987). Physiological bases of acoustic LRT in nonstutterers, mild stutterers, and severe stutterers. *Journal of Speech and Hearing Research*, 30, 434-447.
- Zimmermann, G. (1980a). Articulatory dynamics of fluent utterances of stutterers and nonstutterers. *Journal of Speech and Hearing Research*, 23, 95-107.
- Zimmermann, G. (1980b). Articulatory behaviors associated with stuttering: Cinefluorographic analysis. *Journal of Speech and Hearing Research*, 23, 108-121.
- Zimmermann, G. (1980c). Stuttering: A disorder of movement. *Journal of Speech and Hearing Research*, 23, 122-136.