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## Speech motor correlates of treatment-related changes in stuttering severity and speech naturalness

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### Abstract

Participants of stuttering treatment programs provide an opportunity to evaluate persons who stutter as they demonstrate varying levels of fluency. Identifying physiologic correlates of altered fluency levels may lead to insights about mechanisms of speech disfluency. This study examined respiratory, orofacial kinematic and acoustic measures in 35 persons who stutter prior to and as they were completing a 1-month intensive stuttering treatment program. Participants showed a marked reduction in stuttering severity as they completed the treatment program. Coincident with reduced stuttering severity, participants increased the amplitude and duration of speech breaths, reduced the rate of lung volume change during inspiration, reduced the amplitude and speed of lip movements early in the test utterance, increased lip and jaw movement durations, and reduced syllable rate. A multiple regression model that included two respiratory measures and one orofacial kinematic measure accounted for 62% of the variance in changes in stuttering severity. Finally, there was a weak but significant tendency for speech of participants with the largest reductions in stuttering severity to be rated as more unnatural as they completed the treatment program.

**Learning outcomes:** As a result of this activity, the reader will be able to (1) outline the rationale for studying speech motor correlates of treatment-related variations in fluency levels; (2) identify

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those speech motor behaviors that are associated with reduced stuttering severity; and (3) recognize possible reasons for the associations between speech motor behavior and stuttering severity.

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## 1. Introduction

One contemporary view of stuttering posits that speech disfluencies arise from anomalous speech motor control or the how the motor control system interacts with emotional, linguistic, cognitive, and metabolic processes (Brown, Ingham, Ingham, Laird, & Fox, 2005; Denny & Smith, 1997; Kent, 2000; Max, Guenther, Gracco, Ghosh, & Wallace, 2004; McClean, 1997; Smith & Kelly, 1997; Zimmermann, 1980a). For example, Zimmermann (1980a) suggested that persons who stutter (PS) move their speech articulators in ways that make the underlying motor control process susceptible to disruption from varying sources of input. This view predicts that, in addition to perceptible episodes of speech disfluency, PS exhibit anomalies in speech motor output during their fluent speech. Identifying these aspects of the fluent speech of PS is seen as an important step toward developing a biologically plausible account of speech disfluency. This perspective has led to a variety of studies that have found differences in the fluent speech motor output of PS and individuals who do not stutter (NS) (Caruso, Abbs, & Gracco, 1988; Max, Caruso, & Gracco, 2003; McClean, Tasko, & Runyan, 2004; Smith & Kleinow, 2000; Zimmermann, 1980b). Further support for studying the fluent speech of PS comes from recent neuroimaging studies, which have shown anomalies in the activity of brain regions that mediate speech motor control during fluent speech in PS (Braun et al., 1997; DeNil, Kroll, Kapur, & Houle, 2000; Foundas, Bollich, Corey, Hurley, & Heilman, 2001; Fox et al., 1996, 2000; Salmelin, Schnitzler, Schmitz, & Freund, 2000).

Although these efforts have identified peripheral speech motor variables and central neural activation patterns that distinguish PS and NS, Young (1994) pointed out that the overlap in the distribution of PS and NS groups makes it difficult to infer the nature of speech motor control differences in the two groups. Although the reason for this distributional overlap is unclear, it may be associated with individual differences among PS in the neural processes that underlie disfluency as well as related compensatory mechanisms during fluent speech.

Armson and Kalinowski (1994) have suggested that these shortcomings of PS–NS group comparisons can be overcome by studying the fluent speech of PS as they experience different levels of fluency. If fluctuations in fluency levels are accompanied by global changes in speech motor output, then analysis of relevant measures may provide clues to the conditions under which disfluency is more likely to occur. Variations in fluency levels in PS can be achieved by means of fluency enhancing procedures such as adaptation induced by utterance repetition (Zimmermann & Hanley, 1983), alteration of auditory feedback (Stager, Denman, & Ludlow, 1997), metronome pacing (Boutsen, Brutten, & Watts, 2000), choral reading (Stager et al., 1997), and various forms of stuttering treatment.

Treatment-related fluency changes, which are the focus of this study, differ from other types of fluency enhancement in that they are usually established over a longer period of

time and are intended to be more permanent. It should be pointed out that, within this research design, the efficacy of the treatment itself is not under investigation. The treatment environment simply provides an opportunity to study PS at different levels of fluency. However, the specific nature of the treatment cannot be ignored since many commonly used stuttering treatments directly modify the way speakers physically produce speech. For example, one widely used approach, the precision fluency-shaping program (PFSP), targets prolongation of utterance duration, gradual onset of phonation, and full breath support (Webster, 1975). While many of these “motor”-based forms of stuttering treatment indicate a high degree of success in reducing speech disfluency (Boberg & Kully, 1994; Craig et al., 1996; Onslow, Costa, Andrews, Harrison, & Packman, 1996), they are also reported to elicit speech patterns that listeners deem unnatural (Metz, Schiavetti, & Sacco, 1990; Runyan, Bell, & Prosek, 1990). Therefore, analyses of speech motor changes that accompany stuttering treatment should consider both stuttering severity and speech naturalness.

A relatively small number of studies have evaluated changes in speech production measures in relation to treatment-based changes in speech fluency. Metz, Samar and Sacco investigated a number of acoustic and aerodynamic variables associated largely with stop consonant production in PS before and after treatment-based reductions in stuttering frequency (Metz, Samar, & Sacco, 1983; Samar, Metz, & Sacco, 1986). In their initial study Metz et al. (1983) found that following treatment, PS exhibited longer voice onset times and frication durations for voiceless stops, longer intervocalic intervals for voiced stops, and longer vowel durations. In a later study (Samar et al., 1986), aerodynamic analysis revealed that following treatment PS reduced stop consonant-related peak volume velocity, shortened durations between voicing offset and oral release for stop consonants, and lengthened the volume velocity rise-time. Further, the intervocalic interval of voiced stops, the volume velocity rise-time, and the duration of the interval between peak volume velocity and voice onset were found to be moderately correlated with changes in stuttering severity.

Murdoch, Killin, and McCaul (1989) evaluated respiratory kinematic changes in seven PS who participated in an intensive cognitive-behavioral treatment. The authors found that following treatment, there was an increase in the relative contribution of abdominal wall movement during expiration and decreased frequency of paradoxical chest wall movements. They noted that these respiratory changes could have been due to either direct effects of the speech training or reduced anxiety following treatment.

Story, Alfonso, and Harris (1996) described respiratory, laryngeal, and articulatory motor output in three PS prior to and following their participation in the PFSP (Webster, 1975). Following treatment, all PS showed marked reductions in stuttering severity and exhibited increased lung volumes, increased average expiratory flow rates, reduced amplitude of lip and jaw movements, and increased duration of laryngeal opening during the production of voiceless stop consonants. These results were of particular interest since they suggest that fluency reduction may involve changes across multiple speech subsystems (i.e. respiration, phonation and articulation).

The goal of the present study was to evaluate how multi-system speech motor behavior varied with treatment-related changes in stuttering severity and speech naturalness. The basic structure and methods of the present study are similar to Story et al. (1996), but here

we have dramatically increased the size of the subject pool. This permitted the use of multiple regression analyses to quantify the associations between treatment-related changes in speech motor output, speech naturalness, and stuttering severity. It is important to emphasize that this study was not intended to evaluate the clinical efficacy of a particular form of stuttering treatment. Rather we were motivated by the view that analysis of changes in speech motor output associated with motor-based forms of stuttering treatment can provide insight on the mechanisms of speech disfluency.

