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Systematic Studies of Modified Vocalization: The Effect of Speech Rate on Speech Production Measures During Metronome-Paced Speech in Persons who Stutter

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Abstract

Background—Metronome-paced speech results in the elimination, or substantial reduction, of stuttering moments. The cause of fluency during this fluency-inducing condition is unknown. Several investigations have reported changes in speech pattern characteristics from a control condition to a metronome-paced speech condition, but failure to control speech rate between conditions limits our ability to determine if the changes were necessary for fluency.

Aims—This study examined the effect of speech rate on several speech production variables during one-syllable-per-beat metronomic speech, in order to determine changes that may be important for fluency during this fluency-inducing condition.

Methods and Procedures—Thirteen persons who stutter (PWS), aged 18–62 years, completed a series of speaking tasks. Several speech production variables were compared between conditions produced at different metronome beat rates, and between a control condition and a metronome-paced speech condition produced at a rate equal to the control condition.

Outcomes & Results—Vowel duration, voice onset time, pressure rise time, and phonated intervals were significantly impacted by metronome beat rate. Voice onset time and the percentage of short (30–100 ms) phonated intervals significantly decreased from the control condition to the equivalent rate metronome-paced speech condition.

Conclusions & Implications—A reduction in the percentage of short phonated intervals may be important for fluency during syllable-based metronome-paced speech for PWS. Future studies should continue examining the necessity of this reduction. In addition, speech rate must be controlled in future fluency-inducing condition studies, including neuroimaging investigations, in order for this research to make a substantial contribution to finding the fluency-inducing mechanism of fluency-inducing conditions.

Keywords

stuttering; fluency-inducing conditions; metronome; phonated intervals

Introduction

Metronome-paced speech, or speaking one syllable or word to each beat of a metronome, is amongst the most powerful fluency inducers for persons who stutter (PWS), as it typically results in stuttering frequency levels at or near zero (e.g., Andrews, Howie, Dozsa, & Guitar, 1982; Davidow, Bothe, Andreatta, & Ye, 2009). Metronome-paced speech has been studied extensively, with one line of inquiry involving comparing speech and voice pattern characteristics (e.g., vowel duration and intraoral pressure) during a baseline condition and a metronome-paced speech condition. This line of research was sparked by Wingate (1969) who suggested, in general, that fluency during metronome-paced speech, along with several other powerful fluency-inducing conditions, results from PWS doing something with their speech organs that they normally do not do. Wingate added that although “the manner of implementation differs in these several conditions (and different special features may be adjunctively operative in some), in each of them the stutterer is induced to emphasize phonation and continuity of phonation in the production of some kind of melody or prosody” (p. 682). The general purpose of the metronome-paced speech investigations that followed was to identify a speech production variable (a measure reflecting movements of the speech apparatus) that changed from the baseline condition to the experimental condition, which could signal the importance of that variable for the fluency during this fluency-inducing condition.

If a speech production change is found to be important for fluency during metronome-paced speech, it would not only inform us about the nature of stuttering, but may also provide valuable information for current metronome-paced speech treatments with preschoolers (Trajkovski, Andrews, O’Brian, Onslow, & Packman, 2006; Trajkovski et al., 2011; Trajkovski et al., 2009) and school-age children (Andrews et al., 2012) who stutter. For example, if extended vowel durations are found to be important for fluency during metronome-paced speech, vowel duration could, and should, be measured and monitored throughout the treatment process.

Previous Findings

Changes to several speech production variables from a control condition to a metronome-paced speech condition have been found for PWS, such as an increase in vowel duration (Brayton & Conture, 1978; Klich & May, 1982; Stager, Denman, & Ludlow, 1997), a decrease in intraoral pressure (Hutchinson & Navarre, 1977; Stager et al., 1997), a decrease in rate of airflow (Hutchinson & Navarre, 1977), an increase in intraoral pressure rise time (Stager et al., 1997), and a reduction in the percentage (Davidow et al., 2009) and frequency (Ingham, Bothe, Wang, Purkhiser, & New, 2012) of short phonated intervals¹. Although these changes are interesting, the most important question is: Are the changes necessary for

¹A phonated interval (PI) is a measure of the duration of vibration as measured by an accelerometer from the surface of the throat in between breaks of 10 ms or more. These intervals are interpreted as an estimate of the duration of vocal fold vibration. Speakers produce the majority of PIs in the range of 10–1000 ms during normal speaking tasks (reading, monologue, and conversation), with an average of about 144 PIs in 1 min of speech during these tasks. The use of computer software (Ingham, Moglia, Kilgo, & Felino, 2006) and accompanying hardware allows for the efficient collection of many PIs, resulting in the ability to display a distribution of all PIs. The distribution has commonly been displayed as a series of 20 bins, with one 70-ms (30–100 ms) duration bin, eighteen 50-ms (from 51–1000 ms) duration bins, and one bin encompassing all phonated intervals over 1000 ms (Davidow et al., 2011).

fluency induction during metronome-paced speech, or do they simply occur from speaking in a different manner than the person is used to? A failure to control one important confounding variable, speech rate, limits the ability to answer this question using the available data from previous studies. Several metronome-paced speech investigations included a slower syllables per minute (SPM) or words per minute rate during metronome-paced speech compared to the control condition (e.g., Andrews et al., 1982; Davidow et al., 2009; Ingham et al., 2012; Klich & May, 1982; Martin, Johnson, Siegel, & Haroldson, 1985). The remaining studies did not report rate data during one or both (control and metronome-paced speech) of the conditions (Brayton & Conture, 1978; Hutchinson & Navarre, 1977; Stager et al., 1997). These limitations are significant as several speech production variables have been shown to change with speech rate, including voice onset time (Allen & Miller, 1999; Kessinger & Blumstein, 1997), vowel duration (Kessinger & Blumstein, 1998), and peak intraoral pressure (Boucher & Lamontagne, 2001), just to name a few. Therefore, changes to several speech production variables may have occurred because of the alteration in SPM or words per minute rate from the control to metronome-paced speech condition and may not be critical to the fluency effects of this fluency-inducing condition. Additionally, slowed speech is often accompanied by reductions in stuttering (Ingham, 1984), so this factor should be removed if our goal is to determine whether or not certain speech production changes are necessary for fluency during metronome-paced speech.

