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Investigating motor training in people who stutter using fNIRs

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Abstract

This pilot study investigated motor learning and neuroplasticity in persons who do and do not stutter before and after participation in a phonation onset training protocol. Outcomes included phonation onset time and percent change in oxygenation level of hemoglobin using fNIRS in prescribed brain areas as a result of training. The authors hypothesized that people who stutter (PWS) would 1) exhibit a breakdown in auditory perception to motor production interactions, 2) demonstrate a difference in the way in which they perceive and learn motor information compared to someone who does not stutter (nPWS), and 3) exhibit reduced brain activity correlations between brain regions involved in perceived auditory targets and those involved in automatic motor production. 4 PWS and 4 nPWS between the ages of 20 to 59 participated in the study. There were no statistically significant between-group interactions, although there was a statistically significant within-subject change for production of breathy onset after training. Perception testing resulted in a ceiling effect, which must be addressed before further investigation. Observations were made utilizing graphed fNIRS data, which suggested right-sided auditory overactivation and left-sided suppression in PWS, as was hypothesized. The findings from the present pilot study serve as a cause for further investigation to either confirm or deny hemodynamic trends observed between PWS and nPWS.

I. Introduction

Recently, neuroimaging techniques have been used to begin to understand how speech is perceived and processed in the brain (Guenther, 2006; Hickok & Poeppel, 2000; Poeppel & Hickok, 2004; Tourville, Reilly, & Guenther, 2008). An area of particular interest for the study of speech perception and production is how this pattern is aberrant in the brain of a person who stutters (PWS). Recent neuroimaging studies have confirmed that there are differences in the brains of PWS (Chang, Erickson, Ambrose, Hasegawa-Johnson, & Ludlow, 2008; Lu et al., 2010; Sommer, Koch, Paulus, Weiller, & Buchel, 2002; Sommer, Knappmeyer, Hunter, Gudenberg, Neef, & Paulus, 2009; Watkins, Smith, Davis, & Howell, 2008). Further investigation of these aberrant findings may lead not only to a better understanding of the neuroanatomy and physiology of speech perception and production, but could lead to better service delivery to the PWS impacted by aberrant speech perception and production patterns.

Speech Perception, Speech Production, and Stuttering

The recent findings in the neuroimaging studies with PWS corroborate proposals set forth by the perception and production models of speech perception (Guenther, 2006; Hickok & Poeppel, 2000; Liberman & Mattingly, 1985; Poeppel & Hickok, 2004; Tourville, Reilly, & Guenther, 2008). Bilateral speech perception proposed by Hickok and Poeppel (2000) can be substantiated by the right-sided overactivation found in PWS (Chang et al., 2008; Sommer et al., 2009; Watkins et al., 2008), which is expected to be a compensatory strategy secondary to aberrant left-sided brain activity.

Using the framework of the Directions into Velocities of Articulators (DIVA) Model, Tourville et al. (2008) suggests that stuttering involves “excessive reliance upon

auditory feedback control due to poor feedforward commands" (p. 1441). Therefore, if stuttering originates as an issue with feedforward control, then overactivation of right-sided auditory feedback would result. Instead of becoming independent of auditory feedback as in normal development, differences in brain development in PWS may result in continued reliance on feedback controls in adulthood. Integrating the DIVA model even further, a study found that auditory error cells can be found in the planum temporale (Guenther, 2006). The planum temporale has been shown to be an area that has deficits in the brain of PWS (Chang et al., 2008; Sommer et al., 2009; Watkins et al., 2008). Additionally, compromised white matter tracts beneath the Rolandic operculum, which is the neuroanatomical point for sensorimotor representation for the oropharynx, may further contribute to the issue of perturbed feedforward and feedback patterns in PWS (Sommer et al., 2002; Tourville et al., 2008).

The information above suggests that PWS may have impaired interaction of speech perception and speech production. Most therapies for stuttering have focused on the imitation and production of speech so as to learn motor templates for accurate speech production. However, evidence is lacking as to whether PWS can better internalize motor concepts by means of perceptual learning. In other words, it is not known whether PWS learn to produce speech better when they are asked to produce speech in order to learn it, when they are asked to perceive speech in order to learn it, or whether a combination of the two approaches would be most beneficial.

A perceptual training program developed by Chan and Yiu (2006) trained naïve listeners using a reference matching (RM) or paired comparison (PC) task. Chan & Yiu hoped these protocols would replace internal representation with external references,

which would lead to a more reliable evaluation of voice. They hypothesized that by the end of the reference matching training, the listener would store these references as internal representations by which the listener could compare external stimuli. In the paired comparison program, a naïve listener compares paired stimuli. Hypothetically, the listener learns to shift attention to a particular perceptual feature—in the present study, breathiness—that distinguishes it from a different stimulus. Chan and Yiu found that RM leads to storage of external representation internally, allowing for later retrieval. The present study investigated whether this process might be affected in PWS.

It is possible that these training programs can be used with other perceptual qualities. This is in conjunction with the ideas discussed in the article by Saltuklaroglu, Kalinowski, and Guntupalli (2004) in which the authors suggest that stuttering inhibition improves with an internal, memorized representation "template" to which a PWS can refer in order to inhibit instances of stuttering. If a PWS can be trained to internalize perceptual stimuli, then theoretically, he or she may be able to inhibit stuttering instances after exposure to a RM training program.

So, if mirror motor neurons are activated during speech perception, then it is possible that their activity plays an important role in speech production. The convergence of perception and production, that is, the connecting pathway between these two types of mirror motor neurons so that one informs the other (Hickok & Poeppel, 2000), may be affected in PWS. This theory, in conjunction with hypotheses set forth by Saltuklarogu et al. (2004), would postulate that the human brain can be retrained upon perceiving certain stimuli. However, in PWS, the pathway between perception and production (i.e. the arcuate fasciculus) is abnormal in its white matter configuration (Chang et al., 2008;

Sommer et al., 2009; Watkins et al., 2008). Given the above, if perception informs production, it could be possible that there is a way to engage the brain of PWS so as to actually change the aberrant patterns from which they suffer, thereby alleviating the symptoms that accompany persistent developmental stuttering.

The present study piloted participants' ability to learn to produce and perceptually differentiate breathy versus hard voice onsets by engaging in a production training protocol. The study investigated how PWS learn to produce speech compared to people who do not stutter (nPWS). On a larger scale, the study will contribute to research comparing a production training protocol with a perceptual training protocol and a mixed perception/production training protocol.

Hypotheses

Based on the theories discussed herein and on previous neuroanatomical findings, it was hypothesized that PWS would 1) exhibit a breakdown in auditory perception to motor production interactions, resulting in shortened significant change of phonation onset time and poorer scores on perception testing compared to nPWS; 2) demonstrate a difference in the way in which they perceive and learn motor information compared to nPWS, and 3) exhibit reduced brain activity correlations between brain regions involved in perceived auditory targets and those involved in automatic motor production. These hypotheses were measured based on the hemodynamic response measured by fNIRS, an Electroglottogram (EGG), a pneumotachometer, and a button-press system for the perception task, further described below. The researcher was also investigating whether or not the testing protocols effectively measured the ability to perceive and produce breathy versus hard phonation onsets after participating in a training protocol.

II. Methods

Participants

There were a total of 8 participants (PWS, n = 4; nPWS, n = 4). All PWS were male, and 3 nPWS were male and 1 nPWS was female. Participants were between the ages of 20 and 59 years-old (*M* = 32.375*; SD* = 14.292). Within PWS, participants' ages ranged from 20 years-old to 48 years-old (*M* = 30.75; *SD* = 12.842). The nPWS participants' ages ranged from 22 to 59 (*M* = 34; *SD* = 17.455). All participants demonstrated average or above average receptive language skills as measured by the Peabody Picture Vocabulary Test (PPVT; Dunn & Dunn, 2007) and Revised Token Test (RTT; McNeil & Prescott, 1985). All participants were right-handed as measured by the Edinburgh Handedness Inventory (Oldfield, 1971). All participants with the exception of 1 PWS and 1 nPWS met ASHA's standards for passing a bilateral pure-tone hearing screening (American Speech-Language-Hearing Association, 1997). Of the exceptions, 1 PWS had a unilateral threshold at 80 dB at 4000 Hz, and 1 nPWS had a unilateral threshold of 30 dB at 1000 Hz. These abnormal thresholds did not affect the participants' ability to maintain conversation. None of the participants in either group had an interfering medical disorder or took medications that act on the central nervous system or had previously been diagnosed with a TBI. All participants spoke American English as their primary language, and had no other speech or language diagnosis, with the exception of stuttering in the PWS group. None of the nPWS had previously participated in speech or language therapy, and only 2 of the 4 PWS had previously received intervention for stuttering. The Stuttering Severity Instrument – Revised Edition (Riley, 1980) was used to assess stuttering in both groups. The PWS talker group received scores

ranging from 17 to 33 (M = 22.75; SD = 7.320) and classifications ranging from Mild to Severe. The nPWS talker group received scores ranging from 4 to 7 (M = 5; SD = 1.4142) and all were classified as Very Mild, which is the lowest severity rating one can be assigned.

Procedures

For baseline measures, each participant engaged in a production task and a perception task involving breathy and hard onsets of voice. Often, breathy onsets are used as therapy techniques for PWS (Andrews, Guitar, & Howie, 1980; Peters & Boves, 1988; Borden, Baer, & Kenny, 1985). Participants were randomly assigned to participate in either the production task or the perception task first.

