Changes in Voice Onset Time and Motor Speech Skills in Children following Motor Speech Therapy: Evidence from /pa/ productions

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Abstract

This study evaluated changes in motor speech control and inter-gestural coordination for children with speech sound disorders (SSD) subsequent to PROMPT (Prompts for Restructuring Oral Muscular Phonetic Targets) intervention. We measured the distribution patterns of voice onset time (VOT) for a voiceless stop (/p/) to examine the changes in inter-gestural coordination. Two standardized tests were used (VMPAC, GFTA-2) to assess the changes in motor speech skills and articulation. Data showed positive changes in patterns of VOT with a lower pattern of variability. All children showed significantly higher scores for VMPAC, but only some children showed higher scores for GFTA-2. Results suggest that the proprioceptive feedback provided through PROMPT had a positive influence on motor speech control and inter-gestural coordination in voicing behavior. This set of VOT data for children with SSD adds to our understanding of the speech characteristics underlying motor speech control. Directions for future studies are discussed.

Keywords

speech sound disorders; motor speech disorders; voice onset time; speech motor control; inter-gestural coordination; motor speech therapy

INTRODUCTION

Speech production involves complex speech motor movements that require the control and coordination of multiple oral motor systems. These speech movements occur within the respiratory system, larynx and vocal tract, and extend to the upper level of the speech articulators such as the lips, jaw and tongue. Impairments or an inability to efficiently control and coordinate these motor systems would impact the accuracy of speech production.

Speech sound disorders (SSD) are broadly characterized by deficits in motor speech control of articulatory systems and/or deficits in the general processing and organization of linguistic information (Shriberg, 2002; Strand & McCauley, 2008). Children with SSD form an extremely heterogeneous group, and vary in terms of their severity, speech errors, causality and treatment response (Waring & Knight, 2013). The etiology of most SSD is unknown. Most children with SSD present with restricted speech sound systems without any apparent sensory, structural, or neurological impairment (Gierut, 1998; Waring & Knight, 2013). Differential diagnosis is often challenging in these children as they may show mixed profiles (Strand & McCauley, 2008). For these reasons, it has been a challenge for professionals to select an appropriate intervention that will provide an efficient and effective therapy. In the literature, several intervention techniques have been described with the dual goals of facilitating rehabilitation or the development of the motor speech system, and improving speech intelligibility. Some intervention techniques, for instance, include imitation (Strand & Debertine, 2000; Strand, Stoeckel, & Baas, 2006), melodic and rhythmic methods (Sparks & Deck, 1986; Square, Roy, & Martin, 1997), and multi-sensory approaches such as PROMPT (Prompts for Restructuring Oral and Muscular Phonetic Targets; Hayden, Eigen, Walker, & Olsen, 2010).

PROMPT intervention

The current study used PROMPT, which is an intervention approach that facilitates the productions of sequenced speech movements for children with speech impairments (Bose, Square, Schlosser, & van Lieshout, 2001; Rogers, Hayden, Hepburn, Charlifue-Smith, Hall, & Hayes, 2006; for a summary see Hayden et al., 2010). In PROMPT therapy, the prompts serve to provide multiple sensory inputs regarding the place of articulation contact, extent of jaw opening, voicing, relative timing of segments and manner of articulation. It focuses on teaching precise movement transitions through the explicit use of spatial-temporal cues, which are gradually withdrawn as the child learns to reorganize movement patterns into more normalized movements. The PROMPT approach was established based on an understanding of the importance of sensorimotor information and feedback on motor speech control and emphasizes the re-shaping of the child's motor programming skills by imposing target positions and sequences of movements through proprioceptive information. It was hypothesized that tactile-kinesthetic-proprioceptive input would facilitate modifications of speech movements.

Indeed, the importance of sensorimotor feedback in motor speech coordination and its role in altering speech motor control is well demonstrated in the literature (e.g., Ito & Ostry, 2010; Menard, Perrier, Aubin, Savariaux, & Thibeault, 2008; Green, Moore & Reilly, 2002;

Walsh, Smith, & Weber-Fox, 2006). These studies have shown that articulator gestures will reorganize or compensate as a response to modifications in articulator movements in order to maintain perceptual integrity and acoustic output. Studies have shown that disrupting or manipulating sensorimotor input with respect to speech motor coordination would influence speech production (e.g., De Nil, 1999; Green et al., 2002; Loucks & De Nil, 2006; Max, Guenther, Gracco, Ghosh, & Wallace, 2004; Tremblay, Shiller & Ostry, 2003; van Lieshout, Hulstijn, & Peters, 2004; Walsh, et al., 2006), where jaw movements have been identified as foundational to the integration of the complex movements of the lips and tongue during speech production. While the jaw provides the postural support role for the other articulators, jaw proprioceptive information may be used as a reference signal for the coordination of other articulators (Loucks & De Nil, 2006; Green et al., 2002; Walsh et al., 2006). Since PROMPT is based on the principles of motor kinesthetic therapy through proprioceptive information, in this study, we examined the changes in the oral motor control of speech production in children with SSD following PROMPT. With particular emphasis on examining the inter-gestural coordination related to jaw stabilization, we chose to look at the production of /pa/, which requires precise temporal coordination of the voicing gesture between the larynx and jaw-lip movements.

