Effects of an Intensive Voice Treatment on Articulatory Function and Speech Intelligibility in Children with Motor Speech Disorders

by

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Abstract

Producing speech that is clear, audible, and intelligible to others is a challenge for many children with cerebral palsy (CP) and children with Down syndrome (DS). Previous studies have demonstrated the effectiveness of using the Lee Silverman Voice Treatment (LSVT LOUD®) to increase vocal loudness and improve speech intelligibility in individuals with dysarthria secondary to Parkinson's disease (PD), and some research suggests that it also may be effective for individuals with dysarthria secondary to other conditions, including CP and DS. Although LSVT LOUD only targets vocal loudness, there is some evidence of spreading effects to the articulatory system. Acoustic data from two groups of children with secondary motor speech disorders [one with CP (n= 17) and one with DS (n=9)] who received a full dose of LSVT LOUD and for whom post-treatment intelligibility gains have been previously reported, were analyzed for treatment effects on: *1)* vowel triangle area (VTA) and the ratio of F2/i/ to F2/u/); and *2)* vowel inherent spectral change (VISC) in the monophthongs /i/, /u/, and /ɑ/. Statistically significant changes in VTA occurred PRE to FUP in the CP group, and increased VTA was observed in 5 of the DS participants. A statistically significant change to VISC for F2/ɑ/ occurred PRE to POST in the CP group. The present study provides evidence of LSVT LOUD treatment spreading effects to the articulatory system in children with CP and children with DS consistent with previous findings in other populations. Limitations of the present study and potential directions for future research are discussed.

Keywords: Acoustic analysis, pediatric dysarthria, cerebral palsy, Down syndrome, LSVT LOUD

Preface

This thesis is an original work by Colette Langlois. The research projects, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board: Voice Treatment for Cerebral Palsy, No. 00001568, June 7, 2009; Speech Intelligibility Lee Silverman Voice Treatment on Children with Speech Disorders, No. 00012389, February 11, 2011; Neural Correlates of Intensive Voice Treatment Effects on Children with Cerebral Palsy, No. 000380761, February 23, 2014; and from the University of Colorado-Boulder Institutional Review Board: Project Number: Pro00061081.

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Introduction

Decreased speech intelligibility is often a challenge for both individuals with Down syndrome (DS) (see reviews in: Bunton & Leddy, 2011; and Wood, Wishart, Hardcastle, Cleland, & Timmins, 2009), and individuals with cerebral palsy (CP) (see reviews in: Pennington, Miller, Robson, & Steen, 2010; and Watson & Pennington, 2015). The results of one large group survey using parent report suggest that as many as 95% of children with DS have difficulty being understood at least some of the time, and 80% have difficulties specific to articulation (Kumin, 1994). According to one recent study of over 1300 individuals notified to the Northern Ireland Cerebral Palsy Register, approximately 36% of children with CP have secondary motor speech impairments (Parkes, Hill, Platt, & Donnelly, 2010), however estimates of prevalence vary widely in the literature (see review in Lee, Hustad, & Weismer, 2014, which cites prevalence estimates ranging from 31% to 88%). Prevalence of DS has been estimated at 14.1 per 10,000 live and still births (Public Health Agency Of Canada, 2013), and prevalence of CP at 2.11 per 1,000 live births (Oskoui, Coutinho, Dykeman, Jetté, & Pringsheim, 2013). Although exact figures are not available, it is clear that a significant number of children are affected by motor speech disorders secondary to DS or CP.

In pediatric populations, communication impairments interfere with overall development, and have been associated with depression, reduced quality of life, and increased risk of social isolation and academic difficulties (Fuhrman, Equit, Schmidt, & Von Gontard, 2014; Pennington, Miller, & Robson, 2009). Interventions that improve the speech intelligibility of children with DS or CP may therefore enable increased participation in life activities, and have substantial short and long-term benefits for emotional and social well-being.

There is no general agreement on which factors are responsible for the reduced speech intelligibility nearly always associated with DS, or whether it is best characterized as a motor speech disorder or a developmental phonological delay (Bunton & Leddy, 2011; Mahler & Jones, 2012; Wood et al., 2009). Many acoustic and perceptual observations of this population reported in the literature are consistent with motor speech deficits, which suggests that such deficits do at least play a contributory role in decreased intelligibility for at least some individuals with DS (Bunton & Leddy, 2011; Mahler & Jones, 2012), although they may not be easily categorized due to overlapping symptoms of dysarthria, childhood apraxia of speech and otherwise unspecified motor speech disorders (Rupela, Velleman, & Andrianopoulos, 2016). Perceptual features of voice and speech in individuals with DS that have been reported include: reduced loudness, both hypo- and hypernasality, imprecise articulation of consonants and vowels; atypical pitch patterns and prosody; and breathy, hoarse or harsh voice quality (Mahler & Jones, 2012; see reviews in Roberts, Price, & Malkin, 2007; and Venail, Gardiner, & Mondain, 2004). Possible underlying causes are: structural characteristics that may impact articulation, such as abnormal facial musculature, and a small oral cavity together with a normal-sized tongue; physiological characteristics, such as low muscle tone and abnormal innervation of the articulators; phonological errors; and/or motor speech programming difficulties (see reviews in: Bunton & Leddy, 2011; Mahler & Jones, 2012; Martin, Klusek, Estigarribia, & Roberts, 2009; Roberts et al., 2007; and Wood et al., 2009). Further, DS almost always involves cognitive impairment, and is associated with a high incidence of hearing loss: both of these factors can contribute to an increased risk of overall speech and language delay (see reviews in: Martin et al., 2009; and Roberts et al., 2007).

The most prevalent form of speech disorder in individuals with CP is dysarthria, which may present as imprecise articulation, low pitch, reduced pitch variation, harsh voice, hypernasality, and/or deficient breath control for speech, all of which can contribute to reduced intelligibility (see reviews in Pennington et al., 2010; and Watson & Pennington, 2015). The perceptual characteristics of dysarthrias associated with spastic and dyskinetic types of CP are similar, although the severity is generally greater for individuals with the dyskinetic form (Pennington et al., 2010). While not as prevalent as in DS, cognitive impairment is present in approximately half of children with CP, and may impact speech and language development (Parkes et al., 2010; Surman et al., 2009; Watson & Pennington, 2015).