An fNIRS system (TechEn, Milford, MA, model CW6) was used to record hemodynamic response. fNIRS optodes were used to measure blood oxygenation changes in the neural substrates for premotor, primary motor, and posterior superior temporal gyrus (pSTG) regions on the right and left sides. Emitters and detectors for the fNIRS equipment were placed prior to beginning the testing protocol using Talairach coordinates with the BrainSight neuronavigator system version 1 (Rogue Research, Montreal, QC) using a high-resolution brain anatomical MRI of the subject (Figure 2 and Table 1; Hull, Bortfeld, & Koons, 2009; Lowell, Barkmeier – Kraemer, Hoit, & Story, 2008; Zatorre, Evans, Meyer, & Gjedde, 1992). The coordinates are in millimeters along the left-right (x), anterior-posterior (y), and superior-inferior (z) axes. The measurements from the emitters and detectors measured the change in percent oxygenation level of hemoglobin over the prescribed areas after either a perceptual stimulus or motor production event (described below).

Production Task. During the production baseline task, each participant was provided with definitions and audio clips of the two different types of onsets. For example, a breathy onset was defined as a method in which the individual attempts to control air flow and vocal fold vibration in such a way as to produce smooth, gradual onset of phonation, letting air escape through the vocal folds before they begin to vibrate (Peters, Boves & van Dielen, 1986). A hard onset was defined as a situation in which no air flows through the vocal folds before voicing begins (Stager & Ludlow, 1998). During this measure, the participant was wearing a pneumotachometer connected to a Transducer and Data Analog Computer Interface (Glottal Enterprises, Syracuse, NY, Model MS110). A microphone was inserted into the pneumotachometer to record the speech signal. An EG-2 Two-Channel electroglottograph (EGG; Glottal Enterprises, Syracuse, NY) was used to measure onset and first approximation of the vocal folds during breathy, normal, and hard onsets. A pneumotachometer measures air pressure at the level of the glottis, and the EGG measures vocal fold contact. ADInstruments, Inc. PowerLab 16/SP hardware (Colorado Springs, CO, model ML795) was used for data acquisition. Figure 1a and 1b demonstrate the measurements recorded in LabChart version 7.3.2 (ADInstruments, Colorado Springs, CO). In Figure 1a, it is clear that the airflow begins before vocal fold contact actually occurs. However, in the hard onset in Figure 1b, it is evident that vocal fold contact and airflow onset occur nearly simultaneously. These were the pretest and posttest measures that were recorded of all participants to quantify changes in phonation onsets after training.

The experiment was run using timed Microsoft PowerPoint software. For the production task, the participant engaged in a control period of the following set: a

stimulus picture, a 3 second wait period, a 5 second response period, and a 15 second wait period. The participant did not actually engage in any of the activities, but watched the stimulus screen. This was to obtain a control period for fNIRS.

The participant was then set up with the EGG and pneumotachometer systems, given the aforementioned definitions of normal, breathy, and hard onsets and received instruction regarding the structure of the testing task. The participant then engaged in a training task in which he or she imitated three words each in a normal onset, breathy onset and hard onset. The actual testing task was split into three sections: normal onsets, breathy onset, and hard onsets. Each section had fifteen trials of the predetermined onset type. A trial consisted of the following sequence: a stimulus picture (e.g. apple, acorn or ear), a 3 second wait period, a 5 second response period to produce the stimulus in the given onset and a 15 second wait period. Before beginning the section for each onset type, the participant was given a definition and audio example of the onset to be tested. EGG and pneumotachometer recordings were measured using LabChart. Instructions were the same for pretest and posttest measures.

The outcome measures included changes in blood oxygenation level using the average hemodynamic response starting from the time of onset of production to 18 seconds later, using time recordings in the fNIRS system for time locked averaging of the production responses (Figure 3a). The voice onset behavior measure was based on differences in time between onset of airflow from the pneumotachometer and first vocal fold approximation from the EGG.

Perception Task. The participant was also set up for the fNIRS recording while engaging in the control period and participating in the testing portion of the perception

task. PowerPoint ran the auditory stimuli and pacing for the task. The perception measure was conducted via a paired comparison task as described by Chan and Yiu (2006). The participant was given the definitions for a normal, breathy, and hard onset and then given the following directions: "In just a moment, PowerPoint will be running the experimental task for you. In this task you will hear two samples, Sample 1 and Sample 2. You will then hear a third sample that will be exactly the same as Sample 1 or Sample 2. You will be asked to select whether Sample 3 matched Sample 1 or Sample 2." Instructions were given regarding the format of the task, and the participant was given a training period and an opportunity to ask questions to ensure he or she understood the task. The participant then engaged in a task involving 45 trials where he selected either button 1 or button 2 to show whether sample 3 matched sample 1 or sample 2. The following constituted one trial: Sample 1 (length of sound file plus 250 milliseconds), Sample 2 (length of sound file plus 250 milliseconds), Sample 3 (the same file as either Sample 1 or Sample 2, plus 250 milliseconds), a six-second wait period, a three-second response period, and a twelve-second wait period.

The task was split into two sections: 30 trials of within-vowel comparisons and 15 trials of between-vowel comparisons. In the within-vowel comparison task, participants were instructed to identify matching onsets when given the same vowel (e.g. Sample 1 was /o/ in an breathy onset, Sample 2 was /o/ in a hard onset, and Sample 3 was /o/ in an breathy onset; therefore Sample 3 matched Sample 1). During the between-vowel comparison task, participants were instructed to identify matching onsets in which the first two vowels were the same but the third vowel was different (e.g. Sample 1 was /i/ in an breathy onset, Sample 2 was /i/ in a hard onset, and Sample 3 was /æ/ in a hard onset;

therefore Sample 3 matched Sample 2). Responses were recorded using a response box connected to LabChart. The box had a yellow button on the left labeled "1" and a green button on the right labeled "2." During the 3-second response period, the participant recorded his or her response to the trial by pressing the yellow button if Sample 3 matched Sample 1, or the green button if Sample 3 matched Sample 2.

Vowels used in the within-vowel comparison task were /i/, /o/, and /u/, using onsets that were either breathy, between breathy and normal, normal, between normal and hard, or hard. Participants were asked to make comparisons between all ranges of onset styles. Vowels used in the between-vowel comparison task for Sample 1 and Sample 2 were /i/, /o/, and /u/. The participant matched the onset of the vowel in Sample 1 and Sample 2 to the onset of /æ/ in Sample 3. For this portion of the task, onsets were either breathy, between breathy and normal, normal, between normal and hard, or hard. However, unlike the within-vowel portion, ranges of onsets were at least two steps apart (i.e. breathy was compared to normal, between normal and hard, or hard; breathy was never compared to between breathy and normal). This was to ensure there was enough of a difference in the onset of the vowels so that the participant could actually perceive the difference.

Stimuli for the perceptual task were recorded using Kyma (Scaletti, 2004). Breathy, normal and hard productions were recorded and breathy-normal and normal-hard stimuli were altered using Kyma. Properties of each of the signals (e.g. signal length, length of the signal's onset, mean fundamental frequency and mean loudness) were measured using Computer Speech Lab (CSL; KayPENTAX, Montvale, NJ, model

4400) to insure that only the onset of the signal significantly differed within vowels (Table 2).

Outcome measures included changes in blood oxygenation level using the average hemodynamic response starting from the time of onset of perception to 18 seconds later using a trigger from LabChart as an auxiliary input to the fNIRS system for time-locked averaging of perception responses (Figure 3b). Percent responses correct for button responses were scored for within-vowel trials, between-vowel trials, and an average of all trials combined.

Training Sessions. The baseline measures were followed by two training sessions to instruct participants how to produce breathy versus hard onsets. Participants engaged in the following progression for training: syllable level, word level, flashcard drill, and sentence level. The first session combined syllable and word level training and the second session involved the flashcard drill and sentence level training. Each session lasted between 1 and 2 hours. During each training session, the participant wore the EGG and the pneumotachometer. The training sessions followed the following format for syllable, word and sentence level training: 1) the participant was given onset definitions identical to the testing session, 2) simple instruction regarding the anatomy and physiology of voice was given by the researcher, 3) training in producing breathy, normal or hard onsets at either the syllable, word, or sentence level was conducted, and 4) the participant engaged in an assessment to determine independence in using the different phonation onset types at the given level. Training involved verbal and visual feedback from the researcher. Visual feedback involved displays of EGG and pneumotachometer measures on LabChart. The assessment consisted of 15 stimulus items, in which the researcher

said, “Say this [syllable, word, or sentence] in a/an [breathy, normal or hard] onset.” No feedback was given to the participant during the assessment portion of the training. The flashcard drill was an assessment at the word level, in which the participant had to produce 24 of 30 words correctly at the given onset. If the participant did not meet the established criteria as judged perceptually and objectively given EGG and pneumotachometer data, then he or she received instruction in the area of difficulty and reattempted the assessment. Only 1 participant had to repeat an assessment; the assessment was at the syllable level.

After all training sessions were completed, the participant came back for the posttest task, which was exactly the same as the baseline task. The pneumotachometer, EGG, fNIRS, and microphone measures were used to quantify physiological changes that are present. fNIRS recordings were averaged over 20 control period trials for production, 45 trials of normal, breathy, and hard productions, 20 control period trials for perception stimuli, and 45 trials of response to perceptual testing measures. These trials measured the hemodynamic response as the change in percent oxygenation of hemoglobin in the pre-motor, motor, and pSTG in the left and right hemispheres before and after training. All training and testing was conducted by the first author, a Master’s-level graduate student.

III. Results

Behavioral Data Analysis

Production Task. Behavioral data collected using the EGG and pneumotachometer were analyzed using LabChart. The derivative of each waveform was calculated in LabChart, and the beginning of the wave cycle for airflow and beginning of the wave cycle for EGG were marked. Each of the 15 trials per onset was measured, and the difference in onset of airflow and voicing was calculated in a Microsoft Excel spreadsheet. An average in seconds for each onset style was obtained. This was done with baseline and post-testing data. Participant averages for pretest and posttest onset styles are displayed in Table 3.

Statistical analyses were conducted to compare changes within subjects and between groups for changes in airflow/phonation onsets for normal, breathy and hard voice onsets. Normal onset pretest measures were subtracted from breathy onset pretest measures, and hard onset pretest measures were subtracted from normal onset pretest measures. The same was done for posttest. The adjusted changes were entered into SYSTAT Software (SigmaPlot, Chicago, IL).

