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Phonation interval modification and speech performance quality during fluency-inducing conditions by adults who stutter

Roger J. Ingham[1], **Anne K. Bothe**[2], **Yuedong Wang**[1], **Krystal Purkhiser**[3], and **Anneliese New**[3]

[1]University of California, Santa Barbara

[2]University of Georgia

[3]University of Texas Health Science Center at San Antonio

Abstract

Purpose—To relate changes in four variables previously defined as characteristic of normally fluent speech to changes in phonatory behavior during oral reading by persons who stutter (PWS) and normally fluent controls under multiple fluency-inducing (FI) conditions.

Method—Twelve PWS and 12 controls each completed 4 ABA experiments. During A phases, participants read normally. B phases were 4 different FI conditions: auditory masking, chorus reading, whispering, and rhythmic stimulation. Dependent variables were the durations of accelerometer-recorded phonated intervals; self-judged speech effort; and observer-judged stuttering frequency, speech rate, and speech naturalness. The method enabled a systematic replication of Ingham et al. (2009).

Results—All FI conditions resulted in decreased stuttering and decreases in the number of short phonated intervals, as compared with baseline conditions, but the only FI condition that satisfied all four characteristics of normally fluent speech was chorus reading. Increases in longer phonated intervals were associated with decreased stuttering but also with poorer naturalness and/or increased speech effort. Previous findings concerning the effects of FI conditions on speech naturalness and effort were replicated.

Conclusions—Measuring all relevant characteristics of normally fluent speech, in the context of treatments that aim to reduce the occurrence of short-duration PIs, may aid the search for an explanation of the nature of stuttering and may also maximize treatment outcomes for adults who stutter.

Keywords

stuttering; phonation; fluency-inducing; speech effort; speech naturalness

Corresponding author: Roger J. Ingham Ph.D., Department of Speech and Hearing Sciences, University of California, Santa Barbara, Santa Barbara CA 93106, rjingham@speech.ucsb.edu, Phone: (805) 893-2776.

[3]An alternative theory as to the neural source of influence during chorus reading has been offered by Kalinowski and Saltuklaroglu (2003). Based on findings showing that observing a choral speaker (Kalinowski et al., 2000) reduces stuttering, they have proposed that mirror neurons (see Rizzolatti, &. Arbib, 1998) might be triggered by chorus reading.

1. Introduction

Many speaking conditions are known to reduce stuttering in many persons who stutter (PWS). Often referred to as fluency-inducing (FI) conditions, these include whispering, singing, reading out loud with another person or a recorded accompanist (chorus reading), rhythmic speech, speaking while being exposed to loud broad-band noise (masking), prolonged speech, and many others (Adams & Ramig, 1980; Andrews, Howie, Dozsa, & Guitar, 1982; Barber, 1939, 1940; Colcord & Adams, 1979; Goldiamond, 1965; Ingham, Bothe, Jang, Yates, Cotton, & Seybold, 2009; Johnson & Rosen, 1937; Kalinowski, Stuart, Rastatter, Snyder, & Dayalu, 2000; Martin & Haroldson, 1979). The effects of the FI conditions can be inconsistent or complex (Bothe, Finn, & Bramlett, 2007), and most are known to be temporary, but the predictable variability that they create nevertheless serves as an important element of theory, research, and treatment for and about stuttering.

One weakness of much previous research about FI conditions, however, and of some related attempts to develop full-scale treatment programs based on the FI conditions, is that this work often does not assess whether or not the resulting speech can be characterized as normal or normally fluent in a larger sense (Finn & Ingham, 1989). Normal fluency has been defined for stuttering in terms of four variables or characteristics: the absence of stuttering events, speech rate within a normal range, normal overall naturalness of speech, and normal levels of physical and cognitive effort on the part of the speaker (Starkweather, 1987). Speech rate and the naturalness of posttreatment speech, in particular, have been the subject of substantial investigation (e.g., Ingham & Onslow, 1985). To the authors' knowledge, however, the only study to have addressed all four of these definitive features of normal fluency in both typical speaking conditions and FI conditions with PWS was Ingham et al.'s (2009) recent investigation of masking, chorus reading, whispering, and rhythmic speech in 12 PWS and 12 normally fluent controls. All four conditions reduced stuttering, but most of the FI conditions also resulted in reduced speech rate, decreased overall naturalness, and/or increased physical effort as rated by the speaker (Ingham, Warner, Byrd, & Cotton, 2006). Importantly, chorus reading differed from the other conditions in that it was associated with scores or ratings within the normal range on all four variables (stuttering, rate, naturalness, and effort), a combination that did not occur for any of the other FI conditions. Based on these results, Ingham et al. (2009) suggested that the speech produced under chorus reading conditions might serve as a model for normal fluency in research about the nature of stuttering or in the development of treatment methods or goals.

One problem with this recommendation, however, is that the logical relationship between an FI condition and the resulting speech may not a simple one. In particular, viewing chorus reading, or any other FI condition, as the cause, and the resulting speech as the effect, might be overlooking an intervening variable in the form of underlying physiological changes that the FI condition induces. In particular, in the case of the FI conditions, one issue is that stuttering and laryngeal activity have long been theorized to be related in some way, and their interdependence has also been demonstrated both in basic research and in research about stuttering treatment. It is well established, for example, that PWS produce less stuttering when their speech includes an extreme proportion of phonation, whether at high levels (such as during singing) or at low levels (such as during whispering) (see Ingham, 1984; Wingate, 1969; 1970; 1976). The predictable complement is also true: PWS not only show reduced stuttering when phonation is relatively constant but also show greater difficulty than speakers who do not stutter with the initiation and termination of phonation. Both voice initiation times and voice termination times are slow among PWS (Adams & Hayden, 1976)[1]; stuttering is increased when speech requires rapid alternation of voiced and voiceless sounds (Manning & Coufal, 1976); reducing the occurrence of phonated intervals (PIs) shorter than approximately 150–200 msec, which reduces the number or speed of phonated to nonphonated transitions, decreases stuttering (Gow & Ingham, 1992; Ingham, Montgomery, & Ulliana, 1983); and increasing the occurrence of these very short PIs can increase the frequency of stuttering (Ingham et al., 1983). Some speakers who stutter also demonstrate what appears to be abnormal coordination among articulatory, laryngeal, and respiratory systems (Conture, McCall, & Brewer, 1977; Ludlow & Loucks, 2003; Max, Caruso, & Gracco, 2003; van Lieshout, Hulstijn, & Peters, 2004)[2], and some demonstrate relatively poor speech-motor skill learning more generally (Namasivayam & van Lieshout, 2008). In turn, these factors may be directly related to abnormal neural systems that now appear to be functionally related to stuttering behavior (see Ingham, Cykowski, Ingham, & Fox, 2008).