Vowel Acoustics in Motor Speech Disorders

In studies of motor speech disorders, acoustic vowel space (AVS) and other measures of the first and second formants of vowels (F1 and F2) have been of interest both because of their importance for speech perception (see, e.g., Delattre, Liberman, Cooper, & Gerstman, 1952) and therefore intelligibility to listeners, and because of their relationship to the articulatory system as products of its anatomy and physiology (see, e.g. review in Hixon, Weismer, & Hoit, 2014, 415-454). F1 and F2 are affected by the coordination, strength, and range of motion of the articulators as they alter the shape and space of the oral cavity: in particular F1 has been shown to decrease as tongue height increases, which may be affected by jaw movement as well as by independent lingual movement; F2 has been shown to increase as the tongue moves forward, though movement in the vertical plane may also affect F2 to a lesser extent; and both F1 and F2 have been shown to decrease with lip rounding, with F2 showing the most pronounced effects (Stevens & House, 1955; Hixon et al., 2014; Lee, Shaiman, & Weismer, 2016). Formant values also are affected by overall vocal tract structure both directly, as with the smaller size of children's vocal tracts, which are associated with higher formant frequencies (see, e.g. Lee, Potamianos, & Narayanan, 1998), and indirectly, as with structural anomalies such as the relatively small oral cavity associated with DS, which may restrict the working space of the articulators (Bunton & Leddy, 2011). It has been suggested that both compressed vowel space and reduced formant transitions may be common characteristics across dysarthrias (Weismer & Kim, 2010). Several studies have found decreased AVS in speakers with dysarthria, as well as correlations between smaller vowel spaces and reduced intelligibility (see, e.g., Higgins & Hodge, 2002; Kim, Hasegawa-Johnson, & Perlman, 2011; Kim, Kent, & Weismer, 2011; Lansford & Liss, 2014a; Lansford & Liss, 2014b; Lee et al., 2014; Liu, Tsao, & Kuhl, 2005; Wenke, Cornwell, & Theodoros, 2010). Shallower F2 transition slopes also have been associated with dysarthric speech and reduced intelligibility (see, e.g., Kent et al., 1989; Lee et al., 2014; Lansford & Liss, 2014b).

As yet there has been little research using non-perceptual methods to assess the functioning of the articulatory system in individuals with DS, however some limited evidence from acoustic and physiological studies suggests that this population has a reduced vowel working space (see review in Kent & Vorperian, 2013). Moura et al. (2008) observed that children with DS had an overall smaller acoustic vowel space than age-matched controls, and in particular smaller differences between F1 of /a/ compared with the F1 of /i/ and /u/, and a smaller ratio between the F2 of /i/ and /u/. The authors interpreted the F1 findings to reflect a more limited jaw movement and mouth opening, which would restrict the tongue from descending in order to produce the higher F1 frequency typical of low vowels. The smaller F2i/F2u ratio was interpreted as reflecting restricted tongue movement in the high back position, resulting in a higher than typical F2 value for /u/. Another recent study using both acoustic measures and X-ray microbeam tracking of tongue movements showed decreased acoustic vowel space, decreased articulatory space, and slower articulatory movements in two adults with DS compared with healthy controls (Bunton & Leddy, 2011).

To date there also has been little acoustical or physiological research on the articulatory function of children with CP, although there is some evidence that of all the speech subsystems, the articulatory subsystem may be the most determinative of intelligibility in this population (Lee et al., 2014; Levy, Leone, Moya-Gale, Hsu, Chen, & Ramig, 2016; Nip, 2017), and that patterns of acoustic correlates of dysarthria in children are similar to those of adults (Lee et al., 2014). A recent study of the speech acoustics of children with CP and dysarthria found significantly smaller vowel space, longer vowel durations and shallower F2 transition slopes in diphthongs (i.e., in the words “pipe” and “toys”) and labiolingual glides (i.e., in the word “whip”), compared with control groups of typically developing children and children with CP but without dysarthria (Lee et al., 2014). Further, these acoustic measures of articulatory function were found to predict 58% of the variance in intelligibility measures. The longer vowel durations and shallower F2 transition slopes of the CP-dysarthria group were interpreted by the authors as reflective of slower and reduced articulatory movement. This is consistent with the results of a recent kinematic study, which found reduced ability to coordinate articulatory movements of the jaw and lips among children with CP, and significant correlations between reduced interarticulatory coordination and decreased intelligibility (Nip, 2017).

Treatment approaches

There is currently no consensus on best practices for treatment of speech disorders in children with DS and CP, and the literature on the effectiveness of interventions for pediatric dysarthrias is sparse (Pennington et al., 2009). For individuals with DS, the traditional approach has been articulation therapy to target disordered phonological processes and sound errors (see, e.g. Martin et al., 2009). More recent exploratory work has involved electropalatography, (Wood et al., 2009), and intensive therapy targeting the laryngeal system (Boliek et al., 2012), both of which show some promise. Non-speech oral motor treatments also have been attempted, however current evidence does not support their efficacy (Lee & Gibbon, 2015).

Treatment approaches to improve speech intelligibility of children with CP are similarly varied, and also have included articulation therapies and non-speech interventions of questionable effectiveness (Watson & Pennington, 2015). Some recent single subject and small group studies provide evidence that intensive therapies based on motor learning principles and a singular target of healthy vocal loudness (Boliek & Fox, 2014; Boliek & Fox, 2016; Fox & Boliek, 2012; Levy et al., 2012) or multiple targets of breath support, phonation and speech rate (Levy et al., 2012; Pennington et al., 2010; Pennington et al., 2013) may produce better intelligibility gains for this population. These findings are consistent with neuroplasticity and motor learning principles that are increasingly informing overall rehabilitation strategies for individuals with CP (Garvey, Giannetti, Alter, & Lum, 2007).

The Lee Silverman Voice Treatment (LSVT LOUD®) is a short-term intensive therapy with a single target of achieving healthy vocal loudness. It was originally developed to treat individuals with Parkinson's disease (PD) and dysarthria. Several studies have demonstrated the effectiveness of LSVT LOUD at increasing vocal loudness and improving the intelligibility of speech in individuals with PD (Sapir, Spielman, Ramig, Story, & Fox, 2007; Sauvageau, Roy, Langlois, & Macoir, 2015), and some small group studies suggest that it also may improve speech intelligibility for individuals with dysarthria secondary to other conditions, including adults with DS (Mahler & Jones, 2012), children with DS (Boliek et al., 2012), and children with CP (Boliek & Fox, 2014; Boliek & Fox, 2016; Fox & Boliek, 2012; Levy, Ramig, & Camarata, 2012).