Univariate repeated measures analyses were conducted to compute changes within subjects and between groups for pretest and posttest measures for breathy onsets and for hard onsets. A statistically significant within subject change was indicated for breathy onset measures ($F = 22.240$, $p = .003$), indicating that onset time for breathy onsets had increased after training. However, within-subject changes in hard onset times were not statistically significant ($F = 1.251$, $p = .306$). Additionally, talker group classification was not a predictor for change in breathy onsets ($F = .062$, $p = .811$) or hard

onsets (F = 1.218, p = .312). Between-group changes were not statistically significant for either breathy onsets (F = .023, p = .884) or hard onsets (F = .078, p = .789). A secondary analysis with the Bartlett Chi Square indicated that SSI score was not a predictor for within-subject change in breathy voice onsets (χ^2 = .781, p = .377; Figure 4).

Perception Task. Univariate repeated measures analyses were conducted to compare changes within subjects and between groups for percent correct on overall and between-vowel testing measures after training. For overall perception scores, between-group change was not statistically significant (F = 1.909; p = .216). There was also no indication of statistically significant of within-subject change (F = .324, p = .590), and talker group was not a predictor for change (F = .017, p = .900).

Most participants scored highly on within-vowel perception testing, and most demonstrated lower scores on between-vowel perception of onset type. Therefore, a univariate repeated measures analysis was run for between-group and within-subject change for performance on between-vowel testing. However, no statistically significant differences were found for between-group (F = 3.82, p = .098) or within-subject (F = 0.433, p = .535) change after training for between-vowel testing. However, a graphical display of talker groups' scores indicates that, although not statistically significant, nPWS scored more highly than PWS (Figure 5). Findings may not be statistically significant due to a small sample size.

fNIRS Data Analysis

As previously noted blood oxygenation level was measured over prescribed regions of interest and recorded with the Techen CW6 NIRS system. Recorded data was imported into Hemodynamic Evoked Response version 2 (HomER; TechEn, Milford,

MA). Due to unexplained computer hardware crashes during data collection, three participants did not have perception pretest data, two participants did not have production pretest data, and one participant did not have perception posttest data. Upon review of the raw signals, NIRS channels were not included if there was excessive noise, motion artifact, or absence of a cardiac signal (see Appendix 1 for detailed steps for data analysis using HomER 2). After data was measured in HomER 2 and exported into Microsoft Excel, a SYSTAT program was used to construct graphs of data. Statistical analyses were not run due to the small sample size and data available for comparison of within-subject and between-group changes. Graphs of data were compared across group and condition, and visual observations based on graphed data were used to draw preliminary conclusions and provide direction for further investigation.

During the production task, it was expected that a hemodynamic response would be observed at 7 seconds relative to the stim marker placed in HomER 2 (Figure 3a) in response to production of speech. Motion artifact might occur at 3 seconds relative to the stim marker in HomER 2 when speech occurred, activating the temporalis muscle. When the participant spoke at 3 seconds, motion artifact was evident in a few cases. However, this did not significantly interfere with observing a hemodynamic response at the expected 7-second marker. During the perception task, it was expected that hemodynamic response would be observed in the averaged data at 4 seconds relative to the stim marker placed in HomER 2 (Figure 3b). A second hemodynamic response was also expected at around 13 seconds relative to the motor response initiated at 9 seconds. It was on the basis of these expectations that visual observations were made and preliminary conclusions were drawn.

Production Task. During the production posttest, based on visual inspection, it was observed that during breathy onset trials both PWS and nPWS talker groups demonstrated observable activation in the auditory area on the right side of the brain at around 3 seconds (Figure 6). The breathy onset posttest yielded an observable activation on the left-sided auditory area for one nPWS at around 7 seconds, likely associated with speech production with a similar response at 7 seconds in the PWS (Figure 6). The same test yielded left-sided motor activation at 7 seconds for three of four PWS and two of three nPWS. Similar responses were seen at 7 seconds on the right side in both talker groups (Figure 7). Data for the breathy onset pretest was lacking to determine if right- or left-sided activation was present before training. Furthermore, the hard onset posttest yielded an observable left-sided activation in the motor area in two of three nPWS and for none of the PWS at 7 seconds. In fact, there appeared to be suppression in two of the PWS at 7 seconds (Figure 8). Within-subject changes after testing were difficult to determine for both talker groups, as much of the data did not meet inclusionary criteria or did not demonstrate observable trends. Reasonable observations and conclusions could not be drawn regarding within-subject trends for this reason.

Perception task. During the perception pretest task, based on visual inspection, it was observed that while nPWS exhibited left auditory activation as evidenced by a hemodynamic peak around 4 seconds (Figure 9a), PWS exhibited left auditory suppression at around 5 seconds (Figure 9a). During the posttest perception testing, it was observed that PWS demonstrated auditory suppression on the left side of the brain with auditory activation on the right side of the brain, whereas two nPWS demonstrated no activation on the right side of the brain (Figure 9b). Other data in the perception task was

either scattered, noisy, or did not display observable trends by which conclusions could be drawn.

The observations made based on the graphs are in no way conclusive findings, but do suggest the presence of trends that warrant the need for further investigation.

IV. Discussion

This pilot study resulted in two preliminary findings. First, contrary to what the authors hypothesized, PWS and nPWS did not demonstrate a statistically significant difference in the ability to produce or perceive breathy/hard onset after training. However, there was a statistically significant within-subject change for production of breathy onsets in both talker groups after training. Neither between talker group nor within-subject improvement after training was found for the perception task. This may have been due to the presence of a ceiling effect on task performance, to be discussed below. Second, data recorded from fNIRS suggest left-sided suppression and right-sided activation on both perception and motor conditions in auditory and motor areas in PWS before and after training. Within-subject changes after testing were difficult to determine due to lack of observable trends. Based on the presented findings, it was determined that the production task is an adequate measure for change in motor behavior, but the perception task had a possible ceiling effect and should be revised before further investigation takes place.

Behavioral Changes after Training

Production Testing. Change in phonation onset time was found to be statistically significant after training as a within-subject measure for the breathy onset condition even with the small group size. Change in breathy onset was not statistically significant between talker groups. Hard onset change was statistically significant for neither within-subject nor between-group measures. Several possible explanations exist for the presence of these findings.

Firstly, it is important to note that there has been longstanding difficulty in determining how to measure vocal characteristics, including quantifiable changes in phonation onset time (i.e. airflow preceding onset of voice; Titze, 1995). As was observed in the present study, a participant produced different averages of phonation onset timing relative to flow when told to use a "normal" voice onset (Table 3), suggesting that phonation onset relative to airflow varies from time to time for the same individual. A "breathy" onset has typically been understood to have phonation delayed from the onset of airflow, while a "hard" onset is characterized by simultaneous onset of airflow and vocal fold vibration (Peters, Boves, & van Dielen, 1986; Stager & Ludlow, 1998). Although hard onset of airflow and voice are usually simultaneous and a hard onset is perceptually distinguishable from that of a normal onset, onset time of airflow and vocal fold vibration alone are not always sufficient to classify onset types. Table 3 demonstrates that normal and hard onset times are often, though not always, similar in length even when they are perceptually distinguishable.

Further analysis may be necessary to determine presence of significant change between normal and hard onsets, including perceptual rating and spectrographic analysis. In the present study, quality of the microphone signal due to microphone placement in the pneumotachometer would not allow for appropriate spectrographic analysis. Further investigation should consider between-group differences that may appear in a spectrographic analysis that were not immediately apparent with the present method of measurement.

Perception Testing. No statistically significant improvements were measured for the perception testing, likely due to a ceiling effect with the test and the small number of

subjects tested. Perception testing included 30 within-vowel trials and 15 between-vowel trials. A score was recorded for each section, and an overall score was assigned. However, all participants received a score of at least 80% correct on the overall and within-vowel baseline measures, leaving little room for improvement in the posttest. Participants typically performed more poorly on between-vowel measures than within-vowel measures, but overall performance remained high. Statistical analyses revealed no significant differences for between-group or within-subject change after training for the between-vowel perception subtest.

Due to the likelihood of ceiling effects on the perception testing measure, the current task design is not adequate to measure change in perception of voice onsets. Chan and Yiu (2006) used a reference matching task in conjunction with a paired comparison task, whereas the present study only implemented the paired comparison task. The reference matching task requires the participant to match one stimulus to another within a set of five, and therefore, is much more difficult than the paired comparison task used presently. Additionally, the reference matching task has been determined to be more effective for storing an internal representation of voice. Thus, based on the present findings, it cannot yet be determined if PWS struggle to store perceptual representations as compared to nPWS. The perception task must be revised to address the ceiling effect that influenced the present findings.

Hemodynamic Responses before and after Training in PWS and nPWS

Trends observed in production testing. Right-sided auditory activation was observed in two of four PWS and one of one nPWS. Additionally, left-sided auditory activation was observable for one of one nPWS with no observable trends for three PWS.

Also, hard onset posttest observations revealed left-sided activation in nPWS, while suppression was present with the PWS.

These findings can be corroborated by previously conducted studies. Chang et. al (2008) postulated that structural asymmetries on the right side of the brains of PWS suggested that PWS use right-hemisphere brain mechanisms more frequently than nPWS. Watkins et al. (2008) found that the integrity of white matter connections underneath the abnormally functioning ventral premotor cortex was compromised on the left side. In other words, abnormal brain function may be related to the integrity of the underlying structures in people who stutter. According to Watkins et al. (2008), "Disruption of white matter tracts underlying the ventral premotor cortex is likely to interfere with the integration of sensory and motor information necessary for fluent speech production" (p. 55). Sommer et al. (2002) also postulated white matter dysfunction beneath the Rolandic Operculum on the left side could contribute to stuttering. The findings from the present study may suggest functional differences in the brain of PWS as suggested previously based on anatomical findings (Chang et al., 2008; Watkins et al., 2008).

