Journal of Communication Disorders 46 (2013) 264–280

Contents lists available at SciVerse ScienceDirect

Journal of Communication Disorders

# Relationship between speech motor control and speech intelligibility in children with speech sound disorders

Aravind Kumar Namasivayam [a,b,c,*], Margit Pukonen [a], Debra Goshulak [a], Vickie Y. Yu [d,e], Darren S. Kadis [d,e], Robert Kroll [a], Elizabeth W. Pang [d,e], Luc F. De Nil [c]

[a] The Speech & Stuttering Institute, 2-150 Duncan Mill Road, Toronto, Ontario M3B 3M4, Canada
[b] The Toronto Rehabilitation Institute, 550 University Avenue, Toronto, Ontario M5G 2A2, Canada
[c] Department of Speech-Language Pathology, University of Toronto, 160-500 University Avenue, Toronto, Ontario M5G 1V7, Canada
[d] Neurosciences and Mental Health, Sick Kids Research Institute, 555 University Avenue, Toronto, Ontario M5G 1X8, Canada
[e] Division of Neurology, Hospital for Sick Children, 555 University Avenue, Toronto, Ontario M5G 1X8, Canada

A R T I C L E I N F O

*Article history:*
Received 31 July 2012
Received in revised form 6 February 2013
Accepted 12 February 2013
Available online 6 April 2013

*Keywords:*
Speech intelligibility
PROMPT treatment
Developmental motor speech disorders
Children
Speech sound disorder

A B S T R A C T

The current study was undertaken to investigate the impact of speech motor issues on the speech intelligibility of children with moderate to severe speech sound disorders (SSD) within the context of the PROMPT intervention approach. The word-level Children's Speech Intelligibility Measure (CSIM), the sentence-level Beginner's Intelligibility Test (BIT) and tests of speech motor control and articulation proficiency were administered to 12 children (3:11 to 6:7 years) before and after PROMPT therapy. PROMPT treatment was provided for 45 min twice a week for 8 weeks. Twenty-four naïve adult listeners aged 22–46 years judged the intelligibility of the words and sentences. For CSIM, each time a recorded word was played to the listeners they were asked to look at a list of 12 words (multiple-choice format) and circle the word while for BIT sentences, the listeners were asked to write down everything they heard. Words correctly circled (CSIM) or transcribed (BIT) were averaged across three naïve judges to calculate percentage speech intelligibility. Speech intelligibility at both the word and sentence level was significantly correlated with speech motor control, but not articulatory proficiency. Further, the severity of speech motor planning and sequencing issues may potentially be a limiting factor in connected speech intelligibility and highlights the need to target these issues early and directly in treatment.

**Learning outcomes:** The reader will be able to: (1) outline the advantages and disadvantages of using word- and sentence-level speech intelligibility tests; (2) describe the impact of speech motor control and articulatory proficiency on speech intelligibility; and (3) describe how speech motor control and speech intelligibility data may provide critical information to aid treatment planning.



## 1. Introduction

The term "speech sound disorder" (SSD) encompasses a range of children's speech production disorders including those arising from linguistically based difficulties (i.e., a phonological disorder), and/or production related articulation disorders

* Corresponding author at: Department of Speech-Language Pathology, University of Toronto, 160-500 University Avenue, Toronto, Ontario M5G 1V7, Canada. Tel.: +1 416 946 8552; fax: +1 416 978 1596.
*E-mail address:* a.namasivayam@utoronto.ca (A.K. Namasivayam).

0021-9924/$ – see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.jcomdis.2013.02.003

(i.e., phonetic disorders). In general children with SSDs are at risk for short- and long-term difficulties in reading, writing academic, social and emotional domains, which may ultimately impact their employment and occupational opportunities in adulthood (Felsenfeld, Broen, & McGue, 1994; Raitano, Pennington, Tunick, Boada, & Shriberg, 2004). Thus, to limit the impact of SSD it is important to identify the nature of a child's speech disorder and select an appropriate approach and clinically effective treatment strategies (Strand & McCauley, 2008). Children with SSDs are a heterogeneous group at many levels (severity, error types, causal and maintenance factors) and differential diagnosis is often difficult in these children as they may show ''mixed'' (e.g., speech-motor and linguistic) profiles (Strand & McCauley, 2008). The current study will focus on children with ''a mixed profile'' of SSD who demonstrate moderate to severe speech articulation delays, phonological process errors and varying degrees of difficulty with speech motor control.

There are over 20 treatment approaches for SSDs in use today (e.g., see Williams, McLeod, & McCauley, 2010). However, there are no peer-reviewed published studies measuring treatment effects, efficacy and effectiveness for children with severe SSD characterized by motor speech difficulties. Recent Cochrane reviews on the treatment of motor speech disorders in children have indicated a strong need to generate evidence for the effectiveness of these approaches in terms of speech intelligibility and functional outcomes to advance clinical practice in this area (Morgan & Vogel, 2009; Pennington, Miller, & Robson, 2009). The goal of speech intervention for children with SSD is to enhance their ability to communicate and interact with their environment. A fair portion of the effectiveness of this communicative process depends on speech intelligibility, i.e., how much of speech is understood by the listener (Kumin, 2006). Usually, by 4 years of age, the speech of typically developing children is 100% intelligible (Coplan & Gleason, 1988). For a child who is 4–5 years old, speech therapy is indicated when less than 66% (approximately 2 S.D. below the mean) of words are understood by an unfamiliar listener (Gordon-Brannan & Hodson, 2000). Children whose intelligibility scores are below this value may face difficulty being understood by peers and teachers in the classroom. Thus, intelligibility is a critical factor for social and academic success for preschool-aged children (Gordon-Brannan & Hodson, 2000).

The relationship between speech motor control, speech articulation and speech intelligibility is complex and has been elaborated and discussed in several publications (e.g., Weismer, 2008). It is a reasonable assumption that changes in speech motor control would improve speech articulation, which in turn should improve speech acoustics and thereby influence speech intelligibility. Conversely, decreased ability to control speech movements should systematically alter the level of speech understood by the listener. Several studies on adult speakers have shown systematic relationships between these levels (Weismer, 2008; Weismer, Yunusova, & Bunton, 2012). More recently, Weismer et al. (2012) demonstrated in adults with neurological disorders that tongue control rather than lip-jaw control is more strongly related to speech intelligibility. Studies have also shown that scores from speech articulation tests, e.g., Goldman-Fristoe Test of Articulation-2 (GFTA-2; Goldman & Fristoe, 2000), are moderately correlated with speech intelligibility in pre-school and school age children (Morris, Wilcox, & Schooling, 1995; Stimley & Hambrecht, 1999). Importantly, the correlation between these levels is dependent upon a number of factors such as the type of tasks (word-level vs. connected speech), contextual information and listener familiarity (Ertmer, 2010; Weismer, 2008). For children with moderate-severe SSDs, speech motor control and speech articulation may impact speech intelligibility significantly. Although clinically there is no doubt that speech intelligibility is affected in children with severe SSDs, there is no published data on the impact of the motor impairment on speech intelligibility for this population.

A few examples relating to speech intelligibility and developmental speech motor disorders can be found in the literature. Although, the following studies were not carried out on children with moderate to severe SSDs presenting with speech motor difficulties, they highlight the potential impact that speech motor issues can have on children's speech intelligibility. For example, in a recent study, Ward, Leitao, and Strauss (2009) used the Prompts for Restructuring Oral Muscular Phonetic Targets (PROMPT; Hayden, Eigen, Walker, & Olsen, 2010) approach to improve speech production of children with cerebral palsy. Ward et al. (2009) demonstrated significant positive pre–post treatment changes (approximately 35–50%) in closed-set word-level speech intelligibility test scores in these children. Participants also showed generalization of treatment effects by improving on untrained word sets. Similarly, a systems approach that systematically targetted each speech subsystem and focused on breath support for speech, phonation, nasal resonance, articulation, prosody, and slowing down speech rate, improved word-level speech intelligibility by approximately 15% for a group of children with dysarthria and cerebral palsy (Pennington, Miller, Robson, & Steen, 2010).

## 2. PROMPT intervention: a brief summary

The present study will focus on the PROMPT approach which is established in clinical practice, but has a relatively sparse research literature (Bose, Square, Schlosser, & van Lieshout, 2001; Freed, Marshal, & Frazier, 1997; Rogers et al., 2006; Ward et al., 2009). The PROMPT approach is a tactile-kinesthetic-based intervention for motor speech disorders, wherein place, manner, and timing of speech movements are facilitated by the precise use of tactile-kinesthetic prompts on the child's face (for a summary see Hayden et al., 2010). PROMPT focuses on teaching precision and movement transitions through explicit use of tactile spatial-temporal cues which are gradually withdrawn as the child acquires correct movement patterns. In addition to the additional somatosensory information, the clinician also provides visual cues and auditory models to facilitate accurate speech production which is also linked to cognitive and socially relevant communicative content (Hayden et al., 2010).

There are reports of successfully using PROMPT treatment in adults with neuromotor disorders such as acquired apraxia and Broca's aphasia (Bose et al., 2001; Freed et al., 1997). Adults with motor speech disorders are a very different population and generalizations between them and children with severe SSDs presenting with motor speech issues should be drawn with extreme caution. As eloquently pointed out by Caruso and Strand (1999) "children aren't little adults" (Preface – pp. ix) their cognitive, linguistic, information-processing capacities, sensory-motor networks and motor control abilities are more different than similar to adults (Maas et al., 2008; Sullivan, Kantak, & Burtner, 2008). Given the paucity of published peer-reviewed literature, the current study was undertaken to investigate the impact of speech motor issues on the speech intelligibility of children with moderate to severe SSDs within the context of the PROMPT intervention approach.

### 2.1. Specific research questions

(1) What is the impact of speech motor control and speech articulation impairments on speech intelligibility in children with moderate to severe SSDs?
(2) What is the magnitude of pre–post change in children with moderate to severe SSDs?
(3) What are the possible factors that affect progress in children with moderate to severe SSDs?

## 3. Method

### 3.1. Participants

Twelve children, 9 males and 3 females, between the ages of 3;11 to 6;7 (years;months; mean = 4.5; S.D. = 1.1) with moderate to profound speech sound disorders participated in this study. All children were selected from the waiting list for speech therapy at The Speech and Stuttering Institute, in Toronto, Canada. At the time of recruitment and during the study none of participants were undergoing any additional therapy outside of the study (as reported by caregiver). All speech assessments and treatment were conducted at The Speech and Stuttering Institute (Toronto, ON); cognitive assessments were carried out at the Hospital for Sick Children (Toronto, ON). All assessments were carried out by a licensed Speech-Language Pathologist (not involved in treatment planning or delivery) or neuropsychologist (for cognitive testing) naïve to the purpose of the study.