Speech Rate and Metronome-Paced Speech

Two recent studies reveal the effect of speech rate on several speech production variables during metronome-paced speech. The possibility of a rate confound during the measurement of speech mechanism changes when performing fluency-inducing conditions has been discussed previously (Ingham, 1984; Stager, Jeffries, & Braun, 2003), and it has been shown that metronome-paced speech, accompanied by large stuttering reductions, can be produced without a reduction in SPM or words per minute (e.g., Hanna & Morris, 1977). However, to the best of the author's knowledge, fluency-inducing condition production rate had not been directly manipulated in a study that examined speech and voice pattern characteristics prior to these two recent studies. The more extensive of these two studies, as it examined several acoustic and aerodynamic measures (vowel duration, voice onset time, fundamental frequency, intraoral peak pressure, intraoral pressure rise time, intraoral airflow, and phonated intervals), was a study by Davidow, Bothe, Richardson, and Andreatta (2010) on 11 normally fluent speakers. These authors found that mean vowel duration, mean intraoral pressure rise time, mean voice onset time, and mean maximum airflow were significantly greater during slower metronome-paced speech conditions. These findings suggest that changes reported in previous studies (e.g., increase in vowel duration and increase in intraoral pressure rise time, Stager et al., 1997) may not have been found if the metronome rate was faster in those studies, therefore eliminating the necessity of these changes for fluency during metronome-paced speech. The Davidow et al. findings, however, were only from normally fluent speakers, so replication with PWS is needed to determine the impact of the changes on fluency. A replication is also important because of the differing changes (from a control condition to a metronome-paced speech condition) that have been found for several speech production variables (air flow rate, Hutchinson & Navarre, 1977; phonated

intervals, Ingham et al., 2012; voiced and voiceless segments, Janssen & Wieneke, 1987) in studies examining both PWS and normally fluent controls. Therefore, we cannot assume that the influence of speech rate in Davidow et al. will be identical for PWS.

The other study that manipulated speech rate examined the phonated interval variable in more detail during four fluency-inducing conditions, including syllable-based metronome-paced speech, in 10 adults who stutter (Davidow et al., 2009). Particular attention was focused on phonated intervals in the 30–200-ms region, rather than the mean of all phonated intervals, because the purposeful reduction in the number of phonated intervals in that range has resulted in speech with either no, or minimal, stuttering (Gow & Ingham, 1992; Ingham et al., 2001; Ingham, Montgomery, & Ulliana, 1983). In regard to metronome-paced speech, Davidow et al. (2009) found reductions in the percentage of short (30–150 ms) phonated intervals from a control condition to 92 beats per minute (BPM) and 184 BPM metronome-paced speech conditions. However, the amount of reduction was dependent upon the metronome beat rate, with less of a reduction in the 51–150-ms range during 184 BPM metronome-paced speech. Interestingly, however, there were still large reductions in this range during the 184 BPM condition. It should also be noted that both rates (92 and 184 BPM) resulted in slower SPM rates than the control condition (approximately 219 SPM). Therefore, since syllable-based metronome-paced speech can be produced at faster rates (equal to or faster than habitual rate; Hanna & Morris, 1977), the reduction in the percentage of short phonated intervals must happen at these faster rates in order for it to be a requirement for fluent speech during metronome-paced speech.

The Present Study

The purposes of the present study were (1) to determine the effect of speech rate on certain speech production variables during syllable-based metronome-paced speech, and (2) to determine whether or not changes to these speech production variables were necessary for the fluency resulting during this fluency-inducing condition. The specific speech production variables were chosen because they have previously been found to change from a control to metronome-paced speech condition. Therefore, the present study was designed as a next step in determining the importance of these variables for fluency during metronome-paced speech, by showing the effects of, and controlling, speech rate. In regard to the second purpose, it should be noted that the observational nature of the present study only allowed for the exclusion of speech production variables as necessary for fluent speech during metronome-paced speech. If a speech production variable was found to change from the control to metronome-paced condition, it may or may not have been the cause of fluency and future experimental investigations would be needed to resolve the issue.

The specific research questions were the following:

1. What is the effect of changes in speech rate on the values of several speech production variables during metronome-paced speech?
2. Do the examined speech production variables change from a control condition to a metronome-paced speech condition when speech rates are matched between conditions?

Methods

Participants

Thirteen PWS participated (10 men and 3 women; mean age = 37.3 years, range = 18–62 years). No participant received therapy in the past year, with the average duration since last treatment for twelve of the participants being 17.1 years (range = 1–51 years). One participant had never received treatment. No participant reported any past or present neurological disorder or speech, voice, hearing, oral-motor, or head or neck problems. All procedures were approved by the University of Georgia's and Hofstra University's Institutional Review Boards for the protection of human subjects.

Experimental Protocol

The study was completed over two days using two 3-hour sessions. An example of the experimental activities for Day 1 for one participant can be found in Table 1. The first speaking tasks on each day consisted of four 3-min monologues on self-selected topics, and four 3-min reading trials (from a high school-level textbook), in order to obtain the participant's habitual stuttering and speaking rates. These tasks were alternated for each subsequent participant. The 11 main data-collecting conditions were then initiated, with six conditions completed on one day and five on the other. Conditions designed to examine the issue of speech rate were analyzed for the present study. The 11 conditions were randomized across participants, except that control reading was conducted on the first day and two of the metronome-paced speech conditions involved in the present study were performed on the second day. These exceptions were necessary in order to establish the BPM rates for these two metronome-paced speech conditions (see Control and Experimental Conditions section). Two sets of trials were completed for all conditions: (1) two 75-s trials for the collection of acoustic and phonated interval data; and (2) three 30-s trials for the collection of aerodynamic data. The sets of trials were completed consecutively for each condition and the order was reversed for each subsequent participant (see Table 1). The reading material varied for each condition with the exception of the carrier phrases (see Appendix).