## 2. Methods

### 2.1. Participants

Thirty-five adults (33 M, 2 F) with a history of stuttering since childhood participated in the study. The subject pool has a mean age of 24 years, 11 months and a standard deviation of 6 years. The participants were consecutively enrolled in the Walter Reed Stuttering Treatment Program over a 2-year period. Five participants reported learning English as a second language. Two participants had previously attended the Walter Reed treatment program within the last 2 years.

#### 2.1.1. Overview of treatment program

The Walter Reed Stuttering Treatment Program is an intensive, 1-month, group-based fluency-shaping program consisting of three parts. Part one is largely instructional and addresses the nature of speech production, individual characteristics of stuttering, and attitudes and feelings associated with stuttering. Part two involves establishing behavioral targets including increased abdominal breathing, adequate breath support and volume, continuity of airflow, pre-voiced exhalation, easy articulatory and phonatory onset, continuous phonation, and proper use of phrasing. These targets are established with the assistance of the computer assisted fluency enhancement training (CAFET) program (Gobel, 1988), which provides computer feedback on a number of respiratory and voice–acoustic parameters. CAFET training is closely supervised by a speech-language pathologist to ensure its consistent implementation and that each participant is trained to criteria on the different components of the program. Total time given to the CAFET is about 25 h, but varies depending on how readily a participant trains to criteria. The program's third component is intended to provide opportunities to transfer fluency-enhancing skills to a variety of challenging speaking situations.

### 2.2. Data collection

#### 2.2.1. Clinical-behavioral assessment

A set of videotape and physiologic recordings were acquired immediately before treatment commenced (hereafter termed *pre-Tx*) and a second set of videotape and physiologic recordings were acquired during the latter part of the final week of the treatment program. At this point in the treatment, the participants had fully completed the behavioral target establishment phase and were focused on transferring the behavioral

targets beyond the clinic. Therefore, they were technically completing treatment (hereafter *comp-Tx*) at the time of the second set of recordings. The duration between *pre-Tx* and *comp-Tx* recordings was about 3.5 weeks. Videotape recordings included samples of monologue, reading and telephone conversation. For the present study, the videotaped monologue sample was used to (1) assess stuttering severity using the third edition of the Stuttering Severity Index (Riley, 1994) and hereafter termed the SSI-3, and (2) derive measurements of speech naturalness (Martin & Haroldson, 1992).

The SSI-3 was selected here as a measure of stuttering severity because it was judged to provide a valid continuous measure of the overall strength of the overt characteristics of stuttering.<sup>1</sup> Two certified speech-language pathologists, highly experienced with stuttered speech, carried out SSI-3 measurement procedures using a consensus judgment format. That is, when both judges agreed on the occurrence of an instance of stuttering or physical concomitant being present, it was appropriately marked. When discrepancies occurred, the judges watched the speech sample repeatedly until agreement on the particular case was reached. Reliability measures on the SSI-3 components were not obtained here. Instead, at least 6 months subsequent to this original scoring procedure, a second consensus judgment task was performed by the senior judge (author CMR) and a second experienced judge. During this second task, judges had access to the original scoring sheets. The videotape was watched again and the judges resolved any discrepancies between themselves and the original data by watching the tape as frequently as needed and discussing the sample until agreement was reached.

Speech naturalness ratings were based on a 1 min sample randomly drawn from the *pre-Tx* and *comp-Tx* video recordings of each participant's monologue. No attempt was made to avoid or emphasize disfluent portions of the monologue. These samples were randomized and grouped for presentation to three different listener panels ( $N = 21, 21$  and  $20$ ). Each listener panel consisted of graduate students enrolled in the James Madison University speech and hearing program. Each panel rated a different group of participants. The manner of sample presentation and instructions were identical for each panel. Listeners were instructed to rate the naturalness along a 9-point equal appearing interval scale where 1 was labeled highly natural speech and 9 was labeled highly unnatural speech. All *pre-Tx* samples and all but one *comp-Tx* samples were rated. The mean rating across the listener panel for each sample was derived. Inter-rater reliability was assessed using the intraclass correlation coefficient,  $ICC(2, k)$  (Shrout & Fleiss, 1979). The  $ICC(2, k)$  for the three groups were 0.98, 0.97, and 0.95.

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<sup>1</sup> We recognize the SSI-3 has come under some criticism. Specifically, Lewis (1995) questions its reliability and argues that key clinical information is lost in the overall SSI-3 score. She also notes that generating the score is labor intensive but provides no more information than clinician-based judgments of severity. We chose to use the SSI-3 because we were principally interested in a clinical-behavioral measure of overall stuttering severity. This seemed appropriate since there are reports that the SSI-3 is well correlated with judgments of overall severity (Lewis, 1995; Story et al., 1996). We recently presented 90 s samples of the monologue video recordings (*pre-Tx* only) of this study's subject pool to a panel of 21 graduate student judges. The judges were instructed to rate stuttering severity using a visual analog scale. The intraclass correlation coefficient ( $2, k$ ) (Shrout & Fleiss, 1979) across the pools of judges was 0.97 suggesting the ratings were reliable. The correlation between the mean severity rating and the overall SSI-3 scores that were used as part of this study was 0.71. We feel this evidence supports the use of the SSI-3 in this study as an indicator of overall stuttering severity.

### 2.2.2. Physiological assessment

Within 1 day of the *pre-Tx* and *comp-Tx* videotape recordings, participants underwent a physiologic assessment of the speech motor system. The physiologic assessment involved synchronous recording of orofacial motion, chest wall circumferential motion and voice acoustics as the subject performed a number of speech tasks. The speech tasks included nonsense and real phrase repetition at both habitual and altered speech rates and intensities, extended oral reading, and spontaneous monologue.

### 2.3. Data acquisition and signal processing

Midsagittal, two-dimensional orofacial motion was transduced and recorded with a Carstens AG100 electromagnetic movement analysis system. Three sensor coils (3 mm × 2 mm × 2 mm) were attached with biomedical tape to the bridge of the nose, the vermilion border of the upper (UL) and lower lip (LL). Two more sensor coils were attached with surgical adhesive (Isodent) to the tongue blade (TB) approximately 1 cm from the tip and at the base of the mandibular incisor (MAN). The orofacial movement signals were digitized to computer at 250 Hz per channel. The UL, LL, MAN, and TB movement signals were low-pass filtered at 8 Hz and the nose signal at 3 Hz. Filtering was performed with a fifth-order Butterworth filter with a correction that eliminated any phase lags between signals. Head movements during recording were slight, but the two-dimensional motion of the nose sensor was subtracted from the UL, LL, MAN, and TB movement signals in order to minimize the possibility of head movement contributions. The mean nose position and MAN position at jaw occlusion (which was collected as part of the assessment protocol) was used to re-express the UL, LL, MAN, TB sensors in a Cartesian coordinate system where the ordinate passes through the mean nose and MAN sensor position and the axis origin is the mean MAN position obtained during jaw occlusion. Methods described by Westbury, Lindstrom, and McClean (2002), which take into account jaw rotation, were used to decouple the LL and TB signals from the MAN signal. A three-point central method was used to differentiate the vertical and horizontal displacement signals and obtain speed histories for each of the orofacial structures.