Whereas traditional treatments for dysarthria targeting multiple systems (breathing, laryngeal, velopharyngeal and oral articulatory) separately or in combination, may be effective at improving speech intelligibility in some school-aged children with CP (Levy et al., 2012; Pennington et al., 2010), LSVT LOUD, which has a single treatment target of healthy vocal loudness, and relies primarily on modeling rather than verbal instruction to elicit target behaviour, may be better suited to individuals with cognitive impairments (Fox & Boliek, 2012; Wenke et al., 2010; Youssef, Anter, & Hassen, 2015) and preschool children. This limited cognitive load makes it particularly promising for those children with CP and children with DS who also have reduced intellectual functioning, and also may allow for earlier interventions with preschool-aged children.

Although LSVT LOUD only directly targets the phonatory system, there is some evidence based on perceptual and acoustic measures that it also improves articulation in individuals with PD, individuals with non-progressive dysarthrias, and individuals with flaccid dysarthrias, which may explain some of the gains in intelligibility that cannot be accounted for by increased loudness alone (Sapir et al., 2007; Sauvageau et al., 2015; Wenke et al., 2010; Youssef et al., 2015).

Sapir et al. (2007) found significant post-LSVT LOUD changes in individuals with PD in vocal sound pressure levels, the F2 of the vowels /i/ and /u/, the ratio F2i/F2u, and perceptual vowel goodness ratings. No significant changes were observed in control groups of healthy individuals and individuals with PD who did not receive treatment. AVS was measured, but did not change significantly from pre- to post-treatment. Results from Wenke et al.'s (2010) study indicated that individuals with non-progressive dysarthrias secondary to stroke or traumatic brain injury (TBI) made significant gains in both AVS and perceptual intelligibility ratings post-LSVT LOUD treatment and at six months' follow up. None of the acoustic or perceptual outcomes were significantly different from those of a control group of individuals who received a traditional dysarthria therapy based on multiple targets. Sauvageau et al. (2015) reported increased AVS in individuals with PD who received LSVT LOUD, as well as greater post-treatment distinctiveness in consonant-vowel coarticulations. Youssef et al.'s (2015) study of individuals with flaccid dysarthria secondary to stroke or TBI found statistically significant changes to F1 and F2 of /a/ and /u/, with a tendency for higher F1 values and lower F2 values post-treatment.

Formant Transitions as Indicators of Treatment Effects

As described above, in addition to AVS, reduced F2 transition slopes have previously been associated with both dysarthric speech and reduced intelligibility. However, the studies cited include minimal or no consideration of F2 changes within the corner vowels /i/, /u/ and /ɑ/, instead examining diphthongs, labiolingual glides (as in the word "whip"), mid-vowels, and/or average F2 slope calculated for the entire set of vowels rather than for specific vowels. F1 transitions have not received detailed consideration in this literature. Further, little attention appears have been paid to formant changes in treatment studies on motor speech disorders.

Evidence from speech perception research has shown that within-vowel formant changes provide important acoustic cues for listeners not only in diphthongs and other contexts, such as labiolingual glides, where larger articulatory movements are required, but also in monophthongs (see review in Hillenbrand, 2013), and that these features are in addition to those formant changes that can be explained in the context of consonant-vowel coarticulation (Nearey, 2013). Whereas there are some indications that in typical speech, corner vowels show less vowel inherent spectral change (VISC) than mid-vowels, some movement in these vowels is still discernible (Nearey, 2013; Nearey & Assmann, 1986). It was hypothesized that the F1 and F2 VISCs of the corner vowels measured in the present study might be sensitive to treatment changes in the articulatory subsystem that are not revealed by the steady-state mid-vowel measurements used in measures of AVS, and might help to explain treatment effects on intelligibility.

Purpose

To summarize, motor speech disorders are prevalent among individuals with DS and individuals with CP, affecting many children and adults. LSVT LOUD is an intensive therapy with a single target of healthy vocal loudness that has been shown to increase intelligibility in individuals with Parkinson's disease, through gains not only in the directly targeted phonatory function, but also in the functioning of the articulatory subsystem as evidenced by changes to measures of vowel working space. Recent studies suggest that LSVT LOUD also may produce intelligibility and vocal loudness gains in children with motor speech disorders secondary to DS or CP, however the possibility of treatment spreading effects to the articulatory subsystem in these populations has not yet been investigated. Reduced AVS is thought to be a characteristic common to different types of dysarthria, and treatment effects on AVS have been reported in some studies. Dynamic measures of monophthong formants have received little attention in research on motor speech disorders, but also may be sensitive to treatment effects.

The purpose of the present study was to undertake a retrospective analysis of acoustic data from two previous LSVT LOUD treatment studies, one of children with CP (Boliek and Fox, 2016), and one of children with DS (Boliek, Hardy, Halpern, Fox, & Ramig, 2016; Boliek et al., 2012; Boliek et al., 2010), to test for gains similar to those found in studies of individuals with PD and non-progressive dysarthrias. It was predicted that both the CP group and the DS group would show significant post treatment increases in vowel space and in the VISC of F1 and F2 formants.

Method

A within-group, repeated measures design was selected to test for post-treatment changes to acoustic measures.

Participants

Selection criteria for all participants included: a) presence of a perceptible speech or voice disorder; b) hearing within normal limits (aided or unaided); c) absence of vocal fold pathology; d) cognitive ability to follow directions and perform the voice and speech tasks of the study protocol; and e) medical stability. Exclusion criteria included a) severe velopharyngeal incompetence; and b) severe structural disorders of the speech mechanism.

CP group. Participants were 17 children with CP, aged 6 to 16 years (mean age of 10.6 years), and were recruited and treated in Edmonton, Alberta Canada. All participants had Western Canadian English as their first language. Table 1 provides details of individual participant characteristics. Informed written consent and assent were obtained in accordance with the requirements of the Health Research Ethics Board at the University of Alberta, which approved the study. All participants were diagnosed by certified SLPs with spastic (n= 4), spastic-ataxic (n=2), or spastic-flaccid (n=11) dysarthria, ranging from mild to severe. Four participants also had apraxia of speech diagnoses, and two had dysfluency diagnoses. Table 1 provides further details of participant characteristics.