Participants practiced each metronome-paced speech condition until the experimenter (author) rated two consecutive 30-s trials a 1 or 2 on a 7-point scale ("1" = *definitely producing this condition correctly*, "7" = *definitely not producing this condition correctly*). Ratings were based on a perceptual judgment of matching the syllables to the metronome beat. The metronome conditions were paced via a Matrix Mr550 digital metronome for rates 250 BPM or below, or metronome software using a laptop computer for rates above 250 BPM. The intensity of the tone was specific to each participant and was set by finding the lowest level that could be heard through the earphone while performing the speaking task comfortably. The metronomic beat was delivered via an earpiece, rather than visually, because the conditions involved reading. The low volume level and monaural delivery of the tone, and the finding of virtual elimination of stuttering for all participants, suggest that a masking effect was not responsible for the stuttering reductions during the experimental conditions. Masking typically results in stuttering reductions that are substantially less than during metronome-paced speech (e.g., Ingham et al., 2012).

Each metronome-paced speech condition was followed by 2-min monologues (self-selected topic) in order to control for possible carryover effects. The next condition was initiated when percent syllables stuttered (%SS) and SPM were within 10% of baseline or greater (compared to the four 3-min monologues) for one 2-min monologue, as measured online by the experimenter via the Stuttering Measurement System (Ingham, Bakker, Ingham, Moglia, & Kilgo, 2005) software. This software allows the collection of stutters and syllables by clicking a computer mouse. Post-experiment data, collected by a trained research assistant who completed a stuttering training protocol (Ingham & Ingham, 2004), verified that the participants met the criteria before initiating a new condition. The experimenter and the research assistant used a perceptual threshold definition of stuttering (Martin & Haroldson, 1981), with the only instruction that continuing attempts at the same syllable were to be considered as one stuttering event. Additionally, using the four 3-min monologues as a comparison, the experimenter had to rate the monologue a 1 or 2 on a 7-point scale (“1” = *sounds identical to habitual monologue*; “7” = *sounds completely different from habitual monologue*). The experimenter listened for changes in rate, intonation, vocal quality, and loudness.

Control and Experimental Conditions

Several different comparisons were constructed to examine the influence of metronome beat rate on the dependent variables. The first was matching the beat rate to the participant’s control reading (reading aloud with no prescribed speaking style or rate) stutter-free syllables per minute (SFSPM) rate². This required the participant to read one syllable per beat at a rate equal to his or her own control reading rate (Syllable-Control Reading Rate, or Syll-CRR). The remaining comparisons involved comparing Syll-CRR to two slower syllable-based metronome-paced speech conditions. One required the participant to read one syllable per beat at 140 BPM (Syll-140). The second required the participant to read one syllable per beat at a rate equal to 75% of his or her own control reading rate (Syll-0.75CRR). The use of syllable-based metronome-paced speech in the present study, instead of other forms of rhythmic speech (e.g., producing one word per beat of the metronome), allowed for relating the findings to currently-used rhythmic speech programs (Andrews et al., 2012; Trajkovski et al., 2006; Trajkovski et al., 2011; Trajkovski et al., 2009).

Stuttering Frequency, Speech Rate, and Task Compliance

Percent syllables stuttered, SPM, and SFSPM data for all conditions were gathered, via video recordings, using the Stuttering Measurement System software by the author. For SFSPM, the software only included those 5-s segments that did not contain a stuttering moment in the calculation. Two measures were gathered for task compliance during metronome-paced speech by undergraduate student volunteers. The first was found by measuring the time between the productions of each syllable, for four randomly selected 5-s periods, using the PRAAT acoustic analysis program. The judges were trained by the author

²Speech rate could have been defined in several other ways, such as words per minute or using a measure of articulation rate (number of syllable per second, which includes the removal of pauses beyond a certain length). However, stutter-free syllables per minute is an often used measure of speech rate and is gathered efficiently using computer software. In addition, this measurement was the most appropriate as the goal of the study was to examine changes during different speeds of *syllable*-based metronome-paced speech.

to identify the beginning of syllables. Judges used the PRAAT waveform display, accompanying spectrogram, and audio-recording functions during their measurements. At least ten measurements were gathered for each 5-s period. If 10 values could not be gathered in the 5-s period, measurements continued until 10 were reached, resulting in a minimum of 40 measurements. For data to be included in the final analysis, the average time between the start of uttered syllables had to be within 30 ms from the expected time between beats for Syll-140, or within 20 ms for Syll-CRR and Syll-0.75CRR (Davidow et al., 2010), for both of the two trials.

The second task compliance measure was a rating using a 7-point scale (1 = *definitely sounds like the participant is speaking to a metronome*; 7 = *definitely sounds like the participant is not speaking to a metronome*), gathered by listening to the entire length of both acoustic trials. A score of 3 or lower, along with the above time difference between utterances, was required for inclusion of that participant's data in the final analysis.

Video recordings were also viewed to ensure proper and fluent production of target words. For all data-collection trials, if either the author or a doctoral student (who was also a working clinician) judged a target word or a word adjacent to a target word as improperly produced or stuttered, that target word was discarded. Dialectical variations were allowed.

Aerodynamic Data

A custom designed aerodynamics workstation was used to collect aerodynamic data. Audio signals were collected via a Sennheiser e815S microphone placed approximately 10–12 inches from the participant's mouth. The microphone distance was kept constant across conditions for each participant. Intraoral pressures were collected via a Honeywell® Microswitch pressure transducer, and airflow measures via a full-face mask coupled to a pneumotachometer using standard protocols and procedures and a Windows-based custom-designed software package known as AEROWIN (Neuro Logic, Lawrence, KS; see Barlow, Suing, & Andreatta, 1999 for more details about AEROWIN, including a drawing of this setup). All signals were conditioned and filtered by a bridge amplifier (Biocommunication), and routed to a 16-bit deglitched analog-to-digital converter (National Instruments, Inc.). Additional details regarding the aerodynamic workstation can be found in Davidow et al. (2010). Participants were seated and instructed to keep their head still until the current set of trials was completed. The metronomic beat was provided via an insert earphone in the participant's ear of choice (either ear was allowed, as opposed to during the acoustic trials where the structure of the microphone required using the right ear).