#### 3.1.1. Inclusion criteria

Study inclusion criteria required the children to have English as the primary language spoken by the primary caregiver at home, adequate social and play skills for direct speech intervention (e.g., presence of intentional communication, imaginative play, turn taking, etc.) and have vision, hearing (assessed bilaterally) and oro-facial structural mechanisms within normal limits. Further, all participants underwent a brief pre-treatment assessment with the Peabody Picture Vocabulary Test (PPVT-4; Dunn & Dunn, 2007), Expressive Vocabulary Test (EVT-2; Williams, 2007), and the Wechsler Nonverbal Scale of Ability (WNV; Wechsler & Naglieri, 2006). The PPVT (for receptive vocabulary) and EVT (for expressive vocabulary) were used as surrogates for a VIQ score (general verbal-based intelligence). These measures were within or near the normal range (e.g., a standard score of 85 or higher on PPVT-4; *Note*: in the current study the average standard score was 102 and 108 for PPVT and EVT, respectively – see Table 1) implying that language was intact in the group. The WNV test

**Table 1**
Participant demographics.

| Participant ID | Gender | Age (years;months) | PPVT-4 SS | EVT SS | WNV FSIQ | HCAPP (TOMPD;SEVERITY) | GFTA-2 percentile | VMPAC-FOC (*z*-score/severity) | VMPAC-SEQ (*z*-score/ severity) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | M | 4;2 | 95 | 110 | −1.87 | 102;Low Severe | 4 | −3.7/Severe | −0.9/WNL |
| 2 | M | 4;4 | 113 | 118 | 2.20 | 65;Moderate | 25 | −1.6/Moderate | 0/WNL |
| 3 | M | 6;7 | 101 | 107 | 0.33 | 104;Low Severe | <1 | −7.5/Severe | −0.7/WNL |
| 4 | M | 6;2 | 79 | 85 | −1.47 | 64;Moderate | <1 | −6/Severe | −2.5/Severe |
| 5 | M | 4;0 | 111 | 101 | 0.87 | 106;Low Severe | 5 | −3/Severe | −1.2/Mild |
| 6 | M | 3;11 | 110 | 114 | −0.20 | 130;Severe | 4 | −1.7/Moderate | −1.3/Mild |
| 7 | F | 4;7 | 91 | 98 | 0.93 | 117;Severe | 2 | −3.8/Severe | −1.5/Moderate |
| 8 | M | 3;11 | 122 | 125 | 1.27 | 90;High moderate | 12 | −0.6/WNL | 0.2/WNL |
| 9 | F | 4;9 | 84 | [a] | −0.47 | 214;High Profound | <1 | −5.6/Severe | −2.1/Severe |
| 10 | M | 4;6 | 127 | 123 | −0.87 | 55;Low Moderate | 7 | −1.4/Mild | −0.1/WNL |
| 11 | M | 3;11 | 97 | 110 | −1.67 | 112;Severe | 7 | −0.1/WNL | 0.7/WNL |
| 12 | F | 4;4 | 100 | 98 | 0.13 | 94;High moderate | 4 | −0.8/WNL | 0/WNL |
| | Mean | 4.45 | 102.50 | 108.00 | −0.07 | | | | |
| | S.D. | 1.13 | 14.59 | 11.99 | 1.26 | | | | |

*Note*: PPVT: Peabody Picture Vocabulary Test-Fourth Edition/SS: Standard Score; Expressive Vocabulary Test-Second Edition/SS: Standard Score; WNV FSIQ: Wechsler Nonverbal Scale of Ability-Full Scale IQ estimate-*z* score; HCAPP: Hodson Computerized Analysis of Phonological Patterns (TOMPD: Total occurrences of major phonological deviations); GFTA-2: Goldman-Fristoe Test of Articulation-Second edition; VMPAC-FOC: focal oromotor control subtest of Verbal Motor Production Assessment for Children; VMPAC-SEQ: sequencing subtest of Verbal Motor Production Assessment for Children, *z* scores. VMPAC severity rating scale based on area percent scores/WNL: Within Normal Limits.

[a] Expressive language for participant S9 could not be assessed due to her severely reduced speech intelligibility.

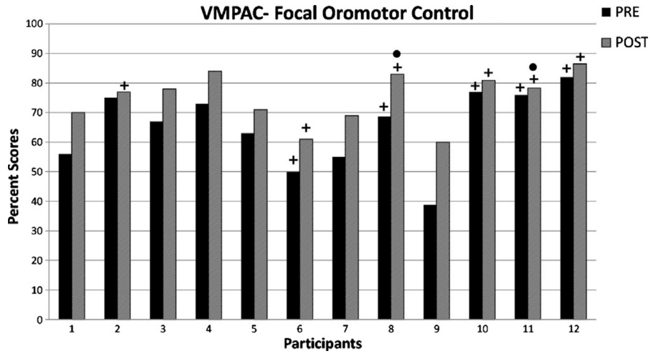


**Fig. 1.** Pre–post treatment percent scores for focal oromotor control subtest of Verbal Motor Production Assessment for Children (VMPAC-FOC). Participant scores relative to typically developing children depicted by symbols ("+" sign: at or above the 5th percentile; • sign: at or above the mean).

(scores were within the normal range) were used as a surrogate of PIQ (performance or non-verbal intelligence) and collectively, these standardized tests of receptive language, expressive language, and nonverbal functioning provided an estimate of gross cognitive functioning.

To be included in the current study, the children also needed to demonstrate speech delays (below the 16th percentile) as assessed by the Goldman-Fristoe Test of Articulation-2 (GFTA-2; Goldman & Fristoe, 2000), moderate to profound speech sound disorder as assessed by the Hodson Computerized Analysis of Phonological Patterns test (HCAPP; Hodson, 2003) and must have at least 4 red flags or markers for motor speech involvement. For example, variable productions (child may produce different sound combinations for the same word), consonant and vowel distortions, nonstandard productions (including dentalization, bilabial fricative, etc. – see Appendix A for additional criteria). Data from Table 1 indicates that all inclusionary requirements were met. *Note*: participant 2 was performing within normal limits on GFTA-2 (25th percentile) but demonstrated moderate impairments in focal oro-motor control and phonological process errors. Therefore, participant 2 was included in the study (for details see Section 3.1.3).

*3.1.2. Exclusion criteria*

Participants were excluded from the study if they had any signs and symptoms suggesting the presence of autism spectrum disorders (Diagnostic and Statistical Manual of Mental Disorders: IV – American Psychiatric Association, 1994) or dysarthria or childhood apraxia of speech (CAS). To identify dysarthria and CAS procedures similar to those reported in the literature were used (Shriberg, Potter, & Strand, 2011). Participants were classified as having dysarthria (and excluded) if they had evidence of any of the following: global motor involvement (suggestive of cerebral palsy); feeding impairments; significant drooling; respiratory incoordination or decreased respiratory support; reduced strength of articulatory contacts; strained or breathy phonatory quality; and equal sentential stress/scanning speech (possible signs of ataxic dysarthria). Similarly, the diagnosis of CAS was based on clinical judgment of whether or not 5 or more of the following features of CAS were present (Shriberg et al., 2011). These features included: (1) inconsistent vowel and consonant errors on repeated productions (or productions were variable, e.g., child may produce different sound combinations for the same word); (2) difficulty in achieving initial articulatory configurations (may be evidenced by initial hesitations, pausing, groping); (3) difficulty transitioning between successive movement gestures (i.e., lengthened and disrupted coarticulatory transitions); (4) distorted substitutions; (5) vowel distortions/abnormal vowel duration; (6) presence of intrusive schwa (e.g., balack – black; bata – bat); (7) difficulty maintaining sound and syllable integrity with increased length and complexity of utterance; (8) voicing errors; (9) and atypical intonation/prosodic abnormalities (may include equal stress or stress on wrong syllables). In the current study, no participant had sufficient characteristics to be diagnosed as CAS (Shriberg et al., 2011).

*3.1.3. Speech characteristics of participants*

In all children, clinical observation indicated varying degrees of jaw and oro-facial involvement. These issues were related to: decreased jaw stability/lateral jaw sliding, limited control of the degree of jaw height (jaw grading) for mid-vowels, jaw movement overshoot/overextension, decreased lip rounding and retraction and overly retracted lips. No apparent jaw control issues were noted in participant 4. The primary difficulty for this participant was at the labio-facial level. A formal assessment of the speech motor system was carried out using the Verbal Motor Production Assessment for Children (VMPAC; Hayden & Square, 1999 – for details see Section 4.4). VMPAC manual provides 5th percentile, mean and 95th percentile scores across different age groups. Figs. 1 and 2 indicate which of the participants in the current study were at or above the 5th percentile (+ sign) and/or the mean (bold circle) of typically developing children. No participants in the study were at or above the 95th percentile. Pre-treatment VMPAC severity ratings and *z* scores in Table 1 indicate that for participants 8, 11 and 12, focal oro-motor control (FOC; assesses volitional control of speech articulators) scores were close to or within normal limits (WNL) for their age. Participants 1-to-7 and 9 were in the moderate-severe range which implies that most participants had significant oro-motor control issues. VMPAC sequencing subtest (SEQ; assesses production of oro-motor/speech

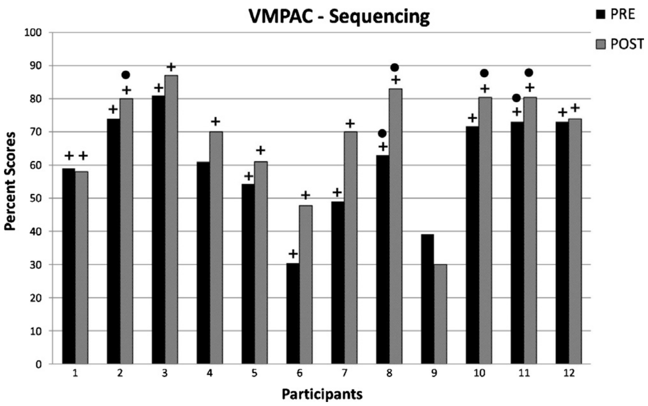


**Fig. 2.** Pre-treatment and post-treatment percent scores for sequencing subtest of Verbal Motor Production Assessment for Children (VMPAC-SEQ). Participant scores relative to typically developing children depicted by symbols ("+" sign: at or above the 5th percentile; • sign: at or above the mean).

movements in correct sequential order) scores indicated that participants 4, 7 and 9 were in the moderate to severe range, while participants 5 and 6 were mild and the rest were within normal limits for their age.

