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Pre- and Posttreatment Comparison of the Kinematics of the Fluent Speech of Persons Who Stutter

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This study reports changes in acoustic, respiratory, laryngeal, and articulatory kinematics of 3 males who stutter, following participation in a version of the Hollins Precision Fluency Shaping Program. Two nonstuttering controls received no treatment. Subjects repeated phrases of the form "He see CVC again" at self-selected slow, normal, and fast speaking rates. For experimental subjects, acoustic duration of the phrases increased significantly in 7 out of 9 comparisons of before- and after-treatment conditions, whereas controls decreased the duration of the phrases in 4 out of 6 comparisons of measurements made over approximately the time interval during which the experimental group received treatment. The experimental group increased inspiratory volume for 7 out of 9 conditions and average expiratory flow significantly for all conditions, whereas the controls decreased both. The experimental group prolonged laryngeal opening in 6 of 7 comparisons, but only 3 of the increases were significant. Lip and jaw movements for consonants were significantly reduced in amplitude for the experimental group for 30 of 36 measures. The direction of change for laryngeal and upper articulator measures was mixed for controls. These results show that behavioral treatment can produce significant changes in the fluent speech of persons who stutter with respect to respiration, laryngeal valving, and articulation. Possible relationships between the observed changes in speech production and the increased fluency of the subjects are discussed.

KEY WORDS: stuttering assessment, stuttering treatment, speech respiration, articulation

Although the cause of stuttering remains unknown, there is general agreement that some behavioral treatments produce significant benefits to adults who stutter (Andrews et al., 1983; Ingham, 1991). However, there are relatively few studies of what changes, if any, the treatment produces in the fluent speech of subjects who stutter, when it is successful in reducing stuttering, and, furthermore, whether these changes are related to the specific instructions of the treatment protocol.

A few acoustic studies (Mallard & Westbrook, 1985; Metz, Onufrak, & Ogburn, 1979; Metz, Samar, & Sacco, 1983) have showed that following treatment adult subjects are likely to speak with longer vowel duration, longer percentages of "vocalized time," and longer voice onset times. However, Zebrowski (1991), in a study of adolescent subjects who received a different clinical protocol from that in the studies cited above, found reduced vowel duration and VOT. Although adolescent subjects have, because of their age, a more limited history of stuttering than adults, this conflict in results is an important one to reexamine with adult subjects because it provides a suggestion that increased fluency following behavioral treatment is not necessarily accompanied by slower rates of speech. In general, such discrepancies indicate a need for more studies of the effects of treatment in different, carefully specified treatment programs.

Another limitation of the literature is that, although physiological changes in some

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aspects of speech following treatment are only indirectly indicated in the acoustic signal, most "before and after" studies are acoustic or perceptual, with some notable exceptions (e.g., Samar, Metz, & Sacco, 1986). In an acoustic study, it is not possible to measure respiration, laryngeal opening and closing, and individual articulator movement. However, studies of the fluent utterances of persons who stutter indicate that these physiological variables may be different in persons who stutter than in those who do not stutter. There is evidence from studies of reaction time (Peters & Boves, 1987; Watson & Alfonso, 1987) that persons who stutter may not build up lung pressure as persons who do not stutter do. Finally, Zimmermann, in a study using the techniques of lateral cinefluorography (1980a, 1980b) indicated abnormalities of lip and jaw movement in some adults who stutter, although limitations of the lateral cinematography technique prevented the collection of substantial databases. Thus, it would seem desirable to study these aspects of articulation in parallel as they change before and after treatment.

The objectives of the present study, then, are to document physiological changes and acoustic changes in parallel, in the fluent speech of adults who stutter before and after they participate in a specified program of treatment, a version of the Precision Fluency Shaping Program, developed by Webster (1979). This structured program details a series of changes in speaking behavior the person who stutters is supposed to achieve and a set of guidelines laid down in interactions between the clinician and client on steps toward achieving these goals. In general, the goals the program specifies are described in physiological terms as changes in respiration ("full breaths"), phonation ("easy onset") and articulation ("light contact"), but the techniques that the clinician uses are those of verbal interaction with the subject, speech modeling, and use of such simple devices as an acoustic instrument, the Voice Monitor. The experimental question is whether phrases in the fluent speech of the subject change following treatment in the way that the program's instructions suggest when there is an overall improvement in the subject's fluency.

The results of this study are of broader interest than providing an assessment of the effects of participation in this particular program. First, what changes can behavioral treatment produce in the way in which clients speak, especially those aspects, like respiration and articulator excursion, that are not readily measured in the treatment interaction? Although the literature is limited, there is some indication that persons who stutter are different from those who do not stutter with respect to their habitual speaking mode. By hypothesis, changes in mode might improve fluency. Second, does behavioral change occur that is responsive to the program's goals? For example, can subjects change articulator excursion as well as respiration? Ultimately, the results of this study should be evaluated in the context of identifying the common elements of change in a range of programs that have been shown to improve fluency.

Methods

Subjects

Three male adults who stutter and 2 male control subjects participated in this study. The experimental subjects were recruited from persons enrolled for fluency treatment at the Communication Reconstruction Center (CRC) in New York City, a site where the Precision Fluency Shaping Program

TABLE 1. Pre- and posttreatment severity measures for experimental subjects.

Subject		Severity ratings		
		CRC clinician	Experimenter	Self-Rating
KH	pre	severe	severe	moderate-severe
	post	mild	mild	mild
PC	pre	severe	severe	moderate
	post	mild	mild	mild
AB	pre	severe	moderate-severe	severe
	post	mild	mild	mild

Subject		Stuttering Severity Index scores				
		Conversation	Reading	Duration 3 longest blocks	Secondary behavior	Total score
KH	pre	9	8	4	4	25 (severe)
	post	2	0	0	0	2 (very mild)
PC	pre	7	8	4	6	25 (severe)
	post	5	5	2	4	16 (mild-moderate)
AB	pre	8	8	3	3	22 (moderate-severe)
	post	2	2	2	0	6 (mild)

was used as the only approach to treatment. The clinician (Catherine Otto Montgomery) in charge of the program was certified by Dr. Ronald Webster in 1979, and the version of PFSP used by CRC reflected her training. We understand that both the clinician's approach and Webster's have changed since that period.

The subjects met the following criteria: (a) they were between 30 and 45 years of age; (b) they reported stuttering since childhood, with no other speech or hearing problems or unrelated neurological disorder known to them, and (c) they had not been enrolled in any treatment program within 4 years of the experiment. The control subjects, who received no treatment, were 2 male staff members from Haskins Laboratories, in the same age range, without a history of any speech or hearing problem. They were not told the purposes of the experiment, nor did they have any clinical background relevant to the experimental study of stuttering. For all subjects, the two experimental sessions fell within a 2-month period, with the 19-day PFSP falling between the two sessions for the subjects who stuttered.

The severity of the subjects' stuttering before and after treatment was evaluated informally by clinical judgments by the subject, the subject's clinician at the Communication Reconstruction Institute, and by one of the authors, (RSS) a speech-language pathologist with a clinical specialization in stuttering, before and after treatment, and formally by evaluation with the Stuttering Severity Index (Riley, 1972). Results of this evaluation and the results of the three parts of the Riley Index are presented in Table 1.