These two bodies of knowledge – on physiological and neurological speech systems - are linked by the possibility that the FI conditions may cause, require, or be associated in some other way with functionally important changes in phonation. Indeed, one of the most influential theories of stuttering in the last decades was Wingate's (1969; 1970; 1976) attempt to explain the FI conditions in terms of what he referred to as increased vocalization. Some of the specifics of Wingate's "modified vocalization hypothesis" have not been upheld, but its most basic tenet, that stuttering and phonation are related, is well supported. Recently, for example, Davidow, Bothe, Andreatta, and Ye (2009) investigated the differential effects on phonatory behavior of four FI conditions known to be among the most effective at reducing stuttering: chorus reading, prolonged speech, singing, and rhythmic speech. The tasks were also performed at two different oral reading rates, approximately 90 and 180 syllables per minute (SPM), to begin to address the related problem that some of the changes previously interpreted as the results of an FI condition might be simply reflective of the reduced rate at which those conditions are often produced. Davidow et al.'s (2009) results, from 10 adults who stuttered, showed that all four of the FI conditions they studied were associated with similar changes in phonatory behavior. Specifically, across all conditions and speech rates, the most common changes were a reduction by approximately 50% in the frequency of very short (in the range of 30 to 150 ms) PIs and an increase by as much as 100% in some longer duration ranges. These results suggest that the most effective FI conditions, and perhaps therefore the most effective treatments for stuttering, might share the common property of being associated with a reduced number or proportion of short intervals of phonation, or of quick transitions between phonated and nonphonated speech production, and/or might be associated with an increased number or proportion of longer, slower, or more consistent phonation. This result, in turn, is consistent with the demonstrated effectiveness and efficiency of treatment programs for stuttering that reduce the speaker's use of very short PIs, operationally defined as reducing by half the number of PIs in the duration range that contained the shortest or bottom 10% to 20% of that speaker's PIs in baseline or typical speaking tasks (referred to as that speaker's bottom decile or bottom quintile, respectively; Ingham, Kilgo, Ingham, Moglia, Belknap, & Sanchez, 2001). Again, the predictable complement is also true: Among the best supported treatment approaches for stuttering are those that emphasize increased, prolonged, or continuous

[1]A recent review by Smits-Bandstra (2010) of reaction-time research with PWS suggests that the effects may be conditioned by task complexity and practice. Nonetheless the findings with respect to voice onset and offset slowness in PWS relative to PNS populations remain robust.

[2]A study by Smith, Denny, Shaffer, Kelly and Hirano (1996) appears to suggest that while there may be unusual laryngeal activity during the speech of PWS, it does not necessarily reflect any deficit in phonatory function. Smith et al. made a variety of intrinsic laryngeal muscle measures of phonatory activity during different speaking tasks with adult 4 PWS and 3 CONT participants. From findings obtained from these small groups they concluded that PWS do not "typically" produce "excessive levels of intrinsic laryngeal muscle activity" (p. 329). This conclusion was reached because the 3 controls had proportionately more activity. This was a challenging investigation to conduct, but its conclusions are even more challenging: it reached the implausible conclusion that data from 4 PWS and 3 controls could be interpreted as being produced by a fair representation of their respective populations. Equally, the demonstration that PWS do not produce excessive levels of muscle activity does not rule out other forms or types of laryngeal or phonatory abnormality.

phonation and/or slower initiation of speech (i.e., prolonged speech treatment programs; see Bothe, Davidow, Bramlett, & Ingham, 2006).

It should be noted that considering responses, such as PIs, in terms of their percentile distribution has been recommended for some time as an efficient basis for shaping or changing the frequency of a segment of such responses (Galbicka, 1994; Platt, 1973). That same principle has recently been employed successfully to modify fMRI feedback from specific neural regions (Bray, Shimojo, & O'Doherty, 2007) and has been used to locate modifiable ranges of PI durations within the MPI treatment program (Ingham et al., 2001). Simply stated, all PI's during baserate are ranked for duration and then the shortest 20% of PIs, followed by the next highest 20% (21%–40%), followed by the 41%–60% and so on, are identified so that a ms range for each speaker's 20% range is calculated, thereby producing each individual's baserate PI quintile range (as is shown in Appendix C). This important addition to the way PI data were derived in the Ingham et al. (2009) and Davidow et al. (2009) studies is integral to the aims of the present study.

In summary, multiple previous theoretical, experimental, and treatment findings have suggested potential relationships among the fluency inducing conditions, changes in phonatory behavior, and the overall normalcy or fluency of the resulting speech, but the precise nature of these relationships remains unclear. The aim of the present study, therefore, was to identify and describe the changes in all four of Starkweather's (1987) aspects of normally fluent speech and also in phonatory behavior that occur as PWS alternate between their typical speech patterns and four different FI conditions. More specifically, this study tested the hypothesis that any FI condition under which all four of Starkweather's (1987) descriptors of normally fluent speech are satisfied would also be characterized by a reduction in short-duration PIs and an increase in longer PIs, as compared with baseline speaking conditions and as compared with other FI conditions. The study also systematically replicated the Ingham et al. (2009) study and made it possible to test the hypothesis that the effects of FI conditions on speech naturalness and speech effort in a new PWS and normally fluent control group were reliable.

2. Methods

2.1. Participants

Twelve adults with persistent stuttering (PWS group; 20–64 years; 7 males) served as participants in the PWS group. All were volunteers selected from a clinic waiting list or from the pretreatment data collection phase of another study. All identified themselves as persons who stuttered, and all had been previously diagnosed, using standard clinical criteria, as persons with persistent chronic developmental stuttering. Prior to participating in this study, each member of the PWS group displayed at least 3.0% syllables stuttered (%SS) during both a 3-min oral reading and a 3-min monologue. Twelve normally fluent speakers, matched pairwise by age (20–64 years) and sex (7 males) with the members of the PWS group, served as the control (CONT) group. CONT participants reported no history of stuttering or any other communication disorder and were judged during the course of this study to display no stuttering. All participants in both groups reported a negative history of reading and hearing problems; all denied any motor, sensory, or cognitive deficits that might interfere with self-measurement of physical effort associated with speech production. All participants passed a hearing screening in both ears at 25 dB HL at 500, 1000, 2000, 4000, 6000, and 8000 Hz. The study was preapproved by the Institutional Review Boards at the University of California, Santa Barbara, and at the University of Georgia, with participants completing approved informed consent procedures before any data were collected.

2.2. Apparatus

All data were gathered using two computers and with participants sitting in a quiet or sound-treated room, either in the presence of one experimenter or monitored by the experimenter from an adjacent control room. Customized software managed presentation of stimuli, data recording, and audiovisual recording of the sessions. The primary computer was used to obtain measures of speech performance. These included measures of phonation intervals, which were collected by means of an accelerometer placed over the prominence of the thyroid cartilage and held in place with an elastic and Velcro collar attached around the participant's neck (see Appendix A). Phonation data were stored to the primary computer by the Modifying Phonation Intervals (MPI) software (Ingham, Moglia, Kilgo, & Felino, 1997). Measures of the three observer-judged dependent variables (stuttering frequency, speech rate, and speech naturalness) for this study were also gathered via the primary computer, through Stuttering Measurement System (SMS) software (Ingham, Bakker, Ingham, Kilgo, & Moglia, 1999). The second computer was used to deliver the experimental stimuli necessary for the masking, chorus recording, and rhythmic stimulus conditions and to store audiovisual digital recordings of all sessions using Windows Movie Maker® files generated through a Canon Z70 digital video camera. A shotgun microphone attached to the camera (approximately 24 in from the participant's mouth) was focused on the participant's mouth to provide high-quality audio recordings.