Chest wall motion was transduced using an Ambulatory Monitoring Respirace system. Participants wore a snug-fitting T-shirt. Respirace bands were placed around the rib cage at the level of the axilla and around the abdomen at the level of the umbilicus caudal to the lower ribs. The bands were secured to the T-shirt using medical tape to minimize the chance for movement during testing. The subject was seated and instructed to minimize trunk movements, particularly when performing the assessment tasks. Prior to collection of speech data, the subject performed a series of isovolume maneuvers (at resting expiratory end level) and a least-squares method was used to equate the gains of the rib cage and abdomen signals. Three to four vital capacity (VC) maneuvers were elicited and the largest maneuver was identified and used to reference speech-related signal magnitudes to a percent of VC. The respiratory signals were digitally sampled at rate of 2 kHz. For this study, all analysis was performed on the sum of the adjusted rib cage and abdomen signals, which we assume to reflect variations in lung volume. Magnitudes for speech-related lung volume change were expressed as a percentage of vital capacity.

The audio signal was transduced with a Shure M93 miniature condenser microphone positioned 7.5 cm from the mouth, and digitally sampled at rate of 16 kHz. The microphone-amplifier setup was calibrated to permit measurement of absolute sound pressure levels.

#### 2.4. Speech sample and data analysis

Analysis of *pre-Tx* and *comp-Tx* articulatory kinematic and acoustic characteristics of speech motor behavior was restricted to the nonsense phrase “a bad daba” (/ə bəd dæbə/) produced at a habitual rate and loudness. This utterance was selected because it included a number of large well-defined opening and closing movements of the vocal tract. Thus, specific movements could be readily identified for analysis. A second reason for using this task was that it involved repetition of a simple token involving minimal variation in linguistic and emotional content. Brain imaging results of Murphy et al. (1997) suggest that the use of such a sample engages the speech motor system in a manner that involves minimal activation of brain regions that mediate language. Fig. 1 shows an example of the acoustic and kinematic signal streams for a single production of the test utterance. The speed histories for orofacial structures show well-defined peaks associated with the /b/ and /d/-related vocal tract opening and closing movements. Speech movement strokes were identified using a simple method that identifies a stroke as the period bounded by two successive minima in the speed history (Tasko & Westbury, 2002). Minima correspond to the moment of sign change in the first time derivative of the speed history. Thus, a stroke is operationally defined as a single period of acceleration and deceleration. Movement strokes were identified and organized by phonetic identity (/b/ versus /d/), orofacial structure (UL, LL, and MAN for /b/ and MAN and TB for /d/), and movement type (vocal tract closing versus opening). The phrase contains two instances of a released /b/. Analysis was limited to the closing (U1, L1, ML1) and opening (U2, L2, ML2) of the early /b/ and closing (U3, L3, ML3) of the late /b/. The late /b/ opening was not included in the analysis because it was difficult to reliably identify opening movements. TB and MAN closing (T1 and MT1) and opening (T2 and MT2) movements related to /d/ production were also extracted for analysis. The articulatory kinematic measures selected for analysis included peak speed, duration and distance traveled by individual strokes. Peak stroke speed (SPD) was defined as the maximum speed identified within the individual movement stroke. Stroke duration (DUR) was defined as the period between stroke onset and offset. Stroke distance (DIS) was calculated by deriving the speed history’s time integral over the duration of the stroke. The acoustically defined measures selected for analysis include syllable rate (RATE) and sound pressure level (SPL). The onset and offset of the acoustic waveform (Fig. 1) was used to derive the syllable rate (syllables/s) for the phrase. Finally, the mean sound pressure level (dB) of the middle 80 ms of the stressed vowels in the words /bəd/ and /dæbə/ was extracted (see SPL1 and SPL2 in Fig. 1). Analysis was restricted to the first 10 fluent productions of the phrase.

Analysis of speech breath characteristics was performed on two speech samples. As with the acoustic and orofacial kinematic analysis, speech breaths associated with production of the nonsense phrase “a bad daba” were analyzed. Only speech breaths that included a single production of the test phrase were included. Speech breath analysis was

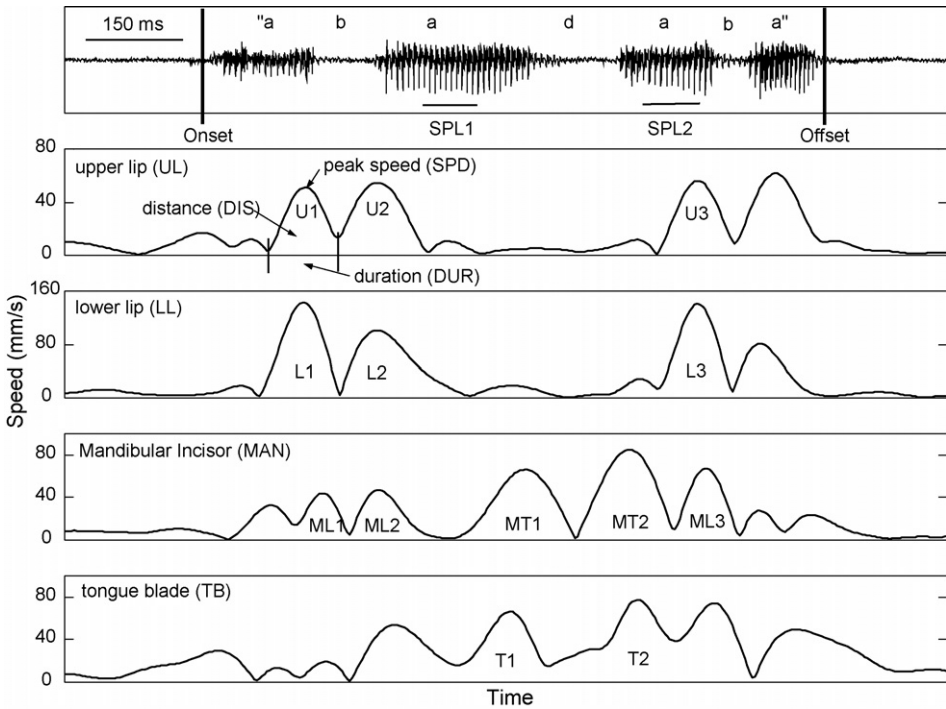


Fig. 1. Sound pressure waveform (top trace) and orofacial speed histories (bottom four traces) associated with a single production of the test utterance, /ə bæd dəbə/. The duration between the acoustically defined onset and offset of the utterance was used to determine syllable rate. The mean sound pressure level (dB) of the middle 80 ms of the stressed vowels in the words /bæd/ and /dəbə/ was extracted (see SPL1 and SPL2). Kinematic analysis was performed on /b/-related lip and mandible vocal tract closing (U1, L1, ML1) and opening (U2, L2, ML2) in /bæd/, /b/-related vocal tract closing in /dəb/ (U3, L3, ML3), /d/-related tongue and mandible vocal tract closing in /bæd/ (TB1, MT1), and /d/-related tongue and mandible vocal tract opening in /dəb/ (TB2, MT2). The peak speed, distance and duration of each movement stroke is extracted.

also extended to include the oral reading of a shortened version of the Hunter Script (Crystal & House, 1982). This was included in response to a concern we had that while the test utterance was helpful for analysis of orofacial kinematic behavior, its brevity resulted in artificially short speech breaths. Fig. 2 shows the summed respitrace signal for a single speech breath. The magnitude (RESP MAG), duration (RESP DUR) and rate (RESP RATE) of relative lung volume change during the inspiratory and expiratory limbs of the speech breath were determined. The percent of the total speech breath duration spent upon inspiration (INS PER) was also determined.