Voice onset time

Variations in the timing and inter-gestural coordination between the laryngeal sub-system and articulators are commonly used to produce linguistic contrasts for consonant voiced and voiceless stops in English. In order to correctly produce a voiceless stop, for instance, /p/, one is required to coordinate the timing of the delay of the laryngeal vibration and the timing of the oral release by precisely controlling the joint movement of the jaw and lips. Voice onset time (VOT) refers to the interval between the release of a plosive consonant and the onset of the vocal fold vibration, which reflects the subtle temporal coordination between laryngeal muscles and oral speech articulators. Thus, during motor speech development, the acquisition of voicing contrast may be an indicator of the developmental changes in speech gestural coordination.

During typical motor speech development, children exhibit a shorter and more variable VOT relative to adults (Barton & Macken, 1980; Macken & Barton, 1980; Whiteside, Dobbin, & Henry, 2003; Zlatin & Koenigsknecht, 1976). Studies reported that younger children find voiced stops easier to produce successfully than voiceless stops (e.g., Macken & Barton, 1980; Preston & Yeni-Komshian, 1967; Preston, Yeni-Komshian, Stark, & Port, 1968), and the adult-like VOT patterns in voiceless stops may not be attained until puberty (e.g., Kewley-Port & Preston, 1974; Macken & Barton, 1980; Ohde, 1985; Zlatin & Koenigsknecht, 1976). Macken and Barton (1980) proposed a three-stage model for the acquisition of VOT stops. In the first stage, children produced a fairly short VOT, showing nearly no distinction in VOT production between voiced and voiceless stops. In the second stage, a distinction starts to develop with voiceless stops as seen with longer VOTs; however, they are still perceived as voiced (Barton & Macken, 1980; also see review by Weismer, 1984). In the third stage, with further development, children produce considerably longer voiceless stops with an overshoot of adult VOT values (over 100 ms). This model suggests that children initially have difficulty producing long VOTs for voiceless stops and they

require a modest number of attempts and practice at learning to delay the onset of the vocal fold vibration relative to the release of the oral closure. They continue to tune the fine temporal coordination of the speech components to gradually master adult-like productions.

Clinical research has used VOT measurements to study the timing and coordination of the articulatory muscles for speech sounds in individuals with motor speech deficits. Findings show lengthened and greater variability in patterns of VOT for adults with apraxia of speech (Auzou, Ozsancak, Morris, Jan, Eustache, & Hannequin, 2000; Freeman, Sands, & Harris, 1978; Kent & Kim 2003; Itoh, Sasanuma, Tatsumi, Murakami, Fukusako, & Suzuki, 1982) and adults with dysarthria (Auzou et al., 2000; Kent & Kim 2003). At this time, however, little is known about the characteristics of VOT patterns in children with motor speech deficits underlying SSD.

The current study

The present study aimed to make a contribution to the literature by reporting the changes in VOT patterns of a stop consonant relative to the changes in oral motor control in young children with SSD. We focused on the changes of oral motor control and inter-gestural coordination subsequent to the PROMPT intervention, where stability of jaw control was the common goal for all the children in the current study. We hypothesized that improvements in oral motor control, that is, the establishment of stability of jaw control, would provide reliable and accurate proprioceptive signals that would then facilitate the inter-gestural coordination between laryngeal systems and supra-laryngeal systems. Following more stable and accurate oral motor control and coordination, speech acoustics should improve and thereby influence speech production. We examined our hypothesis using both acoustic analysis to evaluate improvements in temporal coordination between phonation and speech articulators, as well as two standardized tests to evaluate each child's improvement on oral motor control and articulation accuracy.

METHODS

Participants

Six children with speech sound disorders (mean age = 4; 10 years; months; SD = 10 months) formed the clinical group (hereafter, the SSD group). Children with SSD were selected from the waiting list for speech therapy at The Speech and Stuttering Institute, Toronto, Canada. In this group, children met the following criteria: 1) absence of hearing difficulty and any neurologically related motor speech disorders (e.g., dysarthria) and childhood apraxia of speech (reported by caregivers and clinical observation by speech-language pathologists); 2) presence of speech delays with scores below the 16th percentile on the *Goldman-Fristoe of Articulation 2* (GFTA-2; Goldman & Fristoe, 2000)¹; 3) presence of speech delays with moderate to profound speech sound disorders on the *Hodson Computerized Analysis of Phonological Patterns test* (HCAPP; Hodson, 2003); 4) diagnosis of moderate to severe oral motor control issues on the *Verbal Motor Production Assessment for Children* (VMPAC;

¹S6's GFTA-2 was at the 12th percentile. Given the variability inherent in the data of young children, we calculated the 68% confidence interval for this subject's score. Even at the upper limits of this CI, the score was well below the 16th percentile cut-off which was part of our inclusion criterion.