DS group. Participants were 9 children with DS, aged 4 to 8 years (mean age of 6.8 years), and were recruited and treated in Denver, Colorado. Table 2 provides details of individual participant characteristics. In addition to the exclusion criteria described

Participant	Sex	Age	CP Diagnosis	Speech Diagnosis	GMFCS	Cognitive Level
F0601E	F	6	Spastic Quadriplegia	Spastic-Flaccid Dysarthria, Severe	V	Average
LSVTM5	M	8	Spastic Quadriplegia	Spastic Dysarthria, Mild-Moderate	V	Average
LSVTM8	M	8	Spastic Diplegia	Spastic-Flaccid Dysarthria, Moderate-Severe; Dysfluency, Mild	II	Below Average
F0801E	F	8	Spastic Quadriplegia	Spastic-Flaccid Dysarthria, Mild	I	Above Average
F0802E	F	8	Spastic Quadriplegia	Spastic Dysarthria, Mild	II	Average
F1001E	F	10	Spastic Quadriplegia	Spastic Dysarthria, Moderate	V	Average
F1201E	F	10	Spastic Quadriplegia	Spastic Dysarthria, Mild	III	Above Average
F1202E	F	12	Spastic Quadriplegia	Spastic-Flaccid Dysarthria, Severe; Dysfluency, Severe	II	Average
M0901E	M	10	Spastic Quadriplegia	Spastic-Flaccid Dysarthria, Moderate	III	Average
M1001E	M	10	Spastic Quadriplegia	Spastic-Flaccid Dysarthria, Severe	V	Average
LSVTM2	M	11	Spastic Diplegia	Spastic-Ataxic Dysarthria, Mild	II	Average
LSVTF3	F	12	Spastic Triplegia	Spastic-Flaccid Dysarthria, Mild; AOS, Mild-Moderate	II	Average
LSVTM4	M	12	Spastic Quadriplegia	Spastic-Flaccid Dysarthria, Mild	V	Below Average
LSVTF1	F	13	Spastic Diplegia	Spastic-Flaccid Dysarthria, Moderate	III	Above average
LSVTM6	M	13	Spastic Diplegia	Spastic-Flaccid Dysarthria, Moderate-Severe; AOS, Moderate-Severe	IV	Below Average
LSVTM9	M	13	Spastic-ataxic Quadriplegia	Spastic-Ataxic Dysarthria, Moderate-Severe; AOS, Mild	IV	Average
LSVTF7	F	16	Spastic Diplegia	Spastic-Flaccid Dysarthria, Severe; AOS, Severe	III	Average

Table 1. Description of participants with cerebral palsy including sex, age, speech diagnosis, rating on the Gross Motor Function Classification System (GMFCS), and cognitive level. GMFC = *Gross Motor Function Classification System* (expanded and revised scale; Palisano, Rosenbaum, Bartlett, & Livingston, 2008) (higher number indicates greater severity). Note: Diagnosis was made by a paediatric neurologist, GMFCS was determined by a physical therapist, and speech/voice status was determined by licensed speech-language pathologists.

Participant	Sex	Age	Genetic Diagnosis	Speech Diagnosis
S24	F	4	Trisomy 21	mixed dysarthria
S23	F	5	Trisomy 21	mixed dysarthria
S21	F	6	Trisomy 21	mixed dysarthria
S25	M	7	Trisomy 21	mixed dysarthria
S28	F	7	Mosaic	mixed dysarthria
S22	F	8	Trisomy 21	mixed dysarthria
S26	F	8	Trisomy 21	mixed dysarthria
S27	F	8	Trisomy 21	mixed dysarthria
S29	F	8	Trisomy 21	mixed dysarthria

Table 2. Description of participants with Down syndrome including sex, age and speech diagnosis.

above, participants in this group were excluded if they had a severe articulation disorder, and /or a concomitant speech disorder (e.g., dysfluency). Consent and assent were obtained in accordance with the requirements of the human research ethics board at the University of Colorado, which approved the study. Further ethical approval was provided for the transfer of de-identified data to the University of Alberta for analysis and interpretation. All participants were diagnosed with mixed dysarthria by a certified SLP.

Procedures

Recordings. Recordings for both groups were made within one week prior to treatment (PRE), and within one week following treatment (POST). With the exception of one participant, the CP group was also recorded at twelve weeks follow-up (FUP). Recording sessions ranged from 30 minutes to one hour. CP group participants had a single session at each time. DS group participants had from 1 to 3 sessions at PRE, and from 1 to 2 sessions at POST. The individuals who collected the recordings were not associated with the treatment or data analysis phases of the studies, and were trained to be consistent across participants. Recordings of CP participants were made in a quiet room; recordings of DS participants were made in an Industrial Acoustics Company sound-treated booth. All recordings were collected using either a lapel unidirectional microphone (Shure 185: CP group), or a small omni-directional condenser microphone (Audio-Technica, Model AT 803b: DS group) secured to participants' foreheads to maintain consistent mouth to microphone distances (8 cm for the DS group and 10 cm for the CP group). Signals were sent to a digital audiotape (DAT) recorder [Panasonic Digital Audio Tape Deck, Model SV-3500, 44.5 kHz: DS group; Tascam DA-P1 DAT, 44.1 kHz, or directly to computer using TF32 software (Milenkovic, 2004): CP group. All acoustic data were converted to .wav files compatible with Praat acoustic analysis software (Boersma & Weenink, 2016).

Speech samples. A summary of the speech samples used is presented in Table 3. Speech samples include single words from the Test of Children's Speech Plus (TOCS+) (Hodge, Daniels, & Gotzke, 2006) for the CP group, and the *Goldman-Fristoe Test of Articulation 2* (GFTA) (Goldman & Fristoe, 2000) for the DS group; and the sentences, "The potato stew is in the pot," and "The blue spot is on the key" for both groups. The TOCS+ words were elicited by computer software, which simultaneously displayed a picture and played a recording of a word for the participant to repeat. Most of the GFTA words (97% of those used in this study) were produced spontaneously by the participant (i.e., without first hearing someone else say the word), after being asked to name a picture. The TOCS+ and GFTA words were elicited only one time at each sitting, with the exception of six TOCS+ words (5% of those used in this study), which were produced twice. All of the sentences were produced in direct imitation of a Western Canadian English Speaker, and were repeated three times at each sitting. In most cases, participants were asked to repeat phrases rather than the full sentences (e.g., "the blue spot" / "is on the key"). Participants' total number of repetitions of each token word at each time varied from a minimum of one to a maximum of nine. None of the words used as tokens were trained during the treatment phase.