### 2.5. Statistical analyses

The primary method of analysis of the articulatory and respiratory kinematic measures was the repeated-measures ANOVA. For the articulatory kinematic measures (SPD, DIS, and DUR), time of evaluation, articulator, and movement type were treated as within-

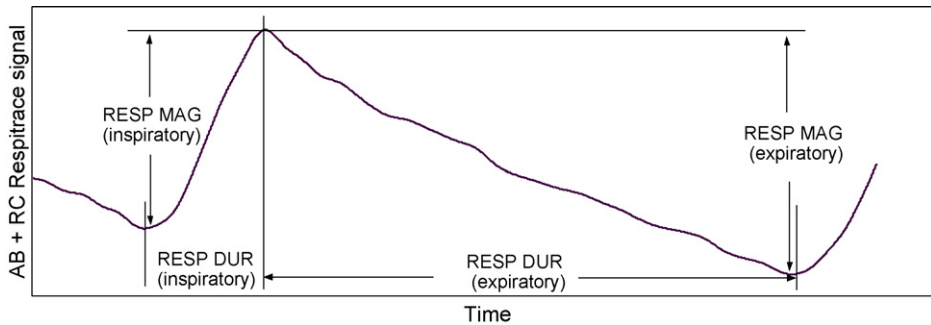


Fig. 2. Summed respiration signal for a single speech breath. Measures that were extracted from each speech breath include the magnitude and duration of the inspiratory limb of the speech breath and the magnitude and duration of the expiratory limb of each speech breath. These measures were used to derive the rate of relative volume change during inspiratory and expiratory limbs of the speech breath. Additionally, the duration measures were used to determine the proportion of the total speech breath duration that is spent on inspiration.

subject effects. The /b/ and /d/-related movements were analyzed separately. For the respiratory kinematic measures (RESP DUR, RESP MAG, and RESP RATE), time of evaluation (*pre-Tx* versus *comp-Tx*), speech task (nonsense versus oral reading), and respiratory limb (inspiratory versus expiratory) were treated as within-subjects effects. For the respiratory measure INS PER, time of evaluation and speech task were treated as factors. For all analyses, a Huynh–Feldt correction was used to adjust the degrees of freedom when there were more than two repeated factors. Behavioral and acoustic measures were submitted to paired *t*-tests. To minimize the inflation of the risk of Type I error, *p*-values were adjusted to hold the experiment-wise risk of Type I error to less than 5%.

Those measures identified to statistically vary as a function of time of evaluation were used as predictor variables in a step-wise linear regression model where the predicted variable is the percent reduction in SSI-3.

### 3. Results

#### 3.1. Clinical-behavioral change following treatment

The upper panel of Fig. 3 plots *comp-Tx* against *pre-Tx* SSI-3 scores across the 35 participants. This plot reveals several noteworthy observations. First, the participants varied widely in both *pre-Tx* and *comp-Tx* SSI-3 scores. Second, all data points fall below the diagonal line of equality indicating that every subject exhibited lower SSI-3 scores as they completed treatment. The mean *pre-Tx* SSI-3 score of 26.1 dropped significantly to a mean *comp-Tx* score of 9.3 (*paired t* = -13.20, *p* < 0.0005). Third, the degree of SSI-3 reduction, as revealed by the vertical distance between the equality line and the data points is also quite variable across the subject pool. This is highlighted in the lower panel of Fig. 3, which is a frequency histogram of the percent SSI-3 reduction for the subject group. Percent SSI-3 reductions range from 20 to 100% across the group with a group mean of 63% reduction.

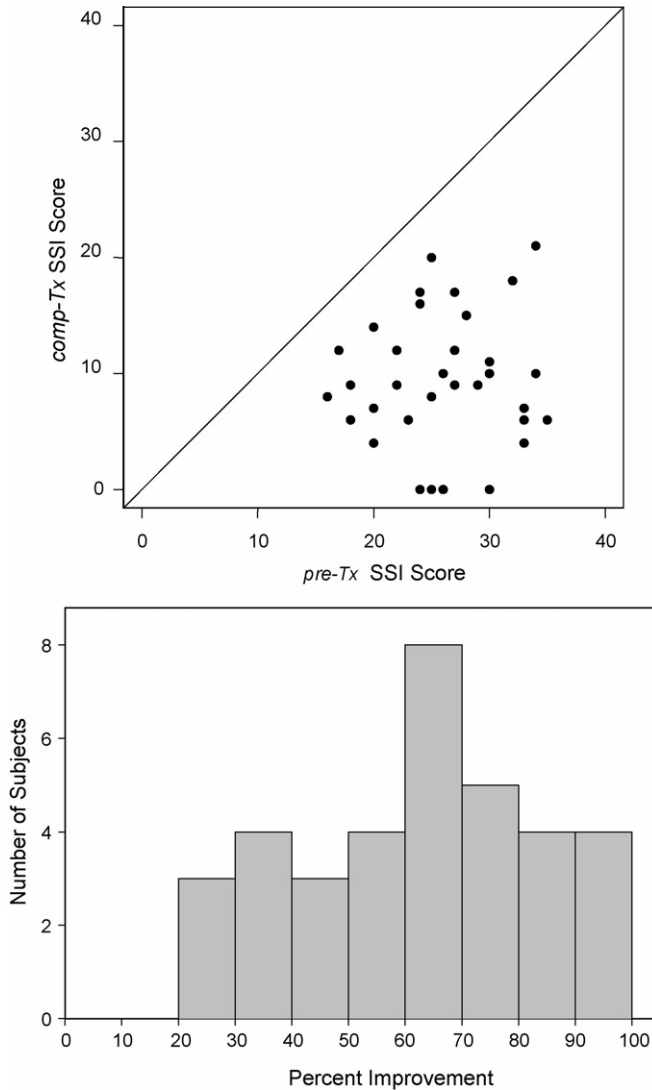


Fig. 3. The top panel plots *comp-Tx* SSI-3 against *pre-Tx* SSI-3. The bottom panel is a frequency histogram showing the distribution of percent improvement in SSI-3 scores as participants completed treatment.

Fig. 4 plots the participants' *comp-Tx* against *pre-Tx* naturalness ratings. Similar to the SSI-3 scores, there is a large range in naturalness ratings for both conditions. However, there is less consistency in the direction of treatment-related changes in naturalness ratings. Some participants were rated more natural in the *comp-Tx* condition, while others were rated less natural. The group as a whole had a mean *pre-Tx* naturalness rating of 4.6 and *comp-Tx* rating of 3.5. Statistical evaluation revealed a modest, but statistically significant reduction in naturalness ratings in the *comp-Tx* condition (paired  $t = -2.71$ ,  $p < 0.01$ ).

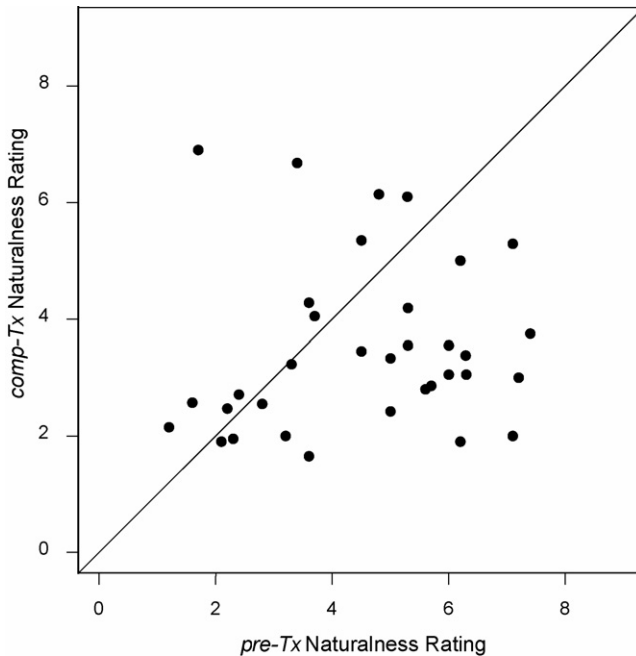


Fig. 4. *Comp-Tx* speech naturalness ratings are plotted as a function of *pre-Tx* speech naturalness ratings.