2.3. Procedure

2.3.1. Experimental Design—The basic design and the procedures for this study were intended to be identical to those used by Ingham et al. (2009), with the exception that that study did not collect PI data. To maintain the continuity between these related studies, much of the description below of this study's methodology is reproduced from Ingham et al. (2009). There was no overlap between participants in the two reports.

In one individual session of approximately 2 hours total duration, each participant completed four sequences of ABA-format (Kazdin, 1998) oral reading trials, one sequence per FI condition. During the A phases, the participants read aloud with no accompanying or altered stimulus condition; during the B phases, the reading tasks included one of the four experimental stimulus conditions (masking, chorus reading, whispering, or rhythmic stimulation). Each phase included five 1-min speaking trials, with each trial followed by approximately 30–60 s for rest and data storage; thus, the ABA triad for each condition required a total of 15 min of speaking time within a total elapsed time of approximately 25 minutes. The rhythmic stimulation triad occurred last in each session, to reduce the known possibility of carryover from this condition (a response trend obtained in the Ingham et al. 2009 study). The other three experimental conditions were presented in random order across participants.

At the beginning of the experiment, each participant read instructions identical to those used in the Ingham et al. (2009) study. The experimenter then asked the participant to explain what was required. When both were satisfied that the participant understood the general format, specific instructions for the first ABA triad were introduced. When those instructions were understood, the first trial of the first condition's A phase was completed. At the end of this 1-min trial, and at the end of all subsequent trials throughout the experiment, the participant was prompted by the program software to enter a rating of speech effort for that minute. Physical effort was rated on a 9-point scale, using only whole numbers, with responses ranging from 1 (*highly effortless speech*) to 9 (*highly effortful speech*). During all conditions except chorus reading, participants read aloud from their choice of three books (Kagan, 1998; Linnea, 1995; Ridley, 1999); reading proceeded through the chosen book, with no material repeated by any one speaker. All trials during the chorus reading triads used the same prepared text, from a fourth source, because of the need for a prerecorded accompanist.

2.3.1.1. Masking: During the B phase of the masking condition, the participant read aloud accompanied by white noise presented bilaterally through Bose TriPort® earphones at a self selected maximal tolerable loudness level. This was established with multiple 5- to 10-s practice readings. Postexperiment evaluations verified that intensity of the signal varied across participants from 91 to 100 dB SPL.

2.3.1.2. Chorus reading: At the beginning of the chorus reading condition, the participant completed multiple 5- to 10-s practice readings, attempting to read in chorus with audio recordings of an adult female accompanist prerecorded at different speech rates. A total of 14 different speech rates were available; they ranged from 70% to 130% of the recorded accompanist's original rate of 249 SPM. The participant selected a most comfortable chorus reading rate and volume level. The experimenter verified that participants were reading with the accompanist via the bilaterally delivered audio signal, that the participant read continuously throughout the trial, and that the participant stopped at the same point in the reading material that the recording was known to stop.

2.3.1.3. Whispering: During the B phase of the whispering triad, the participant orally read in a whisper during each 1-min trial. The absence of phonation was verified in two ways: (a) by a perceptual check from the experimenter during brief practice trials that the reading sounded unambiguously whispered, and (b) by checking the number of PIs produced during each reading via the MPI system. Based on Ingham et al. (2009), whispering was expected to achieve at least an 85% reduction in 30–1000 ms PIs when compared with the participant's average PI data across the surrounding A phases (see Nicolosi, Harryman & Kresheck, 1996).

2.3.1.4. Rhythm: During the B-phase trials of the rhythm triad, the participant read aloud while attempting to match one spoken syllable to each bilaterally presented audible "beat" (a 0.3-s tone) of an accompanying rhythmic stimulus. As in the chorus reading condition, each participant was allowed to select a comfortable rate (from among multiple available rates: 90, 100, 110, 120, 130, 140, 150, 160, 170, or 180 beats per minute) and signal volume level during repeated brief practice trials. Postexperiment verification that participants were producing rhythmic speech was obtained by having research assistants listen to all recordings from the rhythmic speech ABA triads and rate each 1-min trial on a scale on which responses range from 1 (definitely not rhythmic speech) to 7 (definitely rhythmic speech).

2.4. Speech Data and Reliability

Speech data were collected by four research assistants, all of whom had completed the Stuttering Measurement and Assessment Training (SMAAT; Ingham, Cordes, Kilgo, & Moglia, 1998) program, had completed the training program associated with the SMS software (Ingham et al., 1999), and had substantial recent experience in judging the speech of adults who stutter. They used the SMS program to count syllables spoken and syllables stuttered, with stuttering judgments made in accordance with the consensus judgments that serve as the training exemplars in the SMAAT and SMS training programs. The research assistants also rated speech naturalness independently, using Martin, Haroldson and Triden's (1984) 9-point scale, with responses ranging from 1 (*highly natural sounding speech*) to 9 (*highly unnatural sounding speech*) and again in accordance with consensus standards incorporated into the SMS training program.

The SMS software converts the judges' counts of syllables spoken and syllables stuttered into percentage of syllables stuttered (%SS) and syllables per minute (SPM). In addition, because the SMS program also records data in terms of time intervals that either do or do not contain a stuttering judgment, it is possible to derive a measure of speech rate during stutterfree intervals only (stutterfree syllables spoken per minute [SFSPM], calculated for this study from 5-s intervals). SFSPM was used in preference to global SPM for data analyses because it more accurately captures the rate of speech without the influence of stuttering.

To ensure the reliability of these data, counts and ratings were initially completed for each recording independently by two judges, with one of the judges repeating the entire task after at least two weeks. Pairs of judges were assigned to each speaker randomly from the pool of four judges, to prevent observer drift for any pair of judges. The data produced by the pair of judges, and the data from the repeated ratings from the one judge who repeated the task, were required to be within 10% of each other for each minute for %SS and SFSPM, and within one scale point for naturalness. If these criteria were not met for any minute, the necessary judge or judges repeated the entire rating task for that speaker. With one class of exceptions, either the original ratings or the subsequent ratings met these criteria. The exceptions occurred in B-phase trials when the very low rate of stuttering resulted in very large percent differences; when this occurred, a difference of not more than 2 stutters per 1-min trial was accepted if the largest count of stutters per minute was not more than 3. When ratings within these agreement parameters had been obtained for all speakers, the mean of the three ratings (two from one judge, and one from the other) was calculated and used as the data for analyses, to further enhance the replicability of the data as analyzed. In summary, the observer-judged dependent variables for this study included %SS and SFSPM, all derived as the mean of three ratings from two judges that were all within 10% of each other (or within 2 stutters per minute for very low frequency stuttering), and speech naturalness (Na), also derived as the mean of three ratings from two judges that were all within one scale value of each other. These data, and the self-ratings of speech effort (Effort), were analyzed using a repeated measures multifactor analysis of variance (Winer, Brown & Michels, 1991), with protected post hoc comparisons, in order to elucidate the experimental effects.