There were three 30-s aerodynamic trials used to collect speech targets during the production of six carrier phrases (see Appendix), two per trial. The AEROWIN program collected data in 6-s epochs; therefore, the participants began to read and when they reached the first carrier phrase, they paused and the face mask was placed against their nose and mouth. The face mask was removed after 6 s of reading, as the participant continued to read. This process was repeated for the second carrier phrase in the trial, and the participant continued to read until the experimenter signaled the end of the 30-s trial.

Carrier phrases were randomized across all conditions, as were the text sections. Participants were required to maintain their vocal intensity during the trials within a 4-dB range identified via a sound level meter that was consistent with their performance during a 1-min control reading trial. In addition, if the participant deviated from the range more than 3 times outside the data acquisition window, the entire trial was repeated. Repetition occurred on seven trials across the group. Verbal reminders were provided to the participants during the trials if necessary.

Peak intraoral pressure, pressure rise time, maximum airflow, and vowel midpoint airflow measures were gathered from target words (italicized words in the Appendix) using the AEROWIN graphic display, which includes pressure and flow waveforms and a time-locked audio recording waveform (see Davidow, Bothe, & Ye, 2011 for an example of the graphic display). Peak intraoral pressure (displayed in cmH₂O) values were obtained by measuring the maximum pressure value for /p/ and /b/ sounds at the beginning of the italicized words in the carrier phrases. Pressure rise time (in ms) was obtained by calculating the duration from a point immediately before the pressure rise for /p/ or /b/, to the point of peak pressure. Maximum airflow (displayed in cc/s) was defined as the highest point of the airflow trace after the release of /p/ or /b/. Vowel midpoint airflow (displayed in cc/s) was gathered for each vowel following /p/ and /b/ productions by identifying the center of the vowel's production duration. The judges for aerodynamic measurements were the author and a trained research assistant. Each judge finished a complete data set (all four conditions) for approximately half of the participants.

Acoustic and Phonated Interval Data

Acoustic and phonated interval data were collected during two 1.25-min trials in a sound-treated room, with the pacing tone sent through a unilateral insert earphone. Instrumentation details for acoustic data can be found in Davidow et al. (2010) and Davidow et al. (2011). Briefly, acoustic data were collected with the PRAAT version 4.3.27 acoustic analysis program via a signal transduced with an AKG-C420 head-mounted condenser microphone placed approximately 6 cm from the left oral angle. As with the aerodynamic data trials, participants attempted to maintain vocal intensity within a 4-dB range identified during a 1-min control reading trial prior to the first acoustic trial. Vocal intensity was monitored via an LED display and if necessary, the experimenter signaled the participants to adjust their volume to stay within the 4-dB range.

Acoustic dependent variables included vowel duration (in ms) and voice onset time (in ms), and were collected from target words within carrier phrases (italicized words in the Appendix). All measures were gathered using the PRAAT waveform display, accompanying spectrogram, and audio-recording functions. Vowel duration was defined as beginning at the onset of periodic variation in the waveform following the voiceless consonant and ending at the offset of periodic vibration. Voice onset time was defined as the time from the onset of the stop consonant burst to the onset of voicing. Vowel duration measures came from the first vowels in each target word, except for *spectators* and *spectacular* (first and second vowel were measured), and only the second vowel from *attack*. Voice onset time measures were from the initial sound in the target words that begin with /p/, /t/, and /k/, in addition to

the final syllable in *attack*. The judge for these measurements was a 4th-year Ph.D. student with expertise in acoustic phonetics.

Phonated intervals were collected using the Modifying Phonation Intervals (MPI) software program (Ingham, Moglia, Kilgo, & Felino, 2006) during the entire length of the 1.25- min trials (not just during the carrier phrases). Technical details of the MPI system can be found in Davidow et al. (2009) and details of the fitting protocol are also outlined in Davidow et al. (2009), Davidow et al. (2010), and Davidow et al. (2011). Briefly, the MPI system runs in a Windows environment and consists of an accelerometer, a signal conditioning system, computer software, and related hardware. The accelerometer is housed in an elastic collar and placed comfortably around the neck, paralateral to midline and just below the thyroid prominence. Participants were instructed to not make any extraneous movements or sounds (e.g., coughing, throat clearing) because these might inadvertently register a phonated interval. Pre-trial testing ensured that a phonated interval was not registered by head movements. Phonated intervals below 30 ms are discarded since they may be confounded by these and other head and neck movements. The percentage of phonated intervals that fell into one 70-ms bin (30–100 ms) and one 50-ms bin (101–150 ms) was analyzed. This range was analyzed because it showed a reduction in the amount of phonated intervals during metronome-paced speech in two previous investigations (Davidow et al., 2009; Ingham et al., 2012), and because purposefully altering the amount of phonated intervals in this range has been found to control the frequency of stuttering (Gow & Ingham, 1992; Ingham et al., 2001).

Data Analysis

A Friedman test (Green & Salkind, 2003) was conducted for each dependent variable, resulting in a total of eight tests. The Friedman test is the nonparametric equivalent of a one-way ANOVA. Following the significant Friedman tests, Wilcoxon signed rank tests were conducted for the planned comparisons (see above) in order to determine differences between specific conditions. An alpha level of .05 was used for statistical significance for all tests. Bonferroni correction is not recommended for repeated-measures designs with multiple outcome measures that are likely to be correlated (Lix & Sajobi, 2010). In addition, due to the relatively small sample size, no other multiple-testing procedure was used. For small sample sizes, statistical correction procedures can exacerbate the problem of low power and inflate Type II error to the point of obscuring important and interesting findings (Nakagawa, 2004). Effect sizes (Cohen's *d* using a pooled standard deviation; small ES = 0.2, medium ES = 0.5, and large ES = 0.8) were also calculated to examine the magnitude of the differences.