For speech articulation, GFTA-2 values below the 16th percentile were used to identify the presence of impairment in articulation skills. Table 2 depicts the percentage of children producing articulation errors across different word positions (initial, medial, and final) on the sounds-in-words subtest of GFTA-2. A value of 100% indicates that all 12 children did not produce the target sound/cluster correctly (i.e., target production was distorted, substituted or omitted), while 50% indicates that difficulty was present in 6 of the 12 children. Articulation data (from Tables 1 and 2) when taken together indicate that most children in the current study were at or below 7th percentile (except for participant 2 and 8 who were at the 25th and 12th percentile, respectively) and had difficulties in producing even the earliest developing consonants in different contexts (e.g., p, b, and d).

The data on phonological process errors were collected using the HCAPP's "Substitutions and Other Strategies Analysis" form. These data identified the types of substitutions and strategies used when participants did not produce target patterns or sounds. The average number of process errors across participants indicated that the three most prevalent strategies were "stopping" (e.g., /t/ replaces /s/; 14.55 errors) followed by "fronting" (e.g., /t/ replaces /k/; 9.64 errors) and "gliding" (e.g., /w/ replaces /r/; 5.91 errors). In summary, children who were included in the current study demonstrated articulation delays, phonological process errors and varying degrees of difficulty with speech motor control. None of the participants meet criteria for either pure dysarthria or CAS. The study was approved by the Hospital for Sick Children's Research Ethics Board.

**Table 2**
Percentage of children producing errors across word initial, medial and final position (GFTA-2; Sounds-In-Words subtest); e.g., 100% indicates all 12 children did not produce the sound correctly. Blank cells: GFTA-2 does not test these sounds in these positions.

| Consonants and clusters | Initial | Medial | Final | Consonants and clusters | Initial | Medial | Final |
|---|---|---|---|---|---|---|---|
| p | 16.7 | 25.0 | 8.3 | s | 75.0 | 91.7 | 58.3 |
| m | 0.0 | 8.3 | 8.3 | z | 83.3 | 75.0 | 66.7 |
| n | 0.0 | 8.3 | 8.3 | ð | 100.0 | 100.0 | |
| w | 8.3 | 0.0 | 0.0 | bl | 66.7 | | |
| h | 8.3 | 0.0 | 0.0 | br | 91.7 | | |
| b | 16.7 | 16.7 | 8.3 | dr | 91.7 | | |
| g | 58.3 | 58.3 | 66.7 | fl | 91.7 | | |
| k | 66.7 | 25.0 | 50.0 | fr | 100.0 | | |
| f | 50.0 | 41.7 | 58.3 | gl | 100.0 | | |
| d | 0.0 | 41.7 | 33.3 | gr | 100.0 | | |
| ŋ | | 41.7 | 58.3 | kl | 100.0 | | |
| j | 50.0 | | | kr | 100.0 | | |
| t | 25.0 | 25.0 | 58.3 | kw | 83.3 | | |
| ʃ | 83.3 | 91.7 | 83.3 | pl | 75.0 | | |
| /ʧ/ | 50.0 | 50.0 | 50.0 | sl | 91.7 | | |
| l | 75.0 | 75.0 | 66.7 | sp | 91.7 | | |
| r | 83.3 | 75.0 | 75.0 | st | 100.0 | | |
| ʤ | 58.3 | 58.3 | 66.7 | sw | 100.0 | | |
| θ | 100.0 | 100.0 | 100.0 | tr | 91.7 | | |
| v | 66.7 | 58.3 | 75.0 | | | | |

### 3.2. Listeners

To measure children's speech intelligibility, 24 unfamiliar listeners (10 males: 14 females; mean = 26.12 years; S.D. = 5.15) were recruited from the University of Toronto. All listeners passed a pure tone hearing screening at 1, 2, and 4 kHz at 25 dB HL (American Speech-Language-Hearing Association, 1997) and reported little or no exposure to the speech of children with speech disorders. All listeners were native speakers of English who were blind to the identity and treatment protocol of the children.

### 3.3. Study design

This study is a prospective single group pre-test post-test design and could be designated to level III of the ASHA Evidence-Based Practice hierarchy (Dollaghan, 2007). Assessments of the children were carried out before and after PROMPT intervention. However, due to the lack of a control group the study is not a direct evaluation of PROMPT efficacy.

## 4. PROMPT intervention

The PROMPT therapy (see description in Section 1) in this study was provided in individual therapy sessions that were 45 min, in length and scheduled twice a week for 8 weeks for a total of 16 sessions. All participants (except participant 7) attended all 16 treatment sessions. Participant 7 missed 2 treatment sessions due to illness. Treatment duration of approximately 45 min for 1–2×/week over a treatment block of 8–10 weeks represents typical clinical service delivery model in the pre-school speech and language program in Ontario, Canada. These service delivery parameters are also in line with those reported in the literature (e.g., Baker & McLeod, 2011). High treatment frequency (3–5×/week) was not warranted in these participants since none of them had sufficient features to be categorized as CAS (Shriberg et al., 2011). PROMPT therapy was provided by a co-authour (DG) who is a certified PROMPT instructor. *Note*: clinician providing treatment (planning and delivery) did not carry out any of the assessments.

### 4.1. Treatment goals

A distinctive feature of the PROMPT approach is that it uses a motor-speech hierarchy (MSH; Hayden, 2008) to guide clinicians in selecting movement goals for treatment and treatment progression. The MSH assumes hierarchal and interactive development of control of seven 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). In the current study, treatment generally proceeded systematically in a bottom-up fashion starting with the lowest subsystem in the hierarchy where a child has control issues. For example, the clinician ensures that the child has the physiological support for speech in the form of trunk, respiratory, and phonatory control before targeting and organizing the supralaryngeal articulatory systems (stage III and up). Typically jaw control is addressed before facial control which is addressed before lingual control.

Appendix B describes treatment goals for 10 participants in the study (treatment plan records could not be obtained for 2 participants) according to stages in the MSH. Generally, treatment goals were directed at stages III, IV, V and VI of the MSH. Stage III goals were related to increasing jaw control: decreasing over excursion, improving mid line control and facilitating jaw grading for mid vowels. Stage IV goals were generally aimed at: increasing individual lip movement (i.e., independent of jaw) for /f/, increasing lip rounding for /o, u/, decreasing excess lip retraction for /i/ (e.g., for participants 1, 2 and 9). Finally, horizontal lip movements are integrated with vertical jaw movements (e.g., /au/, /wa/). Stage V – lingual goals related to: increasing independent tongue (tip, mid and back) elevation for /t, d, n, l, s, ʃ, k, g/ sounds. Stage VI goals were directed at: increasing sequenced movement for consonant clusters (e.g., /sp, st, sk, sm, sn, gl, kl/) and multisyllabic words. Since PROMPT focuses on improving speech intelligibility and overall communication skills, only real speech is used (i.e., no non-speech exercises or nonsense syllables are used in treatment). The emphasis is on the normalization of speech movement patterns in an age-appropriate and functional communication context. The target stimuli contained simple and early occurring sounds (e.g., /p/, /m/, /t/, and /f/) and syllable shapes (e.g., monosyllabic VC and CVCs words such as "on", "off", "pop" and "pat") to keep the level of task complexity low (e.g., Maas et al., 2008). Children have limited information processing capabilities and any additional cognitive load (e.g., complex lexicon) while learning a complex motor skill (such as speech) may be detrimental to learning itself (Maas et al., 2008).

### 4.2. Treatment structure

Each therapy session followed the same routine. The session began with a review of home practice activities to determine whether it was appropriate to progress to the next goal level or continue with the same goal. This was followed by new skill development wherein focused and massed practice (minimum 30 responses per activity) was provided to support acquisition of new skills in a simple structured activity. Next was distributed practice of targets in 3 or 4 motivating activities in a naturalistic and communicative setting. Target words occurred within the context of an activity (e.g., reading a book, playing a game, doing crafts) and the clinician structured the activity to provide maximum response opportunities to produce target words. The last part of the treatment routine was to provide parents with an opportunity to practice targets and techniques in at least one of the distributed practice activities and review home practice targets and goals. Parents carried out homework given by the clinician during treatment relating to motor speech goals; no other speech-language stimulation approaches were used in this study.

*4.3. Treatment procedure*

Several key elements of motor learning including prepractice considerations, blocked and random practice, knowledge of results (KR; e.g., "that was very good") and knowledge of performance (KP; e.g., "use your small mouth") were strictly followed every therapy session (Maas et al., 2008; Sullivan et al., 2008). Early in treatment, PROMPTs were used extensively to provide children with multisensory input. In addition almost constant feedback relating to KR and KP was provided immediately after each production. Such immediate and high feedback frequency is presumed to enhance motor learning in children by reducing information processing load and cognitive demands (Maas et al., 2008; Sullivan et al., 2008). However, as sessions progressed PROMPTs and feedback frequency were decreased which encouraged the child to self-monitor, and control his own speech output. It is important to note that, initially target movements were practiced in separate and successive blocks to avoid task interference (blocked practice). The clinician initiated the intermixing of two or more targets (random practice) only after high accuracy (e.g., 80% with minimal cueing and PROMPTing) was achieved for earlier targets/goals (Maas et al., 2008). Over all, each child produced approximately 120–150 target responses per session or about 30 responses per activity.

There are several types of PROMPTs. However, for the current study only parameter, complex and surface prompts were used (Hayden, 2008). Additional prompts exist for cueing temporal and other prosodic features in larger phrase and sentence units but these were not used in the current study. Parameter prompts relate to only one plane of movement (either vertical or horizontal) and provide maximal support and stability for speech articulators facilitating either the degree of mandibular excursion or the broad action of rounding-retraction of the lip muscles. For example, when an aberrant movement pattern such as lateral jaw sliding occurred during word production, the child was given a correction using a parameter prompt, (i.e. providing stabilizing support to maintain midline jaw movement). This movement was practiced in the target word in a mass practiced fashion for approximately 5–10 responses to develop more normalized patterns. For this PROMPT, the thumb and index finger are placed on either side of the mandible to limit lateral mandibular sliding.

Complex prompts are used in isolation especially when a child first learns to produce a single phoneme or if a part of a word is incorrectly produced. Complex prompts involve cues on two or more planes of movement with the aim of providing maximum information related to production of a single phoneme. For example, for the production of /s/ the second (middle) finger is used to apply upward pressure behind the mandible (on the mylohyoid muscle) for tongue tip elevation, and thumb and index finger provide slight retraction at corners of the lips. An auditory model is given simultaneously with the facial PROMPT (i.e., lip retraction). Timing and intensity of muscle contraction is cued by the duration and amount of touch pressure applied, respectively.