Treatment protocol. Each participant received a full dose of LSVT LOUD treatment from a certified SLP. Consistent with the standard protocol for LSVT LOUD (Ramig et al., 2001), treatment consisted of 16 one-hour sessions, delivered over a period of four weeks (four days per week) as well as daily homework assignments (one per day on treatment days, and two per day on non-treatment days). The CP group also participated in a maintenance program of at-home practice during the 12 weeks following the treatment. All treatment sessions followed the same protocol during the first 30 minutes: i) at least 15 repetitions each of “long ah” (maximum phonation duration), “high ah” (maximum f_0 range), and “low ah” (minimum f_0 range); and ii) at least five repetitions each of 10 functional phrases chosen by the participants and their parents. The second 30 minutes included individualized practice based on topics of interest, and progressing over the course of the month from short to longer utterances (individual words to paragraphs) and from simple to more complex (repetition without distractors to reading and conversation with distractors). Homework included repeating the exercises and practice used in the sessions, as well as extra assignments such as talking to someone on the phone.

Data set	Source of speech samples	Number of speech samples at each time point	Tokens	Number of productions of each token per sample	Type of speech
CP – Single Words	*Test of Children’s Speech Plus* (each participant was randomly assigned one of 3 word lists)	Pre: 1 Post: 1 FUP: 1	each participant was assigned one of the following sets: “jaw”, “bee”, “two” “paw”, “tea”, “two” “top”, “bee”, “boo” Note: “pooh” was substituted for “two” for one participant.	1 - 2	Imitative.
CP – Phrases	“The blue spot is on the key” and “The potato stew is in the pot.”	Pre: 1 Post: 1 FUP: 1	“blue”, “key”, and “pot”	3	Imitative.
DS – Single Words	*Goldman-Fristoe Test of Articulation 2*	Pre: 1-3 Post: 1-2	“blue”, “tree”, and “watch”	1	Spontaneous: 97% Imitative: 3%
DS - Phrases	“The blue spot is on the key” and “The potato stew is in the pot.”	Pre: 1-3 Post: 1-2	“blue”, “key”, and “pot”	3	Imitative.

Table 3. Description of speech samples and tokens. “CP” refers to the cerebral palsy group; “DS” refers to the Down syndrome group; “FUP” refers to follow-up. Where more than one speech sample was collected for a single time point (e.g., 3 pre-treatment samples), each sample was collected on a separate day.

Acoustic Analyses

Tokens. See Table 3 for a summary of the tokens used. Tokens were selected to provide samples of the vowels /ɑ/, /i/ and /u/. As three separate word lists were used with participants in collecting the TOCS+ words, three sets of tokens were used for this data set: jaw/bee/two (n = 6), paw/tea/two (n=5; in one case “two” was replaced by “pooh” because a recording of “two” by that participant was cut off by an external sound), and top/bee/boo (n = 6). The three tokens used in the GFTA data set were: “watch”, “tree”, and “blue”. The three tokens used for the phrases datasets were “pot”, “key” and “blue”. Tokens produced in isolation in the recordings of phrases (e.g., “key”, instead of “on the key”), were excluded from further analysis. Vowel boundaries were marked on spectrograms using Praat software. Glides and liquids immediately preceding the vowel, including those produced in error (e.g., as in [twi] for “tree”), were included within the vowel boundaries. Tokens were excluded at the boundary-marking stage for one of two reasons: a) the vowel was cut off by an ambient sound, such as a page turning or the voice of another person in the room; and b) the vowel was whispered.

Measurement of formants. Formants were initially measured using a custom-made Praat script which extracted average F1 and F2 values over the 30 ms midsection of each vowel, and F1 and F2 values at the 24% and 64% mark of each vowel. Figure 1 provides a sample spectrogram illustrating how vowel boundaries were marked and where formant measurements were taken. Maximum formant frequency was set at 5,500 Hz for all measures, and the number of formants the script was instructed to search for ranged from three to six. The default setting used was five formants for /ɑ/ and /u/, and four formants for /i/. All spectrograms were manually reviewed using Praat’s formant tracker to verify the number of formants setting that produced the most accurate fit. Following this procedure, boxplots were produced for all measured formant values for each of the vowels for each of the data sets. A second manual review of 180 spectrograms (20%) was conducted to re-check outliers, values that appeared inconsistent or incorrect, and a sample of values that did appear correct. Following these reviews: 55 of a total of 882 tokens (6%) were removed entirely from the data sets because the values produced by the Praat script were clearly incorrect and the reviewer could not accurately identify and/or measure the formants; and the F1 and/or F2 values for 32 tokens (4%) were manually estimated at midpoint sections of the vowels where the reviewer could clearly identify the formants and they appeared stable. Twenty-one tokens were excluded from vowel space analyses only in the TOCS+ data; this was because the vowel space variables required a set of valid measurements for all three vowels at each time point, and with only one repetition available for most tokens to begin with, many sets were incomplete. No attempt was made to manually estimate formant values at the 24% and 64% points of vowels where the script was judged to have made

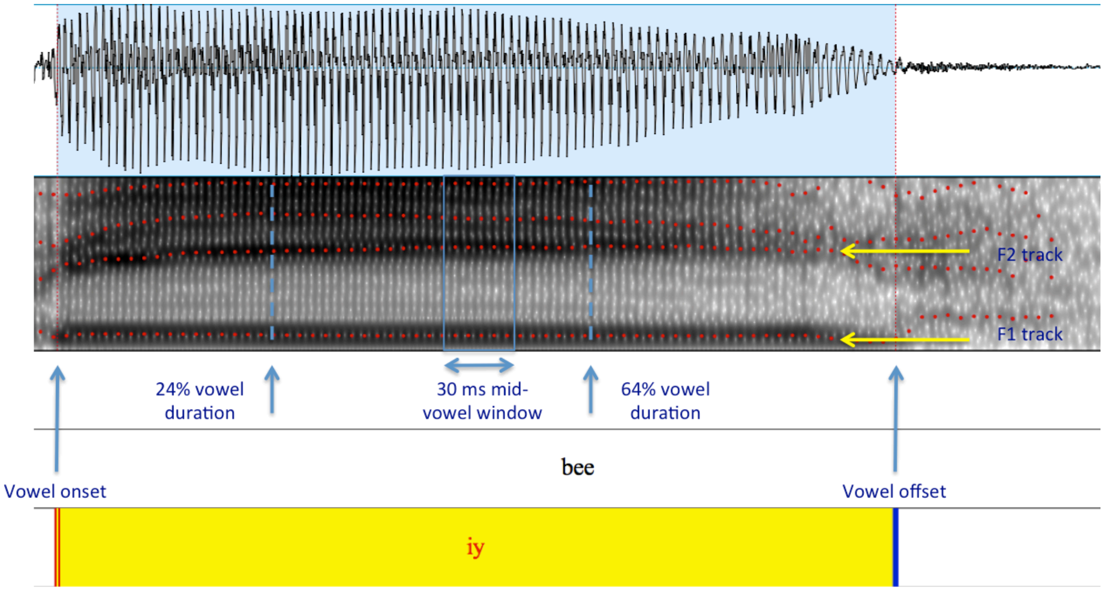

Figure 1. Sample spectrogram of the token “bee” indicating vowel boundaries and formant measurement locations.

incorrect measurements. As a result, the following data for the 24% and 64% time points were removed: the F1 values only for 17 tokens (2%), the F2 values only for 9 tokens (1%), and both the F1 and F2 values for 72 tokens (8%).