Hayden & Square, 1999) with primary difficulties involving jaw and oro-facial control, including decreased jaw stability/lateral jaw sliding, limited control of the degree of jaw height (jaw grading), jaw movement overshoot/overextension, decreased lip rounding and retraction and overly retracted lips, and 5) clinical presence of variable productions for the same phoneme (i.e., child may exhibit inconsistent accuracy or produce different sound combinations for the same phoneme /p/), consonant and vowel distortion, nonstandard productions. At the time of recruitment and during the study, none of children received any additional therapy outside of the study (as reported by caregivers). The motor speech skills assessment and clinical diagnosis for the inclusion criteria and intervention were conducted at The Speech and Stuttering Institute.

An age-matched control group of six typically developing children (mean age = 4; 10 years; months; SD = 6 months; hereafter Control group) was recruited from volunteers in the local community to serve as a reference group for interpretation of the VOT patterns compared to the SSD group. The control group had no history of neurologic and hearing deficits (as reported by parents), and have not been flagged as having speech and language problems at school. Prior to acquiring data in this study, trained members of the research team screened each child's speech for possible articulatory disorders during the Expressive Vocabulary Test (EVT; Williams, 1997) EVT testing (which involves producing a number of age-appropriate words) and spontaneous speech during conversations in the lab. English was the first and primary language for all children in this study.

To ensure that the SSD and control groups differed only on speech, and not vocabulary, the Peabody Picture Vocabulary Test (3rd Ed.) (PPVT-3; Dunn & Dunn, 1997) and the EVT were given to both groups prior to the speech recording. These tests are standardized measures of receptive and expressive vocabulary. Unpaired *t*-tests showed no statistically significant differences between the two groups on the two tests (PPVT-3: $t = -.222$, $p = .829$; EVT: $t = .412$, $p = .987$), and the PPVT-3 scores of all participants were in the average to above-average range. The scores on the PPVT-3 and EVT for each individual and the mean scores for each group are summarized in Table 1. PPVT-3 and EVT assessments were carried out at the Hospital for Sick Children (Toronto, ON) by a neuropsychologist blind to the group assignment of participants. For all participants, parents gave informed consent and children gave assent to participate in the study. This study was approved by the Institutional Research Ethics Board (#1000016645).

PROMPT procedures and goals

Children with SSD received twice-weekly sessions of PROMPT therapy for eight weeks; each session was 45 minutes long and parents were assigned ten minutes of homework to be completed daily with the child. Prior to the start of the study, all parents committed to participate in this study and completing the requirement of completing daily homework with the child. To ensure that parents were compliant with the homework, parents were required to report back to the speech-language pathologist (SLP) about homework success prior to each PROMPT session. A licensed SLP with specialized training in PROMPT (DG) offered all of the treatment sessions. Intervention protocols were individually tailored to reflect each child's needs and age to achieve specific speech targets using a consistent procedure for all

children (see Table 2). The PROMPT approach in this study used a motor-speech hierarchy (Hayden & Square, 1994; Hayden, 2006) to guide clinicians in selecting movement goals for treatment and treatment progression. It assumed a hierarchical and interactive development of control for speech subsystems (i.e., Stage I: tone; Stage II: phonatory control; Stage III: mandibular control; Stage IV: labial-facial control; Stage V: lingual control; Stage VI: sequenced movements; Stage VII: prosody). Treatments generally proceeded systematically in a bottom-up fashion; starting with the lowest subsystem in the hierarchy where the child had control issues.

In this study, the goals for all children with SSD were directed from stage III where the goals were related to increasing jaw control, decreasing overall excursion, improving mid line control and facilitating jaw grading for speech production. Table 2 summarizes the main treatment goals for each individual with SSD. In addition to spatial-temporal prompts that were used to facilitate more accurate speech behaviors of the motor movements/speech targets, knowledge of performance feedback (e.g., “use your small mouth”) and results (e.g., “that was very good”) were provided after each trial.

Acoustic Analysis: Speech Materials and Procedures

The data acquired for acoustic analysis consisted of repetitions of the monosyllable /pa/. Recordings were completed before (PRE-therapy) and after (POST-therapy) the course of PROMPT intervention in children with SSD. The control group only participated in one recording. All recordings were acquired in a sound-proof magnetoencephalography (MEG) room². During the recording, participants were supine on the MEG bed with a microphone positioned 60 cm from their mouths. They were instructed to say the syllable /pa/ once immediately after being cued by the appearance of a white circle on a monitor. Speech productions were acquired with a high-fidelity directional condenser microphone (Model NTG-2, Rode Microphones, Long Beach, FL), converted to a digital signal (48kHz sampling rate) and amplified (dynamic range of 110 dB, 10–50kHz frequency response) with a PreSonus Firebox (PreSonus Audio Electronics, Inc., Baton Rouge, FL) and transmitted (24-bit/96k FireWire connection) to Audacity (v.2.0.0, www.audacity.sourceforge.net), an open-source software program for acquiring and editing digital recordings. Total recording time was six minutes, yielding a total of 115 /pa/ productions.