Finally, a surface prompt provides a one-dimensional tactile cue that contains critical timing, spatial, or contraction information essential for transition and timing in larger linguistic units (words and phrases). For example, during the production of the word "mommy" a sequence of four surface prompts would be given in the following manner: placing back of first (index) and second (middle) fingers lightly and directly on lips while touching the nose with the thumb for /m/, downward pressure on the mandible using thumb for vowel /ɑ/, followed by prompts for /m/ and finally slight retraction of lips using thumb and index finger for /i/ with contact just above the upper lip near the nasolabial folds. The overall assumption is that these multi-sensory PROMPTs facilitate accurate speech production (Hayden et al., 2010). These PROMPTs were applied when teaching new movement patterns and when a child was judged to have produced an error in speech movement.

*4.4. Measures*

The following measures[1] were selected to capture changes in speech motor control, accuracy of speech articulation and speech intelligibility.

*4.4.1. Assessment of speech motor control*

Assessment of the speech motor system was carried out using the Verbal Motor Production Assessment for Children (VMPAC; Hayden & Square, 1999). The VMPAC is standardized on typically developing children ages 3 through 12 years of age and includes reference data for children who have speech sound disorders. The VMPAC uses a 3-point scale (0: incorrect;

[1] A general note of caution: the use of norm-referenced standardized tests to measure change following treatment has serious limitations such as, lack of sensitivity (norm-referenced tests examine gross and stable behaviours and may not be sensitive enough to document behavioural change), regression to mean (i.e., participants with low scores at pre-test improve more than those with high scores) and errors arising from imperfect test-retest reliability (McCauley & Swisher, 1984). These may result in under or over estimation of change. However, tests such as VMPAC/GFTA-2 were selected because these represent typical clinical measures of performance for services delivered in the pre-school speech and language program in Ontario.

1: partly incorrect; 2: correct) to score the accuracy and quality of motor movements and allows for the identification of the level(s) of motor speech disruption. The VMPAC test includes: (a) Global motor control (neurophysiological support for speech: head and neck control, postural control, adequate breath support, etc.), (b) Focal oro-motor control (VMPAC-FOC), (c) sequencing (VMPAC-SEQ), and two supplemental areas (d) connected speech and language control and (e) speech characteristics. Each subsection on VMPAC can be interpreted independently and for purpose of the current study only the VMPAC-FOC and VMPAC-SEQ subsections were analyzed, since they directly relate to volitional oro-motor control. VMPAC-FOC evaluates the volitional oro-motor control for jaw, face-lips, and tongue in both speech and non-speech movements. VMPAC-SEQ evaluates the ability to produce speech and non-speech movements in the correct sequential order. Raw scores from each of these subsections were converted to a percent scale (from 0 to 100) by dividing the raw score by the sum of the corresponding subsection scores. This score was then used to obtain a severity rating and a profile of the child's speech motor performance. The VMPAC provides percentage correct values relating to accuracy and stability of non-speech and speech production and is sensitive to capture change following motor speech treatment (Hayden & Square, 1999).

#### *4.4.2. Articulation analysis*

The study used the Goldman-Fristoe Test of Articulation-2 (GFTA-2; Goldman & Fristoe, 2000). GFTA-2 is a systematic assessment of a child's articulation of English consonants for individuals between 2 and 21 years of age. The GFTA-2 assesses production of sounds of American English in word initial, medial and final positions along with consonant blends in word initial position. For the present study, the sounds-in-words subtest was used as the dependent variable.

#### *4.4.3. Assessment of speech intelligibility*

For the present study, speech intelligibility measures for closed-set word and open-set connected speech sentence imitation tasks were carried out. For the closed-set word identification task, the percentage of imitated single words correctly understood by the listener was evaluated using the Children's Speech Intelligibility Measure (CSIM; Wilcox & Morris, 1999). The test consists of 600 words that have been categorized into 50 sets of 12 phonetically similar words. One randomly chosen word from each of the 50 sets is modeled by the clinician and the child's productions are audio-taped. The child is requested to repeat the words in a direct imitation task. The child's audio-taped productions are played to listeners whose task it is to select (by circling) the word they think they heard from a list of 12 similar sounding words. For each child, the clinician used a different set of randomly chosen words for pre- and post-treatment. For the open-set connected speech sentence imitation task, the percentage of words correctly understood in imitated sentences was assessed using the Beginner's Intelligibility Test (BIT; Osberger, Robbins, Todd, & Riley, 1994). The BIT test involves administration of 1 of 4 available 10-sentence lists. Each sentence contains 2–6 words that are 1 or 2 syllables in length. The sentences are syntactically simple and composed of words that are familiar to children. Similar to the CSIM, the children repeat the sentences in a direct imitation task using the live-voice model of the clinician. All the child's productions are audio-taped, but unlike CSIM, BIT is a transcription based (write-down) procedure where the listeners write down what they hear.

### *4.5. Procedure*

#### *4.5.1. Stimulus materials*

All speech samples were recorded using the H4 Zoom digital recorder[2] at a rate of 44.1 kHz with a resolution of 16 bits per sample and saved as WAV files. From these, files playlists were generated for listeners by digitally removing the speech-language pathologist's speech and extraneous sounds (e.g., doorbell, laughing). Additionally, specific verbal instructions (e.g., "item 5", "item 10"; "List 1 sentence 1 ready", "List 1 sentence 1 again") were inserted in the playlists. Each of the stimulus items were played twice to the listeners. The RMS loudness of the stimuli was adjusted to approximately 70 dB SPL. All sound manipulation and editing were carried out using the PRAAT program Version 5.3.21 (Boersma & Weenink, 2012).

#### *4.5.2. Data collection and scoring*

Twelve children participated in this pre–post design study (pre-test/post-test = 2 data points) and speech intelligibility was measured at word and sentence levels (2 levels), for a total of 48 audio files ($12 \times 2 \times 2$). These 48 audio files were divided into 8 playlists of 6 randomly chosen files per playlist. Each playlist was played to a different group of 3 listeners (8 playlists $\times$ 3 listeners/playlist = 24 listeners in total). The playlists were played from a laptop computer (HP TouchSmart TM2 – Intel Core Duo, 64-bit Windows 7 OS) via headphones (Sony MDR-XD100) connected to a multichannel headphone amplifier (PreSonus HP60) so that each listener could adjust loudness to a comfortable listening level. Instructions for the two intelligibility tests were different. For CSIM, each time a word was played the listeners were asked to look at the appropriate list of 12 words and circle the word while for BIT sentences, the listeners' were asked to write down everything they heard. For both tasks, listeners were encouraged to guess when they were unsure of the word or sentence they heard. For CSIM scoring, the number of circled words that were correct out of the 50 words was used to calculate % words correct. The BIT score for each child was the percentage of target words correctly transcribed. The scores for both tests were averaged across 3 listeners.

[2] http://en.wikipedia.org/wiki/Zoom_H4_Handy_Recorder.

#### *4.5.3. Reliability*

A second experienced and certified speech-language pathologist carried out reliability analysis using audio/video recordings of assessment sessions. Inter-rater reliability analysis was conducted for 33% of data. The point-by-point agreement was derived by comparing the score obtained by each rater for every item on the GFTA and VMPAC. Identical broad transcriptions (diacritics were excluded) were scored as agreements. The average inter-rater reliability was 82.4% for GFTA and 84.7% for VMPAC. Intra-rater reliability was carried out on 20% of the data and yielded 94.3% for GFTA and 91.6% for VMPAC.

#### *4.5.4. Statistical analysis*

For each dependent variable a paired two-tailed *t*-test (i.e., pre–post for GFTA-2, VMPAC-FOC, VMPAC-SEQ, CSIM and BIT) was used to analyze pre–post changes using SPSS software version 20. Since multiple significance tests were conducted a Bonferroni correction was applied (.05/5 = 0.01) to maintain the alpha level at 0.05. Effect sizes were calculated using the Cohen's *d* statistic corrected for dependence between the means (Cohen, 1988) where 0.2, 0.5 and 0.8, are often referred to as small, medium, and large effects, respectively.

## 5. Results

Means and standard deviations for each of the dependent variables are provided in Table 3. There is significant correlation between speech motor control (results of VMPAC) and speech intelligibility. However, the standardized articulation test (GFTA-2) was not significantly correlated with either the speech motor control or the speech intelligibility testing (Table 4).

For speech motor control, mean percent score pre–post change for VMPAC-FOC and VMPAC-SEQ was 9.7 and 7.7, respectively. The results (in Table 5) indicate significant changes in VMPAC-FOC ($p = 0.0001$) and VMPAC-SEQ ($p = 0.011$) scores along with large effect sizes (VMPAC-FOC $d = -2.36$; VMPAC-SEQ $d = -0.89$). At the level of speech articulation the Bonferroni-corrected GFTA-2 score was not statistically significant despite a large effect size ($d > 0.8$). Individual changes in pre-test to post-test scores for speech motor control and articulation can be seen in Figs. 1–3. Although, the overall changes in speech articulation fail to reach statistical significance it is worthwhile to examine individual data. When examining such

**Table 3**
Pre-treatment and post-treatment scores across all participants.

| Participant ID | VMPAC FOC | | VMPAC SEQ | | GFTA-2 | | CSIM | | BIT | |
|---|---|---|---|---|---|---|---|---|---|---|
| | PRE | POST | PRE | POST | PRE | POST | PRE | POST | PRE | POST |
| 1 | 56 | 70 | 59 | 58 | 66 | 66 | 56.6 | 55.1 | 56.87 | 58.36 |
| 2 | 75 | 77 | 74 | 80 | 90 | 107 | 83.8 | 75.33 | 61.3 | 76.3 |
| 3 | 67 | 78 | 81 | 87 | 40 | 54 | 63.9 | 77.3 | 68.5 | 79.83 |
| 4 | 73 | 84 | 61 | 70 | 45 | 42 | 61.1 | 72.8 | 75.4 | 90.55 |
| 5 | 63 | 71 | 54.3 | 61 | 69 | 70 | 45.3 | 50 | 15.46 | 39.1 |
| 6 | 50 | 61 | 30.4 | 47.8 | 65 | 90 | 36 | 51.3 | 15.46 | 56.83 |
| 7 | 55 | 69 | 49 | 70 | 58 | 70 | 47.6 | 62.4 | 30.6 | 41.9 |
| 8 | 68.7 | 83 | 63 | 83 | 82 | 79 | 50 | 57.2 | 48.57 | 70.73 |
| 9 | 38.8 | 60 | 39.1 | 30 | 40 | 40 | 12.9 | 17.3 | 9.53 | 15.8 |
| 10 | 77 | 80.9 | 71.7 | 80.4 | 72 | 87 | 78 | 71.3 | 37.8 | 89.2 |
| 11 | 76 | 78.8 | 73 | 80.4 | 73 | 69 | 42 | 56.7 | 36.76 | 58.95 |
| 12 | 82 | 86.5 | 73 | 73.9 | 64 | 84 | 52 | 68.4 | 38.23 | 52.9 |
| Mean | 65.13 | 74.89 | 60.71 | 68.46 | 63.67 | 71.50 | 52.43 | 59.59 | 41.21 | 60.87 |
| S.D. | 12.91 | 8.71 | 15.32 | 16.73 | 15.73 | 19.69 | 18.79 | 16.35 | 21.53 | 22.02 |

*Note*: VMPAC-FOC: focal oromotor control subtest of Verbal Motor Production Assessment for Children, percent scores; VMPAC-SEQ: sequencing subtest of Verbal Motor Production Assessment for Children, percent scores; GFTA-2: Goldman-Fristoe Test of Articulation (2nd Edition), standard scores; CSIM: Children's Speech Intelligibility Measure, percentage scores; Beginner's Intelligibility Test, percentage scores.