Reliability and Validity

Interjudge and intrajudge reliability data were collected for approximately 12–20% of the aerodynamic, acoustic, %SS, SPM, SFSPM, and task compliance quantitative data. Conditions were randomly selected, with the exception of a maximum of two conditions from any single participant. For %SS and SFSPM data, only the control reading and 3-min speaking tasks were used during the selection of trials, since the experimental conditions had such low levels of stuttering. The mean difference between judges or between the primary

judge's two measurements, the range of differences, and the mean percent deviation between judgments were calculated. Mean percent deviation was defined as the difference between judges (or measurements) for each token divided by the primary judge's (or initial) measurement, all multiplied by 100. The interjudge reliability raters for aerodynamic, acoustic, and task compliance data were students trained specifically for that task by the author. The interjudge reliability rater for %SS, SPM, and SFSPM data was a graduate student who completed a stuttering training protocol (Ingham & Ingham, 2004). The validity of phonated interval measurements has been previously established by comparing individual measurements with those using an acoustic analysis program (Godinho, Ingham, Davidow, & Cotton, 2006; Ingham et al., 2001).

Results

Task Compliance

At least two PWS did not meet the task compliance criteria for each experimental condition. Two participants did not meet the criteria for Syll-140, three for Syll-0.75CRR, and two for Syll-CRR. Table 2 shows the average deviation from the expected time between beats for the participants who met the task compliance criteria, in addition to the task compliance rating on the 1–7 scale. The SPM and SFSPM values can also be used as a basic measure of task compliance and these values are very similar to the intended BPM rates. These three sources of data taken together show that the participants included in the data analyses were performing the conditions correctly.

For the aerodynamic data trials that involved producing the carrier phrase in the 6-s data-gathering window, some words were not attempted, resulting in nonequivalent numbers of words produced in the conditions being compared. Therefore, the same words used in one condition were matched to the words used in the other condition, for a particular comparison. The average number of tokens used for the comparisons were as follows: 15.3 for Syll-CRR versus Syll-0.75CRR, 13.7 for Control reading versus Syll-CRR, and 12.67 for Syll-140 versus Syll-CRR. Equating the number of tokens in this manner was not necessary for the acoustic trials because all carrier phrases were completed in the allotted time.

Stuttering Frequency

Percent syllables stuttered for all speaking tasks can be found in Table 2. There were large reductions in stuttering for all of the metronome conditions from the control reading and monologue tasks, with zero or near-zero stuttering during all metronome conditions. Only two participants stuttered during the metronome conditions.

Comparisons

Table 3 displays the values for all acoustic, aerodynamic, and phonated interval data. Friedman tests for the following dependent variables were significant: pressure rise time ($p < .0001$), vowel duration ($p < .0001$), voice onset time ($p < .0001$), the 30–100-ms phonated interval bin ($p = .045$), and the 101–150-ms phonated interval bin ($p = .001$). The subsequent Wilcoxon signed rank tests identified several significant differences for the comparisons involving two metronome-paced speech conditions. Pressure rise time and

vowel duration were significantly shorter during Syll-CRR compared to Syll-0.75CRR (pressure rise time, $p = .005$; vowel duration, $p = .005$) and Syll-140 (pressure rise time, $p = .008$; vowel duration, $p = .008$). Voice onset time was significantly shorter ($p = .04$) during Syll-CRR compared to Syll-140. Lastly, the percentage of 101–150-ms phonated intervals was significantly greater during Syll-CRR than during Syll-0.75CRR ($p = .005$) and Syll-140 ($p = .015$). The other notable finding was a medium effect size for maximum airflow during the Syll-140 versus Syll-CRR comparison, with greater maximum airflow in the slower condition.

There were two significant Wilcoxon signed rank tests for the Control Reading versus Syll-CRR comparison. Voice onset time was significantly shorter ($p = .005$), and the percentage of 30–100-ms phonated intervals was significantly less ($p = .017$), during Syll-CRR compared to Control Reading.

Reliability

Interjudge and intrajudge reliability data for aerodynamic data, acoustic, SPM, SFSPM, and time between utterances can be found in Table 4. The average percent deviation for interjudge reliability across all dependent variables in Table 4 was 3.62, with a range from 0 to 8.06. These values are superior to those in the Davidow et al. (2010) study that involved a similar reliability analysis. Interjudge reliability for %SS was also considered satisfactory. For 40 trials, 31 differed by 1%SS or less, six differed by 1–2%SS, one differed by 2–3%SS, and 2 differed between by 4–6%SS.

The average percent deviation for intrajudge reliability across all dependent variables was 2.20, with a range of 0 to 4.67. For the 40 trials rejudged for %SS data, 32 differed by 1%SS, six differed by 1–2%SS, and two differed by 2–3%SS. Interjudge and intrajudge reliability data for all dependent variables were considered satisfactory to support the conclusions presented.

Discussion

The present study was designed to determine the effect of speech rate on speech production variables during metronome-paced speech in PWS, in order to better understand if certain speech production changes are necessary for fluency during this fluency-inducing condition. The specific research questions were as follows: (1) What is the effect of changes in speech rate on the values of several speech production variables during metronome-paced speech?; and (2) Do the examined speech production variables change from a control condition to a metronome-paced speech condition when speech rates are matched between conditions?

In regard to research question #1, pressure rise time, vowel duration, and voice onset time were significantly longer, and the percentage of 101–150 ms phonated intervals was significantly less, during the slower metronome-paced speech condition when the mean difference in rate between conditions was 102.31 SFSPM. All of the significant differences remained, except for voice onset time, when there was a smaller difference in rate between metronome-paced speech conditions (54.31 SFSPM across the group).

In regard to the second research question, voice onset time and the percentage of short (30–100 ms) phonated intervals were significantly altered (reduced) from Control Reading to a syllable-based metronome-paced speech condition produced at a rate equal to the Control Reading condition, which was accompanied by the near elimination of stuttering. The other dependent variables (peak pressure, pressure rise time, maximum airflow, vowel midpoint airflow, and the percentage of 101–150-ms phonated intervals) did not change significantly between conditions. These latter findings suggest that changes to these speech production variables are not necessary for fluency induction during syllable-based metronome-paced speech.