All the recordings of /pa/ were coded blindly without knowledge of PRE- or POST-therapy. VOT measures of /p/ were made (VY), using Praat acoustic analysis software (Boersma & Weenink, 2007), directly from the spectrograms by measuring the distance between the release of the plosive and onset of the first formant of the following vowel. The productions where the release burst could not be identified (e.g., plosives released with affrication or background noise from body movement), or where the place of articulation did not match the target, were excluded from the analysis. To ensure consistency in VOT measurements, 50% of all tokens for each recording were randomly selected and measured by another experimenter (AO), using identical procedures and criteria. The mean difference in VOT values between the two experimenters was 17.19 ms (SD = 6.89). A Pearson’s product-

²These data were recorded as part of a larger neuroimaging study where brain regions involved in production of these stimuli were also measured.

moment correlation analyses showed a significant correlation coefficient ($r = .933$, $p = .001$) indicating a high level of inter-rater reliability.

Coefficient of variance (CoV) values were used to represent the variability of the VOT productions. The CoV is the ratio of the standard deviation (SD) to the mean (in percent, %) which is used to control for higher SDs due to larger mean values. Two comparisons were performed on the /p/ VOT distribution and variability patterns: group and individual. For the group comparisons, the pattern of CoV in the SSD group, PRE-therapy, was compared to the control group. Also, comparisons of the patterns for PRE-therapy to POST-therapy were made in the SSD group to evaluate the intervention efficacy. For the individual comparison, the pattern for PRE-therapy to POST-therapy for each SSD individual was examined.

Standardized Measures of Motor Speech Control and Articulation

Two standardized tests were selected for the purpose of this study, the VMPAC and GFTA-2. The VMPAC is used to assess the neuromotor integrity of speech motor system and is standardized on typically developing children ages 3 through 12 years old and includes reference data for children with SSD. The VMPAC uses a 3-point scale (0 = incorrect; 1 = partly incorrect; 2 = correct) to score the accuracy and quality of motor movements and allows the identification of the levels of motor speech disruption. This test is divided into a number of subsections (each subsection can be interpreted independently), and for the purposes of this study, only the Focal oral motor (VM-F) and Sequencing (VM-S) sub-tests were utilized as they are most pertinent to volitional oral motor control. VM-F assesses the volitional oral motor control for jaw, face-lips, tongue and in both speech and non-speech movements in isolation and in combination with each other. The VM-S evaluates the ability to produce speech and non-speech movements in the correct sequential order. The VMPAC provides percent correct values relating to accuracy and stability to non-speech and speech production and is sensitive to capturing changes following speech motor treatment (Hayden & Square, 1999).

The GFTA-2 is a systematic assessment of a child's articulation of English consonants for individuals between ages 2 and 21 years old. It requires the child to name 35 picture plates and is used to assess the articulation of English consonants in all positions within words. This test supplemented the VMPAC by assessing the functional motor speech skills that reflect articulation.

Both tests were administered by licensed SLPs, unrelated to the study, who were blinded to diagnosis and treatment for the pre-assessments before the start of PROMPT therapy. Again, another SLP, who were blinded to diagnosis and treatment, administered the post-assessment after the children received a course of PROMPT therapy. All tests were performed in a quiet room and were audio- and video- recorded. As an estimate of inter-rater reliability, a random sample consisting of 33% of the standardized test responses was re-scored independently by two certified SLPs. The item-by-item agreement was derived by comparing the score obtained by each rater for every item on the VMPAC and GFTA-2. For example, for each item on the standardized test, the result from the first SLP was compared to that from the second SLP. If their results matched in board transcriptions, it then was scored as an 'agreement'; if not, it was counted as a 'disagreement'. Reliability was calculated as

‘percentage agreement’ using the formula: $(\text{number of agreements} / (\text{number of agreements} + \text{disagreements})) \times 100$. The average inter-rater reliability was 84.7% for the VMPAC and 82.4% for the GFTA-2. Computations of intra-rater reliability was carried out on 20% of the data and the results yielded 94.3% agreement for GFTA-2 and 91.6% for VMPAC.

Results

Acoustic Analysis: Group Comparisons

A total of 655 /pa/ productions for PRE-therapy, 682 for POST-therapy for the SSD group, and 676 for the Control group were used for the VOT analysis. Table 3 summarizes the mean, minimum (Min), maximum (Max), standard deviation (SD), coefficient of variance (CoV), skew and kurtosis for the VOT distributions for the SSD and Control groups.