We performed correlations between naturalness ratings and SSI-3 scores to evaluate the degree to which these measures provide similar information. *Pre-Tx* naturalness ratings were positively correlated with *pre-Tx* SSI-3 scores ( $r = 0.66$ ,  $p < 0.0005$ ), suggesting that prior to treatment, perceptions of speech naturalness were related in part to the severity of the fluency disorder. *Comp-Tx* naturalness ratings showed a weak negative association with *comp-Tx* SSI-3 scores ( $r = -0.32$ ,  $p < 0.06$ ) and a weak positive correlation with the percent change in SSI-3 scores ( $r = 0.38$ ,  $p < 0.02$ ). These last two findings indicate that the participants who made the most improvement (and have the lowest *comp-Tx* SSI-3 scores) sounded the most unnatural to listeners. However, it is important to note that these associations only account for 10–15% of the total variance in the data.

### 3.2. Speech motor behavior changes following treatment

#### 3.2.1. Articulatory kinematic measures

Fig. 5 is a trio of barplots comparing *pre-Tx* and *comp-Tx* results for the duration, peak speed and distance of /b/-related lip and mandible movements. Accompanying ANOVA results for these measures are outlined in Table 1. The time (*pre-Tx* versus *comp-Tx*) main effect and time interaction results are highlighted in bold.

The top panel of Fig. 5 shows a trend for the subject group to exhibit longer LL and MAN movement durations in the *comp-Tx* condition. This observation was supported in the ANOVA results. There was a significant time main effect. There was no significant interaction between time, articulator, and movement type.

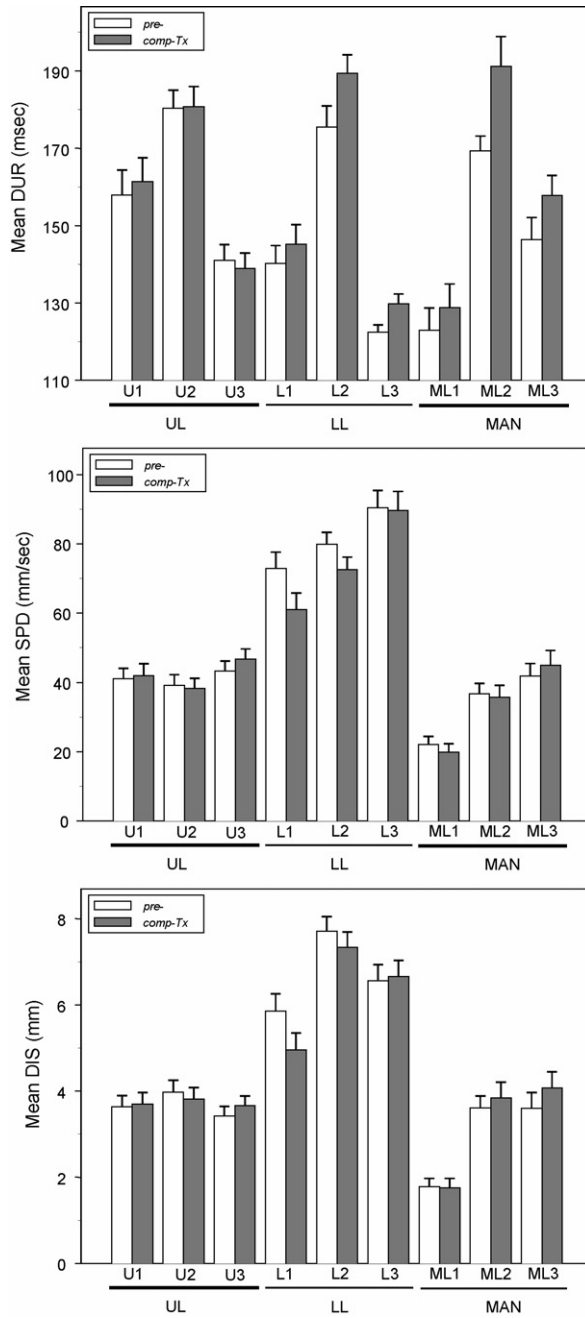


Fig. 5. Paired barplots showing changes in articulatory kinematic measures as a function of time of evaluation (*pre-Tx* vs. *comp-Tx*). The error bars reflect the standard error about the mean.

Table 1  
ANOVA results for /b/-related movements of the UL, LL and MAN

	DUR		SPD		DIS	
	d.f. (Adjusted)	F-ratio	d.f. (Adjusted)	F-ratio	d.f. (Adjusted)	F-ratio
<b>Time</b>	1.00	<b>8.99*</b>	1.00	<b>0.72</b>	1.00	<b>0.02</b>
Error (time)	32.00		32.00		32.00	
Art	1.79	10.45*	2.00	69.38*	2.00	53.01*
Error (Art)	57.34		64.00		64.00	
Mov	2.00	56.56*	1.82	40.30*	1.88	94.60*
Error (Mov)	64.00		58.24		60.27	
<b>Time-by-Art</b>	1.91	<b>3.91</b>	1.98	<b>3.10</b>	2.00	<b>1.83</b>
Error (time-by-Art)	61.20		63.24		64.00	
<b>Time-by-Mov</b>	2.00	<b>0.15</b>	1.63	<b>7.78*</b>	1.65	<b>7.12*</b>
Error (time-by-Mov)	64.00		52.18		52.66	
Art-by-Mov	3.59	20.90*	3.05	20.83*	3.51	21.70*
Error (Art-by-Mov)	114.73		97.44		112.22	
<b>Time-by-Art-by-Mov</b>	3.28	<b>0.98</b>	3.16	<b>2.13</b>	3.32	<b>2.25</b>
Error (time-by-Art-by-Mov)	105.03		101.24		106.10	

The time main effect and time interaction results are highlighted in bold. Time = *pre-Tx* vs. *comp-Tx*, Art = articulator, Mov = movement type, d.f. = degrees of freedom, SPD = peak movement speed, DIS = movement distance, DUR = movement duration.

\*  $p < 0.005$ .

The middle and bottom panels of Fig. 5 show the results for peak stroke speed and stroke distance, respectively. The pattern for these measures is similar enough to be described together. Compared to the DUR results, the SPD and DIS data are more complex. As indicated in Table 1, the time main effect was not significant, but there was a significant time-by-movement type interaction for both SPD and DIS. These interactions can be sourced to reduced peak speed and distance of LL closing movements early in the utterance.

For the /d/-related tongue and mandible movements, there were no significant time-related main effects or interactions. However, a number of significant effects were present. For DUR, there is a significant articulator-by-movement type interaction ( $F = 15.58$ ,  $p < 0.005$ ). For SPD, there was a significant main effect for articulator ( $F = 24.68$ ,  $p < 0.005$ ) and movement type ( $F = 18.24$ ,  $p < 0.005$ ). A significant main effect for articulator type ( $F = 24.30$ ,  $p < 0.005$ ) was observed for DIS.

To summarize the articulatory kinematic results, in the *comp-Tx* condition, participants demonstrated an increase in the duration of bilabial stop-related lip and mandible movements and smaller, slower lower lip movements for bilabial stop closure movements early in the utterance.