Agreement between PI duration and acoustically recorded phonation was established by analyzing 20 consecutive PIs from the second trial in the initial A phase of each condition, from each of 12 participants (6 PWS and 6 CONT) using the PRAAT (version 4.2.07) acoustic analysis program (Boersma & Weenink, 2003). The resulting 240 intervals ranged from 36 to 778 ms as measured using PRAAT. For 197 intervals, the duration as measured by the PI software and as measured by PRAAT differed by 20 ms or less. For the remaining intervals, 23 differed by 22–26 ms and 20 differed by 31–40 ms. The mean duration difference was 17.6 ms. These values are comparable to those reported in previous validations of PI data (Godinho, Ingham, Davidow, & Cotton, 2006; Ingham et al., 2001). The MPI system ignores PIs that would be recorded as less than 10 ms, so the accuracy of the PI measures used in this study was considered satisfactory.

2.5. Experimental Fidelity

As in the Ingham et al. (2009) study, experimental fidelity for each of the conditions was obtained by various means. The auditory input volume/intensity level was verified for each participant after completion of trials (see above) and for chorus reading online judgments by the experimenter were used to confirm task compliance. During whispering for the PWS group there was an 85% reduction in PI totals during the B phase (relative to both A phases) and an 89% reduction for the control group. Ratings for the level of rhythmic speech pattern reflected the same high experimental fidelity shown in the Ingham et al. (2009) and

Davidow et al. (2009) studies: mean 1.08 on the 1–7 scale (range 1–2, with the exception of two trials rated as 3) during A phases, indicating nonrhythmic speech, and means of 6.50 (range 5–7) for the PWS group during B-phase trials, and 6.75 (range 5–7) for the Control group during B-phase trials, indicating consistently very rhythmic speech.

2.6. PI Data and Analyses

PI analyses were based on quintile-derived data, or divisions created by separating each participant's baseline PIs into five bins, each of which contained 20% of those PIs. More specifically, each participant's PI quintile range was derived from his or her initial baseline A phase for the first ABA sequence completed in the study by the MPI software, which ranks all PIs between 30 and 1000 ms; determines the total number of PIs ranked; and then divides the PIs into a specified number of bins (in this case, five, each containing 20% of PIs, or quintile bins) and identifies the boundaries of those bins in terms of the shortest and longest PIs included.

Comparisons between PWS and CONT groups were conducted using Wilcoxon signed rank tests (Siegel, 1956). For example, a comparison of difference between the PWS and control group in terms of SFSPM scores was conducted for each combination of condition, phase, and quintile. The average SFSPM score was derived for each participant and then the Wilcoxon signed rank test was applied to participant samples so as to compute *p* values for the null hypothesis of no difference between groups. The False Discovery Rate (FDR) was used to correct for multiple comparisons (Benjamini, & Hochberg, 1995). The FDR controls for the expected proportion of incorrectly rejected null hypotheses (type I errors) by denoting p_i for I = 1,…,m as *p*-values for m tests and $p_{(i)}$ as the ordered values of p_i. With k defined as the largest i for which $p_{(i)} \leq q\ i/m$, we then classified tests with *p*-values less or equal to p_k as significant. This approach guarantees FDR ≤ q. We set $q = 0.05$ in the analysis.

Semi-parametric mixed effects models were used to investigate the relationship between a response variable and the dependent variables (Wang, 1998). For example, in analyzing how PI change within the first quintile might affect %SS for PWS group in phase A, the percent of PI changes in the first quintile was derived relative to the PI counts in the first quintile during the initial baseline (A1) phase (denoted as % change). To deal with relatively large variations between subjects and possible correlations among repeated scores within each subject, a semi-parametric mixed effects model was used:

$$y_{ij}=f(x_{ij})+b_i+e_{ij}$$

where y_{ij} is the jth observation of %SS from participant i, x_{ij} is the jth observation of % change by participant i, b_i is a random effect for participant i accounting for variations between participants, and e_{ij} denotes random errors. It was assumed that both b_i and e_{ij} are independent and identically distributed as normal. The regression function f describes how %SS depends on % change. For flexibility, the regression function was modeled nonparametrically using a cubic spline (see Wang, 1998).

All computations were carried out in R (version 2.9.1), a language and environment for statistical computing and graphics (www.r-project.org). The semi-parametric mixed effects model was fitted using the slm function in the ASSIST package (Wang & Ke, 2002).

3. Results

3.1. Four Characteristics of Normally Fluent Speech

Figure 1 displays mean values for all four dependent variables defined by Starkweather (1987) as characteristics of normally fluent speech: stuttering (%SS), speech rate (SFSPM), observer-judged speech naturalness (Na), and self-judged speech effort (Effort). Means and standard deviations are provided in Appendix B. Several data trends are apparent for the PWS group in Figure 1, including reduced stuttering during all B phases; improvements in naturalness and/or effort in some FI conditions, but improvements in both naturalness and effort only during chorus reading; and improved stuttering and effort but with no improvement in overall naturalness for whispering and rhythm. The CONT group's effort ratings, in contrast, suggested that these speakers found all four FI conditions to be more effortful than typical speaking conditions.

Table 1 shows the results of the protected post hoc comparisons analyzing these differences between groups, phases, and conditions. As shown in the top left quadrant of the table, %SS and Effort were significantly different in B phases as compared with the combined A phases (comparisons between A1 and A2 phases were all nonsignificant) for all four FI conditions for the PWS group; these differences were all in the direction of improvements (Figure 1). The CONT group showed significantly decreased rate, less natural speech, and more speech effort under most FI conditions, as compared with their baseline conditions (top right of Table 1). The bottom right quadrant of Table 1 also shows the lack of any significant differences between the PWS group and the CONT group in speech rate, naturalness, or effort during chorus reading, another important finding.

3.2. Phonated Intervals During Fluency-Inducing Conditions

The PI durations that constituted each participant's quintile ranges, when PIs from that participant's first A phase were divided into five bins each containing an equal number of PIs, are provided in Appendix C. Figure 2 shows mean percent change in the number of PIs that occurred in each of these duration ranges, when the B phases were compared with the A phases for each condition, for each group (i.e., the negative percent change in PIs shown at the top left of Figure 2 refers to a decrease in first-quintile, or shortest, PIs as PWS moved from baseline conditions to masking conditions). It appears from Figure 2 that the number of shorter PIs (quintiles 1 and/or 2) decreased significantly under all FI conditions for one or both groups; that any increases in the number of longer PIs (quintiles 4 and 5) were not significant except in the case of the PWS group during rhythmic speech; and that whispering differed from the other FI conditions in being characterized by a reduction in phonation across all PI durations for both groups. Wilcoxen signed rank tests identified no significant differences between the PWS group and the CONT group in the absolute numbers of PIs produced in any quintile range during the B phases. (Similar tests were not conducted for A phases, to minimize the total number of tests conducted and because the quintiles were defined in terms of equal divisions of baseline or Aphase data.).