Trends observed in perception testing. In concordance with the hypothesis proposed by the authors, nPWS exhibited left auditory activation while PWS exhibited left auditory suppression and right-sided auditory activation. This finding was observed in baseline and posttesting data for the perception testing condition. As described above, these findings corroborate suggestions made previously (Chang et al., 2008; Watkins et al., 2008).

The sample size of the present study is small, resulting in preliminary findings that are by no means conclusive, but are suggestive of the presence of trends that warrant

further investigation. Findings were not entirely consistent with the hypotheses, although some trends may suggest right-sided overactivation with left-sided suppression in PWS. A greater participant pool is needed to either confirm or deny preliminary findings.

V. Caveats

Some limitations exist in this pilot study. Each limitation is discussed below.

Sample Size

The sample size in the present study was small (PWS, $n = 4$; nPWS, $n = 4$). A larger scale study will utilize a larger sample size from which more conclusive findings can be drawn.

Perception Testing Ceiling Effect

The perception testing task had a ceiling effect, resulting in the inability to make assertions about PWS' and nPWS' differing abilities to learn to perceive new stimuli. In a larger scale study, the perception task will be revised to adjust for the ceiling effect in the present study, possibly by implementing a reference matching task as opposed to a paired comparison task (Chan & Yiu, 2006).

Length of Testing Sessions

Testing sessions were excessively long and did not allot for necessary breaks for the participant. Test trials were repetitive and lengthy, resulting in reduced attention and sleepiness in some of the participants. It is possible that best performance was not measured due to the length of the trials. Additionally, the control period for fNIRS should be shortened and include no stimuli (pictures, sound, etc.), as such factors can result in a hemodynamic response from attention to environmental stimuli or testing stimuli presented at rest.

Movement Artifacts in HomER

Some movement artifacts were observed during the production trials due to optodes placed over the temporalis muscle. When a participant spoke, the temporalis

muscle contracted and the optode recorded temporalis activation instead of hemodynamic response. As was done in the present study, the larger-scale study should account for this expected artifact in data analysis.

Auxiliary Channel for Production Testing in HomER

An auxiliary channel recorded in fNIRS for the purpose of placing stim markers was excessively noisy and would have led to unreliable placement of stim markers for production testing. The present study utilized recorded times from session notes to place stim markers. However, it would be more reliable to determine a less noisy auxiliary channel that is recorded in LabChart to minimize potential error.

VI. Conclusion

The present study was determined to be an effective measure of phonation onset time relative to onset of airflow. Statistically significant differences in breathy onsets were found within-subjects after training, although between-group differences were not indicated. The perception task did not yield statistically significant changes after training, likely due to a ceiling effect. The perception task must be revised before further investigation. Trends in hemodynamic responses have suggested the presence of left-sided suppression with right-sided overactivation in PWS, as suggested by previous studies (Chang et al., 2008; Sommer et. al, 2002; Watkins et al., 2008). Further investigation on a larger scale is justified based on the preliminary findings of the present study.

Appendix

HOMER Analysis — Perception/Production Pre- and Posttest

1. If the participant has more than one data file, then these files should be put in the same folder. Load data by folders into Homer 2.
2. Check the connection (A1, A2, B3, C6, D4, D5) at 690 & 830 for noise and cardiac response. Once the signals have been checked, enter into the Excel Chart titled "[Participant Number] NIRS Signals" one of the following classifications into each field on the Excel File:
    a. OK (met criteria and is an acceptable signal)
    b. Noisy (not suitable for analysis)
    c. No cardiac response (not suitable for analysis)
3. Ensure that all channels that did not meet criteria are turned off. In addition, the following channels should be turned off, as their connections are not pertinent to data analysis: A3, B1, B2, C4, C5, D4, D6. Click "save" underneath the box that lists the files.
4. Add stim markers. These processes are different for perception/production tests.
    a. Perception Test Stim Markers
        i. Add stim markers by selecting "Tools" then "StimGUI."
        ii. Select the sixth aux.
        iii. In the box "Add Stim Marks Using Aux, select Threshold = 1, t min (s) = 17.
        iv. Click "Apply," then "New Label", then "Aud Stim."
        v. Click the "save" button on the bottom left.

vi. The stims will appear in the main window once the data is "run" (see directions below).

vii. Double check that there is one stim marker per signal from Aux 6.

viii. Only the stim markers for the 45 perception trials are included. Perception rest signals are not included, as it was determined that only one rest period need be used for each NIRS session.

b. Production Test Stim Markers

i. Add stim markers by selecting "Tools" then "StimGUI."

ii. Stim markers are added in the "Add/Delete/Edit Stim Marks" box.

iii. Enter in the following format:

1. Rest Period:

a. Enter 2 stim periods, as there was a 9 second break.

b. The first stim period is 390s, and the second is 130s, with a 9s break in between. Do not include the intro period.

c. From the start time recorded on the NIRS session timesheet filled out during participant session, add 13.

d. START TIME OF CONDITION: STIM FREQUENCY : END TIME

e. For example, the format will be: 120: 26 : 510 (first stim period); 519: 26: 649 (second stim period)

f. A new window will pop up. Click “new condition,” then “new label,” then type “REST” and click “OK.” The stim markers will appear in StimGUI.

g. Click “save” on StimGUI after entering each period.

h. All units are in seconds.

2. Normal, Breathy, Hard Trials:

a. Enter 3 stim periods since there are 3 conditions.

b. Each condition is 390s long, plus a 16s intro period. Do not include the intro period, which is likely recorded on the session notes sheet.

c. From the start time recorded on the timesheet, add 13s.

d. Double check stim periods with time written on “Session Notes” sheet.

e. START TIME OF CONDITION: STIM FREQ: END TIME

f. For example, the format entered into StimGUI will resemble: 1162: 26: 1552 (normal trials); 1741: 26; 2131 (breathy trials); 2185: 26: 2575 (hard trials).

g. After each condition, create a new label as was done for the rest period. In StimGUI, this will appear as three differently colored conditions (breathy, normal, hard).

h. Click “save” on StimGUI after entering EACH period. Four names should be given for stim: Rest, Normal, Breathy, Hard

i. All units are in seconds.

iv. After entering stim for rest, normal, breathy, and hard trials, there will be four conditions, and therefore, four differently-colored stim markers.

5. Determine Artifacts. Motion artifacts are “pretty subjective” and are spikes within data that differ significantly from the rest of the data set (R. Dewsnap, personal communication, April 2, 2012).
    a. Artifacts should be disabled for perception test and control periods.
    b. In production trials, motion artifacts at the beginning of a trial should not be disabled, as this is due to probe placement over the temporalis muscle.
6. Filter the signal and compute averages. Averages will be computed for all of the different sets of stim markers.
    a. Click “Options.”
    b. Enter the following parameters:
        i. Lpf= .8
        ii. Hpf= .016
        iii. HmrBlockAvg: Trange= -1.0 18.0
        iv. hmrMotionArtifact: tMotion = 0.0
        v. All other specifications remain at default setting.

7. After the signal is filtered for one of the conditions, data must be exported. B. Dewsnap from Techen provided directions for exportation to a Microsoft Excel file (personal communication, April 2, 2012). Directions have been revised to be more specific to the present study:
    a. After processing data in Homer, save the participants' folder/files to a new file titled "Processed HomER data."
    b. Load the .nirs file into MatLab and look at the variable "procResult". This is not in the original data file, but put there by Homer.
    c. In the workspace, double click on "procResult." An array of processed data will be displayed in the editor window.
    d. The HRF data is located in procResult.dcAVG. Type >>size(procResult.dcAvg) [Enter] to view file dimensions (e.g. 476, 3, 12, 5).
        i. 476 = The number of samples (.4 per second)
        ii. 3 = Hb0, HbR, HbT measures calculated in HomER 2
        iii. 12 = number of connections (i.e. number of possible analyses by the NIRS emitters and detectors)
        iv. 5 = number of conditions (rest, normal, breathy, hard, plus the default setting that was unused)
    e. To save this data to a Microsoft Excel file:
        i. Type: >> dlmwrite('101pretestperception.xls', procResult.dcAvg, ',')

ii. To export only one condition (e.g. condition 1): Type:
>>dlmwrite('myfile1.xls', procResult.dcAvg(:,:,:,1), ',')

8. Exported data is recorded for the participant in an Excel Chart and saved in a MatLab folder. The data will need to be reformatted as it was exported as a delimited file. Resave the data file into the participant's folder in the "Processed Homer Data" folder.
9. In Microsoft Excel, the file is exported as a delimited file. It will need to be reformatted.
    a. Highlight the first column. Click the "Data" tab, then "Text to Columns," then "Delimited" bubble followed by "Next," then check the "comma" box, followed by "Next," then click "Finish." The data should now all be in columns and rows.
    b. Format the files.
        i. Insert four rows at the top.
        ii. In the first row, number each column 1 to 36 as many times as necessary (it should be one time for perception tests and four times for production tests).
        iii. The second row will be the conditions.
            1. For perception condition, label the second row Perception across the entire second row until reaching the number "36" from the first row.
            2. For the production condition, the second row will be labeled according to the order of the stim. The order of the

stim can be determined in the StimGUI in Homer 2. The order in which the conditions were exported are the order in which they appear in the "Condition Key" in the graph on StimGUI. For example, if the order is rest, normal, breathy, hard, then the first set of 1-36 will be labeled "rest" in row 3, the second set of 1-36 will be labeled "normal" in row 3, etcetera.

iv. For each connection, there are three columns of data. The first column is the Hb0, the second is HbR, and the third is HbT. Make Hb0, HbR, and HbT labels across the third row of the Excel file.

v. The fourth row will be the connections. All possible connections were exported from Homer 2. Each connection has three columns (representing Hb0, HbR, and HbT, as labeled in row three). Therefore, the fourth row should be labeled "A1" in the first three columns, "A2" in the next three, "A3" in the next three, "B1" in the next three, and so forth. This will be done for each condition.