It should be noted that Subject PC stuttered on 6%–9% of words in both reading and conversation tasks after treatment in the Riley evaluation, but did not seem different from the other 2 subjects to either clinician in general evaluation. However, the treatment had a substantial effect on overt stuttering for the 3 subjects, by all measures. Furthermore, the 3 subjects were quite different in the percentages of utterances judged stuttered by either subject or experimenter during the two recording sessions combined. Subject AB stuttered on less than 1% of utterances during the experiments, Subject PC stuttered on 12%, whereas Subject KH stuttered on 4%. No attempts were made to assess the durability of the change in fluency beyond the posttreatment session, nor was the speech assessed for naturalness.

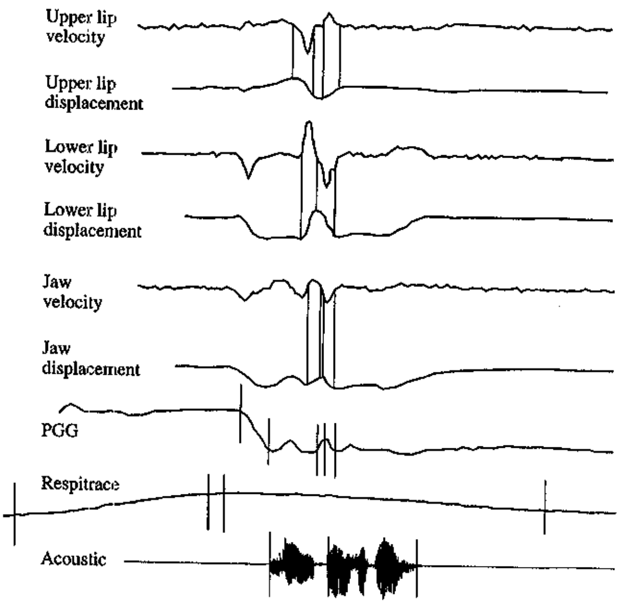

FIGURE 1. This figure is a semi-schematic representation of the computer display of the measures made for a single token. The acoustic signal was measured from onset to offset. The Respitrace signal was measured from the onset of expansion to peak expansion (inspiration) and from peak expansion to phrase offset (expiration). Both amplitude and duration were measured. The velocity trace was used to define temporal offsets and onsets. The transillumination signal (PGG) was measured from onset to opening peak, from opening peak, and from opening peak to offset. These measures were summed. The top six traces show paired displacement and velocity traces for upper lip, lower lip minus jaw, and jaw in the y dimension. Displacement amplitude measures were made, using the corresponding velocity trace to define onsets, peaks, and offsets of displacement.

Treatment Program

The Precision Fluency Shaping Program has been extensively described by its originator, R. L. Webster (Webster 1974, 1975, 1979). It was selected for the present study because (a) it was intended for intensive, structured treatment, with little deviation from subject to subject, so consistency of the effects of treatment across subjects might be expected; (b) the targets or program goals were given as verbal instructions to change the physiological characteristics of speech behavior; and (c) although the experienced clinicians who normally evaluated PFSP clients had considerable insight into how the program was succeeding, they did not evaluate what the client was doing at a physiological level during treatment.

Briefly, the targets of the program, as described by the clinician to the client, were five:

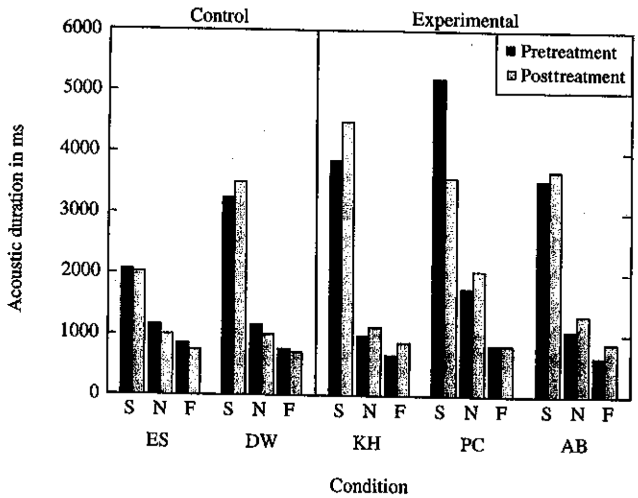

FIGURE 2. Phrase duration in ms, averaged over all words. Each pair of bars shows the average values for under the pre- and posttreatment conditions for a single subject. The speaking rate condition (slow, normal, or fast) and the speakers' initials are indicated on the abscissa.

TABLE 2. Phrase duration in ms.

Subjects	Slow				Normal				Fast			
	pre		post		pre		post		pre		post	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Controls												
ES	2057.2	74.1	2020.8	(114.7)**	1164.8	45.2	1003.6	39.2**	859.3	38.1	749.6	39.4**
DW	3259.3	315.7	3506.3	(314.7)**	1167.6	48.4	998.3	45.4**	769.2	51.3	714.2	48.9
Persons who stutter												
KH	3853.7	417.2	4498	(257.3)**	991.9	66.6	1134	53.4**	675.3	57	877.8	115.3**
PC	5216.8	568.4	3591.6	(152)**	1769.9	120.4	2050.2	80.7**	835.3	39.9	834.6	37.6
AB	3550.6	134	3690	(190.2)**	1067.3	46.3	1315.8	76.6**	638.7	44.6	870.5	40.7

*$p < .05$
**$p < .01$

1. The Stretched Syllable target. At the onset of treatment, subjects are instructed to exaggerate the duration of a syllable well beyond normal limits, using a stopwatch for timing. At the conclusion of treatment, they are expected to speak at a "slow, normal" rate.
2. The Full Breath target. The client is instructed to take a slow, comfortably full breath of air before beginning to speak.
3. The Voice Initiation target. The client is instructed to initiate voicing with a gradual onset of phonation. An instrument, the Voice Monitor, essentially a VU meter monitoring auditory signal amplitude, was provided for feedback during treatment to help attain this target.
4. The Slow Change target. The client is instructed to make articulatory transitions in a slow, deliberate fashion.
5. The Reduced Pressure target. Subjects are instructed to produce voiceless consonants with reduced pressure.

Instrumentation

All acoustic and kinematic data were recorded at Haskins Laboratories. The recordings were made simultaneously, and, after suitable transduction and amplification, laid down as parallel tracks on a multichannel SE Model 7000 FM tape recorder. Two channels of the tape recorder were used for a timing code track, which provided a way of locating specific parts of the approximately one-hour session, and, in addition, was used in the software calculation of the duration of recorded signals. Subjects were seated in a dental chair with attached head support to restrict head movements.

Acoustic data. Acoustic signals were recorded with a directional microphone (Sennheiser Model MKH 816 T). After suitable amplification, the signal was laid down as one track on the tape recorder.