3.3 Relationships Between Fluency Characteristics and Phonation

Together, data from the PWS group in Figures 1 and 2 and in Table 1 reveal several noteworthy results. First, masking produced much less of a reduction in stuttering than any other FI condition, resulted in naturalness ratings closer to the unnatural end of the scale, and also did not produce a significant reduction in PIs in the first (shortest) quintile range. Whispering, rather predictably, reduced the occurrence of PIs in all quintile ranges for both groups; it was also associated with significantly reduced stuttering for the PWS group and significantly worsened naturalness for the CONT group. Rhythmic stimulation produced a significant reduction in short duration PIs for both groups, as well as a significant increase in

PIs in the fourth quintile for the PWS group, a change that appears compatible with a syllable-timed speech pattern (Ingham, 1984). Rhythmic stimulation also resulted in significantly decreased stuttering and reduced speech effort for the PWS group, but there was no change in naturalness, which remained at levels of approximately 5–6 on the 9-point scale throughout the rhythmic speech triad (Appendix B).

Finally, Figure 2 shows that the Chorus reading effects were markedly different from the effects obtained in the other three FI conditions. The PWS group reduced stuttering by approximately 90% during chorus reading, along with significant improvements (reductions) in Naturalness and Effort ratings. The improvements in Naturalness ratings resulted in mean ratings that were on the upper margin of the range reported for normally fluent speakers (mean = 3.7; normal range 1.0 – <5.0; see Ingham, Gow, & Costello, 1985). The PWS group also showed greater than a 50% reduction in their mean Effort ratings, to only 1.1 units larger than the control group's mean Effort rating during baseline oral reading. These changes in speech fluency were accompanied by significant reductions in PI frequencies in the first and second quintile ranges (Figure 2). Similar significant reductions occurred in the control group: Mean reductions of 39.54% for the PWS group and 33.15% for the control group occurred in the first and second quintile ranges combined (30–176 ms).

These and other combinations of effects on speech fluency variables and PI data were further assessed, as described in the Method section, using a semi-parametric mixed effects model to investigate the relationship between stuttering frequency and PI frequency change within each quintile (Wang, 1998). The A-phase data within the experimental triads for the PWS group were used to identify any relationship between variability in %SS scores and PI variability within each quintile. The estimated relationship is depicted in Figure 3, which shows the range of %SS scores on the y-axis and the changes in PI frequency relative to the mean baseline PI frequency within each quintile range on the x-axis. Thus, as illustrated in the top left panel of Figure 3, the mean %SS score was 13.1%SS, which equated with the first quintile range mean baseline PI frequency (23.58, or % change equals zero). Changes in mean %SS scores were then related to % changes (positive and negative) from zero in the mean baseline PI frequency counts. A horizontal line would indicate that the changes were unrelated.

The regression functions between the baseline %SS scores and changes in mean PIs within each of the five quintile ranges are shown in Figure 3. The fitted line depicts the results of the regression function, which was modeled nonparametrically using a cubic spline; the shaded region depicts the 95% confidence intervals (see Methods). The top left panel shows a strong relationship between reduced stuttering and reduced PIs in the first quintile (30–99 ms) but with no apparent relationship between %SS and an increase in PIs of this duration. That same relationship was essentially absent in the second quintile. The relationship between %SS scores and changing PI counts within the longer quintile ranges clearly differs from the relationships obtained for the shortest PIs; that is, decreases in stuttering were associated with an increase in longer duration (quintiles 3–5) PI counts.

4. Discussion

4.1. Four Characteristics of Normally Fluent Speech: Relationships to Previous Research and Future Directions

The results of this study show, as did the results of the related Ingham et al. (2009) study, that each of the FI conditions produced different effects on the PWS and control groups' speech performance. Mean %SS scores during the B phases in this study, relative to the mean of the A phases, were reduced by 25.4% during masking, 90.5% during chorus reading, 77.3% during whispering, and 94.2% during rhythm. These values closely approximate the reductions in stuttering produced by the same procedures in the 2009 study (Masking = 22.6%; Chorus = 87.5%; Whispering = 76.2%; Rhythm = 95.2%). With the exception of masking, the positive effects of the FI conditions on speech effort were also replicated. Results for the CONT group were also fully replicated, with the exception of the Effort rating effect for whispering (significantly larger in the present study but not in the 2009 study).

The Naturalness and Effort ratings obtained during chorus reading conditions are of particular interest because of previous studies using chorus reading (Davidow et al., 2009; Ingham et al., 2006). In the B phases of both the present study and the Ingham et al. (2009) study, the PWS and CONT groups produced mean Naturalness ratings that were not significantly different. In the Ingham et al. (2009) study, the mean Effort ratings during chorus reading conditions for the CONT group were significantly higher than for the PWS group, but they were not significantly different in the present study. Nonetheless, the mean Effort ratings for the PWS group during chorus reading in both studies (3.0 vs. 2.3) were not significantly different. In general, therefore, the findings of the present study have essentially replicated those reported by Ingham et al. (2009) with respect to the similarity of effects of the four FI conditions on %SS and Effort ratings.

The combination of the current results and Ingham et al.'s previous data also allow the calculation of a mean Effort rating across studies of 2.1, for CONT speakers during typical or baseline oral-reading conditions. By comparison, PWS in the present study rated speech effort as 5.4 during masking, 3.0 during chorus reading, 2.8 during whispering, and 2.9 during rhythm, all of which represented significant improvements from mean Effort ratings between 5.7 and 6.9 during baseline conditions (Appendix B). Of these, chorus reading showed by far the best naturalness (3.7, compared with values between 5.6 and 6.6 during the other FI conditions) and one of the best combinations of stuttering and speech rate. Taken together, these results suggest that speech effort training and self-measurement might be further investigated by using, for example, direct variations in speech rate in order to construct individualized units on the 9-point effort scale. Those units could then be further refined for their reliability and then utility as a functional measure within treatment, which might reasonably target speech effort values approaching 2, if treatments are intended to result in speech that is characterized by normal levels of speech effort.

4.2. Phonation Duration Data: Relationship to Previous Research and Future Directions

The other important feature of the present study is that it extended previous research about the FI conditions to study interactions between those conditions and phonation duration, as measured in terms of PIs. The general aim of these studies (Godinho et al., 2006; Gow & Ingham, 1992; Ingham et al., 1983) has been to determine the extent to which reductions in the frequency of short PIs during different speaking tasks are both necessary and sufficient for PWS to achieve normally fluent speech, either temporarily or permanently. Temporary reductions in stuttering are achieved reliably and predictably by a number of well established FI strategies that appear to rely on either auditory and/or speech-motor factors (see Wingate, 1969, 1970; Ingham, 1984) that are not well understood. The search for ways to convert those strategies into therapy procedures has preoccupied clinical research on this disorder for many decades (see Bothe et al., 2006; Ingham, 1984). Superficially perhaps, most FI strategies seem to have had limited therapy value because they induce the production of non-normal speech (e.g., rhythm) or they require support from a continuously delivered stimulus (e.g., masking). However, the prospect that the most powerful of these strategies – those that almost immediately reduce or remove stuttering – may share a common mechanism has driven the search for a critical variable responsible for their effects to the peripheral speech-motor system or, more likely, the central nervous system. The possible gains for therapy practice from such a search seem rather obvious. What is less obvious, and remains unknown, is whether sustained (even permanent) reductions in stuttering produced by therapy rely on sustained reductions in the occurrence of short PIs or increases in the occurrence of longer PIs by adult PWS. The present study sought to begin answering this question by comparing all four characteristics of normally fluent speech, ostensibly the goal of speech interventions for stuttering, with changes in both shorter and longer PIs.