10. The data is now formatted and ready to be pasted into a master file with all participant data.

Tables

Table I

Talairach Coordinates for placement of fNIRS probes (Based on Hull et al, 2009; Lowell et al., 2008; Zatorre, et al., 1992).

Regions	*x*	*y*	*z*
Left			
Dorsolateral Prefrontal Cortex –Emitter	-53	8	8
Premotor – Detector (6)	-53	6	38
Primary Sensory Cortex – Detector (5)	-57	-9	25
Posterior Superior Temporal Gyrus – Detector (4)	-64	-30	2
Supramarginal Gyrus – Emitter	-57	-37	31
Right			
Dorsolateral Prefrontal Cortex – Emitter	53	8	8
Premotor – Detector (6)	53	6	38
Primary Sensory Cortex – Detector (5)	57	-9	25
Posterior Superior Temporal Gyrus – Detector (4)	72	-30	4
Supramarginal Gyrus – Emitter	57	-37	31

Table II

Measurements of Signals for Perception Task

Vowel	Onset (OS) Type	Length (s)	OS Length (s)	Mean Hz	Mean dB
/i/	Easy	.836	.485	266.49	72.26
	Easy-Normal	.836	.334	261.61	74.17
	Normal	.835	.094	261.6	77.16
	Normal-Hard	.835	.141	275.44	80.47
	Hard	.834	.165	275.99	82.1
/o/	Easy	.815	.456	258.62	69.79
	Easy-Normal	.816	.282	250.56	70.8
	Normal	.816	.165	250.35	73.93
	Normal-Hard	.817	.166	260.05	77.66
	Hard	.816	.078	260.12	79.6
/u/	Easy	1.05	.553	290.71	73.51
	Easy-Normal	1.05	.231	295.78	73.1
	Normal	1.05	.142	295.53	74.61
	Normal-Hard	1.05	.158	288.49	76.54
	Hard	1.05	.113	288.94	77.77
/æ/	Easy	1.05	.614	234.55	70.44
	Easy-Normal	1.05	.205	226.49	72.61
	Normal	1.05	.169	226.1	74.38

Normal-Hard	1.05	.171	224.39	74
Hard	1.05	.173	225.03	75.05

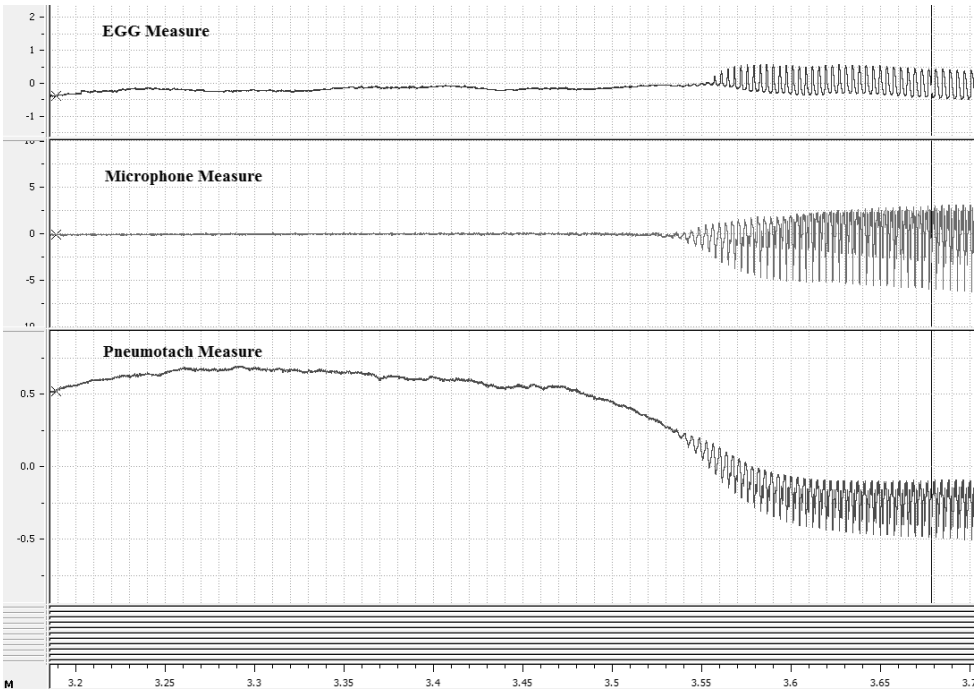
Table III

Participant Averages of Voice Onsets for Pretesting and Posttesting Trials

#	Talker Group	Pretest			Post-Test		
		Normal	Easy	Hard	Normal	Easy	Hard
1	nPWS	.0058	.0073	.0031	.0027	.0110	.0016
2	nPWS	.0055	.0057	.0019	.0046	.0118	.00012
3	nPWS	.0074	.0079	.0051	.0047	.0079	.0034
4	nPWS	.0080	.0283	.0068	.0062	.0382	.0021
5	PWS	.0088	.0133	.0028	.0063	.0269	.0011
6	PWS	.0059	.0080	.0090	.0108	.0133	.0009
7	PWS	.0036	.0101	.0027	.0043	.01653	.0035
8	PWS	.0034	.0111	.0035	.0058	.0263	.0031

Figures

Figure 1a. Breathy onset of a schwa vowel, in which the pneumotachometer and the EGG indicate initiation of airflow before voicing begins. The EGG measure is displayed in the top window, the microphone in the middle window, and the pneumotachometer measure is displayed in the bottom window. *Figure 1b.* Hard onset of a schwa vowel, where initiation of airflow and voice are almost simultaneous.



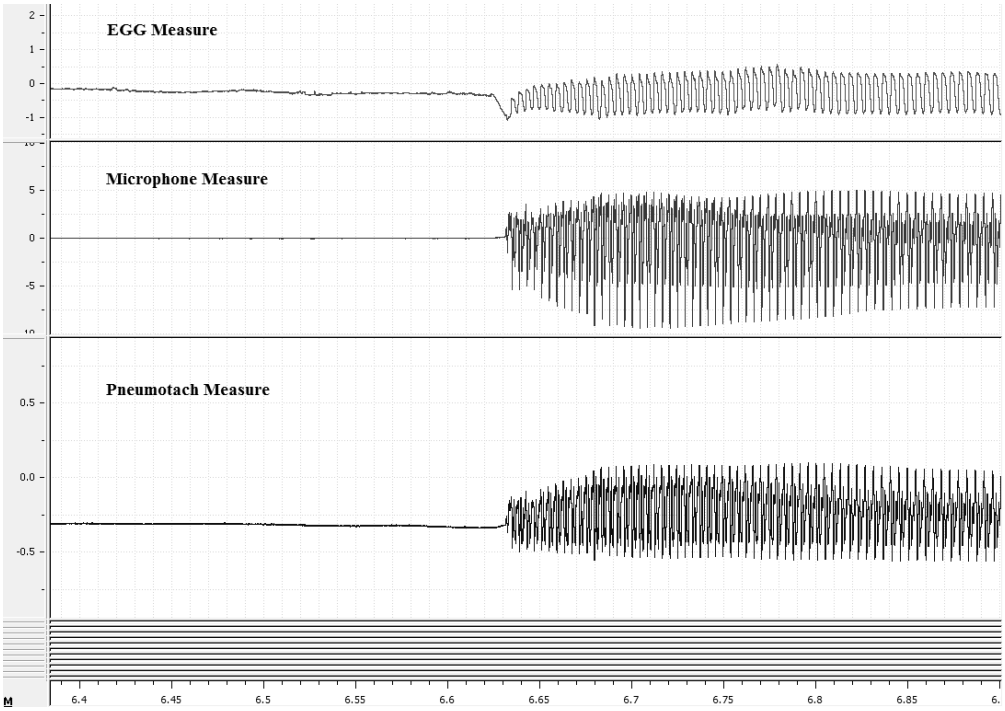


Figure 2. Placement of fNIRS optodes on the left side of the brain, where *C* and *D* indicate emitters and *4*, *5*, and *6* indicate detectors. *C* is placed over the premotor area, *D* is placed over the supramarginal gyrus, *4* is placed over the posterior superior temporal gyrus, *5* is placed over the sensory area, and *6* is placed over the motor area. The black bars represent connection areas in which hemodynamic flow were being measured. Connection *C6* measures hemodynamic responses to motor movement, *D4* measures hemodynamic responses to auditory stimulation, and *D5* measures hemodynamic response to orofacial sensory stimulation. Detectors and emitters were placed in corresponding brain areas on the right side as well.

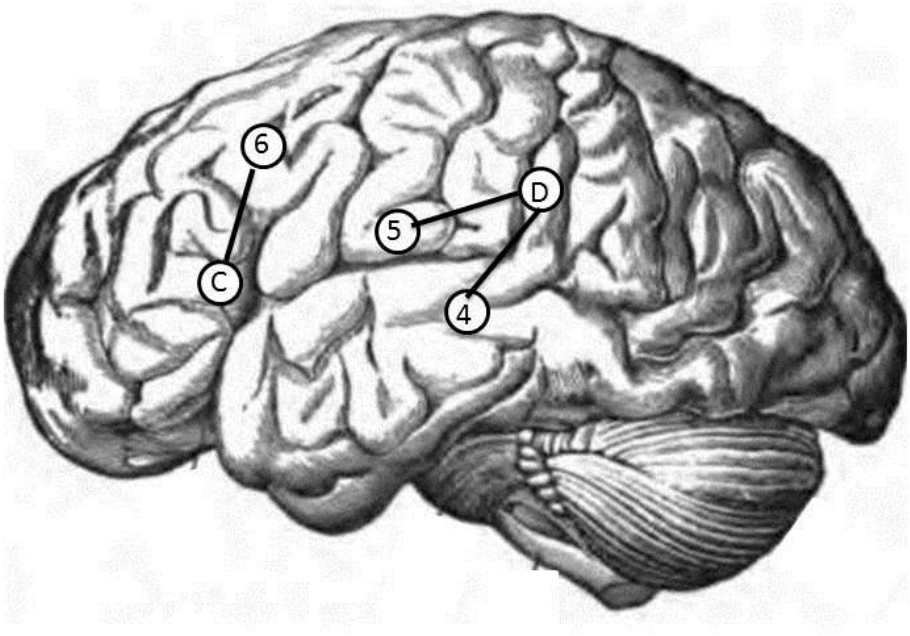


Figure 3a. Projected image of hemodynamic response for production trials recorded in fNIRS. Zero to three seconds indicates the time at which each participant was prompted to produce the stimuli. Due to optode placement, motion artifact was expected at this time. Hemodynamic response was expected between five and seven seconds.