Voice Onset Time

The matched rate comparison eliminated the influence of speech rate, as measured by SFSPM, on the reduction of stuttering and the values of the speech production variables. Therefore, one may argue that the reduction in voice onset time during this comparison may have been important for fluency during metronome-paced speech at this rate. There are, however, several reasons to believe that shorter voice onset times are likely not instrumental in fluency enhancement. First, speech after prolonged speech-type treatments (e.g., Packman, Onslow, & van Doorn, 1994; Riley & Ingham, 2000), a variation of rhythmic speech (alternating between 1 s of speech and 1 s pauses; Davidow et al., 2011), and even treatments not involving fluency-shaping techniques (Extended Length of Utterance; Riley & Ingham, 2000) has been shown to have increases or no change in voice onset time from pre- to post-treatment. Second, voice onset time has been shown to decrease with an increase in speech rate (Allen & Miller, 1999; Kessinger & Blumstein, 1997), including in the present study as metronome beat rate increased. Third, individual data from the present study show that the most severe participant (24.41 %SS during control reading; 0.0 %SS during Syll-CRR) had basically no change (0.01 ms reduction) in voice onset time from control reading to Syll-CRR. These findings, taken together, suggest that the decrease in mean voice onset time from control reading to Syll-CRR was likely a byproduct of producing metronome-paced speech at a fast pace and not necessary for fluency. It must be stated, however, that although it appears that a reduction in voice onset time is not responsible for fluency during syllable-based metronomic speech, further testing is needed for a definitive conclusion.

Phonated Intervals

The findings regarding phonated intervals are consistent with previous findings; that is, the present study is the third investigation to find a significant reduction in the amount of phonated intervals in the 30–100-ms range from a control condition to a syllable-based metronome-paced speech condition. Davidow et al. (2009) found a reduction in the percentage³, and Ingham et al. (2012) in the frequency, of phonated intervals in this range. The present study, however, found a reduction when there was an *increase* in speech rate of 8.14 SPM from the control condition to the metronome-paced speech condition. Previous

³Percentage was chosen in the Davidow et al (2009) study, instead of frequency, to control for the hypothesized influence of speech rate on phonated intervals; that is, it was expected that the experimental conditions would induce slower speech than the control conditions, producing less phonated intervals overall. This would mean, therefore, that a decrease in the frequency of phonated intervals may have occurred simply because of decreased speech rate.

studies reported reductions with decreases in SPM rates of 14.75 (Ingham et al., 2012), 45.72 (Davidow et al., 2009), and 131.67 (Davidow et al., 2009) from a control condition to a syllable-based metronome-paced speech condition. Collectively, these findings demonstrate that a reduction in the amount of short phonated intervals may be important for fluency during the production of syllable-based metronome-paced speech at several different rates. A significant reduction in the 30–100-ms range was also found from a control condition to a rhythmic stimulation condition that involved alternating 1 s of reading with 1-s pauses (Davidow et al., 2011), revealing that a reduction in this range may be important for various types of rhythmic speech.

Previous Research

The findings of the present study bring further skepticism to the conclusion that previously found speech adjustments are necessary for fluency during metronome-paced speech. Almost all previous changes to speech production variables in PWS from a control to metronome-paced speech condition may have been the result of changes in speech rate between conditions. Brayton and Conture (1978), Klich and May (1982), and Stager et al. (1997) found increases in vowel duration in PWS during metronome-paced speech. Brayton and Conture and Stager et al. do not provide data for their control condition, but the metronome beat rates in those studies were 92 BPM or less, which are substantially slower than average reading rates (188.4 words per minute, Walker, 1988). Klich and May reported a rate of 14 WPM less during their metronome condition.

Increases in pressure rise time during metronome-paced speech in previous studies (Hutchinson & Navarre, 1977; Stager et al., 1997) may also be explained by a slower rate during the experimental condition. Intraoral peak pressure had also been found to decrease during rhythmic speech (Hutchinson & Navarre, 1977; Stager et al., 1997). Although this dependent variable was not found to change significantly in the present study with a change in metronome beat rate, there was a small effect size with a large beat rate difference (Syll-CRR vs. Syll-140). In addition, vocal intensity was not controlled in those studies, and in fact, there was a reduction in vowel intensity from the control to metronome-paced speech condition for the group of PWS in the Stager et al. study. This is noteworthy due to the positive correlation between vocal intensity and pressure in the vocal tract (e.g., Finnegan, Luschei, & Hoffman, 2000). Therefore, contrary to the suggestions based on previous findings, an increase in mean vowel duration and intraoral pressure rise time, and a decrease in peak intraoral pressure, are likely not necessary for fluency induction during syllable-based metronome-paced speech.

Future Research

The most evident extension of the present study is to continue examining the necessity of a reduction in the amount of short (30–100 ms) phonated intervals during metronome-paced speech. There are several ways that this can be done. First, a control condition can be compared to a metronome-paced speech condition produced at a much faster rate than the control condition. If the reduction is necessary for fluency during metronome-paced speech, it should also occur at this faster rate. Second, a specific production style can be prescribed during the metronome-paced speech condition. That is, some participants in the present

study used a more halting syllable production and others seemed to lengthen their syllables more. For instance, if the metronome was set at 140 BPM during a one syllable per beat condition, there should be one syllable produced every 430 ms; the participants were allowed to accomplish this in whatever manner they chose. Some participants appeared to use, for example, 300 ms to finish the syllable with 130 ms remaining until production of the next syllable was required, while some used 230 ms to complete the syllable, with 200 ms remaining. These production variations within the same condition may have impacted the length of phonated intervals (and may have been responsible for the different levels of reduction across the group), and a study could be designed where both styles are used. If a reduction in the amount of short phonated intervals is necessary for fluency during metronome-paced speech, it should occur during both production styles. Third, as discussed in our most recent vocalization and fluency-inducing condition study (Davidow et al., 2011), PWS could produce metronome-paced speech while attempting to not reduce the amount of short phonated intervals. It has been shown that PWS can alter the frequency of short phonated intervals during normal speech production (Gow & Ingham, 1992; Ingham et al., 2001; Ingham et al., 1983). If, during metronome-paced speech, the speaker can increase the number of short phonated intervals back to or above the amount produced during habitual speech (and stuttering is still eliminated), that would rule out a reduction as important for fluency. Lastly, it would be interesting to measure short phonated intervals during the various stages of current syllable-based metronome-paced speech treatment programs (e.g., Trajkovski et al., 2009) to determine how they fluctuate with changes in stuttering frequency.