The specific hypothesis tested in this study, that normal fluency during FI conditions would be associated with a reduction in short PIs and an increase in longer PIs as compared with baseline conditions, was not supported, primarily because the only significant increase in longer PIs that occurred in this study was associated with rhythmic speech, which was not perceived as natural-sounding by listeners. The clinical significance of changes in shorter duration PIs become reasonably evident, however, with the finding that chorus reading produced the most discrete quintile range changes, with positive effects on both speech naturalness and speech effort. However, the modest 20.6% reduction in PI scores obscured the fact that three participants only showed an approximate 60% reduction in stuttering; the other nine showed a greater than 95% reduction in stuttering. The latter nine participants, who arguably showed a more clinically significant chorus reading effect, actually produced a 39.54% reduction in PIs within their average 30–176 ms range. These reductions in an average 30–176 ms PI duration range are relatively similar to the changes that clients are being trained to achieve within the MPI therapy program (Ingham et al., 2001). Their change criterion is a 50% PI reduction in that range, which is approximately 10% more than the mean of 39.54% produced during chorus reading in the present study. The determination of that 50% reduction criterion, however, has not been the result of systematic research. Davidow et al. (2009) recently reported that a different combination of four FI strategies (rhythm, singing, prolonged speech, and chorus reading, each produced at different speech rates) all shared a common 50% reduction in 30–150 ms PIs produced by normally fluent speakers. It is tempting, therefore, to infer that a common speech-motor factor that produces reduced stuttering during FI strategies might be a 40–50% reduction in PIs that occur within the lower 20 to 40th percentile of PI duration. This is certainly a factor that needs to be studied using more direct experimental manipulation.

With respect to an increase in longer-duration PIs, by contrast, the results of this study show that such changes do reduce stuttering but are not associated with natural sounding or effortless speech. This is, essentially, the problem long known with treatments for stuttering that use prolonged speech, which increases phonation durations: It does lead to nonstuttered speech, but the effort required, and especially the effort required to increase the naturalness of the result, is problematic for some speakers. One potentially informative avenue for research, therefore, might be to identify speakers who have successfully incorporated prolonged speech techniques into their daily lives, to determine how their speech and PI distributions compare to other speakers.

Perhaps most intriguingly, the present results also showed that an increase in short-duration PI frequency was not necessarily associated with an increase in stuttering (Figure 3), despite the association between reduced stuttering and reduced short-duration PIs. This result is actually consistent with previous findings that increased stuttering was not consistently related to increased short-duration PI frequency (cf. Gow & Ingham, 1992; Ingham et al., 1983). For that reason the nature of any functional relationship between PI frequency and stuttering frequency, if it exists, remains to be elucidated; that is, the cause and effect problems identified in the Introduction have not been solved and deserve further investigation, perhaps at the level of neurological intervening variables (see below).

4.3. Combining Fluency Data and PI Data: Future Research

At least three experiments would be useful extensions from the present study. The first might be to determine if PI changes associated with improved fluency in PWS are related to neural systems that have been found to be functionally related to stuttering (see Brown, Ingham, Ingham, Laird, & Fox, 2005). Investigations of the effects of manipulating phonation in normal speakers by Wildgruber, Ackermann, and Grodd (2001) and Riecker, Kassubek, Groschel, Grodd, and Ackermann (2006) have shown important changes in basal ganglia and cerebellum activations. Replicating these investigations with PWS by manipulating short-duration PI frequencies during repeated syllable production would help to clarify the neural basis of short-duration PI reductions during FI conditions. The second would have more immediate clinical implications: that is, to determine if the most fluency-beneficial PI-range reduction identified in the present study (a 40% reduction in 30–176 ms PIs) is able to be used by PWS to directly modify stuttering with the least impact on their quality of fluency as judged by observers (speech naturalness) and the speaker (speech effort). A third would be to extend the methodology employed in the present study to the investigation of the differential effects of response-contingent stimulation on stuttering in adults. The two logical contenders in this regard are experimenter- and self-delivered time out from speaking contingent on stuttering (Martin & Haroldson, 1982). The findings would further clarify the role of changes in phonation durations not only with respect to the modification of stuttering but, more importantly, with respect to the search for methods that can help persons who stutter to produce speech that satisfies all four important characteristics of normal fluency.

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APPENDIX A. Collection of Phonation Interval (PI) Data

During the experiment, participants sat alone in a sound-controlled room where their PIs were recorded using the MPI software program system. As described in Ingham et al. (2001), the MPI program uses customized software and is operated using Windows XP on a desktop personal computer. The MPI program uses two other hardware items: an accelerometer (ACH-01–04) and a customized preamplifier unit for conditioning the accelerometer signal. The accelerometer is a piezo-electronic transducer with no sensitivity relative to earth and a 2-Hz to 20-kHz frequency response. It is housed within a Velcro neckband and is wired to the preamplifier, which is, in turn, connected to the computer. Vocal fold vibration is registered by the accelerometer, which is positioned within the neckband so that its surface is just below the thyroid prominence. The accelerometer signal is routed to a bandpass (80–300 Hz) filter and to the preamplifier unit. The MPI system uses a Sound Blaster Live card (16-bit sampling) with a 10–44-kHz frequency response. The system sets the digitization rate for the sound card at 12 kHz and ignores 11/12 samples, providing an effective sampling rate of 1 kHz. The input signals are integrated and smoothed over a 10-ms window after which only alternate values are retained, thereby producing a 500-Hz sampling rate for the conditioned signal. Before each MPI session, the system noise floor is established. When the intensity of the input signal exceeds 10% above the noise floor, a PI signal is initiated, and it ceases when the signal recedes below the noise floor. PI data are collected in the 30–1000 ms range. Within-lab testing by the first author routinely shows that including signals below 30 ms tends to include false positive PIs activated by head movement and swallowing; above 1000 ms produces less than 0.02 percent PIs

APPENDIX B. Mean (and standard deviation) performance measure scores for persistent stutterer (PWS) and control (CONT) groups for two baseline (A1 and A2) phases and one experimental (B) phase for each of four fluency-inducing conditions