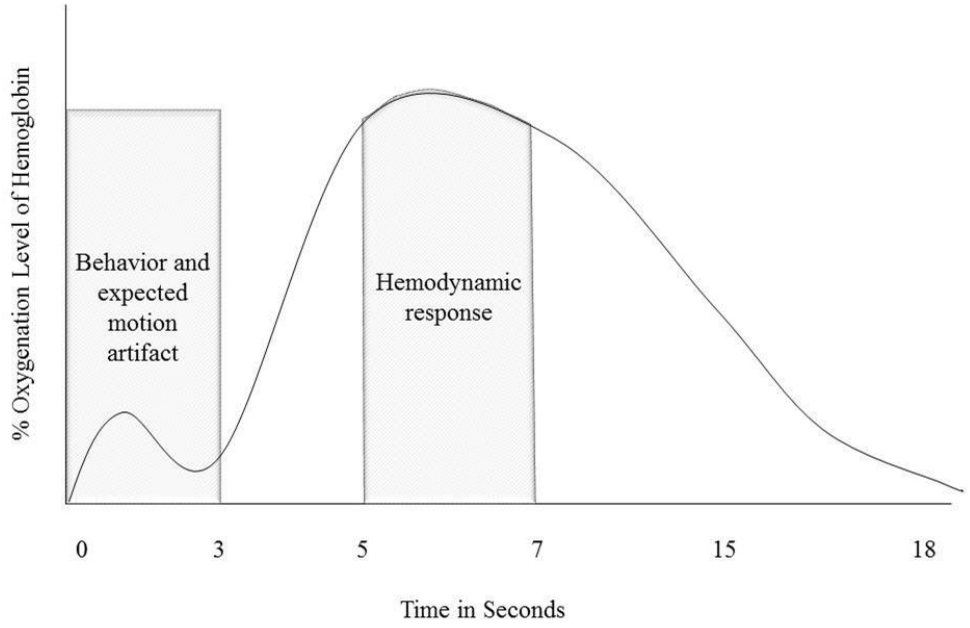


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Figure 3b. Projected image of hemodynamic response for perception trials recorded in fNIRS. Sound stimuli were played at zero to three seconds, with hemodynamic response expected at 4 seconds. Motor response was expected at thirteen seconds from the participant moving for the button press.

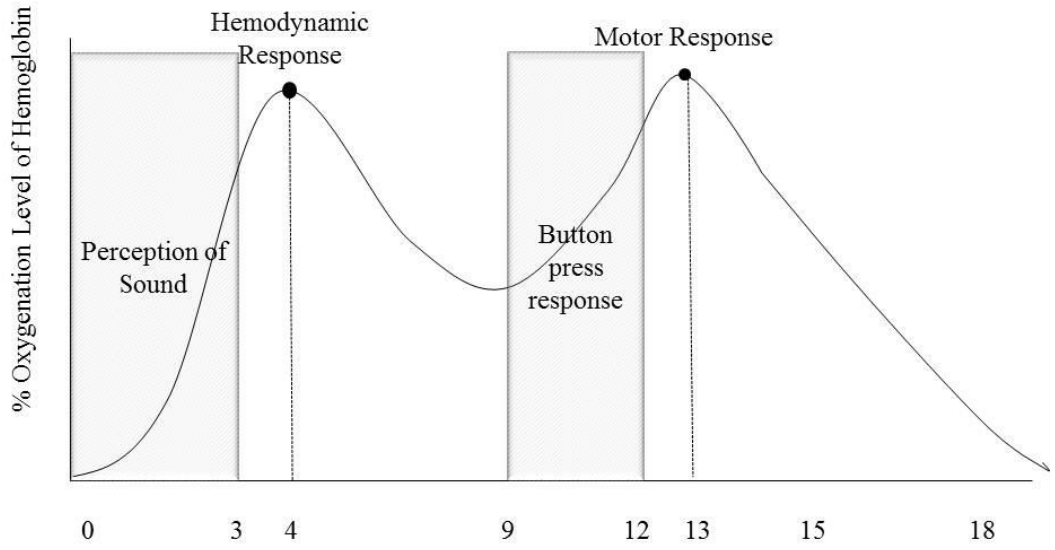


Figure 4. SSI as a predictor for change in breathy onset time.

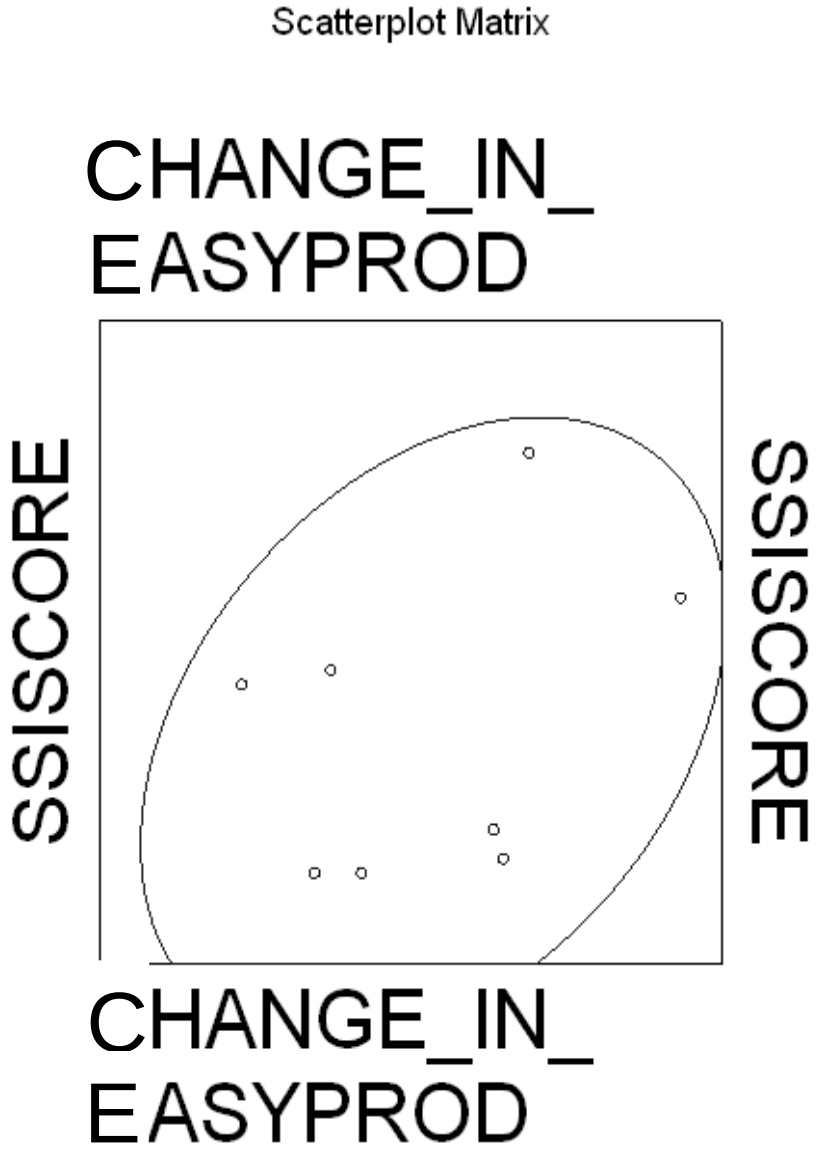


Figure 5. Pre- and posttest between vowel scores for nPWS and PWS. nPWS scores, by observation are higher than 3 of 4 PWS.

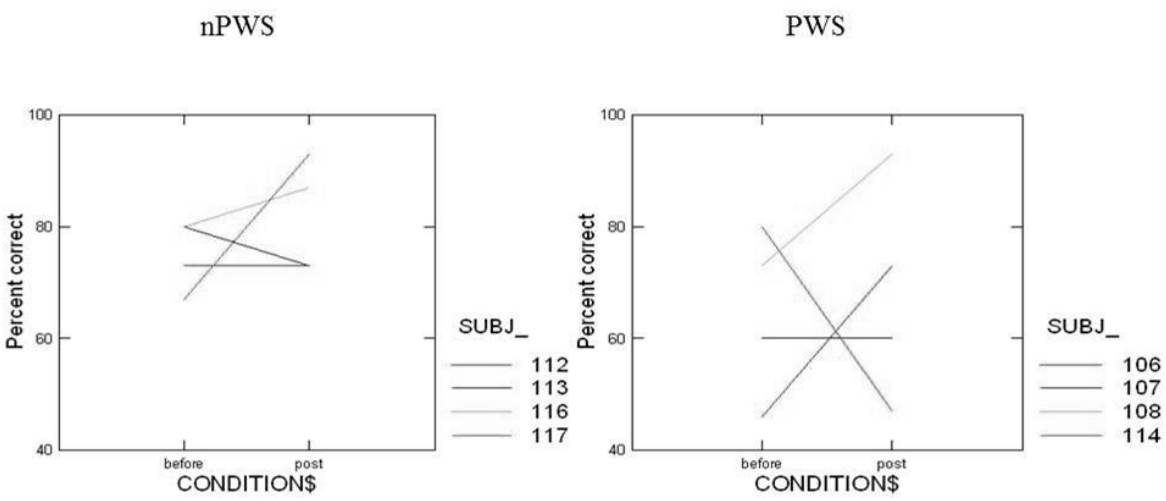


Figure 6. PWS and nPWS right-sided auditory activation in breathy onset posttest trials for both talker groups, and observable left-sided auditory activation for 1of 1 nPWS and for 1 of 3 PWS. Some motion artifact is expected at 3 seconds and peak hemodynamic response is expected at 7 seconds.