**Table 4**
Pearson correlations between speech motor control (VMPAC-FOC and SEQ), speech articulation (GFTA-2) and speech intelligibility (CSIM and BIT) across all participants ($N = 12$).

| | VMPAC-FOC | VMPAC-SEQ | CSIM | BIT |
|---|---|---|---|---|
| GFTA-2 | 0.156 | 0.351 | 0.377 | 0.241 |
| VMPAC-FOC | | 0.827** | 0.735** | 0.697* |
| VMPAC-SEQ | | | 0.857** | 0.731** |
| CSIM | | | | 0.840** |

*Note*: VMPAC-FOC: focal oromotor control subtest of Verbal Motor Production Assessment for Children, percent scores; VMPAC-SEQ: sequencing subtest of Verbal Motor Production Assessment for Children, percent scores; GFTA-2: Goldman-Fristoe Test of Articulation (2nd Edition), standard scores; CSIM: Children's Speech Intelligibility Measure, percentage scores; Beginner's Intelligibility Test, percentage scores.

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

**Table 5**
Changes in speech motor control (VMPAC-FOC and SEQ), speech articulation (GFTA-2) and speech intelligibility (CSIM and BIT) following PROMPT therapy.

| Dependent variable | *t* value | df | *p* value | 95% CI | Cohen's *d* |
|---|---|---|---|---|---|
| VMPAC-FOC | −5.7 | 11 | 0.0001 | −13.46 to −6.06 | −2.36 |
| VMPAC-SEQ | −3.0 | 11 | 0.011 | −13.28 to −2.21 | −0.89 |
| GFTA-2 | −2.6 | 11 | 0.024 | −14.41 to −1.26 | −0.81 |
| CSIM | −2.8 | 11 | 0.017 | −12.75 to −1.57 | −0.85 |
| BIT | −4.7 | 11 | 0.001 | −28.69 to −10.63 | −1.38 |

*Note*: VMPAC-FOC: focal oromotor control subtest of Verbal Motor Production Assessment for Children, percent scores; VMPAC-SEQ: sequencing subtest of Verbal Motor Production Assessment for Children, percent scores; GFTA-2: Goldman-Fristoe Test of Articulation (2nd Edition), standard scores; CSIM: Children's Speech Intelligibility Measure, percentage scores; Beginner's Intelligibility Test, percentage scores. CI: confidence intervals.

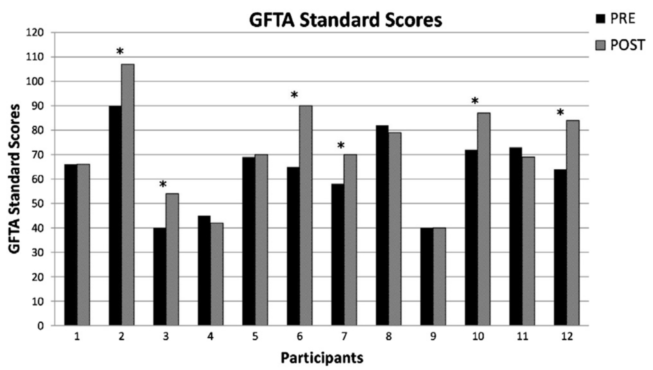


**Fig. 3.** Pre-treatment and post-treatment standard scores for Goldman-Fristoe Test of Articulation (2nd Edition). Pre–post difference outside the standard error of measurement (SEM) is indicated by *. See text for additional details.

data it is critical to investigate whether or not differences in pre–post test scores are outside the standard error of measurement (SEM) to ensure that changes were not due to measurement error. For example, the mean SEM across all age groups in GFTA-2 is 3.7 for males and 3.0 for females. Using a conservative criterion of 4 as the cutoff for this study we find that scores for participants 2, 3, 6, 7, 10 and 12 fall outside of the SEM cutoff point which indicates that changes in articulation skills are not due to measurement error in these participants (data outside SEM is indicated by * in Fig. 3).

With regards to speech intelligibility, although the scores improved at both the word and at the sentence-level (approximate change: CSIM = 7% and BIT = 20%; see Figs. 4 and 5), only the sentence-level (BIT) speech intelligibility results were statistically significant ($p = 0.001$). Word-level (CSIM) test showed a strong trend but was not statistically significant after Bonferroni correction ($p = 0.017$). The 90% confidence intervals (CI) for percentage scores are available for CSIM (CSIM manual – Wilcox & Morris, 1999). Post-test scores outside of this 90% CI indicate an actual change in child's performance. Using this criteria, only participants 3, 4, 6, 7, 11 and 12 showed actual change in CSIM scores in the post-treatment session (indicated by * in Fig. 4). Effect sizes relating to sentence-level speech intelligibility (BIT; $d = -1.38$) were also larger than the word-level ($d = -0.85$) test. Overall, the standardized effect size (Cohen's *d*) showed large magnitude of change across all

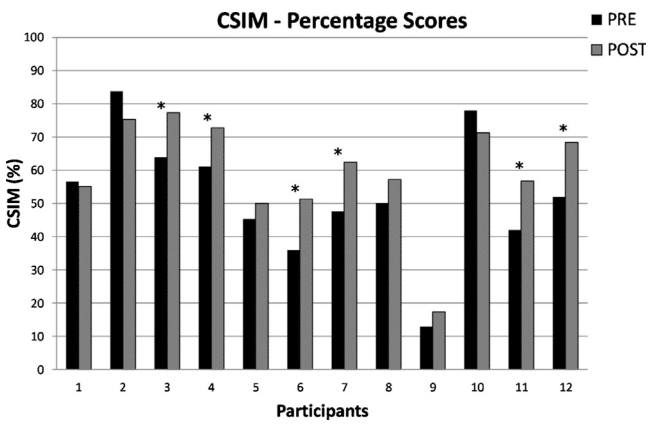


**Fig. 4.** Pre-treatment and post-treatment percentage scores for word-level Children's Speech Intelligibility Measure. Post-test scores outside of 90% confidence intervals indicate an actual change in child's performance (indicated by *). See text for details.

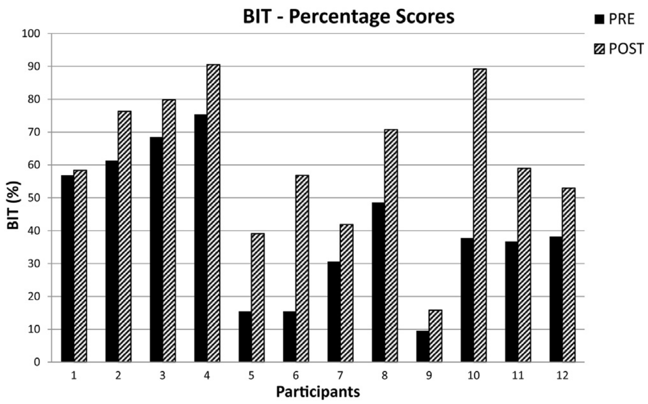


**Fig. 5.** Pre-treatment and post-treatment percentage scores for sentence-level Beginner's Intelligibility Test.

variables (range $d = -0.081$ to $-2.36$) along with the 95% confidence intervals not encompassing 0 (Table 5). In general, these results indicate that pre-test to post-test changes are robust and significant for intelligibility.

## 6. Discussion

This study examined the impact of speech motor impairments on the speech intelligibility of children with moderate to severe SSDs within the context of the PROMPT treatment approach. The results of the current study indicate a high and significant correlation between speech motor control and speech intelligibility. Scores from standardized articulation test were not significantly correlated with either the speech motor control or the speech intelligibility testing. Although, all variables yielded large effect sizes ($d > 0.8$), only the speech motor control and sentence-level speech intelligibility testing resulted in significant pre–post change. Speech articulation and word-level speech intelligibility testing failed to reach statistical significance. Further, not all participants demonstrated similar amounts of pre–post change in speech intelligibility. In fact, the data from the current study suggest a tentative relationship between an individual's gains in connected speech intelligibility and their degree of speech motor difficulty. Specifically, the findings suggest that the presence of speech planning/sequencing issues has a detrimental effect on sentence-level speech intelligibility scores.

### *6.1. What is the impact of speech motor control and speech articulation impairments on speech intelligibility in children with moderate to severe SSDs characterized by varying degrees of speech motor difficulties?*

Data from Table 4 demonstrates high and significant correlations between oro-motor control (VMPAC-FOC) and sequencing abilities (VMPAC-SEQ) and word and sentence-level speech intelligibility scores. However, similar to previous studies, speech articulation (GFTA-2 sounds-in-words subtest) demonstrates only mild correlation with word-level speech intelligibility and minimal to no correlation with the connected speech sentence-level intelligibility measure (Ertmer, 2010; Morris et al., 1995). Ertmer (2010) has indicated several reasons for limited correspondence between children's word-level articulation proficiency (e.g., on GFTA-2) and sentence-level intelligibility scores. Apart from simple length differences, sentences also involve more complex linguistic (e.g., syntax) and suprasegmental features (e.g., intonation) than word-level production (in GFTA-2). It is thought that these differences contribute to decreased sentence-level intelligibility scores relative to word-level production abilities (Ertmer, 2010). The mechanism underlying "how and why" linguistic and suprasegmental features affect speech production and intelligibility is complex, but a speculative answer may be found in speech kinematic and coordination studies. It has been shown that increases in syntactic and phonological length and complexity result in articulatory instabilities and adversely affect the speech motor control in typically developing children (e.g., Maner, Smith, & Grayson, 2000). We expect this effect to be stronger in children with MSD, given their presumed limited abilities in controlling and coordinating speech subsystems for accurate and efficient speech production.