Respiratory data. Inspiratory and expiratory data were collected using Respitrace instrumentation (Chadha et al., 1982; Cohen, Watson, Weisshaut, Stott, & Sackner, 1977; Tabachnik, Muller, Toye, & Levison, 1981; Warren, Morr, Rochet, & Dalston, 1989). Changes in chest wall and thorax

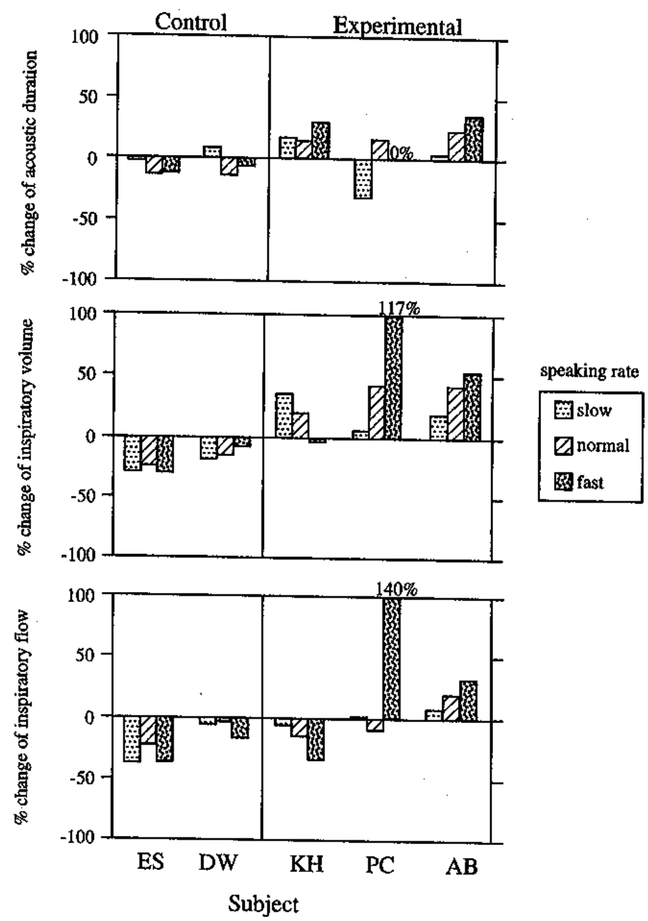

FIGURE 3. The percent change in acoustic duration, inspiratory volume, and inspiratory flow, before versus after treatment. The change in acoustic duration for PC in the fast condition was too small to indicate on the scale of the graph. "Slow," "normal," and "fast" conditions are indicated by histogram fill pattern. The subjects' initials are indicated on the abscissa.

TABLE 3. Inspiratory volume and flow.

Subjects	Conditions											
	Slow				Normal				Fast			
	pre		post		pre		post		pre		post	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Controls												
ES	1227.1	(192.9)	870.6	(149.0)**	1008.5	(228.9)	767	(118.2)**	1143.3	(196.7)	803.4	(86.9)**
DW	980.9	(157.1)	803.7	(173.9)**	757.5	(120.7)	648.3	(148.6)**	675.1	(114.9)	624.2	(118.2)*
Persons who stutter												
KH	1211.4	(349.3)	1642.4	(412.1)**	777.6	(219.4)	935.3	(132)**	1110.7	(215.3)	1079.5	(118.7)
PC	513.8	(108.4)	543.7	(50.5)*	375.6	(112.4)	537.8	(56.9)**	222.1	(51.8)	481.7	(57.4)**
AB	651.5	(261)	775.9	(147.4)**	444.7	(124.8)	635.5	(115.6)**	453.3	(206.8)	697.1	(135.9)**
	Inspiratory average flow in cc/s											
Controls												
ES	718.8	(162.9)	451.2	(84.4)**	647.2	(124.6)	504.9	(78.5)**	747.3	(136.4)	479.6	(68.1)**
DW	918.5	(172.4)	863.2	(154.4)*	910	(158.9)	872.1	(252.4)	1427.7	(247.5)	1185.5	(269.1)**
Persons who stutter												
KH	853.4	(229.5)	806.3	(119.7)*	640.1	(207.4)	545.8	(110.0)**	881.5	(213.5)	577.9	(111.4)**
PC	414.8	(113.3)	420.3	(56.9)	528.4	(141.9)	477.7	(72.9)**	234.4	(107.2)	562.4	(77.2)**
AB	709.4	(238.4)	765.9	(121.1)	636.1	(187.8)	763.1	(196.0)**	761	(291.0)	1008.5	(197.8)**

$p < .05$
$^{**}p < .01$

size were measured by fixing elastic tapes containing inductance coils around rib cage and abdomen. The inductance coils, energized by oscillators, transduce cross-sectional areas of the portions of the rib cage and abdomen underlying the bands into electrical analogs that can be interpreted as lung volume changes when appropriately calibrated. The simultaneous equation method was used for calibration. This method utilizes the relationship of the rib cage and abdomen compartments to respiratory volume. Volume measured at the mouth equals the sum of volume changes of the rib cage and abdominal compartments. The sum of the signals from the rib cage and abdomen was calibrated by asking the subject to breathe into a bag of known volume, supplied by the manufacturer of the equipment, in two positions, sitting and reclining. Five repetitions in each position were averaged. The relative contribution of the abdomen and rib cage to respiratory volume are different in these two positions so that their respective scaling factors can be discovered by solving simultaneous equations, or by using an equivalent graphic method. Only the summed signal was monitored.

Laryngeal data. The movement of the vocal folds was monitored using an optical technique, transillumination. A flexible fiber bundle was inserted into the subject's nose. The light from the fiber bundle was used as part of a transillumination system, whereby the amount of light passing through the glottis was sensed by a photo transistor placed on the surface of the neck just below the cricoid cartilage, held in position by a neck band. The amount of light reaching the photocell was used as a measure of glottal opening. This measure has been shown to be highly correlated with measurements of vocal fold separation obtained from frame-by-frame measurement of fiber optic film (Löfqvist & Yoshioka, 1980). Simultaneous videotaping of the vocal folds using the optical fibers of the fiberscope provided direct views of the upper surface of the vocal folds. These films were viewed so that tokens occurring during periods in which the photocell signal was contaminated by epiglottis or tongue root blockage of the light path from fiber bundle to photocell could be eliminated from the data corpus.

Although the transillumination technique is well adapted to comparing the time course and amplitudes of glottal opening events within a single session, there is no way of assuring comparable placements of the tip of the fiber bundle on different occasions; hence, glottal aperture amplitude measures cannot be compared across sessions. However, given that the magnitude of the signal is adequate, as was true in these sessions, the onset and offset of laryngeal opening can be compared across sessions.

Upper articulator data. Vertical displacements of upper lip, lower lip, and jaw were monitored using an optical tracking system (a modification developed at the University of Washington of the commercial Selspot system). Lightweight infrared light-emitting diodes (LEDs) were placed on the midline of the vermilion border of the upper and lower lips and the jaw midline over the mental protuberance. A reference LED was placed on the bridge of the nose so that a software correction could be made in later signal processing for the subject's head movements in the plane of the camera. At the same time, in software processing, the

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TABLE 4. Expiratory volume and flow.