### 3.2.2. Respiratory measures

Fig. 6 shows *pre-Tx* and *comp-Tx* results for the duration of respiratory limbs (top left panel), volume of respiratory limbs (top right panel), rate of relative volume change of

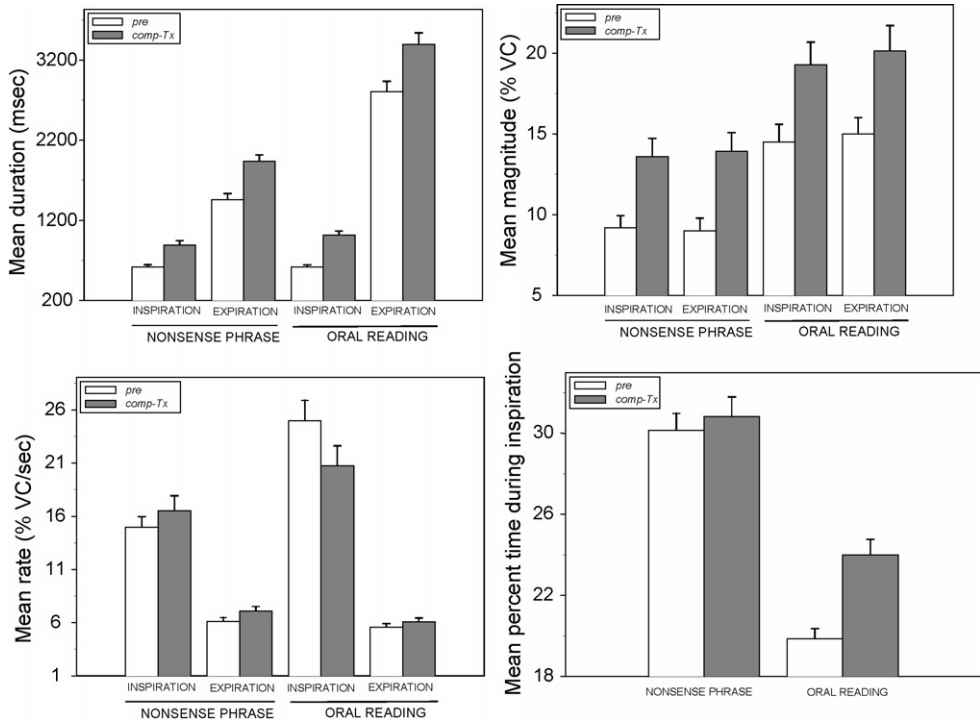


Fig. 6. Paired barplots showing changes in respiratory measures as a function of time of evaluation (*pre-Tx* vs. *comp-Tx*). The error bars reflect the standard error about the mean.

respiratory limbs (lower left panel) and percentage of speech breath dedicated to inspiration (lower right panel). The data are broken out by task (nonsense phrase recitation versus oral reading) and “limb” of the speech breath (inspiratory versus expiratory). Table 2 shows the results of the ANOVA analysis. Fig. 6 clearly illustrates that the duration of the respiratory limbs consistently increased for the *comp-Tx* condition. This was observed for both speech tasks and both limbs of the speech breath. This observation was statistically supported by a significant main effect for time. There was also a significant time-by-respiratory limb interaction indicating that the time-related increases in duration were larger for the expiratory limb of the speech breath. Fig. 6 also shows that participants consistently increased relative lung volume excursions following treatment. Table 2 reveals that this large main effect for time did not interact with factors such as task or limb of the speech breath. In contrast, there was not a significant time main effect for the rate of relative volume change. However, time-by-task and time-by-task-by-limb interactions were significant. This is evident from the barplots in the bottom left panel of Fig. 6. There was a trend toward a small increase in the rate of volume change for all tasks and limbs except for the oral reading task. Here, the rate of relative volume change was reduced for the inspiratory limb.

The bottom right panel of Fig. 6 plots the percentage of speech breath dedicated to inspiration (INS PER) for the two speech tasks. There is a large increase in INS PER for the

Table 2

ANOVA results for measures of the duration (ms), magnitude (% VC) and rates (% VC/ms) associated with speech-related respiratory movements

	RESP DUR		RESP MAG		RESP RATE	
	d.f. (Adjusted)	F-ratio	d.f. (Adjusted)	F-ratio	d.f. (Adjusted)	F-ratio
<b>Time</b>	1	<b>48.20*</b>	1	<b>26.86*</b>	1	<b>0.087</b>
Error (time)	29		29		29	
<b>Task</b>	1	99.18*	1	37.03*	1	45.33*
Error (task)	29		29		29	
<b>Limb</b>	1	677.97*	1	7.91	1	131.31*
Error (limb)	29		29		29	
<b>Time-by-task</b>	1	<b>2.60</b>	1	<b>0.18</b>	1	<b>11.59*</b>
Error (time-by-task)	29		29		29	
<b>Time-by-limb</b>	1	<b>9.86*</b>	1	<b>4.20</b>	1	<b>2.77</b>
Error (time-by-limb)	29		29		29	
<b>Task-by-limb</b>	1	156.10*	1	6.47	1	92.33*
Error (task-by-limb)	29		29		29	
<b>Time-by-task-by-limb</b>	1	<b>0.42</b>	1	<b>0.004</b>	1	<b>15.20*</b>
Error (time-by-task-by-limb)	29		29		29	

The time main effect and time interaction results are highlighted in bold. Time = *pre-Tx* vs. *comp-Tx*, task = nonsense phrase vs. oral reading, limb = respiratory limb (inspiration vs. expiration), RESP DUR = length of respiratory event, RESP MAG = magnitude of respiratory event, RESP RATE = rate of relative volume change for respiratory event.

\*  $p < 0.005$ .

Table 3

ANOVA results for the respiratory measure INS PER, which refers to the percentage of the speech breath dedicated to inspiration

	INS PER	
	d.f. (Adjusted)	F-ratio
<b>Time</b>	1	<b>9.89*</b>
Error (time)	29	
<b>Task</b>	1	149.51*
Error (task)	29	
<b>Time-by-task</b>	1	<b>9.89*</b>
Error (time-by-task)	29	

The time main effect and time interaction results are highlighted in bold. Time = *Pre-Tx* vs. *Comp-Tx*, task = nonsense phrase vs. oral reading.

\*  $p < 0.005$ .

oral reading passage that is much less pronounced for the nonsense phrase. The ANOVA results (Table 3) confirm this observation. There was a significant time main effect and a significant time-by-task interaction. Post hoc testing revealed an increase in the percent time spent inspiring for the oral reading task only ( $t = 5.54$ ,  $p < 0.0005$ ).

### 3.2.3. Acoustic measures

For the nonsense phrase, the participant group exhibited a statistically significant reduction from a *pre-Tx* mean speech rate of 4.5 syllables/s to a *comp-Tx* mean speech rate of 3.8 syllables/s ( $t = -5.86$ ,  $p < 0.0005$ ). Time-related changes in SPL for the nonsense phrase were also evaluated. The subject group showed no systematic time-related differences in sound pressure level for either syllable.