Figure 1 illustrates the pooled data for the three groups (Controls, SSD PRE-therapy, SSD POST-therapy) for the frequency distributions of /p/ VOT productions. For each group, VOT data were pooled across participants and frequency distributions were compiled. The X axis represents the VOT values in milliseconds (ms), and the Y axis represents the number of occurrences (NOC, calculated as a percent). In Figure 1, the top graph represents the /p/ VOT distribution patterns for typically developing children (control group). The middle and the bottom graphs represent the /p/ VOT distribution patterns for SSD PRE-therapy and POST-therapy, respectively. As indicated in Table 3, none of the distributions in Figure 1 were significantly kurtotic. However, the control group showed a significant right-skew with a well-organized distribution pattern for /p/ VOT production with 73% of the VOT values in a range from 40 to 89 ms along the VOT continuum. The control group occasionally produced longer VOTs greater than 130 ms. In contrast to this right-skewed distribution pattern for the control group, the distribution pattern for SSD PRE-therapy showed a slight tendency of a left-skew (not statistically significant) with about 30% of the VOT values shorter than 40 ms. The SSD group exhibited a considerably scattered pattern for PRE-therapy with a greater dispersion of VOT values along the VOT continuum. This markedly variable VOT pattern for the SSD group (PRE-therapy) was confirmed by an unpaired *t*-test, where the SSD group showed significantly higher CoV values than the control group ($t = 3.783$, $p = .013$; Cohen's $d = 0.8$).

In terms of the intervention effect, the VOT distribution patterns for the SSD group changed dramatically between PRE-therapy and POST-therapy. In contrast to the tendency of a left-skewed distribution for PRE-therapy, the distribution for POST-therapy was significantly right-skewed (Table 3). Unlike the widely dispersed distribution of VOT productions (range from 0 to 219 ms) for PRE-therapy, the range of the distribution for VOT production for POST-therapy was markedly tighter, with 50% of the VOT values lying in the range from 80 to 109 ms along the VOT continuum. A paired samples *t*-test confirmed a significant difference for CoV values between PRE- and POST-therapy ($t = 4.536$, $p = .006$; Cohen's $d = 4.3$), where the CoV value for POST-therapy was significantly lower than that for PRE-therapy. No significant difference in CoV was found between POST-therapy and the control group ($t = .774$, $p = .474$).

Acoustic Analysis: Individual Comparisons

Figure 2 presents the VOT distribution patterns for each child with SSD for PRE-therapy and POST-therapy where the white bars indicate the VOT values for PRE-therapy and the gray bars indicate the VOT values for POST-therapy. As Figure 2 and Table 4 indicate, each individual child with SSD showed a marked change in the distribution patterns of VOT at POST-therapy. As shown in Figure 2, a markedly rightward shift of the patterns for POST-therapy was observed across all children with SSD, indicating an increase of VOT values. In terms of the range of the distribution patterns, in contrast to the widely dispersed VOT values, all children except S6, exhibited a relatively decreased range for the distribution for VOT patterns. Unlike the other participants who demonstrated a widely distributed pattern of VOT values, S6 produced a relatively narrow range of VOT values with 50% of productions shorter than 30 ms at PRE-therapy. Following therapy for S6, the range of VOT values markedly increased (Table 4) with considerably longer VOT values.

Comparison of Standardized Tests

Table 5 summarizes the PRE- and POST-therapy scores for each standardized test. A paired sample *t*-test showed significant mean score differences for VM-F ($t = 6.541$, $p = .001$) and VM-S ($t = 4.266$, $p = .008$), with large effect sizes (VM-F: Cohen's $d = 1.5$; VM-S: Cohen's $d = 1.1$). Figure 3 indicates that all children performed better on the VM-F and VM-S tests POST-therapy. The scores for the GFTA-2 (GF; $t = 1.713$, $p = .147$) between PRE- and POST-therapy did not reach statistical significance. Three of six participants (S1, S2, S4) showed higher scores POST-therapy on the GFTA-2, as shown in Figure 3; however, the changes in participant S3, S5 and S6 were equivocal.

Discussion

In this study, changes in VOT measures and scores on the VMPAC and GFTA-2 for children with SSD subsequent to PROMPT intervention were evaluated. The VOT measures were used to assess inter-gestural coordination and the VMPAC and GFTA-2 were used to evaluate motor speech control and articulation, respectively. The acoustic measures of the VOT for /pa/ productions were also compared to a group of age-matched typically developing peers. This allowed us to examine differences in the temporal aspects of inter-gestural coordination in children with SSD, prior to intervention, compared to what is seen in their typically developing peers. This also allowed us to examine whether the temporal aspects of inter-gestural coordination in the children with SSD after the intervention, became more similar to typically developing peers. Our data showed positive changes in the measures of inter-gestural coordination and oral motor control for all children with SSD after intervention.