Subjects	Conditions											
	Slow				Normal				Fast			
	pre		post		pre		post		pre		post	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
	Expiratory volume in cc											
Controls												
ES	773.4	(79.6)	648.1	(76.3)**	419.2	(44.2)	346	(54.2)**	256.7	(48.9)	207.8	(64.7)**
DW	814.8	(116.9)	688.7	(94.8)**	381.6	(55.9)	256.5	(42.6)**	302.1	(45.9)	264.8	(46.6)**
Persons who stutter												
KH	1112.4	(185.5)	1981.1	(125.9)**	320.0	(40.0)	607.5	(82.5)**	269.8	(32.1)	505.3	(83.1)**
PC	467.1	(73.0)	545.4	(61.9)**	259.7	(43.8)	406.6	(50.1)**	148.3	(23.3)	241	(27.6)**
AB	464.1	(55.6)	666	(100.5)**	194.8	(81.0)	292.7	(35.4)**	111.9	(41.7)	192.4	(41.5)**
	Average expiratory flow in cc/s											
Controls												
ES	324.4	(32.9)	242.5	(34.9)**	325.5	(32.6)	263.4	(43.2)**	247.4	(44.5)	196.2	(60.6)**
DW	226.1	(28.8)	181.4	(20.1)**	281.5	(39.1)	219.5	(36.9)**	339.8	(39.5)	315.3	(53.3)**
Persons who stutter												
KH	267.6	(30.9)	370.2	(19.2)**	264.7	(37.5)	332	(37.8)**	348.9	(44.4)	371.1	(42.1)**
PC	82.7	(13.1)	134.7	(13.8)**	127.6	(19.1)	168.4	(18.3)**	151.4	(23.9)	247.9	(26.4)**
AB	121.9	(14.2)	165.9	(20.7)**	152.1	(45.6)	186.7	(21.5)**	155.3	(50.8)	193.9	(36.5)**

*$p < .05$
**$p < .01$

contribution of jaw movement was subtracted from lower lip movement.

Modulated light from the diodes was captured by a Schottky planar diode located in the focal plane. The output of the photodiode was fed to associated electronics that decoded the signals and computed pairs of x and y coordinates. The x coordinate information was not used further in the following analysis. The coordinate values were transmitted by de coupled amplifiers and recorded on the multichannel tape recorder. Calibration of the system was accomplished by raising and lowering the camera a known distance (2 cm) while recording the output of the lower lip electrode.

Signal Processing

The acoustic and kinematic data were recorded on 16 channel FM instrumentation tape. Analog signals were played back from the tape for subsequent analysis in digital form. All signals were A/D converted by a Datel model ST-PDP converter and the digitized results stored on disk. The acoustical signal was input at 10,000 cps. Kinematic and laryngeal data were sampled at a rate of 200 samples/s, with 12 bit resolution. The first derivatives of these data were computed in software, after smoothing the data to reduce high frequency noise with a seven-point Bartlett (triangular) window. The details of the signal processing system are described in a paper by Kay, Munhall, Vatikiotis-Bateson, and Kelso (1985).

Experimental Protocol

Subjects produced the four CVCs /pit/, /pet/, /fit/, and /fet/ in the frame sentence "He see CVC again." The frame was chosen for an initial voiceless consonant, to reflect "easy onset" whereas front vowels were used because their tongue position made blockage of the light path from pharynx to glottis less likely. Consonants in the target CVC were chosen that would show substantial lip and jaw movement. The subjects repeated the four tokens in semi-random order in response to cue cards. Subjects were required to initiate each utterance on a new breath and were not pressed to respond as soon as a new cue card appeared.

As each token was produced, an experimenter (RSS), as well as the subject, judged it to be stuttered or fluent and recorded the judgment on the experimental tape. Data collection in a given condition was terminated after 20 tokens judged fluent by both had been recorded. Each subject produced a set of tokens first at a self-selected "normal" rate, then at a "faster-than-normal" rate, then at a "slower-than-normal" rate. The experimenter practiced the three rates with each subject before the recorded session. Although she did not define a particular ratio by which the subject should increase or decrease rate, she did urge the subject, by modeling, to increase (or decrease) the rates to the limits he felt he could sustain. A reference to the data in Table 2 and in Figure 2 shows that for all 3 subjects, before and after treatment, the three rate conditions are in the desired ordinal relationship to each other. However, we did

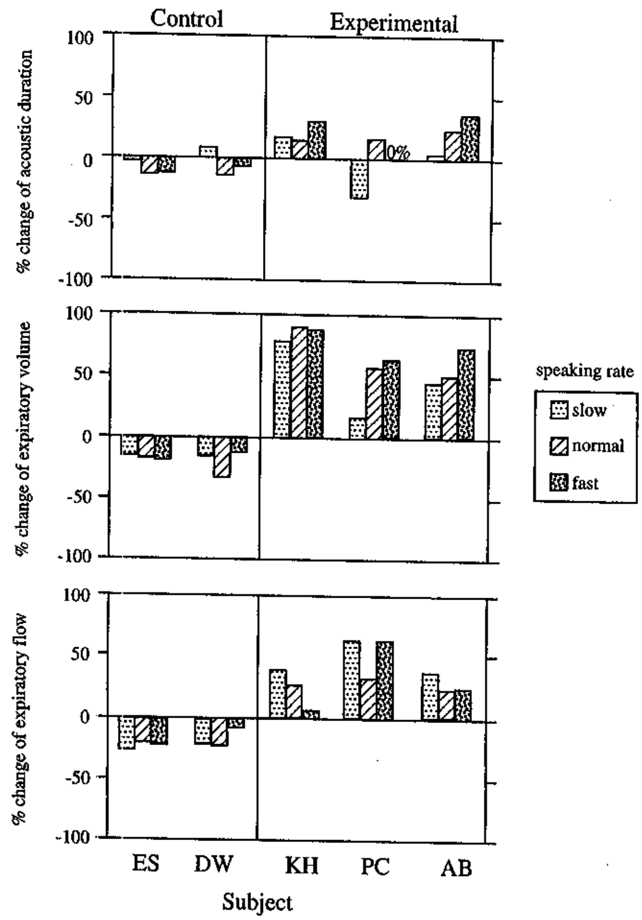

FIGURE 4. The percent change in acoustic duration, expiratory volume, and expiratory flow, before versus after treatment. The change in acoustic duration for PC in the fast condition was too small to indicate on the scale of the graph. "Slow," "normal," and "fast" conditions are indicated by histogram fill pattern. The subjects' initials are indicated on the abscissa.

not test to see whether the rate changes were perceptually noticeably different, either comparing "slow" versus "normal" versus "fast" for any subject or comparing "before" versus "after" for any subject.

The three speaking rate conditions were chosen because of the emphasis in the PFSP training protocol on a gradual increase in speaking rate from slow to faster rates. We reasoned that any important physiological changes in fluent speech following treatment should be available to the subjects at any speaking rate they would use to produce normal speech.

After treatment for the experimental subjects, or an equivalent temporal interval for the controls, the whole protocol was repeated. Thus, for each subject, 20 tokens × 4 utterances × 3 speaking rates × 2 conditions were processed, or a total of approximately 2400 utterances for the 5 subjects. Although any of several technical problems during processing caused the omission of some tokens from each condition, in no case was the number less than 12 in a given cell of the experimental design.

After the experiment, a listening tape was made of 8 utterances from each speaking rate for each subject who stuttered, before and after treatment, a total of 48 utterances for each subject, dubbed from the audiotape of the experiment. The utterances were chosen close to the temporal middle of the recording for the condition, with the additional requirement that both utterances judged stuttered and fluent be included for each subject. The resulting 144-utterance tape, completely randomized as to speaker and speaking rate condition, was presented to a second listener, an ASHA-certified speech-language pathologist with clinical experience in stuttering treatment. She was instructed that she would hear several speakers under several conditions (unspecified) and was to judge each utterance as stuttered or fluent. The second listener agreed with the judgment made during the experiment in 141 out of 144 assignments. In all three cases of disagreement, the second listener believed an utterance to be fluent that had been judged as stuttered by experimenter or subject during the experiment.