Calculation of Variables. Both vowel space and the F2i/F2u ratio were calculated using the average F1 and F2 values for each participant from the 30 ms midsections of the vowels. Vowel space was calculated as the area of a triangle formed by the locations of the three vowels in the F1-F2 space using absolute values of the equation $\Delta = 0.5(-x_2y_1 + x_3y_1 + x_1y_2 - x_3y_2 - x_1y_3 + x_2y_3)$, with x_1, x_2, x_3 = mean F1 values in Hz, and y_1, y_2, y_3 = mean F2 values in Hz. The F2i/F2u ratio was calculated using $\log_{10}$ transformed values. All formant values used in the VISC calculations were $\log_{10}$ transformed prior to any further steps. VISC for F1 and F2 were calculated in $\log_{10}$Hz as the difference between F(64%) and F(24%) for each formant of each vowel (VISCd). VISC slopes were calculated as $\log_{10}$Hz/s by dividing this difference by 40% of the vowel duration (VISCs). Both differences and slopes were calculated for F2 1) because the literature is inconsistent on which type of VISC measure best predicts speech perception (see, e.g., Morrison, 2013; Sims, Tucker, & Nearey, 2012); 2) to allow for comparisons with previous studies, noted above, where reduced F2 slopes have been correlated with dysarthria and reduced intelligibility; and 3) because VISCs, which measures rate of change in formant frequency, might be more or less sensitive to treatment effects than VISCd, which only measures the amount of change.

Variable	Description	Location of formant measurements	Calculation
Vowel triangle area	area of the triangle formed by the locations of the three vowels /i/, /u/, and /ɑ/ in the F1-F2 space	30 ms midsection of vowel	absolute values of the equation $\Delta = 0.5(-x_2y_1 + x_3y_1 + x_1y_2 - x_3y_2 - x_1y_3 + x_2y_3)$, with x_1, x_2, x_3 = mean F1 values in Hz, and y_1, y_2, y_3 = mean F2 values in Hz
F2i/F2u ratio	ratio of the values in $\log_{10}$Hz of F2 of /i/ and F2 of /u/	30 ms midsection of vowel	$\log_{10}$ F2i / $\log_{10}$ F2u
VISCd1 (for each of /i/, /u/, and /ɑ/)	the difference in $\log_{10}$Hz between F1 at 64% of the vowel and F1 at 24% of the vowel	24% and 64% points of vowel duration	$\log_{10} F1_{64\%} - \log_{10} F1_{24\%}$
VISCd2 (for each of /i/, /u/, and /ɑ/)	the difference in $\log_{10}$Hz between F2 at 64% of the vowel and F2 at 24% of the vowel	24% and 64% points of vowel duration	$\log_{10} F2_{64\%} - \log_{10} F2_{24\%}$
VISCs2 (for each of /i/, /u/, and /ɑ/)	the slope of VISCd2 (rise over run)	24% and 64% points of vowel duration	VISCd2 / [vowel duration * (64%-24%)]

Table 4. List of dependent variables. “VISC” refers to vowel inherent spectral change.

Perceptual Ratings of Single Word Intelligibility

Single word intelligibility data is from previously reported studies of the same groups of participants (Boliek & Fox [in preparation], Boliek & Fox, 2016, Boliek et al., 2016; Boliek et al., 2012; Boliek et al., 2010), and represents percent whole word correct as reported by naïve listeners. Tokens for the CP group were words and phrases from TOCS+. Tokens for the DS group were words from the GFTA. All listeners in those studies were tested for normal hearing, were aged between 18 and 60 years, had English as a first language, and no training in speech-language pathology or experience with dysarthric speech. Listeners were randomly assigned subsets of recordings to evaluate, heard each token one time, and recorded what they heard each speaker say on a form or typed directly into the computer using an open set procedure. Intelligibility was evaluated from the mean responses from a total of five listeners per speaker.

Reliability

To assess intra-measurer reliability of acoustic measurements, 10% of tokens were randomly selected and vowel boundaries were re-marked by the original measurer. The formant measures used to calculate the variables were derived using the Praat script with the same settings used for each token as in the original measurements. The intraclass correlation coefficients (ICCs) obtained for vowel space variables were: vowel triangle area (VTA), $r = 0.78$; ratio of F2i/F2u, $r = 0.85$. It should be noted that the ICCs for these variables reflect errors in six formant measurements and two formant measurements, respectively. ICCs for VISCd measurements for F1 (VISCd1) were $r = 0.97$ for /ɑ/, $r = 0.96$ for /i/, and $r = 0.87$ for /u/. ICCs for VISCd measurements for F2 (VISCd2) were $r = 0.99$ for /ɑ/, $r = 0.96$ for /i/, and $r = 0.90$ for /u/. ICCs for VISCs measurements for F2 (VISCs2) were $r = 0.99$ for /ɑ/, $r = 0.92$ for /i/ and $r = 0.87$ for /u/. The ICCs for all VISC variables reflect errors in two formant measurements; for the VISCs variables they also reflect errors in the measurement of vowel duration.

To assess inter-measurer reliability of acoustic measurements, 10% of tokens were randomly selected and vowel boundaries were re-marked by a second person trained in the protocol for determining vowel boundaries. The formant measures used to calculate the variables were derived using the Praat script with the same settings used for each token as in the original measurements. The following ICCs were obtained for vowel space variables: VTA, $r = 0.60$; ratio of F2i/F2u, $r = 0.72$. ICCs for VISCd1 were $r = 0.98$ for /ɑ/, $r = 0.96$ for /i/, and $r = 0.78$ for /u/. ICCs for VISCd 2 were $r = 0.99$ for /ɑ/, $r = 0.96$ for /i/, and $r = 0.92$ for /u/. ICCs for VISCs2 were $r = 0.96$ for /ɑ/, $r = 0.92$ for /i/ and $r = 0.83$ for /u/.