Changes in VOT patterns

We observed significant changes in the distribution patterns and variability for /p/ after intervention. Prior to intervention, the /p/ productions were highly variable with a wide range in VOT values with some very short (less than 30 ms) productions. Subsequent to the intervention, the distribution patterns became more similar to those seen in age-matched typically developing children. Consistent with the observation of less dispersion patterns of

production after intervention, children with SSD demonstrated less variable VOT patterns, indicating better control in the timing and coordination of laryngeal and articulatory muscles to produce the voiceless /p/ sounds. In Figure 1 (bottom), the overall distribution patterns of the VOT values after the intervention showed a shift rightward, indicating that after the intervention, children with SSD were able to delay the laryngeal vibration to make production patterns more similar to those seen in the typically developing controls. This observation was particularly evident from S6's VOT distribution patterns. Before intervention (Figure 2), S6 produced 50% of VOT productions within less than 30 ms with a narrow range of distribution; this could be due to a number of different reasons. One possibility is that S6 had poor temporal coordination for delaying the laryngeal vibration relative to oral closure release, another is that this subject distinguished the phonemes in a non-ambient way, or the child lacked a phonological distinction between the phonemes. It is impossible to determine the cause of this VOT distribution without additional information outside the scope of this paper; however, it is important to note that after intervention, this participant's VOT productions showed a marked increase in latency with a wider range of distribution patterns.

Of note, we observed that the children with SSD, as a group, produced exaggerated VOTs (i.e., longer) POST-therapy. While not statistically significant, these were longer than what were observed in the control group. These long VOT values after POST-therapy may be due to over-generalization, that is, children may try to make a differentiated voiceless /p/ (i.e., at adult-like VOTs) by intentionally lengthening the interval between the release of a /p/ and the onset of the vocal fold vibration. However, the children's exaggerated VOTs could also be attributed to developmental changes in speech gestural coordination. This may be consistent with stage 3 in Macken and Barton's (1980) model of VOT acquisition. In this stage, children are able to produce voiceless stops with adult-like VOT values; however, there may be some "overshoot" resulting in instances of longer, or exaggerated, VOTs. In our study, prior to intervention, these children's VOT patterns generally exhibited a wide range of values on the VOT continuum. Some productions displayed no distinctions between voiced and voiceless forms (VOTs less than 30 ms) and some showed excessively long lags (longer than 100 ms). This suggests that these children were at a stage where they were in the process of mastering the coordination of vocal fold vibration relative to oral release. After eight weeks, VOTs in these children changed and became exaggerated and longer with a narrower range of values on the VOT continuum. While our study cannot dissociate if this is a function of maturation or the intervention, our results suggest that some consistent change occurred such that children in this stage were able to be better at inter-gestural coordination for producing correct /p/.

Changes in motor speech control

The data from the two sub-tests of the VMPAC indicate a significant improvement of oral motor control for children with SSD after intervention. However, our data did not show consistent improvements on articulation accuracy. Based on the GFTA-2 scores, positive changes of articulation accuracy were only evident for some children in this study. With the improvement of oral motor control, children appeared to be better at producing speech sounds correctly after PROMPT intervention. Two children (S3 and S6) did not perform

better on the GFTA-2 test, though they still showed a greater improvement on motor speech skills after therapy. Likewise, compared to the VMPAC sub-tests, S4 and S5 appeared to make smaller gains as measured by the GFTA-2 test (Figure 3). One possible explanation of why the GFTA-2 articulation test did not reflect the positive improvement of motor speech control for these children may be due to unrelated speech behaviors measured, in the GFTA-2, which were not targeted in treatment. It is important to note that not all consonants were targeted in the treatment and some consonants may not even be age appropriate for children in this study (for instance, consonants /l, r, s, ʃ, tʃ, j, v, z/ may not be fully mastered until age 7 or 8 (McLeod, van Doorn, & Reed, 2001; Shriberg, 1993; Shriberg, Kwiatkowski, & Gruber, 1994)). Alternatively, it could be attributed to the different language modality required during the GFTA-2 test compared to the VMPAC tests. The GFTA-2 test requires the child to retrieve a word related to the presentation of pictures and then to produce the target word correctly. That is, the GFTA-2 test involves integration across multiple modalities and the double load of language and speech demands that might have influenced the child's speech output, resulting in a lower performance. In contrast, speech output was elicited by speech modeling during the VMPAC-Sequencing test, which uses sound sequences rather than words. This requires less word retrieval processing and may allow the child to pay more attention to speech production and the self-monitoring of their own speech.