TABLE 5. Duration of laryngeal gesture in ms (total of abduction and adduction).

	Conditions											
	Slow				Normal				Fast			
	pre		post		pre		post		pre		post	
Subjects	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***
Controls												
ES	280.7	(42.5)	275.1	(33.8)	211.4	(18.6)	191.5	(20.2)**	140.3	(16.8)	133.8	(18.6)
DW	363.9	(95.8)	394.3	(67.1)	268.6	(45.7)	221.4	(23.7)	192.5	(25.7)	207.6	(29.9)*
Persons who stutter												
KH	370.9	(135.8)	323.4	(78.3)**	177.9	(18.9)	188.9	(20.0)	128.1	(13.3)	145.4	(26.2)
PC	MV	MV	MV	MV	206.7	(35.7)	299.3	(48.6)**	153.2	(32.7)	159.6	(22.1)
AB	360.9	(67.1)	370.9	(51.9)	211.5	(24.1)	248.9	(37.9)**	MV	MV	MV	MV

Note: MV indicates a missing value.
$^*p < .05$
$^{**}p < .01$

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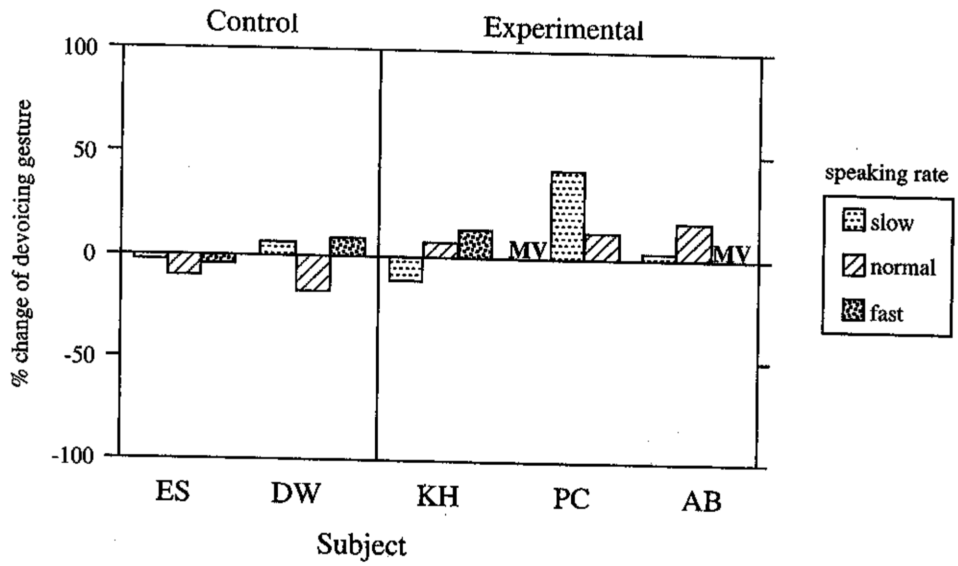

FIGURE 5. The percent change in the duration of the laryngeal devoicing gesture, before versus after treatment. Speaking rate condition is indicated by histogram fill pattern. The subjects' initials are indicated on the abscissa. "MV" indicates a missing value.

Measures

The measures made are indicated in Figure 1, a schematic copy of a computer display.

The experimenter first called up all channels of the display for general inspection and verified the phonetic identity of the sample by audio playback. Following an inspection of the general display, the experimenter displayed the channels one channel at a time, with such amplification in time or amplitude as the signal at issue required. Cursors were then laid on the display at the relevant temporal points. Software permitted a readout of the amplitude of the relevant signal at that point, or the amplitude difference between two measures, calculated from calibration signals laid down at the time of the original recording. In the case of the duration measures, calculations were made with reference to the 60 cps code track. All measures were stored in data files.

The measures were of four types. In some cases, measures beyond those discussed below were made and are discussed in the thesis forming the basis for the present article (Story, 1990).

Acoustic measures. The total duration of the phrase "He see CVC again" and the duration of parts of the CVC word were measured. Only total phrase duration will be discussed here.

Respiratory measures. Volume changes from the onset of inspiration to peak inspiration and from peak inspiration to the end of expiration corresponding to the acoustic end of /n/ were measured from the first derivative of the total volume signal using a 5% criterion, that is, defining onset as the time the velocity signal rose 5% from baseline and other movement measures analogously. The duration of inspiration and expiration were also measured. As in the example shown schematically in Figure 1, the offset of inspiration did not necessarily correspond to the onset of expiration, since periods during which the signal fell below a 5% velocity criterion at peak were not included in the measure. A value for inspiratory and expiratory air flow for each phrase in cc/s was computed from measures of volume and duration.

Laryngeal measures. Since PFSP instructs clients to use the "easy onset" target, it was the intention in designing the experiment to focus on measures of the initial adduction of the utterance, as indicated in Figure 1. However, a preliminary analysis of the data from control speakers showed that the initial adduction was quite variable. Hence, the measures discussed here represent only the summed duration of laryngeal opening and closing for the initial consonant in the target CVC, defining onset and offset with respect to the 5% velocity criterion.

Upper articulator measures. Displacement measures were made for upper lip, lower lip, and jaw. For each articulator, the amplitude of displacement for the opening and closing gestures was measured between the baseline value and peak displacement, and peak displacement and the following baseline. An overall displacement value was calculated for consonant closure and consonant release. Thus, the value for /p/ closure, for example, is the sum of the upward displacements of lower lip and jaw and the downward displacement of the upper lip. The summed measure was expected to be less variable than its components taken individually (Gracco & Abbs, 1986).

Data Analysis

Statistical analyses were made subject by subject, in a repeated measures design (Winer, 1971) with the three variables: condition, rate of speech, and target CVC. Initial analyses showed little effect of vowel, so vowels were analyzed together. Analyses were made in BMDP ANOVA (Davidson & Toporek, 1985). There were a total of 50 ANOVA analyses for the measures discussed here. Because of the large number of ANOVA tests performed, we might expect some significant changes due to chance alone and should adopt a stringent significance criterion. For this reason, although both significance levels of $p = < .05$ and $p = < .01$ are reported in the tables that follow, only values of $p = < .01$ are described as significant. However, we believe that coherence in the direction of change, over the different experimental conditions and over the 3 subjects, although not formally statistically tested, is of perhaps greater behavioral importance.

Results

For each subject and each variable, there was a significant overall Rate effect and a significant Condition by Rate interaction (CR), with three exceptions: AB shows significant main effects of Condition and Rate, but no significant interaction for expiratory flow; PC shows the same pattern for /p/ closure whereas ES shows it for /p/ release. For each subject and each variable, CR effects have been further broken down by Rate and are shown in the tables. Other details of the individual ANOVA tables and additional measures not discussed here may be found in Story's thesis (Story, 1990).

Acoustic Measures

The overall phrase durations are shown in Figure 2, in Table 2, and as percent change in the top panel of Figure 3. The Condition by Rate interactions are broken down by rate for each subject and significance is indicated by stars in Table 2.