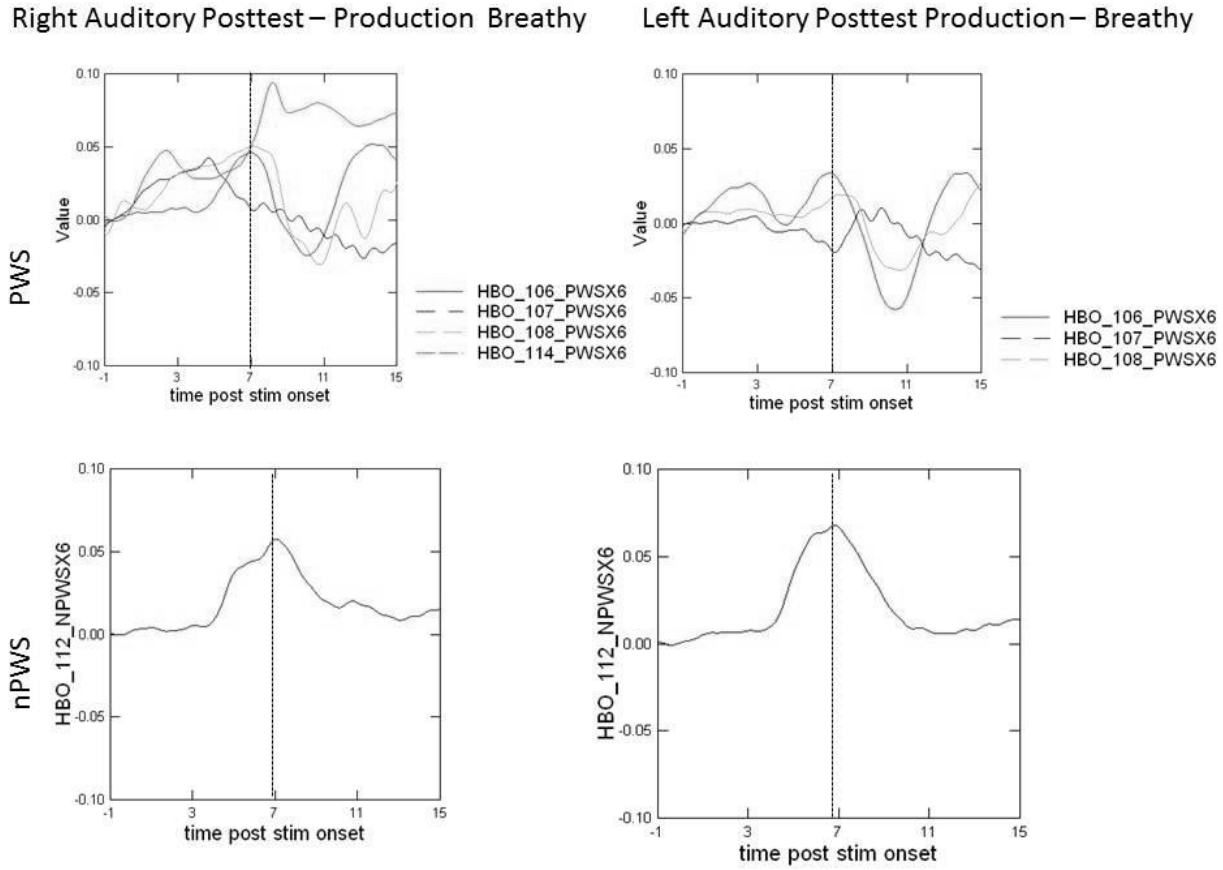


Figure 7. Left-sided motor activation for 3 of 4 PWS and 2 of 3 nPWS. Similar observations can be seen on the right side in both talker groups. It is notable that within-subject improvements in breathy onset were statistically significant, and that the fNIRS data suggests the presence of a hemodynamic response for this condition in both talker groups. Motion artifact is observable at 3 seconds and peak hemodynamic response is expected at 7 seconds.

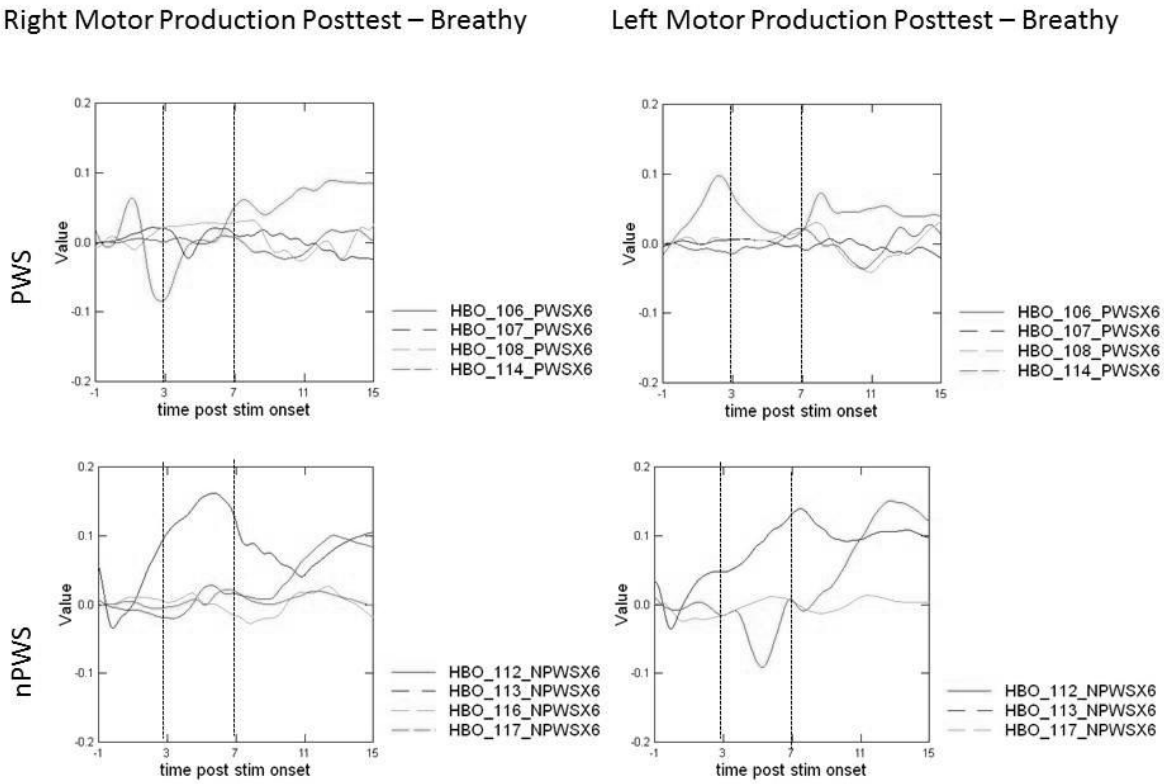


Figure 8. Left-sided activation in the motor area in 2 of 3 nPWS, but not in PWS for hard onset posttest trials. In fact, suppression is observed in 2 of the PWS at 7. Motion artifact is observable at 3 seconds and peak hemodynamic response is expected at 7 seconds.

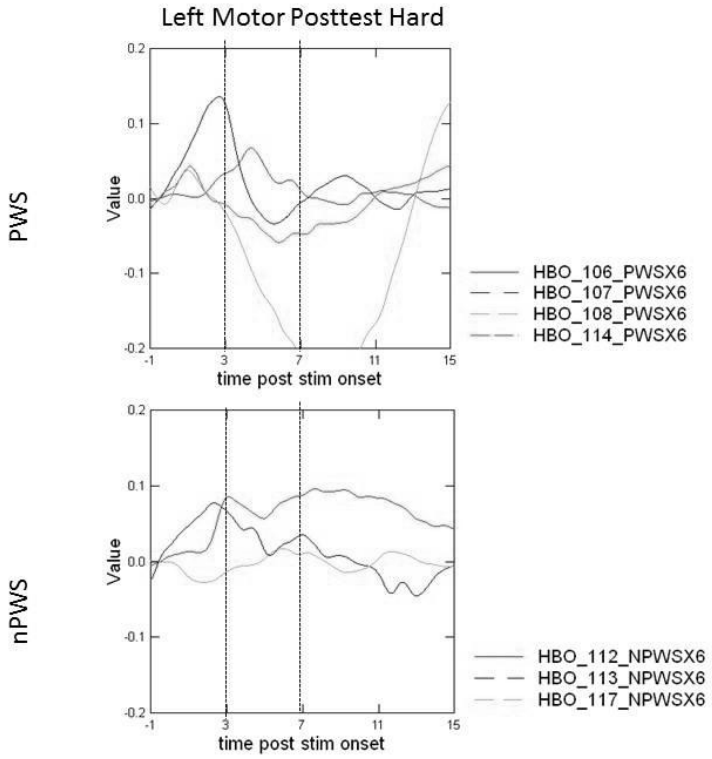


Figure 9a. Pretest perception auditory response on the left side indicates nPWS activation and PWS suppression. The dotted line indicates the time at which a hemodynamic response was expected (4 seconds).