Sensorimotor information in motor speech control

Subsequent to intervention, all children with SSD showed significant improvements on motor control of the jaw, lips and tongue with markedly higher scores for VMPAC tests. In conjunction with the VOT data, the changes in VOT patterns may be a result of the increased control and coordination of oral motor system. In this study, prior to intervention, all children exhibited moderate to severe oral motor control difficulty with high instability with the production of /p/. The speech behaviors of voicing and stability in speech production were not directly addressed in the therapy goals, but control of jaw/lips movement was the targeted goal for all children with SSD. Thus, better oral motor control after intervention may account for the observed changes in VOT patterns. This finding supports our hypothesis that stabilization of jaw control would facilitate inter-gestural coordination. Specifically, the established jaw and lips control would provide a stable platform for consistent, reliable and accurate proprioceptive feedback that could then facilitate temporal coordination between larynx and articulators (i.e., /p/). The evidence of the importance of jaw proprioception in speech production has been reported in studies with normal speakers (Nasir & Ostry, 2006; Saltzman, Lofqvist, Kay, Kinsella-Shaw, & Rubin, 1998), adults who stutter (Loucks & De Nil, 2006; Namasivayam, van Lieshout, McIlroy, & De Nil, 2009) and children with cerebral palsy (Hong, Chen, Yang, Wu, Cheng, & Wong, 2011; Ortega, Guimaraes, Ciamponi, & Marie, 2008; Ward, Strauss, & Leitão, 2013). The findings from these studies suggest sensorimotor feedback provided from the jaw is critical for speech motor coordination; thus, the increased jaw or jaw-lip control provides more stable sensory feedback that improves speech accuracy and intelligibility.

This study used PROMPT as an intervention approach for children with SSD. The results suggest that the use of tactile-kinaesthetic proprioceptive input, applied systematically and

directly to specific orofacial regions during motor speech activity, may contribute to modifying the control and coordination in motor speech movements and inter-gestural coordination in voicing behavior. Our data supported the importance of sensorimotor information for speech that has been addressed in the literature in speech production (e.g., Loucks, & De Nil, 2006; Namasivayam et al., 2009; Saltzman et al., 1998; Ward et al., 2013).

Of note, the therapy goals in this study did not directly address VOT production; however, after intervention, children were able to produce /p/ with less VOT variation, probably this was due to improved control of their jaw movements. This transference of gestures has been seen with other body parts and in other speech intervention studies. There are studies of motor learning associated with physical rehabilitation which provide evidence that practicing a previously acquired gesture helps to coordinate it with an unpracticed gesture. In these studies (e.g., Hanlon, 1996; Shea & Morgan, 1979), patients with a right/left hemiparesis practised movements with the hemiparetic limb (e.g., pointing, touching specific spots) during the therapy. Results showed that they were able to perform untrained movements (e.g., opening a cupboard door, grasping a coffee cup by the handle, lifting the cup off its shelf, etc.), suggesting a transferring of their motor skills. Likewise, the transferring of gestures has been seen in studies using a multi-sensory treatment approach for children with motor speech disorders (Grigos, Hayden, & Eigen, 2010; Namasivayam, Pukonen, Hard, Jahnke, Kearney, Kroll, & van Lieshout, 2013) and in populations with aphasia (Bose et al., 2001). In these studies, the participants showed improvements on motor speech control and speech intelligibility following intervention. They observed that most of the participants demonstrated positive changes in producing both trained and untrained words or sentences after intervention, indicating a generalization of the target features to untrained words. While speculative, our finding is in line with these studies and may provide additional support for this evidence that practiced motor speech movements can transfer to untrained speech gestures and contexts.

Conclusions and Future Directions

The results of this study suggest that PROMPT intervention may have a positive effect in supporting changes to oral motor control and inter-gestural coordination with regard to the timing of voicing speech behavior, as evidenced by changes in the stability of VOT productions and VMPAC scores. The GFTA-2 test in this study, unexpectedly, was probably not sensitive enough to capture the treatment changes on motor speech control. This serves as a good reminder of the value of incorporating other standardized tests for measuring overall speech intelligibility levels in future studies.

This study represents an initial attempt to use acoustic analysis with measures of voice onset time to capture the changes in inter-gestural speech motor coordination by measuring the distribution patterns for voiceless aspirated stop /p/. These data provide acoustic information on VOT changes in children with SSD that will enhance our understanding of the speech characteristics in relation to oral motor control for speech sound disorders and their treatments.

While the goals of this study are consistent with the tenets of evidence-based practice and provide valuable clinical data in developmental SSD, this study employed a one-group pretest-posttest design. In future, the inclusion of different experimental designs would help to increase the validity of the findings. For example, a pre-post design for the control group would increase internal validity by controlling for the effects of typical maturation. Another design would be a randomized control trial, where a larger sample of children with SSD are randomly assigned to an experimental or control condition, and the changes are compared. Alternatively, a single subject design, wherein each participant acts as his/her own control and changes are recorded over time, would allow in-depth insight into therapy efficacy. Finally, another consideration for future studies is with regard to our use of parent self-report of homework compliance. A more objective method for tracking parental compliance with homework would increase confidence in the findings as level of compliance may affect the effect size of the intervention. For these reasons, the results of this study should be interpreted with caution and further replication is required.

Future studies also are needed to investigate the distribution patterns of voice onset time for both voiceless versus voiced stop consonants with a different place of articulation (e.g., /p/-b/, /k/-g/, /t/-d/) to have a better understanding of the inter-gestural coordination of speech articulators for children with SSD. This study employed a pre- and post-treatment design to evaluate the efficacy of PROMPT intervention. In addition, to fully understand the efficacy of PROMPT, further research is needed to compare the effectiveness of PROMPT to other intervention approaches in a larger group of children with SSD.