### 3.3. Association between changes in clinical-behavioral measures and speech motor output

The results reported in the last section clearly demonstrate that participants altered their speech motor behavior across the two recording times. What is not clear is the degree to which these changes are associated with reductions in stuttering severity. Regression analysis was used to determine if changes in speech motor measures were associated with reductions in SSI-3 scores. The predicted variable was the percent SSI-3 reduction. Prior to submission to regression analysis, these percentages were arcsin transformed to stabilize the variance. The measures of speech motor output that showed the most pronounced time-related changes were treated as potential predictor variables. These variables included significant time-related change in DUR, SPD, and DIS of /b/-related movements, changes in overall RESP DUR, RESP MAG, changes in reading-related inspiratory RESP RATE and changes in reading-related INS PER. The variables were added and removed in a step-wise fashion in order to identify the best predictors of behavioral improvement. Three variables, RESP MAG ( $p = 0.008$ ), inspiratory RESP RATE ( $p < 0.00005$ ) for oral reading and the DUR of early LL vocal tract opening gestures ( $p = 0.0004$ ) were found to account for 62% of the variance in percent SSI-3 reduction ( $p < 0.00001$ ).<sup>2</sup> Variance inflation factors for the predictors were less than 1.7 suggesting a minimal contribution of multi-collinearity. The model suggests that those participants who experienced the largest reductions in their *comp-Tx* SSI-3 scores tended to use larger respiratory volumes, smaller rates of relative volume change during inspiration, and longer lower lip opening movements.

Due to the weak positive association between SSI-3 improvement and *comp-Tx* naturalness ratings, we were concerned that *comp-Tx* naturalness might serve as a confounding and/or interacting variable within our regression model. To address this concern we employed methods outlined by Kleinbaum, Kupper, and Muller (1988). This involved expanding the aforementioned regression model to include the three speech motor variables, *comp-Tx* naturalness and all interaction terms. The results showed that *comp-Tx* naturalness ratings did not interact with any of the other terms in the model. We also assessed the role of *comp-Tx* naturalness as a potentially confounding variable. We compared the coefficients for each of the three speech motor terms from the original model with an (additive) regression model that also included *comp-Tx* naturalness. The coefficients changed very little across the two models suggesting that *comp-Tx* naturalness had a minimal confounding effect on our results (Kleinbaum et al., 1988).

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<sup>2</sup> We ran a similar regression model using the same predictor variables and using percent stuttered words instead of SSI-3 scores as the predicted variable. Findings were very similar to those described above ( $R^2 = 0.68$ ,  $p < 0.00001$ ).

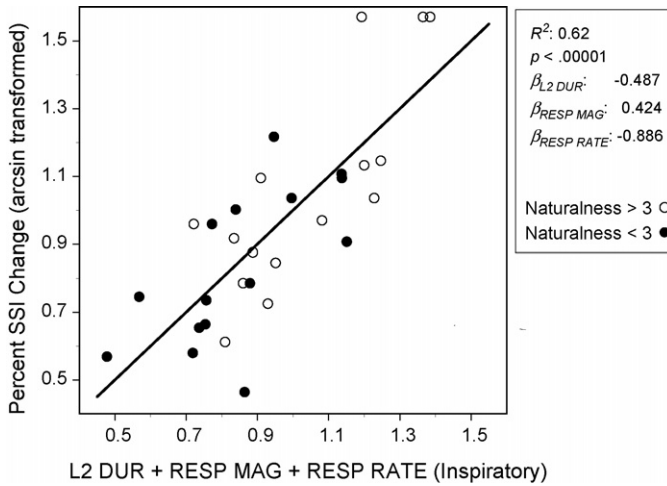


Fig. 7. Scatterplot showing percent change in SSI-3 scores (arcsin transformed) plotted against a linear combination of three speech motor measures (change in L2 duration, change in respiratory extent and change in the rate of relative volume change during inspiration). Symbols are coded according to mean speech naturalness ratings as participants completed treatment. Filled symbols represent participants with mean ratings less than 3. Unfilled symbols represent participants with mean ratings greater than 3. The  $R^2$  value,  $p$ -value, and Beta coefficients for each term are listed in the box to the right.

The relationship between speech motor behavior, stuttering severity and *comp-Tx* speech naturalness is revealed graphically in Fig. 7, which plots severity change against linear combination of the three speech motor variables. The linear association is clearly evident. The individual subject data points are coded according to their *comp-Tx* naturalness ratings. A median split (median  $\sim 3$ ) was employed to break the group into a high (rating  $< 3$ ) and low naturalness (rating  $> 3$ ) groups. It can be observed that while those participants that exhibited the largest reduction in severity tend to be in the low naturalness group and those that made the smallest severity reductions tend to be in the high naturalness group, the middle of the distribution shows a mixture of high and low naturalness ratings.

Finally, bivariate correlation was used to identify possible associations between *comp-Tx* speech motor measures and naturalness ratings. Results indicate that syllable rate ( $r = -0.40, p < 0.05$ ) and the rate of relative volume change during inspiration ( $r = -0.38, p < 0.05$ ) and expiration ( $r = -0.34, p < 0.05$ ) were negatively correlated with *comp-Tx* naturalness ratings. In summary, speech samples rated as unnatural were associated with reduced syllable rates, and smaller rates of relative lung volume exchange. However, it should be noted that none of these correlations account for a very large proportion of the variance in the data.

#### 4. Discussion

The principal goal of this study was to evaluate how multi-system speech motor behavior changed with variations in stuttering severity in participants of an intensive stuttering

treatment program. As a group, PS exhibited a range of speech motor changes coincident with reduced stuttering severity including an overall increase in the magnitude and duration of speech breaths, task specific reductions in the relative rate of inspiration and increase in relative inspiratory duration, longer articulatory movement durations, context specific reduction in articulator speed and amplitude, and a reduction in syllable rate. Multiple regression analyses revealed that a linear combination of two respiratory-based change measures and one orofacial kinematic change measure accounted for 62% of the variance in the percent reduction in stuttering severity. Coincident with reductions in stuttering severity, many participants also showed reduced speech naturalness as they completed treatment. However, this variable did not appear to interact or confound the regression results. Finally, the speech naturalness ratings of the participants when they were completing therapy showed a weak correlation with syllable rate and relative rate of lung volume change.

As the participants were completing therapy, they clearly altered the way they controlled their speech breathing. The trend for the participants to take larger and longer inspirations and expirations is a finding that is generally consistent with the results reported by Story et al. (1996). The increase in breath size appears to be uniform across both limbs of both speech tasks. Respiratory durations are also larger across speech breath limbs and speech tasks, although in a less uniform way, as revealed by the interaction between recording time (*pre-Tx* and *comp-Tx*) and respiratory limb. This up-scaling of speech breath size and duration may be attributed to the therapeutic target “adequate breath support and volume”. Participants were provided biofeedback of chest wall motion as they establish the various targets. Therefore, while not surprising, it appears that participants were actually implementing the therapeutic target. Participants demonstrated less uniformity for other respiratory measures. The rate of relative volume change was reduced for only the inspiratory limb of the oral reading task. Also, participants spent a larger proportion of their speech breath duration on inspiration during the oral reading task. This differential effect of speech task for these two measures may be the result of differences in the respiratory demands of the two speech tasks. The respiratory analysis performed on the nonsense phrase was limited to speech breaths that include single repetitions of the four syllable test phrase. It is likely that the brevity of the breath groups does not fully reflect participant behavior for longer breath groups that is more typical of communication. During the oral reading task, the number of syllables per breath group was much greater and the associated lung volume curves qualitatively appeared more like those typical of speech. Therefore, a connected speech task, such as oral reading is more likely to reveal differences in speech breathing behavior. It should be noted that the reduced rate of relative volume change during inspiration and increased relative time spent inspiring is also consistent with therapeutic targets, which focus rather heavily on controlling the inspiratory limb prior to speech production. Overall, our participants exhibited marked adjustments in speech breathing behavior that are largely consistent with therapeutic targets. Recognizing the speculative nature of the question, how might such changes aid in reducing the frequency of stuttering? Denny and Smith (1997) have argued that respiratory muscle systems are influenced by three functionally and anatomically distinct neuromotor control systems responsible for (1) regulation of vegetative breathing, (2) emotional control and nonspeech vocalization, and (3) speech production. They also suggest that heightened input from the nonspeech control systems during speech production may create

the conditions necessary for speech fluency breakdown. Denny and Smith (2000) identified a subgroup of PS who exhibited speech-related respiratory EMG coherence patterns that were similar to vegetative breathing. One interpretation of the present data is that the substantial adjustments in speech breathing behavior in our PS group reflect a heightened influence from neural systems involved in voluntary control of respiration. This could serve to override possible neuromuscular instabilities due to more automatic nonspeech control mechanisms.