		Masking			Chorus			Whispering			Rhythm		
Variable	**Group**	**A1**	**B**	**A2**	**A1**	**B**	**A2**	**A1**	**B**	**A2**	**A1**	**B**	**A2**
%SS	PWS	13.2	9.4	12.0	12.7	1.1	10.4	14.3	3.0	12.1	12.3	0.7	11.7
		(8.5)	(7.5)	(9.2)	(8.3)	(1.3)	(8.0)	(9.0)	(4.7)	(8.3)	(9.7)	(1.3)	(7.6)
	CONT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		-	-	-	-	-	-	-	-	-	-	-	-
SFSPM	PWS	159.4	192.9	174.7	177.1	210.8	192.4	164.5	213.1	173.6	175.9	158.9	171.4
		(81.9)	(72.4)	(74.2)	(71.3)	(32.0)	(76.9)	(74.7)	(53.1)	(66.2)	(74.0)	(53.8)	(73.5)

Variable	Group	Masking			Chorus			Whispering			Rhythm		
		A1	B	A2	A1	B	A2	A1	B	A2	A1	B	A2
	CONT	291.1	288.4	291.4	280.4	228.5	278.7	289.3	267.4	279.5	289.6	164.9	286.9
		(33.3)	(28.9)	(34.9)	(28.6)	(28.3)	(28.9)	(33.3)	(34.2)	(35.0)	(32.2)	(37.6)	(27.9)
NA	PWS	6.4	5.6	6.2	6.3	3.7	6.1	6.6	6.0	6.4	6.1	6.5	6.5
		(2.0)	(2.0)	(1.8)	(1.6)	(1.0)	(1.6)	(1.6)	(1.8)	(1.9)	(2.1)	(1.4)	(1.5)
	CONT	1.5	1.5	1.4	1.5	3.4	1.4	1.3	4.4	1.3	1.5	6.2	1.4
		(0.6)	(0.6)	(0.7)	(0.5)	(1.0)	(0.5)	(0.5)	(1.5)	(0.5)	(0.8)	(1.6)	(0.8)
EFFORT	PWS	6.9	5.4	6.0	6.5	3.0	5.7	6.4	2.8	6.2	6.5	2.9	5.7
		(1.7)	(1.9)	(2.0)	(1.8)	(2.0)	(2.0)	(1.7)	(1.6)	(1.5)	(1.9)	(2.2)	(1.9)
	CONT	2.0	2.8	1.9	1.9	3.7	1.7	1.7	2.6	1.7	1.7	3.2	1.5
		(1.2)	(1.9)	(1.1)	(1.1)	(1.9)	(1.1)	(0.9)	(1.5)	(1.0)	(0.8)	(1.9)	(0.8)

Note. %SS = observer-judged percent syllables stuttered; SFSPM = observer-judged stutterfree speech rate; NA = observer-judged speech naturalness, 1–9; EFFORT = self-rated speech effort, 1–9.

APPENDIX C. Quintile ranges (in msec) for each participant, shown separately for persons who stutter (PWS) and normally fluent controls (CONT)

	Boundaries of individual quintile ranges (msec)				
PWS #	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**
1	30–190	191–264	265–334	335–432	433–915
2	30–97	98–181	182–266	267–399	400–932
3	30–51	52–122	123–212	213–341	342–940
4	30–134	135–218	219–304	305–422	423–980
5	30–127	128–254	255–381	382–508	509–633
6	30–95	96–190	191–285	286–380	381–475
7	30–69	70–112	113–212	213–350	351–994
8	30–92	93–146	147–204	205–318	319–912
9	30–60	61–103	104–206	207–366	367–903
10	30–113	114–172	173–232	233–346	347–1000
11	30–50	51–105	106–206	207–323	324–924
12	30–112	113–244	245–398	399–578	579–996
Mean	**30 – 99**	**100–176**	**177–270**	**271–397**	**398–1000**
CONT #					
1	30–129	130–206	207–301	302–477	478–993
2	30–142	143–209	210–307	308–468	469–1000
3	30–121	122–179	180–288	289–421	422–990
4	30–95	96–140	141–204	205–315	316–942
5	30–99	100–185	186–259	260–426	427–995
6	31–145	146–227	228–319	320–491	492–990
7	31–98	99–162	163–249	250–377	378–986

Boundaries of individual quintile ranges (msec)					
PWS #	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**
8	30–121	122–201	202–305	306–457	458–955
9	30–107	108–163	164–245	246–388	389–924
10	30–95	96–143	144–239	240–363	364–999
11	30–58	59–88	89–126	127–180	181–606
12	30–96	97–142	143–206	207–308	309–998
Mean	**30–109**	**110–170**	**171–254**	**255–389**	**390–1000**

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Learning outcomes

The reader will be able to (1) understand the differential effects of four well established fluency-inducing conditions on the quality of fluency of adult PWS and controls, (2) learn how intervals of phonation are modified during these conditions and (3) how the duration of specific intervals of phonation may be identified for their potential application in stuttering treatment.

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Research Highlights

- Fluency-inducing conditions produce distinctive effects on stuttering.
- Measures of stuttering frequency, speech naturalness and speech effort distinguish among these effects.
- Frequency of intervals of phonation can also be shown to distinguish among these effects and are shown to be associated with the production of perceptually normal fluency.

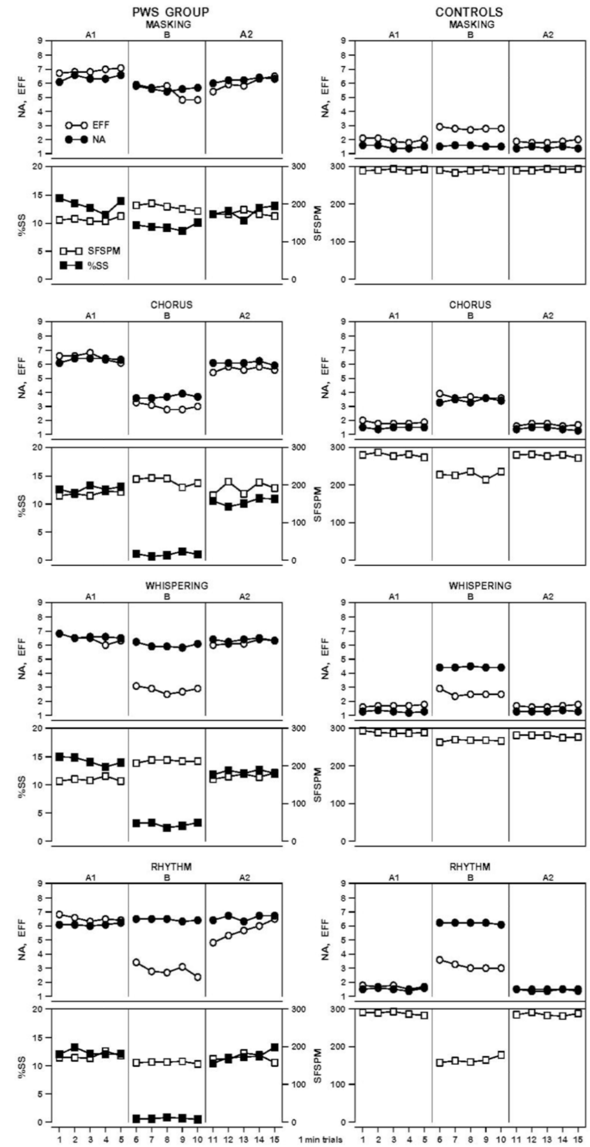

Figure 1.