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Figure 1. Distribution patterns for VOT (ms) while producing /p/ for the control group, and children with SSD, PRE- and POST-therapy.

Figure 2.
Distribution patterns of VOT for /p/ production for each individual child in the SSD group, PRE- and POST-therapy.

Figure 3.
Percent improvement for GFTA (GF), VMPAC-Focal (VM-F) and VMPAC-Sequencing (VM-S) tests for each individual with SSD.

Scores for PPVT-3 and EVT for SSD and Control groups. Age (years; months) at first test is indicated in parenthesis. (No significant differences were found between groups.)

Table 1

SSD (age) (sex)	PPVT-3	EVT	Control (age) (sex)	PPVT-3	EVT
S1 (4;2); M	95	110	C1 (4;4); F	120	125
S2 (6;0); M	101	107	C2 (4;2); M	116	105
S3 (6;0); M	110	114	C3 (5;2); M	112	99
S4 (4;7); F	91	98	C4 (4;8); M	88	104
S5 (4;4); M	111	101	C5 (5;5); F	99	98
S6 (4;0); M	122	125	C6 (5;0); F	104	110
Mean	105.00	109.17	Mean	106.50	106.83)
(SD)	(11.51)	(9.70)	(SD)	(11.90)	(9.71

Table 2

Treatment goals for each SSD individual

SSD	Stage III: Jaw	Stage IV: Lips	Stage V: Tongue
S1	Increase jaw stability and midline movement in words	Increase labio-facial control for lip rounding. Reduce excess lip retraction	Develop tongue control for back /k, g/, mid /ʃ/ and anterior /s/ sounds
S2	Reduce excessive jaw opening and facilitate jaw grading on low vowels	Increase labio-facial control for lip movement. Facilitate lip rounding on /o, u/	Facilitate independent tongue elevation for /k, g, l/
S3	Increase jaw stability and midline movement in words	Increase labio-facial control and individual lip movement for /f, v/	Facilitate anterior lingual elevation for post-vocalic /s, ʃ/ and /tʃ/
S4	Increase jaw and midline control. Facilitate jaw grading on mid vowels.	Increase individual lip movement for /f/	Increase lingual control for /k, g, s/
S5	Increase jaw control, decrease over excursion. Maintain midline stability on mid vowels	Increase individual lip movement for /f/. Increase lip rounding for /o, u/	Facilitate independent lingual movement /t, d, n, s/
S6	Increase vertical jaw control, and reduce over excursion in words	Develop individual movement for /f/	Develop tongue control for back /k, g/, mid /ʃ/ and anterior /s/ sounds.

Table 3

Mean, SD, CoV, skew and kurtosis of VOT distributions for Control and SSD groups

	Mean VOT (SD)	CoV	Skewness (SE)	Kurtosis (SE)
Control	76.3 ms. (17.7)	23%	1.20 (0.49) *	0.07 (0.95)
SSD-Pre	78.7 ms. (48.9)	62%	0.11 (0.50)	-1.38 (0.97)
SSD-Post	105.5 ms. (34.6)	25%	1.06 (0.49) *	0.56 (0.96)

* significant skew ($p < .05$).

Table 4
Mean, SD, Co V, minimum (Min) and maximum (Max) of VOT for /p/ for SSD individuals pre- and post-intervention.

	Mean VOT (ms.)		Co V		Min/Max	
	PRE	POST	PRE	POST	PRE	POST
S1	72 (52.1)	109 (20.0)	72%	18%	8 / 206	79 / 169
S2	59 (30.5)	90 (24.1)	52%	27%	18 / 134	50 / 157
S3	104 (39.2)	116 (37.5)	38%	32%	31 / 219	63 / 204
S4	104 (58.2)	150 (21.2)	51%	14%	8 / 208	114 / 185
S5	52 (35.0)	78 (22.7)	67%	29%	5 / 128	43 / 123
S6	33 (16.9)	86 (22.8)	51%	27%	17 / 64	45 / 160

Table 5

Standardized Scores for VMPAC – Focal and VMPAC – Sequencing sub-tests. Standardized scores and percentiles (%ile) for the GFTA-2 acquired at PRE-therapy (PRE) and POST-therapy (POST) testing for the SSD group.

SSD	VMPAC - Focal		VMPAC - Sequencing		GFTA-2	
	PRE	POST	PRE	POST	PRE (%ile)	POST (%ile)
S1	77	81	72	80	72 (7)	87 (2)
S2	67	78	81	87	40 (< 1)	54 (3)
S3	73	84	61	70	45 (< 1)	42 (< 1)
S4	55	69	49	70	58 (2)	70 (6)
S5	63	71	54	61	69 (5)	70 (6)
S6	69	83	63	83	82 (12)	79 (11)
Mean	67	78	63	75	61	67
SD	7.7	6.3	11.7	9.8	16.3	16.5