Another extension of the present study could involve performing a more refined analysis of the dependent variables. It appears that a change in the means of several dependent variables is not responsible for the fluency resulting during syllable-based metronome-paced speech. It is possible that a more detailed analysis of those variables, as was done for the phonated interval data, may reveal a change from the control to metronome-paced speech conditions. For example, Davidow et al. (2011) found that mean phonated interval duration did not significantly change from a control condition to a rhythmic pattern involving alternating between 1 s of speech and 1-s pauses, but there was a significant reduction in the percentage of 30–100-ms phonated intervals. This type of fine-grained analysis may be necessary to find the subtle changes in speech production that may be responsible for (or contributing to) the fluency-inducing effects of the fluency-inducing conditions, particularly for a fluency-inducing condition like chorus reading that perceptually sounds more similar to habitual speaking styles than other powerful fluency-inducing conditions (Ingham et al., 2009).

Additionally, the present study could be replicated, and the suggested future studies conducted, by including monologue and/or conversational speech, since these speaking contexts and reading have produced different values for certain speech production variables. For example, F_0 and pausing behavior (e.g., Howell & Kadi-Hanifi, 1991); percentage of unstressed vowels (Lowit-Leuschel & Docherty, 2001); and expiratory and total respiratory cycle durations (McFarland, 2001) have been found to be different between speaking tasks. Finally, other types of metronome-paced speech should be examined with PWS, as changes to speech production variables may differ with different instatement (production) styles. Producing one word per beat of a metronome has been shown to produce significantly

different values for mean vowel duration, mean voice onset time, and mean phonated length compared to syllable-based metronome-paced speech in normally fluent speakers (Davidow et al., 2010).

Brain imaging

The search for the underlying fluency-inducing mechanisms of the fluency-inducing conditions will most likely include examination of brain activity, as our discipline continues to publish an increasing number of neuroimaging studies. Several investigations have already examined brain activity during various fluency-inducing conditions, including singing (Stager et al., 2003), metronome-paced speech (Stager et al., 2003; Toyomura, Fujii, & Kuriki, 2011), chorus reading (e.g., Fox et al., 1996; Fox et al., 2000), delayed auditory feedback (Sakai, Masuda, Shimotomai, & Kori, 2009), and prolonged speech (De Nil et al., 2008). If future neuroimaging studies seek to find the cause of fluency-induction during the fluency-inducing conditions, they will certainly have to consider the speech rate issue highlighted in the present study, since several studies have found activity in multiple regions of the brain, including those that are abnormally activated during the speech of PWS (e.g., superior temporal gyrus and cerebellum, Brown, Ingham, Ingham, Laird, & Fox, 2005), to be correlated with syllable production rate (e.g., Fox et al., 2000; Riecker, Kassubek, Gröschel, Grodd, & Ackermann, 2006). If this confound is not considered, several years of neurophysiological research may be conducted that contributes little to our understanding of the fluency-inducing mechanism of the fluency-inducing conditions.

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Appendix

Carrier Phrases Used for Aerodynamic Data

1. The *pitifully* sad guard saw *Bobby* in the *basement*.
2. Wendy *panicked* when the *boozer* fell over *Pablo*.
3. My *bulging* arms grow *bigger* and very *powerful*.
4. She saw *Peter* on the new *better* and high *podium*.
5. Her *biting* dog *Snow* *painfully* began *chewing*.
6. Toy *batteries* cost a few *pennies* from my *bookkeeper's* store.

Carrier Phrases Used for Acoustic Data

1. Those ladies, near the fence, are *taking* the *paper sacks* to the barn.
2. He seems *thoughtful* to spend a lot of time and help *search* the house.
3. The *people* in the corner of the yard look like *puppets* *faithfully* working.
4. The nicely dressed man is *touching* the *shirt* while *checking* out the very beautiful view.
5. If you look closely, you can see a *calf* on the gigantic hill in the back of the *picture*.
6. That small boy is *keeping* a watchful eye on the large, wooden treasure bucket.
7. The girls with the extremely long hair are *shockingly* surprised at how he *fights*.
8. The *sassy* ladies appear to be waiting *patiently* and want to *attack* the valuable treasure.
9. Nobody is *speaking*, as all of the *spectators* really just want to *focus* on the show.
10. They may be saying that he *put* on a *spectacular* show for the *special* occasion.

Table 1

Example order for experimental tasks for the first day. Each grouping of data-collecting trials (acoustic and aerodynamic) was preceded by 30-s practice trials.

Day 1
Four 3-min monologues
Four 3-min readings
Syll-140: 30-s aerodynamic trials, 75-s acoustic trials
Rest period (2-min monologues)
Condition X: 75-s acoustic trials, 30-s aerodynamic trials
Rest period (2-min monologues)
Condition X: 30-s aerodynamic trials, 75-s acoustic trials
Rest period (2-min monologues)
Control reading: 75-s acoustic trials, 30-s aerodynamic trials
Rest period (2-min monologues)
Condition X: 30-s aerodynamic trials, 75-s acoustic trials

Note. Condition X refers to the conditions not analyzed for the present study. Syll = one syllable per beat; 140 = 140 beats per minute.

Table 2

Mean Stuttering Frequency, Speech Rate, and Task Compliance Data (standard deviations in parentheses) for all speaking conditions.