Mean percent syllables stuttered (%SS), stutter-free syllables per minute (SFSPM), speech naturalness (NA) and speech effort (EFF) scores for each 1-min trial within each ABA experimental triad for persons who stutter (PWS) and control groups. Naturalness and Effort are scored from 1 (preferable: highly natural or highly effortless) to 9 (less preferable: highly unnatural or highly effortful); decreases in these variables are interpreted as improvements.

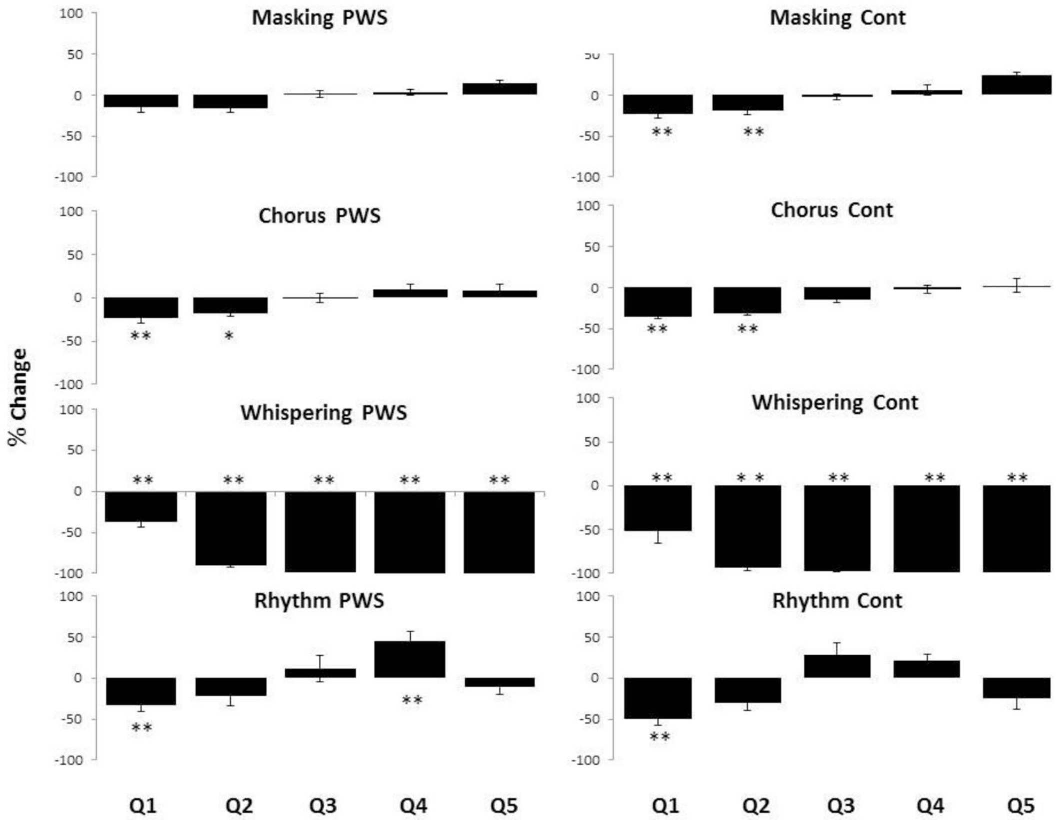

Figure 2.
Mean (and standard deviation) percent change from A to B phases in number of PIs per quintile (Q) for persons who stutter (PWS) and control (CONT) groups. Double asterisks indicate Wilcoxon signed rank tests with adjustments for false discovery rate significant at FDR *q* =.01.

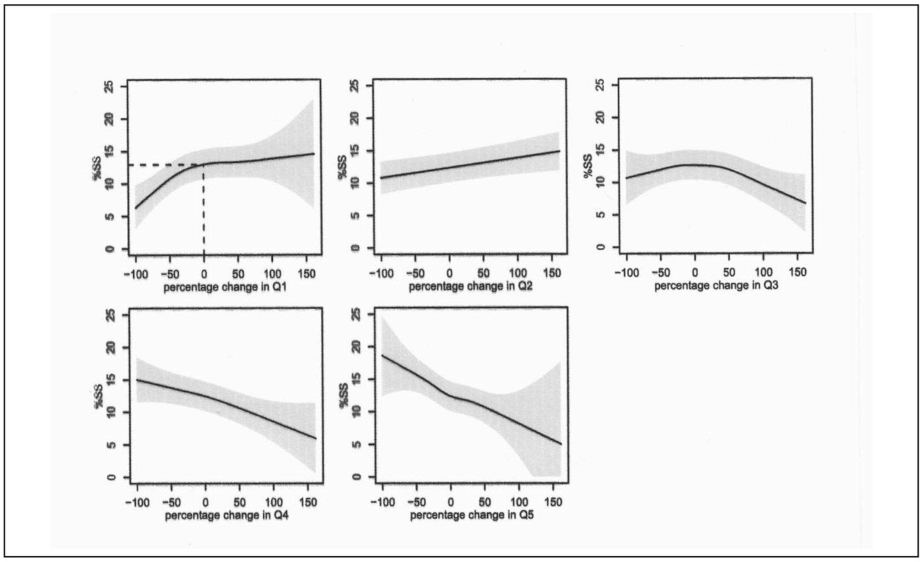

Figure 3.

Results of regression function which tested whether %SS is associated with percent change in PI counts, for each of five PI quintile ranges. Stuttering frequencies (%SS scores) are shown on the y axis; changes in PI frequency relative to the mean (with mean values shown as a 0% change) are shown of the x axis. Lines of best fit depict the results of the regression analysis; shaded regions depict 95% confidence intervals (see Methods). A horizontal line would suggest no relationship between the %SS scores and % changes in PI frequency counts.

Table 1

Results of repeated measures ANOVA showing protected post hoc comparisons between baseline and FI conditions separately for each group (top), and between participant groups separately for each phase (bottom). Double asterisks indicate tests significant at FDR q=.01.

Baseline (A) phases versus fluency-inducing (B) phases, by group

	PWS Group				*CONT Group*		
	%SS	**SFSPM**	**Na**	**Effort**	**SFSPM**	**Na**	**Effort**
Masking	**	**	*	**	NS	NS	NS
Chorus	**	NS	**	**	**	**	**
Whispering	**	**	NS	**	**	**	*
Rhythm	**	NS	NS	**	**	**	**

PWS group versus CONT group, by phase

	Baseline (A phases)			*FI Conditions (B phases)*		
	SFSPM	**Na**	**Effort**	**SFSPM**	**Na**	**Effort**
Masking	**	**	**	**	**	**
Chorus	**	**	**	NS	NS	NS
Whispering	**	**	**	**	**	NS
Rhythm	**	**	**	NS	NS	NS

Note. %SS = observer-judged percent syllables stuttered; SFSPM = observer-judged stutterfree speech rate; NA = observer-judged speech naturalness, 1–9; EFFORT = self-rated speech effort, 1–9. PWS = Persons who stutter; CONT = Control group.