With one reversal and one nonsignificant change, control subjects decreased phrase duration in the second session. The experimental subjects generally increased phrase duration, although for PC the change was in the opposite direction in the slow condition and was nonsignificant in the fast condition. The change in the direction of increased duration for the experimental subjects might have been anticipated, given the heavy emphasis in training on the "stretched syllable." It should be noted, however, that although the overall direction of change was opposite in the two groups, and the rates chosen in the slow condition were generally longer for the experimental group, the rates for the subjects who received "stretched syllable" treatment were not outside the normal range for normal and fast rates.

Respiratory Measures

The measures of inspiratory volume and calculated flow are presented in two forms. Table 3 shows, in the middle, volume in cc. for each subject, before and after treatment, for the three speaking rates, with indications of the significance of the individual condition by rate interactions.

The table shows that, in parallel with overall phrase duration, there is a general tendency for the controls to decrease inspiratory volume in the second session, whereas the experimental subjects, with the exception of KH F, increase volume. This result is shown graphically in Figure 3, plotted as percent change between conditions.

This result would appear to support the notion that, posttreatment, the experimental subjects were routinely inflating their lungs to greater volumes for speech breathing. Although the result might be a byproduct of the general tendency of the subjects to take deeper breaths before utterances of longer duration (Gelfer, 1987; Gelfer, Harris, Collier, & Baer, 1983; Winkworth, Davis, Adams, & Ellis, 1995; Winkworth, Davis, Ellis, and Adams, 1994) the first row of Figure 3, showing the percent change in acoustic duration, does not closely parallel the changes in respiratory volume, so the changes cannot directly reflect one another.

The bottom rows of Table 3 and Figure 3 show the measures of calculated inspiratory flow. The CR interaction terms are always significant. They are broken down by rate, and indicated in Table 3.

For the controls, the results show a consistent decrease in flow, significant in 4 of the 6 cases. For the experimental group, the results are inconsistent, in that KH shows consistent decreases in inspiratory flow, whereas PC and AB show mixed effects or increase consistently.

The results for expiratory volume and flow are shown in Table 4 and Figure 4. For comparison, the change in acoustic duration is again shown at the top of Figure 4. All CR interaction terms are significant and are shown for individual rates on the tables.

For both expiratory volume and flow, the changes are consistently, and significantly, in opposite directions for control and experimental groups. Again, the results do not directly parallel the changes in acoustic duration. Of course, the effect of the consistent average increase in expiratory flow in the experimental group is to make it likely that their voices were more breathy overall following treatment.

Laryngeal Devoicing Gestures

The duration of laryngeal devoicing for /f/ or /p/ are shown in Table 5 and Figure 5. On the basis of the "voice initiation target" we might expect an increase in the duration of laryngeal opening and closing gestures, reflected at utterance initiation and in the duration of the consonant laryngeal abduction gesture, the measure reported here. The interpretation of the results is complicated by the fact that 2 of the 9 values for the experimental group are missing for technical reasons. Of the 6 measures of the control group, 4 are decreases in duration, but only 2 are significant changes. For the experimental subjects, due to the missing values, there are only 7 rather than 9 comparisons available. Six of the comparisons are increases, but only 3 are significant. Thus, overall, the changes between conditions for the experimental group are in the expected direction, that is, they are increases, but are not substantial.

Amplitude of Upper Articulator Displacement

The data for the summed upper articulator displacement is shown in three forms, separately for closure formation and closure release. As before, the effects of CR interaction were

TABLE 6. Articulator Displacement in mm.

Subjects	Slow pre *M*	Slow pre *SD*	Slow post *M*	Slow post *SD*	Normal pre *M*	Normal pre *SD*	Normal post *M*	Normal post *SD*	Fast pre *M*	Fast pre *SD*	Fast post *M*	Fast post *SD*
/pit/ Closure												
Controls												
ES	15.21	(1.57)	13.19	(1.55)	18.28	(2.31)	18.13	(1.68)	17.67	(1.18))	17.75	(1.19)
DW	6.79	(2.23)	6.86	(0.95)	7.24	(0.75)	8.02	(1.15)	8.23	(0.76)	9.47	(1.49)
Persons who stutter												
KH	7.38	(0.97)	5.26	(0.76)	7.76	(0.71)	6.7	(0.54)	8.26	(1.0)	6.19	(0.6)
PC	8.88	(1.68)	5.8	(1.27)	9.45	(0.92)	7.13	(0.64)	7.77	(0.90)	5.5	(0.51)
AB	5.69	(0.95)	4.9	(0.69)	7.92	(0.87)	5.48	(0.96)	8.67	(0.68)	5.94	(0.56)
/pet/ Closure												
Controls												
ES	15.18	(1.78)	13.70	(1.34)	17.99	(2.10)	17.57	(1.80)	18.11	(1.21)	18.15	(1.46)
DW	7.70	(1.78)	6.85	(1.33)	8.03	(1.30)	8.76	(1.15)	8.60	(1.09)	10.00	(2.02)
Persons who stutter												
KH	7.52	(0.90)	5.71	(0.78)	8.59	(0.68)	7.39	(0.62)	8.72	(0.90)	6.49	(0.67)
PC	8.98	(0.29)	6.73	(0.88)	9.62	(1.27)	7.05	(0.87)	7.55	(0.60)	5.46	(0.69)
AB	7.37	(0.74)	5.20	(0.93)	7.95	(1.04)	5.60	(0.76)	9.28	(0.92)	6.01	(0.79)
/fit/ Closure												
Controls												
ES	8.21	(1.44)	7.62	(0.97)	13.9	(1.25)	15.00	(1.07)	13.82	(0.90)	14.01	(2.03)
DW	14.78	(1.65)	16.6	(2.48)	15.63	(2.30)	16.37	(1.15)	14.88	(1.10)	15.37	(1.47)
Persons who stutter												
KH	5.36	(1.24)	2.27	(0.80)	5.61	(0.37)	4.31	(0.52)	6.25	(0.75)	4.6	(0.46)
PC	6.47	(0.87)	4.10	(1.11)	4.70	(0.80)	4.77	(0.72)	4.67	(0.56)	3.62	(0.71)
AB	5.57	(0.65)	4.18	(0.44)	4.87	(0.40)	4.38	(0.51)	6.64	(0.85)	5.01	(0.38)
/fet/ Closure												
Controls												
ES	9.29	(1.51)	7.69	(0.84)	14.76	(1.44)	14.82	(1.29)	14.99	(1.55)	14.76	(1.93)
DW	15.64	(1.40)	16.05	(2.06)	15.60	(2.01)	16.04	(0.52)	15.27	(1.02)	16.27	(1.73)
Persons who stutter												
KH	4.28	(0.89)	2.39	(0.66)	6.03	(0.64)	4.61	*(MV)	6.47	(0.83)	4.7	(0.51)
PC	6.9	(0.96)	4.16	(0.60)	5.33	(0.68)	4.52	(0.77)	4.62	(0.49)	3.48	(0.68)
AB	5.73	(0.12)	4.15	(0.57)	5.64	(0.56)	4.43	(0.34)	6.76	(0.64)	5.57	(0.47)
/pit/ Release												
Controls												
ES	15.01	(1.41)	13.22	(1.50)	16.53	(1.80)	15.91	(1.43)	14.58	(1.09)	14.28	(1.05)
DW	7.91	(0.96)	7.78	(1.37)	8.37	(0.96)	7.89	(0.67)	9.57	(0.99)	7.83	(1.46)