Participants also made a number of adjustments in articulatory kinematic and speech acoustic behavior across the two recording times. The articulatory kinematic scaling changes were less uniform than the respiratory measures and varied as a function of phonetic context, articulator identity and position of the movement within the utterance. It should be noted that, for reasons outlined earlier, this study limits analysis of articulatory kinematic behavior to the simple nonsense phrase. We recently showed that articulatory kinematic data of normal speakers are influenced by speech task in complex ways (Tasko & McClean, 2004). Observing task interactions with treatment participation for articulatory movements of PS is an important avenue to explore in future studies. Such work could test the generalizability of the current results and allow more comprehensive speech motor profiling of PS. That said, only movements related to the bilabial context showed *pre-Tx* versus *comp-Tx* differences. Specifically, in the *comp-Tx* condition, participants reduced the amplitude and peak speed of early /b/-related lower lip closing. This re-scaling of size and speed was not observed for movements later in the utterance. From a therapeutic perspective, this result is consistent with the target termed easy articulatory onset. Story et al. (1996) also found evidence of smaller orofacial movement amplitudes following treatment participation, although reductions were observed for both opening and closing movements. Reducing the amplitude and speed of lip movements into a bilabial closure is likely to reduce the magnitude of collision forces at closure and result in a smaller degree of discharge from pressure-sensitive mechanoreceptors. A reduced level of afferent drive to motoneuron pools may reduce the probability of unstable motor output (Zimmermann, 1980a). Of course, at this point, these suggestions are speculative.

A second, more uniform result is that the duration of /b/-related lower lip and jaw movements were longer after treatment, and syllable rates were markedly reduced in the *comp-Tx* condition. This slowing of acoustic and articulatory measures is consistent with results reported in previous studies, although specific measures do differ between our results and others (Metz et al., 1983; Story et al., 1996). The articulatory timing changes observed in this study cannot be readily traced to any particular therapeutic target, because participants were not specifically instructed to slow speech. In fact, when combined with the respiratory data, there was an overall pattern that suggests that as participants completed treatment they showed a general increase in the durational aspects (i.e. slowing) of speech motor output. This slowing pattern occurs across speech events that have relatively large time scales (i.e. the speech breath and utterance) and relatively small time scales (i.e. individual movements within the utterance). As noted above, the overall pattern of slowing is not as easy to explain in terms of therapeutic targets, since speech rate reduction was not a specific therapeutic goal. One view is that this slowing of motor output is a consequence of the participant having to learn to speak in a novel way. There is evidence from the motor learning literature that developing expertise in a movement task is

associated with a reduction in its duration (Wulf & Shea, 2002). There is a substantial motor learning component to the Walter Reed program. In fact, any intensive fluency-shaping program requires PS to make marked voluntary changes in what is largely an unconscious motor behavior (speech production) in a relatively short period of time. Thus it is possible that PS continued to struggle to skillfully execute the therapeutic targets even, though from a clinical standpoint, the targets had been established. This may also account for why many participants had unnatural sound speech patterns as they completed treatment. The strongest speech motor correlate of reduced speech naturalness was a reduced syllable rate. Those participants who have unnatural sounding speech may have been struggling with acquisition of the therapeutic targets.

This is not to say that these temporal changes cannot possibly be related to the goal of fluency enhancement. One interpretation is that any alteration of speech motor behavior from its habituated form (as is done in many stuttering treatments) may make speech production in PS a more conscious, volitional process. This may be revealed in greater speech motor planning and more ongoing monitoring of the quality of the speech signal. A slowing such as we observe in this study could serve both purposes. An increased inspiratory duration may provide the necessary time for speech motor planning (Whalen & Kinsella-Shaw, 1997), while slowed speech motor output, as revealed by longer movement durations and reduced syllable rates may enhance the role of auditory and somatosensory feedback systems in motor control processes. The interpretation that some of this general slowing of motor behavior is in response to speech motor skill acquisition is consistent with recent neuroimaging results in PS. De Nil, Kroll, Lafaille, and Houle (2003), used PET imaging to evaluate a PS group before, immediately after and 1 year following participation in a stuttering treatment program that emphasizes altering speech motor behavior. De Nil et al. argue that this observation reflects increased monitoring of speech motor events. This idea is supported by recent fMRI imaging data showing elevated activity in the sensorimotor centers of the left hemisphere following fluency shaping therapy (Neumann et al., 2005). Future studies that evaluate treatment-related variation in PS speech motor output obviously would benefit from long term follow up assessment of speech motor behavior.

Finally, the observation that reductions in stuttering severity are associated with a combination of respiratory and orofacial kinematic measures highlights the utility in using multi-system measures to understand PS and provides support that system-wide changes in how speech is produced may be important for fluency enhancement. This is consistent with recent evidence that PS and NS differ in the way they “couple” speech subsystems to produce fluent speech (McClellan & Tasko, 2004). However, it is important to note that the present study did not specifically evaluate how coupling or coordination between speech muscle subsystems varied with treatment-related variations in stuttering severity. This is a topic for future work.

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participants was approved by the institutional review boards of both institutions. We thank Suganya Velauthem for her work in collecting the stuttering severity ratings described in Footnote 1.

### **Appendix A. Self-study questions**

1. What best describes the goal for this study?
  - a. To identify measures of speech physiology that are associated with changes in stuttering severity and speech naturalness
  - b. To determine the efficacy of a particular treatment program
  - c. To determine what brain regions are active before and after stuttering treatment
  - d. To identify measures of speech physiology that are associated with changes in speaking rate in persons who stutter
  - e. None of the above
2. In the current study, what strategy was used to alter fluency level varied within the participant group?
  - a. Utterance repetition
  - b. Metronome pacing
  - c. Stuttering treatment
  - d. Altered feedback
  - e. None of the above
3. In the current study, what types of measures were included?
  - a. Respiratory kinematic, electroglottographic, speech acoustic
  - b. Orofacial electromyographic, respiratory kinematic, speech acoustic
  - c. Orofacial kinematic, electroglottographic, speech acoustic
  - d. Respiratory kinematic, orofacial kinematic, speech acoustic
  - e. Aerodynamic, orofacial kinematic, respiratory kinematic
4. In the results of the current study, which variables were included in the regression model that was used to predict reductions in stuttering severity?
  - a. Lip movement amplitude, magnitude of respiratory movements and syllable rate
  - b. Lip movement duration, rate of lung volume change (inspiration), syllable rate
  - c. Lip movement duration, rate of lung volume change (inspiration), magnitude of respiratory movements
  - d. Lip movement speed, rate of lung volume change (inspiration), syllable rate
  - e. Lip movement duration, lip movement speed, magnitude of respiratory movements
5. What measures were most strongly associated with reduced speech naturalness?
  - a. Peak speed of lip movements
  - b. Syllable rate
  - c. Rate of relative lung volume change
  - d. a and b
  - e. b and c

Answer key: 1—a; 2—c; 3—d; 4—c; 5—e.

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