Statistical Analyses

Data for each participant at each time point was averaged to provide mean formant values, which are listed in Appendix A: Supplementary Tables 1 and 2. Because one of the CP group participants did not attend a follow-up session, the mean value of all the other participants was computed at FUP for each variable, and inserted into the data set for that participant for the purposes of comparing means between the three time points. Friedman's tests were used to compare CP group variables at PRE, POST and FUP, as all datasets either included outliers, or did not meet the assumption of normality for parametric tests, or both. Post hoc comparisons were made using Wilcoxon tests for paired samples, with no corrections consistent with liberal tolerance for Type 1 error in Phase I research (Robey, 2004). A second set of comparisons was made for CP group variables in the phrases condition excluding three participants (F1202, M6 and F7) with comorbid apraxia of speech or dysfluency diagnoses of moderate or greater severity (CP group dysarthria-only). These comparisons were not made in the single word condition, because of the already smaller sample sizes due to the reduced number of available tokens. Only four DS group participants had sufficient data to yield vowel space and VISC/u/ measurements for phrases, and these results are reported descriptively only. All other DS group variables were compared using Wilcoxon tests for paired samples, as all datasets either included outliers, or did not meet the assumption of normality for parametric tests, or both.

Results

Eleven variables were measured at each time point: VTA, the ratio of F2i/F2u, VISCd1 for each of the three vowels, VISCd2 for each of the three vowels, and VISCs2 for each of the three vowels. For summary descriptions and explanations of the variables see Table 4. N-values are reported for each variable, as insufficient tokens that met criteria (see above) were available to calculate some variables for some participants.

Vowel Space

Table 5 provides group means of the F1 and F2 values for each of the vowels used in the vowel space calculations.

CP Group. Results are reported in Table 6, which includes the medians, lower and upper quartiles and results of statistical tests for VTA and F2i/F2u. Statistically significant results were found in this group for for VTA phrases and time,for both the full group (n = 16, $\chi^2(2) = 6.125$, $p = 0.047$) and the dysarthria-only sub-group (n = 13, $\chi^2(2) = 6.000$, $p = 0.050$) (see Figures 2 and 3), and VTA single words and time (n = 12, $\chi^2(2) = 4.667$, $p = 0.097$). Post-hoc analysis with Wilcoxon signed-rank tests was conducted. Median VTA for phrases at PRE, POST and FUP were, in Hz^2, 250923, 182678, and 149295, respectively in the full group, and 256381, 182928, and 155104 respectively in the dysarthria-only sub-group. The only significant differences were between PRE and FUP, with medium-to-large effect sizes in both the full group ($Z = -2.844$, $p = 0.004$, $r = 0.41$) and the dysarthria-only sub-group ($Z = -2.900$, $p = 0.004$, $r = 0.46$), however PRE to POST also approached significance in the dysarthria-only sub-group ($Z = -1.712$, $p = 0.087$). Median VTA for single words at PRE, POST and FUP were, in Hz^2, 223575, 238445, and 275190, respectively. Post-hoc analysis with Wilcoxon signed-rank tests showed a significant difference between PRE and FUP with a medium effect size ($Z = -2.118$, $p = 0.034$, $r = 0.35$). No significant results were found for F2i/F2u.

In Figures 2 and 3 double circles represent normative values for eight-year-old males with no known speech pathologies reported in Lee, Potamianos, and Narayanan (1999).

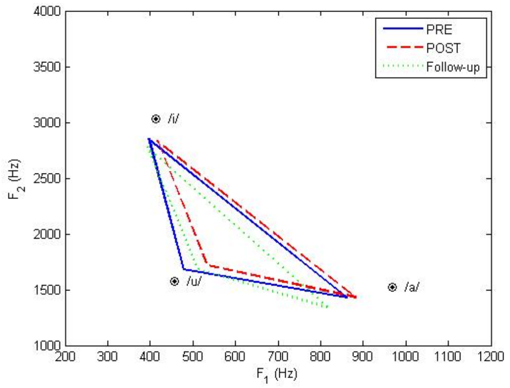

Figure 2. Vowel triangle area in phrases of children with cerebral palsy: full group.

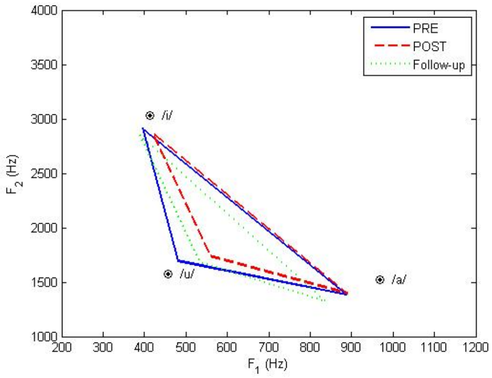

Figure 3. Vowel triangle area in phrases of children with cerebral palsy: dysarthria-only sub-group.

DS Group. There were no significant results in the single words condition for either VTA or F2i/F2u (see Table 7), however all four participants showed PRE to POST vowel space gains in both variables in the phrases condition (see Table 8 and Figures 4-7 for illustration of results). Results for the phrases condition are reported descriptively, as only four participants had sufficient valid tokens to calculate the variables, and no statistical tests could be carried out. The failure to find significance in the single word condition should be interpreted with caution, as it may be due to the small sample size.

VISC

CP Group. Table 9 reports results for all VISCd variables, and includes mean formant values at 24% and 64% of vowel durations, and results of statistical tests for both the phrases and single words conditions. Table 10 reports VISCs medians, upper and lower quartiles, and results of statistical tests for both the phrases and single words conditions. There were no significant results for any of the single word variables. The only statistically significant result in this group was for VISCd2/ɑ/ in phrases, for

	F1 ɑ PRE	F1 ɑ POST	F1 ɑ FUP	F2 ɑ PRE	F2 ɑ POST	F2 ɑ FUP	F1 i PRE	F1 i POST	F1 i FUP	F2 i PRE	F2 i POST	F2 i FUP	F1 u PRE	F1 u POST	F1 u FUP	F2 u PRE	F2 u POST	F2 u FUP
CPSingle (n=11)																		
Mean	929	937	923	1401	1380	1415	376	390	378	2864	2869	2871	520	502	482	1808	1887	1599
SD	103	122	89	219	290	232	54	86	91	381	329	331	143	87	92	403	574	227
CPPhrases (n=16)																		
Mean	863	883	820	1430	1434	1335	397	418	393	2853	2839	2779	478	534	511	1682	1718	1684
SD	153	150	137	241	213	216	58	66	73	313	385	366	77	149	108	333	284	247
DSSingle (n=8)																		
Mean	1015	932	-	1701	1531	-	479	465	-	3136	3205	-	522	592	-	2186	2267	-
SD	240	169	-	282	243	-	67	71	-	412	243	-	67	146	-	364	297	-
DSPhrases (n=4)																		
Mean	973	1036	-	1606	1537	-	413	411	-	2959	3260	-	500	487	-	1923	1719	-
SD	103	104	-	123	91	-	42	55	-	270	385	-	41	76	-	320	385	-