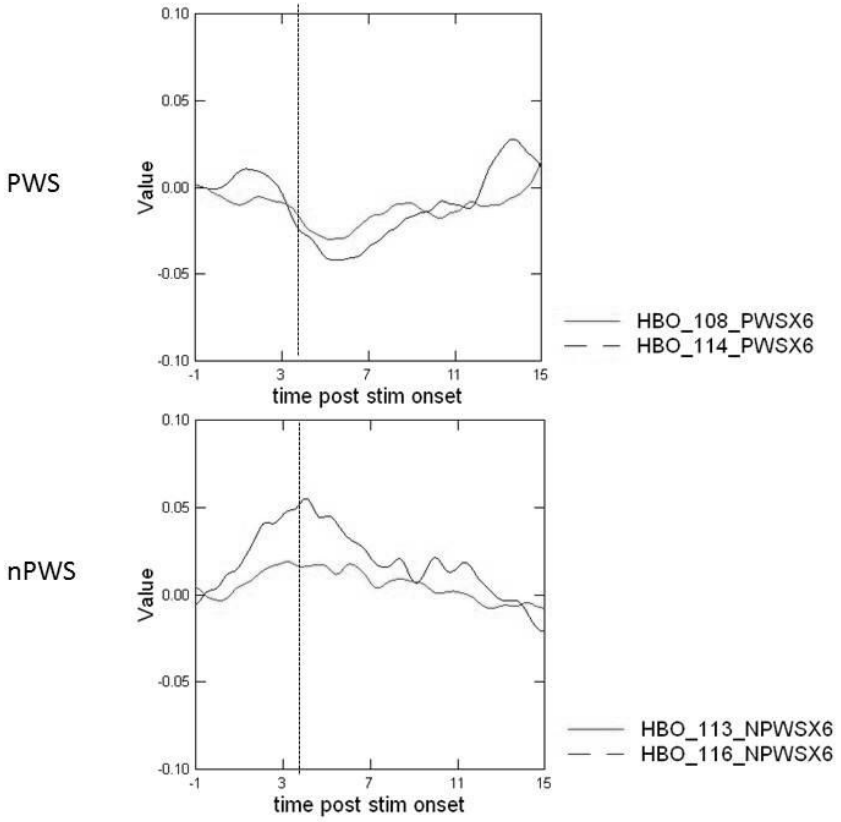
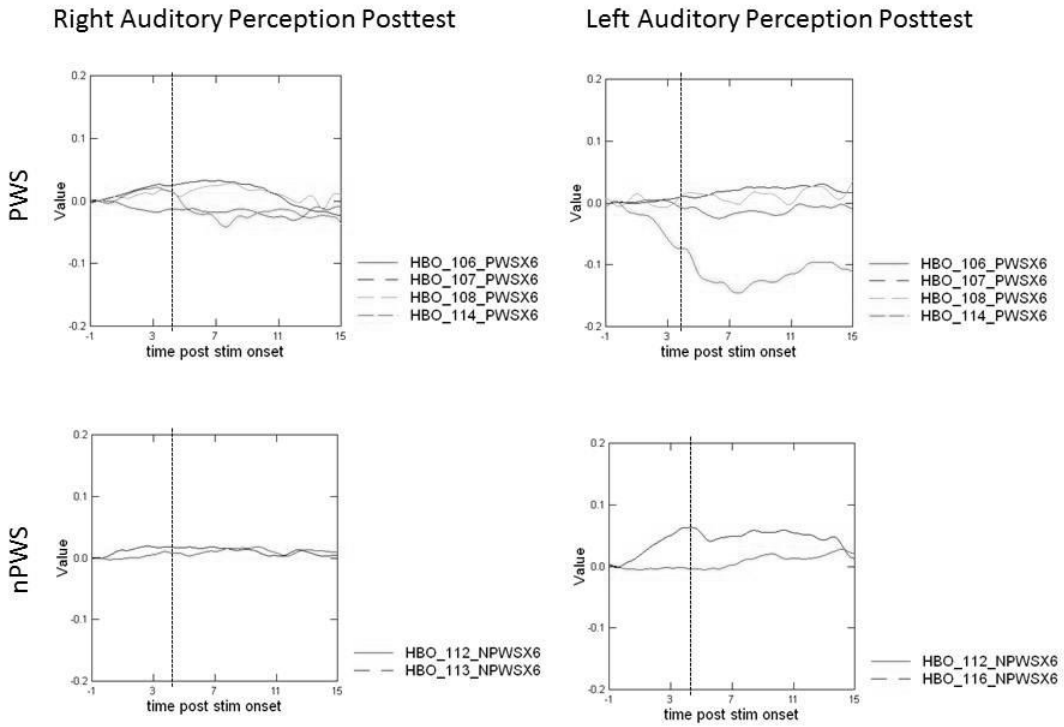


Figure 9b. Auditory activation and suppression differences in nPWS and PWS.



References

American Speech-Language-Hearing Association. (1997). Guidelines for Audiologic Screening [Guidelines]. Available from www.asha.org/policy.

Andrews, G., Guitar, B., & Howie, P. (1980). Meta-analysis of the effects of stuttering treatment. *Journal of Speech and Hearing Disorders,45,* 287-307.

Borden, G.J., Baer, T., & Kenny, M.K. (1985). Onset of voicing in stuttered and fluent utterances. *Journal of Speech and Hearing Research, 28*, 363-372.

Brown, S., Ngan, E., & Liotti, M. (2008). A larynx area in the human motor cortex. *Cerebral Cortex, 18*, 837-845. doi: 10.1093/cercor/bhm131

Chan, K.M.K. & Yiu, E. M-L. (2006). A comparison of two perceptual voice evaluation training programs for naïve listeners. *Journal of Voice, 20* (2), 229-241. doi: 10.1016/j.jvoice.2005.03.007

Chang, S-E., Erickson, K.I., Ambrose, N.G., Hasegawa-Johnson, M.A., & Ludlow, C.L. (2008). Brain anatomy differences in childhood stuttering. *NeuroImage, 39*, 1333-1344. doi: 10.1016/j.neuroimage.2007.09.067

Dunn, L.M. & Dunn, D.M. (2007). Peabody picture vocabulary test (4th ed.). Minneapolis, MN: NCS Pearson, Inc.

Guenther, F.H. (2006). Cortical interactions underlying the production of speech sounds. *Journal of Communication Disorders, 39*, 350-365. doi: 10.1016/j.comdis.2006.06.013

Hickok, G., & Poeppel, D. (2000). Towards a functional neuroanatomy of speech perception. *Trends in Cognitive Sciences, 4*, 131-138.

Hull, R., Bortfeld, H., & Koons, S. (2009). Near-infrared spectroscopy and cortical

responses to speech production. *The Open Neuroimaging Journal, 3*, 26-30.

Liberman, A.M. & Mattingly, I.G. (1985). The motor theory of speech perception revised. *Cognition, 21*, 1-36.

Lowell, S.Y., Barkmeier – Kraemer, J.M., Hoit, J.D., & Story, B.H. (2008). Respiratory and laryngeal function during spontaneous speaking in teachers with voice disorders. *Journal of Speech, Language, and Hearing Research, 51* (2), 333-349. doi: 10.1044/1092-4388(2008/025)

Lu, C., Chen, C., Ning, N., Ding, G., Guo, T., Peng, D., Yang, Y., Li, K., & Lin, C. (2010). The neural substrates for atypical planning and execution of word production in stuttering. *Experimental Neurology, 221*, 146-156. doi: 10.1016/j.expneurol.2009.10.016

McNeil, M.R. & Prescott, T.E. (1985). Revised token test (2nd ed.). Austin, TX: Pro-Ed.

Oldfield, R.C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9,* 97-113.

Peters, H.F.M. & Boves, L. Coordination of aerodynamic and phonatory processes in fluent speech utterances of stutterers. *Journal of Speech and Hearing Research, 31*, 352-361.

Peters, H., Boves, L., & van Dielen, I. (1986). Perceptual judgment of hardness of voice onset in vowels as function of the amplitude envelope. *Journal of Speech and Hearing Disorders, 51*, 299-308.

Poeppel, D., & Hickok, G. (2004). Towards a new functional anatomy of language. *Cognition, 92*, 1-12. doi: 10.1016/j.cognition.2003.11.001

Riley, G.D. (1980). Stuttering severity instrument for children and adults (Revised

edition). Tigard, OR: C.C. Publications, Inc.

Saltuklaroglu, T., Kalinowski, J., & Guntupalli, V.K. (2004). Towards a common neural substrate in the immediate and effective inhibition of stuttering. *International Journal of Neuroscience, 114*, 435-350. doi: 10.1080/00207450490422687

Scaletti, C. Kyma X [Software]. Champaigne: IL: Symbolic Sound Corporation.

Sommer, M., Koch, M.A., Paulus, W., Weiller, C., & Buchel, C. (2002). Disconnection of speech-relevant brain areas in persistent developmental stuttering. *Lancet, 360*, 380-383.

Sommer, M., Knappmeyer, K., Hunter, E.J., Gudenberg, A.W., Neef, N., & Paulus, W. (2009). Normal interhemispheric inhibition in persistent developmental stuttering. *Movement Disorders, 24* (5), 769-773. doi: 10.1002/mds.22383

Stager, S.V. & Ludlow, C.L. (1998). The effects of fluency-evoking conditions on voicing onset types in persons who do and do not stutter. *Journal of Communication Disorders, 31*, 33-51.

Titze, I.R. (1995). *Workshop on acoustic voice analysis: Summary statement.* National Center for Voice and Speech, Denver, CO.

Tourville, J.A., Reilly, K.J., & Guenther, F.H. (2008). Neural mechanisms underlying auditory feedback control of speech. *NeuroImage, 39*, 1429-1443. doi: 10.1016/j.neuroimage.2007.09.054

Watkins, K.E., Smith, S.M., Davis, S., & Howell, P. (2008). Structural and functional abnormalities of the motor system in developmental stuttering. *Brain, 131*, 50-59. doi: 10.1093/brain/awm241

Zatorre, R.J., Evans, A.C., Meyer, E., and Gjedde, A. (1992) Lateralization of phonetic

and pitch processing in speech perception. *Science, 256*, 846-849.