Further, GFTA-2 intelligibility correlations in the present study are lower than what was found by Morris et al. (1995) with their word-level preschool speech intelligibility measure (PSIM; precursor to CSIM). They found PSIM-GFTA $r = 0.73$ ($p < 0.01$) whereas our data indicate non-significant $r = 0.37$. It is possible that some of these differences are related to changes in stimulus items between the two versions of the test and also due to differences in the population tested; Children with severe SSDs characterized by speech motor difficulties vs. typically developing pre-school children (Morris et al., 1995). Another possible reason why GFTA does not have a strong correlation with intelligibility measures may be related to vowel production. The GFTA-2 does not analyze and report on vowel production or vowel distortions, which may have been affected in some participants. For example, in the current study only participants 3, 6 and 9 had vowel neutralization errors, where a target vowel changes to a schwa or another vowel close to that position (e.g., /ə/ or /ʌ/) which may alter the meaning of the word and decrease speech intelligibility.

Furthermore, several articulatory dimensions (tongue height, front-back position of tongue and labial-facial control) may account for up to 50% of variance in speech intelligibility scores (Sapir, Ramig, Spielman, & Fox, 2010; Weismer et al., 2012). Several of these articulatory dimensions are possibly impaired to differing degrees in children with severe SSDs who demonstrate speech motor control issues (as evidenced by VMPAC scores) and standardized articulation tests rarely take this into account (e.g., Shriberg et al., 2011; Strand & McCauley, 2008). Thus, the results from the study indicate that more than speech articulation (as measured by GFTA-2), underlying speech motor control and speech sequencing (VMPAC subtests) are better indicators for overall speech intelligibility levels in children with moderate to severe SSDs who demonstrate speech motor control issues.

### *6.2. What is the magnitude of pre–post change in children with moderate to severe SSDs characterized by varying degrees of speech motor difficulties?*

Our second research question pertained to the magnitude of pre–post change. From Table 5, it is evident that large effect sizes were found for all variables (i.e., speech motor control, articulation, and speech intelligibility) with the biggest magnitude of change (1–2 S.D. pre–post difference) evidenced for focal oro-motor control and sentence-level (connected) speech intelligibility.

As mentioned earlier in the current study, pre–post speech intelligibility scores increased by 7.2% (Cohen's $d = -0.85$) at the word-level and by 19.7% (Cohen's $d = -1.38$) at the sentence-level. The CSIM and BIT pre-treatment means are approximately 50% and 40%, respectively (Table 3). The slightly lower pre-treatment intelligibility scores for connected speech as compared to single words probably indicates the difficulty children with severe SSDs (especially with added speech motor control issues) have when faced with increased demands on the speech motor system such as producing longer and more complex utterances (Maner et al., 2000; Pennington et al., 2009).

### *6.3. What are the possible factors that affect progress in children with moderate to severe SSDs characterized by varying degrees of speech motor difficulties?*

Our third research question examines some of the factors that contribute to progress in children with severe SSDs characterized by varying degrees of speech motor difficulties. Three-, four-, five- and six-year old typically developing English (as first language) speaking children (with speech-language and hearing WNL) are expected to have BIT sentence-level intelligibility scores that approximate 71%, 95%, 96% and 99%, respectively (Chin, Tsai, & Gao, 2003). Several researchers have suggested that speech less than 59%-to-60% intelligible is tremendously difficult for unfamiliar listeners to understand and may negatively impact a child's interaction with teachers and peers in a regular class room (Ertmer, 2010; Monsen, 1981; Monsen, Moog, & Geers, 1988). The data from the present study indicate that mean post-test word and sentence-level intelligibility scores were approximately 60% (Table 3), which is still well below the values for typically developing children and at the threshold for negatively impacting a child's social interactions. Since connected speech (sentence-level) intelligibility has high social significance and reflects real-world communicative interactions it is critical to develop a deeper understanding of the underlying factors that contribute to higher or better speech intelligibility scores.

The relationship between segmental errors and speech intelligibility has been described in hearing impaired children and children with SSDs (Hodge & Gotzke, 2011; Osberger & Mcgarr, 1982). Generally, there is a high negative correlation between total number of vowel/consonantal errors and speech intelligibility. Segmental errors such as omission of initial consonants, errors involving compound consonants and clusters, errors affecting syllable and word shapes affect speech intelligibility to a greater extent than omission of final consonants, nasality and substitution errors (Hodge & Gotzke, 2011; Osberger & Mcgarr, 1982). The negative impact of segmental factors on speech intelligibility is clearly demonstrated in participant 9 in the current study, who has a limited consonant repertoire (could produce only /h, m, n, w, t, j, l, d/), severely restricted word/syllable shape (words reduced to CV or CVC shape) and was able to produce only one consonant (/m/) in the word final position (Appendix C).

It is also possible to divide the participants a posteriori into broad categories based on data from Table 1. Due to small sample size this was not carried out a priori, but is discussed here to illustrate the potential relationship between speech motor control and speech intelligibility. For example, participants 8, 10, 11 and 12 who demonstrate moderate to severe articulation and phonological process issues in the absence of any major speech motor control difficulties (VMPAC-FOC and SEQ scores generally WNL) could be assigned to Group A. Participants (1, 2, 3, 5 and 6) who demonstrate moderate to severe articulation/phonological process errors and significant focal oro-motor control difficulties (VMPAC-FOC scores range: moderate to severe) in the absence of any major oro-motor/speech sequencing problems (VMPAC-SEQ scores generally mild-to-WNL) could be assigned to Group B. Similarly, participants (4,7 and 9) who demonstrate moderate to severe articulation, phonological process issues along with significant focal oro-motor control and sequencing difficulties (VMPAC-FOC and SEQ scores range: moderate to severe) could be assigned to Group C. Interestingly, when we categorized participants this way there was a quantitative difference between the three groups: mean pre–post increase in sentence-level speech intelligibility scores was 27.6% for Group A (average increase across participants 8, 10, 11 and 12); 18.5% for Group B (average increase across participants 1, 2, 3, 5 and 6) and; 10.9% for Group C (average increase across participants 4, 7 and 9; data extracted from Table 3). These results suggest a tentative relationship between speech motor control issues and speech intelligibility; viz., the greater the speech motor control difficulty the less the progress/gains in connected speech intelligibility.

Furthermore, the data reveal that low connected speech (BIT post-test) intelligibility scores may be related to the compound effect of two factors: (a) initial severity of VMPAC-SEQ scores and (b) whether or not children improve on VMPAC-SEQ scores at post-test. For example, participant 9 has very low pre-test VMPAC-SEQ scores (39.1) which did not improve at the time of post-test (score actually decreases to 30). VMPAC-SEQ scores reveal the ability to sequence non-speech movements and speech sounds/words which is a key feature of CAS. Thus, severity of planning and sequencing issues may potentially be a limiting factor in connected speech intelligibility. Additional research with larger sample sizes and multivariate analysis may be required to tease apart these complex relationships between speech motor control, speech articulation and speech intelligibility.

The above findings are in line with what has been reported in the literature, (e.g., children with Down syndrome who have clinical symptoms of childhood verbal apraxia (Kumin, 2006). Children with Down syndrome who have oro-motor control and speech planning difficulties had lower speech intelligibility scores than children who only had oro-motor control issues. Thus, early identification of verbal planning and sequencing difficulties would be imperative so that early treatment can focus on forming those critical speech motor templates in the brain that will allow children to combine and sequence sounds into syllables, words, phrases and sentences (Kumin, 2006). The results imply that more severe verbal planning and sequencing difficulties (CAS features) may adversely influence intelligibility results.

### *6.4. Limitations*

In the current study, a detailed description of the participants and treatment procedures were provided and outcomes were evaluated with sufficient blinding. However, the study has several weaknesses including (a) a small sample size ($N = 12$) that increases the probability of beta-errors (due to lower statistical power) and may limit generalization of the findings to a larger population, (b) a heterogeneous group that increases variability in the data, (c) lack of a control group or repeated baseline measures to account for extraneous variables such as maturation, and (d) no maintenance or follow-up assessments. For these reasons the results of the current study should be interpreted with caution and considered preliminary. In general, causal inference (i.e., PROMPT was responsible for the measured change) cannot be concluded in such single group pre-test post-test studies (Shadish, Cook, & Campbell, 2002). Nevertheless, the results from the current study provide level III evidence on the Evidence-Based Practice hierarchy (Dollaghan, 2007) and make an important contribution to the small body of literature relating to the impact of speech motor control issues on speech intelligibility of children with moderate to severe SSDs.

## 7. Conclusions

Overall, the findings from this present study indicate that speech intelligibility at both the word and sentence-level is significantly correlated with speech motor control (VMPAC: oro-motor control and sequencing subtests), but not articulatory proficiency (as assessed by a standardized articulation test – GFTA-2). Notably, the presence of speech planning/sequencing issues in children may decrease sentence-level speech intelligibility scores. This may highlight the need to consider speech motor control in addition to articulation skills at assessment and to address it directly and early on in treatment.

## Acknowledgements

The study was supported by a Canadian Institutes of Health Research operating grant (CIHR MOP-89961) to the last two authors (EWP and LDN) and a treatment research grant from the Childhood Apraxia of Speech Association of North America (CASANA) awarded to the first author (AKN). The authors also acknowledge the support of Toronto Rehabilitation Institute which receives funding under the Provincial Rehabilitation Research Program from the Ministry of Health and Long-Term Care in Ontario. The views expressed do not necessarily reflect those of the Ministry. The authors would like to thank Anna Oh for conducting the speech intelligibility tests and James Le for editorial assistance. The authors would like to thank Nina Jobanputra and Rene Jahnke who performed the reliability tests and speech assessments for children in the study.

## Conflict of Interest Statement

The authors of this article have not reported any financial or non-financial conflict of interest.

## Appendix A. Study inclusion criteria – red flags – for motor speech involvement

| The child MUST have at least 4 (“yes”) of these red flags to be included in the study. | | |
|---|---|---|
| | Yes | No |
| 1. Limited variety of speech motor movements (e.g., uses jaw as primary articulator). | ☐ | ☐ |
| 2. Productions are variable (may produce different sound combinations for the same word). | ☐ | ☐ |
| 3. Child has limited vowels and/or has vowel distortions. | ☐ | ☐ |
| 4. Child has limited consonants and/or has consonant distortions (nonstandard productions – e.g., dentalization, glottal stop, bilabial fricative, etc.). | ☐ | ☐ |

| | | |
|---|---|---|
| 5. Child has limited syllable and word shapes. | ☐ | ☐ |
| 6. Child demonstrates a number of age inappropriate phonological processes (e.g., persistence of early developing phonological processes such as final consonant deletion, reduplication, syllable deletion) and/or atypical processes (backing, initial consonant deletion). | ☐ | ☐ |
| 7. Child has atypical intonation (e.g., flat, choppy, staccato, stress on wrong syllables). | ☐ | ☐ |
| 8. Child has inappropriate pitch, rate, loudness and nasality. | ☐ | ☐ |
| Child has difficulty maintaining sound and syllable integrity with increased length and complexity of utterance (Check all that apply). | | |
| 9. Increased variability of errors. | ☐ | ☐ |
| 10. Groping. | ☐ | ☐ |
| 11. Fatigue. | ☐ | ☐ |
| 12. Decreased Intelligibility. | ☐ | ☐ |

**Acknowledgement:** Checklist developed based on recommendations by the Ministry of Child and Youth Services, Ontario – Motor Speech Working Group (February 2010) in collaboration with The Speech and Stuttering Institute.