TABLE 6. (Continued)

Subjects	Conditions											
	Slow				Normal				Fast			
	pre		post		pre		post		pre		post	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Persons who stutter												
KH	10.58	(1.38)	7.60	(0.78)	9.69	(0.75)	8.5	(0.69)	8.95	(0.70)	7.98	(0.65)
PC	9.00	(1.94)	5.14	(1.53)	11.11	(0.90)	7.25	(1.01)	9.12	(1.17)	4.98	(0.68)
AB	6.28	1.37	5.2	1.04	9.88	1.16	6.08	1.1	11.52	0.72	7.78	0.84
/pet/ Release												
Controls												
ES	15.77	(1.19)	15.32	(2.12)	17.96	(1.66)	17.64	(1.53)	16.64	(0.85)	16.5	(1.32)
DW	11.12	(1.18)	11.52	(1.17)	11.7	(1.97)	11.09	(1.08)	12.29	(1.62)	11.18	(1.19)
Persons who stutter												
KH	12.16	(1.36)	10.34	(1.07)	12.13	(1.04)	11.03	(1.13)	10.49	(0.64)	9.95	(0.98)
PC	11.24	(1.90)	8.29	(1.32)	13.23	(1.03)	8.98	(1.24)	10.88	(1.21)	6.04	(0.90)
AB	11.78	(2.31)	7.2	(1.84)	12.58	(1.25)	8.96	(1.01)	13.59	(1.28)	8.26	(2.59)
/fet/ Release												
Controls												
ES	7.82	(0.92)	6.53	(0.62)	9.34	(0.70)	6.52	(0.74)	8.49	(0.69)	6.63	(0.74)
DW	13.29	(1.61)	15.1	(2.01)	13.62	(2.28)	15.23	(0.67)	19.83	(1.27)	17.5	(2.28)
Persons who stutter												
KH	7.44	(0.87)	5.13	(1.34)	7.8	(0.42)	7.18	(0.41)	8.04	(1.08)	6.70	(0.33)
PC	8.39	(1.22)	6.49	(0.86)	7.71	(0.98)	6.54	(0.69)	6.30	(0.72)	4.22	(0.81)
AB	4.73	(1.07)	4.15	(0.57)	5.64	(0.56)	4.29	(0.53)	6.51	(0.69)	5.57	(0.47)

*$p < .05$
**$p < .01$

TABLE 7. Significance of changes in articulatory displacement.

Subjects		Conditions						
		Slow	Normal	Fast		Slow	Normal	Fast
Controls								
ES	pclosure	** ↓	—	—	fclosure	** ↓	—	—
	prelease	** ↓	—	—	frelease	** ↓	** ↓	** ↓
DW	pclosure	** ↓	** ↑	** ↑	fclosure	—	** ↑	** ↑
	prelease	** ↓	** ↓	** ↓	frelease	* ↓	** ↓	** ↓
Persons who stutter								
KH	pclosure	** ↓	** ↓	** ↓	fclosure	** ↓	** ↓	** ↓
	prelease	—	** ↓	** ↓	frelease	** ↓	** ↓	** ↓
PC	pclosure	* ↓	** ↓	** ↓	fclosure	** ↓	—	** ↓
	prelease	** ↓	** ↓	** ↓	frelease	** ↓	** ↓	** ↓
AB	pclosure	** ↓	** ↓	** ↓	fclosure	—	** ↓	** ↓
	prelease	* ↓	** ↓	—	frelease	** ↓	** ↓	** ↓

*$p < .05$
**$p < .01$

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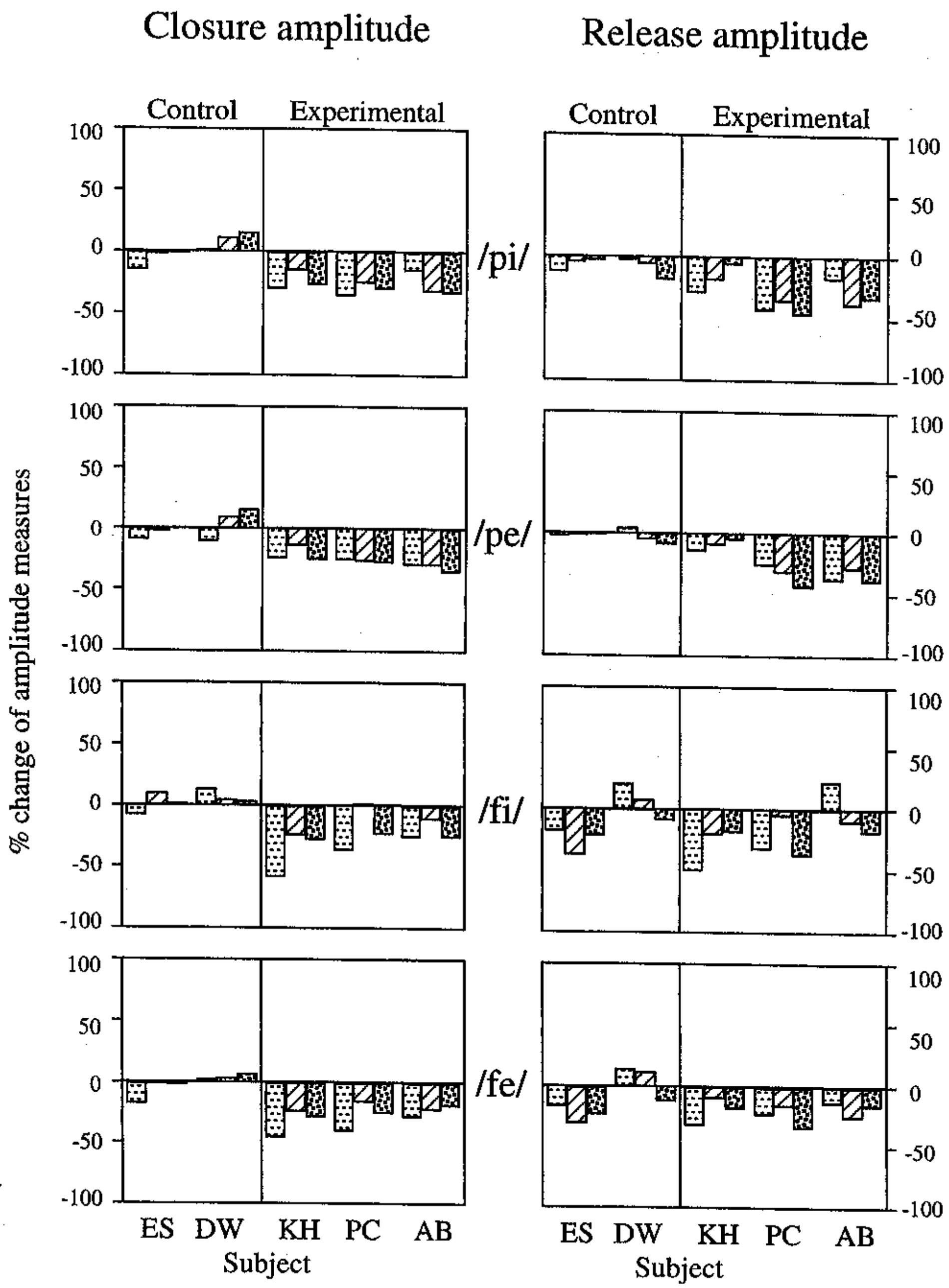

FIGURE 6. The percent change of the amplitude of the closure gesture (left side of the figure) and the release gesture (right side of the figure) for the target nonsense words /pi/, /pe/, /fi/ /fe/ before versus after treatment. "Slow," "normal," and "fast" conditions are indicated by histogram fill pattern. The subjects' initials are indicated on the abscissa.

generally significant, and are reported in Table 7. The changes in amplitude are reported, broken down by consonant and vowel, in Table 6, and as percent change in Figure 6. There are substantial and consistent differences between control and experimental groups on these measures. For control subjects, of 24 comparisons, 16 show significant change, but the directions are mixed. For experimental subjects, of 36 comparisons, 30 are significant, and all are decreases. The pattern is very striking when we examine Figure 6.