Measure	Speaking Condition				
	12 MM	12 MR	Control reading	Syll-140	Syll-CRR
%SS	7.41 (6.28)	5.29 (7.59)	3.77 (5.63)	0.06 (0.21)	0.17 (0.52)
SPM	163.83 (46.40)	207.54 (74.00)	220.72 (54.87)	133.81 (4.26)	235.05 (45.46)
SFSPM	175.86 (44.80)	227.20 (61.16)	228.08 (55.53)	133.91 (4.18)	236.22 (45.21)
Difference from expected time between beats	--	--	--	12.09 (10.95)	7.43 (5.93)
Task compliance rating	--	--	--	1.14 (0.32)	1.41 (0.56)
Number of participants meeting task compliance criteria	--	--	--	11	11
					10

Note. MM = minutes of monologue; MR = minutes of reading; Syll = one syllable per beat; CRR = control reading rate; 0.75CRR = 75% of control reading rate; 140 = 140 beats per minute; %SS = percent of syllables stuttered; SPM = syllables per minute; SFSPM = stutter free SPM; -- = data not analyzed for task.

Table 3

Means, standard deviations (in parentheses), and effect sizes (Cohen's d) for each comparison. A negative effect size indicates that the value was shorter or less during the first condition in the comparison. A positive effect size indicates that the value was longer or more during the first condition in the comparison.

Measure	Comparison		
	Syll-140 vs. Syll-CRR	Syll-0.75CRR vs. Syll-CRR	Control reading vs. Syll-CRR
Peak pressure (cmH ₂ O)			
1 st cond.	6.18 (1.80)	6.52 (1.99)	6.25 (2.01)
2 nd cond.	6.93 (2.20)	6.82 (2.03)	6.74 (2.08)
ES	-0.37	-0.15	-0.24
Pressure rise time (ms)			
1 st cond.	137.43 (26.57)	118.63 (17.99)	93.53 (27.07)
2 nd cond.	87.92 (17.28)	88.17 (17.74)	88.25 (19.84)
ES	2.21*	1.70*	0.22
Maximum airflow (cc/s)			
1 st cond.	617.33 (193.51)	563.79 (181.63)	554.54 (247.29)
2 nd cond.	516.97 (182.21)	512.58 (165.96)	510.14 (175.27)
ES	0.53	0.29	0.21
Vowel midpoint airflow (cc/s)			
1 st cond.	166.28 (71.00)	162.64 (71.80)	151.88 (75.65)
2 nd cond.	183.59 (99.41)	179.70 (90.00)	179.26 (91.50)
ES	-0.20	-0.21	-0.33
Vowel duration (ms)			
1 st cond.	175.58 (25.23)	143.85 (27.52)	129.57 (30.40)
2 nd cond.	121.67 (26.50)	121.38 (25.00)	121.38 (25.00)
ES	2.08*	0.85*	0.29
Voice onset time (ms)			
1 st cond.	52.58 (16.40)	45.63 (14.84)	54.19 (14.74)
2 nd cond.	40.86 (18.84)	40.84 (17.76)	40.84 (17.76)
ES	0.66*	0.29	0.82*
Phonated interval (30–100 ms)			

Measure	Comparison		
	Syll-140 vs. Syll-CRR	Syll-0.75CRR vs. Syll-CRR	Control reading vs. Syll-CRR
1 st cond.	6.85 (5.07)	10.44 (10.30)	17.40 (13.27)
2 nd cond.	10.43 (9.28)	9.91 (8.95)	9.96 (8.92)
ES	-0.48	0.05	0.66*
Phonated interval (101–150 ms)			
1 st cond.	10.36 (12.62)	15.74 (10.43)	16.16 (4.15)
2 nd cond.	21.33 (10.70)	21.99 (10.75)	22.14 (10.65)
ES	-0.94*	-0.59*	-0.74
Number of participants per comparison	9	10	10

Note. ES = effect size; Syll = one syllable per beat; CRR = control reading rate; 0.75CRR = 75% of control reading rate; 140 = 140 beats per minute. An asterisk indicates a significant Wilcoxon signed rank test at alpha = .05.

Table 4

Interjudge and intrajudge reliability data. The mean difference, range of differences, mean percent deviation, and the number of tokens or trials (for syllables per minute and stutter-free syllables per minute) are displayed for the dependent variables.

Reliability	Variable								
	Peak pressure (cm H ₂ O)	Pressure rise time (ms)	Maximum airflow (cc/s)	Vowel midpoint airflow (cc/s)	Vowel duration (ms)	Voice onset time (ms)	Syllables per minute (syllables)	Stutter-free syllables per minutes (syllables)	Time between utterances (ms)
Interjudge									
Mean difference	0.00	7.81	0.08	9.61	3.54	2.27	13.31	9.59	9.18
Range of differences	0.00–0.01	0.00–55.90	0.00–0.48	0.00–97.70	0.00–20.11	0.10–9.52	0.80–46.4	0.41–28.91	0.07–67.83
Mean percent deviation	0.01	7.42	0.03	5.72	2.69	5.03	6.45	6.72	3.09
# of tokens	111	111	111	111	218	105	35	40	120
Intrajudge									
Mean difference	0.00	1.35	0.04	5.76	2.35	1.73	6.85	9.29	1.17
Range of differences	0.00–0.01	0.00–25.55	0.00–0.05	0.00–37.88	0.01–18.01	0.00–11.73	0.00–27.33	0.73–13.8	0.00–19.23
Mean percent deviation	0.00	1.06	0.01	3.55	2.12	4.53	3.16	4.67	0.37
# of tokens	89	89	89	89	187	79	30	40	110

Note. *Mean difference* refers to the average difference between the measurements of the two judges (interjudge) or the two measurement occasions (intrajudge). The absolute values of the differences were used. *Range of differences* shows the smallest and largest difference for any one token. Percent deviation was calculated using the following formula: the difference between judges (interjudge), or measurement occasions (intrajudge), for each token divided by the primary judge's (interjudge), or initial (intrajudge), measurement, all multiplied by 100. *Mean percent deviation* refers to the average of the calculated values for each token. Using percent deviation allowed for standardization of the differences (between judges or judgment occasions) across the different dependent variables.