## Appendix B

| ID | PROMPT treatment goals | MSH |
|---|---|---|
| 1 | **Main targets**: Stridents and strident clusters | |
| | **Overall program goals**: | |
| | Consistent VOT for initial voiceless phonemes | Stage II |
| | Increase jaw control in connected speech | Stage III |
| | Increase labio-facial control for lip rounding, decrease excess lip retraction | Stage IV |
| | Development of individual lip movement for /f/ | Stage IV |
| | Independent tongue tip elevation for /s, ʃ and /tʃ/ / | Stage V |
| 2 | **Main targets**: Stridents and strident clusters – 10 sessions; Nasals and velar blends | |
| | **Overall program goals**: | |
| | Increase jaw stability and midline movement in connected speech | Stage III |
| | Decrease facial movement of eyes and nose and excess retraction for /i/ | Stage IV |
| | Monitor consistent upper lip contribution for bilabials. | Stage IV |
| | Independent tongue tip elevation for post-vocalic / s, ʃ and /tʃ/ / | Stage V |
| 3 | **Main targets**: Strident blends and velars and /l/ blends (last treated 3–4 sessions) | |
| | **Overall program goals**: | |
| | Decrease excessive jaw opening for /a/ and facilitate jaw grading for /o/ | Stage III |
| | Increase labio-facial control and consistent bilabial contact for /p, b, m/ especially in medial position | Stage IV |
| | Increased lip rounding for /o, u/ | Stage IV |
| | Individual lip movement for /v/ | Stage IV |
| | Increase independent tongue elevation for /k, g, l/ | Stage V |
| | Increase prosodic features for connected speech, e.g., stress on first syllable | Stage VII |
| 4 | **Main targets**: Stridents 14 sessions and Liquids /r, l/ probed in the last 1 session | |
| | **Overall program goals**: | |
| | Increase labio-facial control and individual lip movement for /f/ and /v/ | Stage IV |
| | Independent tongue tip elevation for / s and ʃ / | Stage V |
| | Independent tongue tip elevation for /l/ in word initial and medial positions | Stage V |
| | Develop sequenced movement clusters for /sp, st, sk, sm, sn, sw, pl, bl, fl, kl, gl, sl/ | Stage VI |
| 5 | **Main targets**: Jaw height control for mid vowels and stridents – 12 sessions | |
| | **Overall program goals**: | |
| | Increase jaw control – decrease over excursion, improve mid line control i.e., no lateral or anterior sliding | Stage III |
| | Increase individual lip movement for /f/, increased lip rounding /o, u/ | Stage IV |
| | Increased independent tongue movement (/t, d, n, s/) | Stage V |
| | Increase sequenced movement for consonant clusters /sp, st, sk, sm, sn/ in words | Stage VI |
| 6 | **Main targets**: Jaw control and velars first – 12 sessions; fricatives /f/ and /s/ clusters – 4 sessions | |
| | **Overall program goals**: | |
| | Increase jaw control – decrease over excursion, improve mid line control. | Stage III |
| | Increase lip rounding for /o/ and /u/ | Stage IV |
| | Develop individual movement for /f/ | Stage IV |
| | Develop tongue control for back (/k, g/), mid (/ ʃ /) and tip (/s/) sounds | Stage V |
| | Develop sequenced movement consonant clusters /sp, st, sk, sm, sn/ | Stage VI |
| 7 | **Main targets**: Jaw control and velars first 5–6 sessions and Strident clusters remaining 9 sessions | |
| | **Overall program goals**: | |
| | Increase jaw control – decrease over excursion, improve mid line control and facilitate jaw grading (mid vowels) | Stage III |
| | Develop final consonants CVC, e.g., "pop" | |

**Appendix B** (*Continued*)

| ID | PROMPT treatment goals | MSH |
|---|---|---|
| | Increase individual lip movement for /f/ | Stage IV |
| | Increase lingual control for /k, g, s/ | Stage V |
| | Develop integration of vertical jaw movement with horizontal lip movement (e.g., /au/, /wa/) | Stage VI |
| | Increased sequenced movement for /sp, st, sk, sm, sn/) | Stage VI |
| 8 | **Main targets**: Jaw movement control and focus on velars and stridents | |
| | **Overall program goals**: | |
| | Increase vertical jaw control – for /h/ (e.g., "hop"); integrate with horizontal lip movement "he" and "hoop" | Stage III |
| | Develop individual movement for /f/ | Stage IV |
| | Develop tongue control for back (/k, g/), mid (/ ʃ /) and tip (/s/) sounds | Stage V |
| 9 | **Main targets**: Lip rounding/retraction, bilabials, nasalization | |
| | **Overall program goals**: | |
| | Increase jaw control – decrease over excursion, lateral sliding, and develop graded jaw opening for mid vowels. | Stage III |
| | Increase labio-facial control for lip movements /b, p/ | Stage IV |
| | Improved lip rounding (e.g., for /o, u/) and retraction (e.g., for /i/ and /s/) independent from jaw movement | Stage IV |
| | Develop individual movement for /f/ | Stage IV |
| | Develop tongue control for back (/k, g/), mid (/ ʃ /) and tip (/s/) sounds | Stage V |
| 10 | **Main targets**: Jaw control, lip rounding, multisyllabic word targets with Liquids/glides | |
| | **Overall program goals**: | |
| | Increase jaw stability and midline movement in connected speech | Stage III |
| | Increase labio-facial control for lip rounding, decrease excess lip retraction | Stage IV |
| | Develop tongue control for back (/k, g/), mid (/ ʃ /) and tip (/s/) sounds | Stage V |
| | Sequenced movement (integrating vertical and horizontal movement, e.g., /au/, /wa/, /j/) in multi-syllabic words | Stage VI |

## Appendix C

| ID | Syllable and word structure analysis | Syllable/word structures present (C: consonant; V: vowel) |
|---|---|---|
| 1 | - inserts a schwa into most consonant clusters<br>- can produce CVC structures but sometimes simplifies to CV<br>- can produce multisyllabic words | CV, CVV, CVC, VCVC, CVCV, CVVC, CCVC, CVCVC, CVVCV, CVCCV, CVCCVC, CVCVCVC. |
| 2 | - inserts schwa into some consonant clusters<br>- can produce CVC but sometimes drops final C<br>- can produce multisyllabic words (telephone) but sometimes collapses syllables (balloons → blun) | CV, CCV, CVC, CVCV, CCVC, CVCC, CVCVC, CCVCVC, CVCCV, CVCCVC, CVCVCVC. |
| 3 | - inserts schwa into some consonant clusters<br>- frequently produces open syllables by adding a schwa word finally, though able to produce CVC | CV, CVV, CVC, CVCV, CCVV, CVCC, CVVC, VCVCC, CVCVC, CVCCVV, CVCCVC, CVCCV, CVCVCV, CVCVCVC, CVCCVCC, CVCVCVC. |
| 4 | -simplifies some clusters by dropping a C<br>- able to produce multisyllabic words | CV, CCV, CVC, CCVC, VCVC, CCVV, CVCV, CVCCV, CVVCC, CCVVC, CVCVC, CVCVCV, CVCCVC, CCVCVC CVVCV, CVCVCVC. |
| 5 | -able to produce three syllable words, but sometimes drops a syllable<br>- one instance of metathesis – sound sequencing error (orange →/ ʤoʤez)<br>- syllable shapes fairly accurate<br>- many voicing errors (t/d, k/g switched – difficulty with voicing) | CV, CCV, CVC, CVCV, CVCC, CCVC, CVCVC, CVCCV, CVCCVC, CVCCVCC, CVCVCVC. |
| 6 | - able to produce a variety of syllable shapes and multisyllabic words<br>- reduced consonant repertoire – no consonants farther back than alveo-palatal (ŋ produced once in imitation)<br>- Velar fronting of /k, g/ to /t, d/ but deletes or voicing errors /t, d/ when required to produce them<br>- deletes initial consonant if not in repertoire, creating V__ word, sometimes adds a schwa word initially<br>- reduced sound inventory impacting syllable shapes (due to dropped C) | CV, VC, VVC, CVC, CCVC, CVCC, CVCV, VCVC, CVCVC, CVCCV, VCVCC, CVCCVC, VCVCVCVC |
| 7 | - able to produce three syllable words, though often drops a syllable<br>- one instance of metathesis – sound sequencing error (orange →"owigen")<br>- consonant clusters often reduced<br>- uses /ts/ inconsistently as a substitution for different consonants (/t/, / ʃ /, /k/) | CV, CVV, CVC, CVCV, CVCC, CVCCV, CVCVC, CCVCV, CVCCVC, CCVCVC, VCVCVC, |
| 8 | - mostly intact syllable shapes with some simplification of consonant clusters<br>- deletion of final C in plurals<br>- inserts extra syllable at times and deletes syllable at times | CV, VC, CCV, VCC, CVC, CVCV, CCVV, CCVC, CVCC, CVCCV, CCVCVC CVCVC, CVCVCV, CVCCVC, CVCVCVC, CVCVCVCVC. |
| 9 | - severely restricted syllable shape – most words reduced to CV or CVC shape<br>- three syllable words consistently reduced to two syllables<br>- only final C produced is/ m/<br>- limited consonant repertoire – /h, m, n, w, t, j, l, d/ | V, CV, CVC, VCV, CVCV, CVCC, CVVC. |