Discussion

For all types of measures made, that is, measures of utterance duration, measures of respiration, measures of laryngeal behavior, and measures of articulator displacement, there were significant changes in the posttreatment fluent speech of the subjects who stutter, whereas the controls changed in the opposite direction, or did not change consistently. In general, the changes made by the experimental subjects were in the direction one might expect knowing the instructions provided by the treatment.

First, with respect to speaking rate, with one exception, the experimental subjects generally increased the total duration of their utterances following treatment. One characteristic of this group was that their self-selected slow rates were quite slow, both before and after treatment. However, when compared with the controls, the phrase duration was not very different for the self-selected "normal" and "fast" rates. Although no tests were made of the naturalness of the speech of the subjects who stutter, their speaking rates were not far outside the range of measures of those who do not stutter.

The respiratory measures show that the experimental subjects also changed respiratory behavior in the direction suggested by PFSP instructions. Following treatment, the subjects took "full breaths"—that is, inspiratory volume increased in 8 of 9 comparisons, whereas inspiratory flow did not increase in a consistent direction. Expiratory volume increased as well, perhaps because of the change in utterance duration, but one unexpected consequence of the change in respiration was a change in expiratory flow. This result deserves fuller investigation because the measure made, derived from the overall relation between volume and duration, is too general for specification of whether phonation was breathier or whether the change in the duration of the devoicing gestures was sufficient to account for the difference in flow. In future work, it would be desirable to assess flow more directly, perhaps with a Rothenberg mask. A change in flow is not specified, even by analogy, in the PFSP instructions, and, indeed, one instruction, that is, the "Reduced Pressure target" appears to suggest a mode of speech that would be counterindicated by this result.

Attempts to assess changes in laryngeal behavior were not entirely successful. Due to the difficulty of placing the fiber bundle, changes in laryngeal adduction at phrase onset were not measured. Since the laryngeal devoicing gesture generally changed in the direction of increase, there is some modest indication of "easy onset" of voicing.

Finally, the amplitude of upper articulator contact and release gestures was consistently reduced following treatment. This finding suggests that the subjects who stutter were avoiding large amplitude gestures after treatment, perhaps in response to instructions for "slow change." This result is reminiscent of Zimmermann's observation (1980a, 1980b) that in perceptually fluent speech, persons who stutter had smaller lip and jaw displacements than control subjects. Overall, then, the subjects made changes in their articulation that were consistent with the goals of PFSP treatment, to the extent that the clinician's instructions could be given an unequivocal kinematic interpretation.

An obvious question about these results is the relation of the changed articulation and the increased fluency. If the subjects had shown no consistent changes in articulation but had increased fluency, we could infer nothing about the relation of the specific instruction of the program to the increased fluency. However, it is clear that the changes seen in kinematics in this study are at least consistent with increased fluency.

It remains possible that the changes in fluency might be due to some very general effect of treatment rather than the specific instruction about articulation given by the clinician. For example, the interaction between client and clinician could result in a change in attitude on the part of the client such as increased self-confidence or decreased anxiety about speaking that might, in turn, increase fluency. Another possibility is that any change in articulation induced by treatment resulting in a changed mode of speaking might be responsible for increased fluency. This possibility is recognized by Bloodstein (1995, p. 407) who suggests that "stutterers are likely to speak fluently as soon as they adopt almost any novel manner of speaking."

In spite of these alternative possibilities, the premise adopted by behavioral therapy is that the specific changes in articulation implemented by the program result in increased fluency. One way of getting insight into this broad question is to examine articulation change in persons who stutter who have been exposed to a different kind of treatment program or persons who stutter whose fluency is enhanced by the so-called "fluency-enhancing" conditions (Alfonso, Kalinowski, & Story, 1991).

Several studies (e.g., Metz et al.) show the same result we have seen here with respect to lengthened duration of utterance following treatment. However, Zebrowski (1991), in a study of speech changes of two adolescents following treatment, did not find prolonged phrase duration. She believed that her results were different because the treatment her subjects received put less emphasis on prolonging speech duration. Similarly, Kalinowski (1994), in a study of 4 subjects who received a treatment program at the University of New York at Geneseo, described by its sponsors as based on the principles of van Riper, found no consistent changes in phrase duration following treatment. It is not entirely clear precisely what instructions the subjects received. The essential elements in the treatment are described as "a) detailed analysis of all core and accessory stuttering behaviors and b) training the stutterer to modify core stuttering behaviors through strategies like maintenance of air flow and continuous articulatory forward movements" (Metz, Samar, & Sacco, 1983). Tentatively, we conclude that although slowing speaking rate may be sufficient to enhance fluency, it does not seem to be a necessary condition.

A second result seen here is increased airflow following treatment, also observed by Kalinowski, using similar instrumentation. This result, increased overall airflow, is not what we might expect on the basis of Wingate's hypothesis (Wingate, 1969) that one factor in the effectiveness of the fluency-enhancing conditions is the resulting prolonged phonation. The tendency of the subjects in the present study to prolong laryngeal opening for voiceless stops following treatment may be an indirect result of the overall increased duration of speech or it may be a concomitant of an increased breathiness.

Samar et al. (1986), in a study of the subjects in the Geneseo program cited above, found that in the production of voiceless bilabial stops, subjects produced lower peak glottal flows following treatment and longer rise times to peak flow. This could be because of smaller laryngeal abduction gestures, or alternatively, less tight lip closures, perhaps because of generally reduced extent of lip closure. This last finding, that is, smaller lip closures, was found both by us and by Kalinowski.

Although, overall, the limited literature suggests that changes in speaking rate are not essential to increased fluency after treatment, there are too few studies on the physiological variables explored here to extract individual essential components.

Another approach that we intend to pursue is to examine articulatory changes in the so-called "fluency-enhancing" conditions. There are two advantages of this approach, apart from the relative convenience of comparing experimental conditions in a single session, rather than before and after a protracted period. First, the nature of the environmental change for the person who stutters can be more precisely specified than in the case of the behavioral therapy protocols, where it is difficult to be entirely sure of the nature of clinician-client interactions. Second, the environmental change is reversible, that is, the fluency-enhancing condition can be "turned on and off" so that the correlation between environment and articulation can be experimentally examined. Following such studies, we can perhaps return to treatment studies with more precisely defined hypotheses.

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