**Appendix C** (*Continued*)

| ID | Syllable and word structure analysis | Syllable/word structures present (C: consonant; V: vowel) |
|---|---|---|
| 10 | - mostly intact syllable shapes, with some cluster simplification<br>- clinician noted fast speech, labial retraction, generally clenched jaw/restricted jaw opening | CCV, CVV, CVC, CVCV, CVCC, CVVC, CCVC, VCVCC, CCVCC, CVCVC, CCVVC, CCVCV, CCVCVC, CVCCVC, CVCVCVC, CVCCVCC |
| 11 | - mostly intact syllable shapes with some cluster simplification | CV, CVC, CVCC, CVVC, CVCV, CCVC, CVCVC, CVCCV, VCVCV, VCVCC CVCCVC, CVCCVCC, CVCVCVC. |
| 12 | - able to produce three syllable words<br>- some cluster simplification<br>- occasionally drops final C | C, CV, VC, CVC, CCV, CVCC, CCVC, CVCV, VCVCC, CCVCC, CVCVC, CVVCV, CVCCV, CVCCVC, CVCVCV, CVCVCC, CVCVCCC, CVCCVCV, CVCVCVC |

## Appendix D. Continuing education

1. Prompts for Restructuring Oral Muscular Phonetic Targets (PROMPT) approach is a
   a. tactile-kinesthetic-based intervention.
   b. Phonological treatment technique.
   c. uses the Motor-Speech Hierarchy.
   d. (a) and (c).
   e. (b) and (c).
2. Closed-set word identification task used in the study is least influenced by
   a. listener experience with test materials.
   b. listener experience with language.
   c. suprasegmental features and contextual factors.
   d. All of the above.
   e. None of the above.
3. In general, word- and sentence-level speech intelligibility tests demonstrate
   a. high correlation with speech articulation tests.
   b. low correlation with speech articulation tests.
   c. significant correlation with speech motor control and sequencing tests.
   d. (a) and (c).
   e. (b) and (c).
4. In a prospective single group pre-test post-test design which of the following is true
   a. does not have a control group.
   b. cannot account for extraneous variables such as maturation.
   c. causal inference (i.e., PROMPT was responsible for the measured change) cannot be concluded.
   d. All of the above.
   e. None of the above.
5. Which of the following impedes motor learning in children
   a. immediate and high feedback (knowledge of results and performance) frequency.
   b. reduce information processing load and cognitive demands.
   c. start treatment with random practice followed by blocked practice.
   d. (a) and (b).
   e. (a) and (c).

## References


American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders* (4th ed.). Washington, DC: Author.

American Speech-Language-Hearing Association. (1997). *Guidelines for audiologic screening* Retrieved from http://www.asha.org/docs/html/GL1997-00199.html.

Baker, E., & McLeod, S. (2011). Evidence-based practice for children with speech sound disorders: Part 1. Narrative review. *Language, Speech and Hearing Services in Schools, 42*, 102–139.

Boersma, P., & Weenink, D. (2012). *PRAAT: Doing phonetics by computer version 5.3.21* (computer program). Available from http://www.praat.org/.

Bose, A., Square, P. A., Schlosser, R., & van Lieshout, P. (2001). Effects of PROMPT therapy on speech motor function in a person with aphasia and apraxia of speech. *Aphasiology, 15*(8), 767–785.

Caruso, A. J., & Strand, E. A. (1999). *Clinical management of motor speech disorders in children*. New York: Thieme.

Chin, S. B., Tsai, P. L., & Gao, S. (2003). Connected speech intelligibility of children with cochlear implants and children with normal hearing. *American Journal of Speech-Language Pathology, 12*, 440–451.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Earlbaum Associates.

Coplan, J., & Gleason, J. R. (1988). Unclear speech: Recognition and significance of unintelligible speech in preschool children. *Pediatrics, 82*, 447–452.

Dollaghan, C. A. (2007). *The handbook for evidence-based practice in communication disorders*. Baltimore: Paul H Brookes.

Dunn, M., & Dunn, L. M. (2007). *Peabody Picture Vocabulary Test – 4*. Circle Pines, MN: AGS.
Ertmer, D. J. (2010). Relationships between speech intelligibility and word articulation scores in children with hearing loss. *Journal of Speech, Language, and Hearing Research, 53*, 1075–1086.
Felsenfeld, S., Broen, P. A., & McGue, M. (1994). A 28-year follow-up of adults with a history of moderate phonological disorder: Educational and occupational results. *Journal of Speech and Hearing Research, 37*, 1341–1353.
Freed, D. B., Marshal, R. C., & Frazier, K. E. (1997). Long-term effectiveness of PROMPT treatment in a severely apraxic-aphasic speaker. *Aphasiology, 11* 365–342.
Goldman, R., & Fristoe, M. (2000). *Goldman Fristoe Test of Articulation-2*. Circle Pines, MN: American Guidance Service.
Gordon-Brannan, M., & Hodson, B. (2000). Intelligibility/severity measurements of prekindergarten children's speech. *American Journal of Speech-Language Pathology, 9*, 141–150.
Hayden, D. A. (2008). *Prompts for Restructuring Oral Muscular Phonetic Targets (PROMPT), introduction to technique: A manual* (2nd ed.). Santa Fe, NM: The PROMPT Institute.
Hayden, D., Eigen, J., Walker, A., & Olsen, L. (2010). PROMPT: A tactually grounded model for the treatment of childhood speech production disorders. In L. Williams, S. McLeod, & R. McCauley (Eds.), *Treatment for speech sound disorders in children* (pp. 453–474). Baltimore, MD: Brookes Publishing.
Hayden, D., & Square, P. (1999). *Verbal Motor Production Assessment for Children*. San Antonio, TX: The Psychological Corporation.
Hodge, M. M., & Gotzke, C. L. (2011). Minimal pair distinctions and intelligibility in preschool children with and without speech sound disorders. *Clinical Linguistics & Phonetics, 25*, 853–863.
Hodson, B. W. (2003). *Hodson computerized analysis of phonological patterns*. Wichita, KS: Phono-Comp Software (computer software).
Kumin, L. (2006). Speech intelligibility and childhood verbal apraxia in children with Down syndrome. *Down Syndrome Research and Practice, 10*, 10–22.
Maas, E., Robin, D. A., Austermann Hula, S. N., Freedman, S. E., Wulf, G., Ballard, K., et al. (2008). Principles of motor learning in treatment of motor speech disorders. *American Journal of Speech-Language Pathology, 17*, 277–298.
Maner, K. J., Smith, A., & Grayson, L. (2000). Influences of utterance length and complexity on speech motor performance in children and adults. *Journal of Speech, Language and Hearing Research, 43*, 560–573.
McCauley, R., & Swisher, L. (1984). Psychometric review of language and articulation tests for preschool children. *Journal of Speech and Hearing Disorders, 49*, 34–42.
Monsen, R. B. (1981). A usable test for the speech intelligibility of deaf talkers. *American Annals of the Deaf, 126*, 845–852.
Monsen, R. B., Moog, J., & Geers, A. (1988). *Picture Speech Intelligibility Evaluation*. St. Louis, MO Central Institute for the Deaf.
Morgan, A. T., & Vogel, A. P. (2009). A Cochrane review of treatment for childhood apraxia of speech. *European Journal of Physical and Rehabilitation Medicine, 45*, 103–110.
Morris, S. R., Wilcox, K. A., & Schooling, T. L. (1995). The preschool speech intelligibility measure. *American Journal of Speech-Language Pathology, 4*, 22–28.
Osberger, M., & Mcgarr, N. S. (1982). Speech production characteristics of the hearing impaired. *Speech and Language, 8*, 222–283.
Osberger, M., Robbins, A., Todd, S., & Riley, A. (1994). Speech intelligibility of children with cochlear implants. *Volta Review, 96*, 169–180.
Pennington, L., Miller, N., & Robson, S. (2009). Speech therapy for children with dysarthria acquired below three years of age. *Cochrane Database of Systematic Reviews, 4*, CD006937.
Pennington, L., Miller, N., Robson, S., & Steen, N. (2010). Intensive speech and language therapy for older children with cerebral palsy: A systems approach. *Developmental Medicine and Child Neurology, 52*, 337–344.
Raitano, N. A., Pennington, B. F., Tunick, R. A., Boada, R., & Shriberg, L. D. (2004). Pre-literacy skills of subgroups of children with speech sound disorders. *Journal of Child Psychology and Psychiatry, 45*, 821–835.
Rogers, S. J., Hayden, D., Hepburn, S., Charlifue-Smith, R., Hall, T., & Hayes, A. (2006). Teaching young nonverbal children with autism useful speech: A pilot study of the Denver model and PROMPT interventions. *Journal of Autism and Developmental Disorders, 36*, 1007–1024.
Sapir, S., Ramig, L., Spielman, J., & Fox, C. (2010). Formant centralization ratio: A proposal for a new acoustic measure of dysarthric speech. *Journal of Speech, Language and Hearing Research, 53*, 114–125.
Shadish, W. R., Cook, T. D., & Campbell, D. T. (2002). *Experimental and quasi-experimental designs for generalized causal inference*. Boston, MA: Houghton Mifflin.
Shriberg, L. D., Potter, N. L., & Strand, E. A. (2011). Prevalence and phenotype of childhood apraxia of speech in youth with galactosemia. *Journal of Speech, Language, and Hearing Research, 54*, 487–519.
Stimley, M. A., & Hambrecht, G. (1999). Comparisons of children's single-word articulation proficiency, single-word speech intelligibility, and conversational speech intelligibility. *Canadian Journal of Speech-Language Pathology and Audiology, 23*, 19–23.
Strand, E. A., & McCauley, R. J. (August 2008). Differential diagnosis of severe speech impairment in young children. *The ASHA Leader*, 10–13.
Sullivan, K. S., Kantak, S., & Burtner, P. A. (2008). Motor learning in children: Feedback effects on skill acquisition. *Physical Therapy, 88* 820–732.
Ward, R., Leitao, S., & Strauss, G. (2009). The effectiveness of PROMPT therapy for children with cerebral palsy. *Developmental Medicine & Child Neurology, 51*(s5), 76.
Wechsler, D., & Naglieri, J. A. (2006). *Wechsler Nonverbal Scale of Ability*. San Antonio, TX: Harcourt Assessment.
Weismer, G. (2008). Speech intelligibility. In M. J. Ball, M. Perkins, N. Müller, & S. Howard (Eds.), *The handbook of clinical linguistics* (pp. 568–582). Oxford, UK: Blackwell Publishers.
Weismer, G., Yunusova, Y., & Bunton, K. (2012). Measures to evaluate the effects of DBS on speech production. *Journal of Neurolinguistics, 25*, 74–94.
Wilcox, K., & Morris, S. (1999). *Children's speech intelligibility measure*. San Antonio, TX: Harcourt Brace.
Williams, K. T. (2007). *Expressive Vocabulary Test, Second Edition: Manual*. Minneapolis, MN: Pearson Assessments.
Williams, A. L., McLeod, S., & McCauley, R. J. (2010). *Interventions for speech sound disorders in children*. Baltimore, MA: Paul H Brookes Publishing.