Table 5: Formant values at 30 ms mid-section of vowels, group means (Hz). Cerebral palsy (CP), Down syndrome (DS), single words condition (single). "FUP" refers to "follow-up"

						Post-hoc Contrasts					
	PRE	POST	FUP	Time Main Effect		PRE-POST		PRE-FUP		POST-FUP	
	median (lower quartile, upper quartile)			χ^2	*p*	*Z*	*p*	*Z*	*p*	*Z*	*p*
Phrases Full VTA (Hz^2) n = 16	250933 (123264, 354813)	182678 (62293, 250643)	149295 (53978, 214606)	6.125	0.047*	-1.344	0.179	-2.844	0.004*	-1.344	0.179
Phrases Dys VTA (Hz^2) n = 13	256381 (146549, 358472)	182928 (35524, 238589)	155105 (54089, 206317)	6.000	0.050*	-1.712	0.087†	-2.900	0.004*	-0.664	0.507
Single VTA (Hz^2) n = 12	223575 (72053, 256222)	238445 (77332, 287080)	275190 (230003, 351533)	4.667	0.097†	-0.314	0.754	-2.118	0.034*	-1.334	0.182
Phrases Full f2i/f2u n = 16	1.084 (1.054, 1.093)	1.063 (1.047, 1.083)	1.069 (1.047, 1.074)	0.875	0.646						
Phrases Dys f2i/f2u n = 13	1.081 (1.055, 1.096)	1.065 (1.044, 1.094)	1.070 (1.056, 1.081)	1.077	0.584						
Single f2i/f2u n = 12	1.053 (1.036, 1.092)	1.064 (1.029, 1.088)	1.083 (1.067, 1.102)	0.667	0.717						

Table 6. Children with cerebral palsy, vowel space measures. "Full" refers to the full cerebral palsy (CP) group; "dys" refers to the dysarthria-only CP subgroup, "single" refers to the single words condition, "FUP" refers to follow-up. Vowel triangle areas (VTA) are in Hz^2; f2i/f2u is the ratio of the mean F2 values of /i/ and /u/ in log$_{10}$Hz. VTAs are in Hz^2; f2i/f2u is the ratio of the mean F2 values of /i/ and /u/ in log$_{10}$Hz. *Statistically significant. † Approaching statistical significance.

	PRE	POST	PRE-POST Comparison	
	median (lower quartile, upper quartile)		*Z*	*p*
Single Words VTA (Hz^2) n = 8	264578 (64661, 374623)	173214 (68904, 314172)	-0.700	0.484
Single Words f2i/f2u n = 8	1.063 (1.017, 1.069)	1.036 (1.034, 1.063)	0.000	1.000

Table 7. Children with Down syndrome, vowel space measures (single words). Vowel triangle areas (VTAs) s are in Hz^2; f2i/f2u is the ratio of the mean F2 values of /i/ and /u/ in log_{10}Hz.

Participant	PRE VTA	POST VTA	PRE f2i/f2u	POST f2i/f2u
S25	282845	381906	1.081	1.087
S26	251872	825336	1.049	1.133
S28	134960	157386	1.043	1.050
S29	214446	393453	1.060	1.088

Table 8. Children with Down syndrome, vowel space measures: individual means (phrases). Vowel triangle ares (VTAs) are in Hz^2; f2i/f2u is the ratio of the mean F2 values of /i/ and /u/ in log_{10}Hz.

In Figures 4 –7, double circles represent normative values for eight-year-old males with no known speech pathologies reported in Lee, Potamianos, and Narayanan (1999).

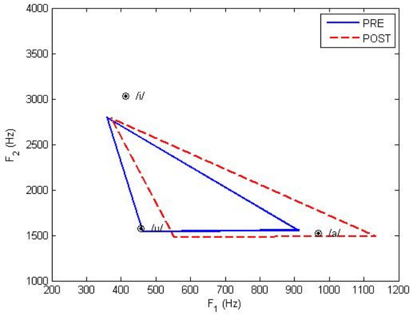

Figure 4. Vowel triangle area in phrases: participant S25.

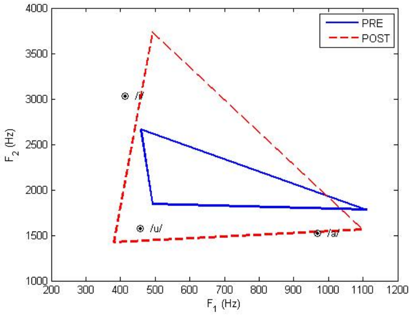

Figure 5. Vowel triangle area in phrases: participant S26.

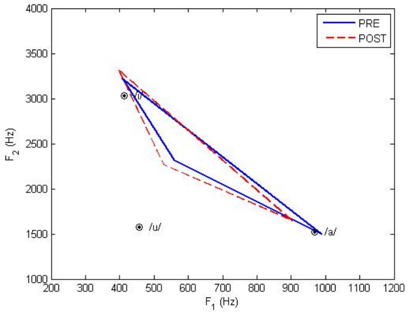

Figure 6. Vowel triangle area in phrases: participant S28.

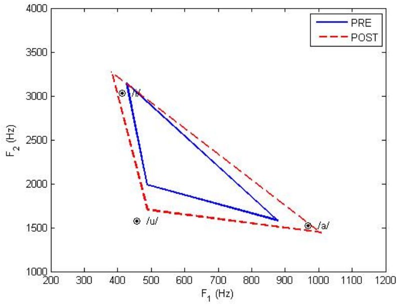

Figure 7. Vowel triangle area in phrases: participant S29.

both the full group (n = 13, $\chi^2(2) = 7.538$, $p = 0.023$) and the dysarthria-only sub-group (n = 11, $\chi^2(2) = 7.818$, $p = 0.020$). Post-hoc analysis with Wilcoxon signed-rank tests was conducted, and showed PRE-POST significance with a large effect size in both the full group (*Z* = -2.900, *p* = 0.004, *r* = 0.46) and the dysarthria-only sub-group (*Z* = -2.934, *p* = 0.003, *r* = 0.51). PRE-FUP and POST-FUP results were insignificant in both groups (*Z* = -0.524, *p* = 0.600; *Z* = -0.1572, *p* = 0.116) respectively for the full group and (*Z* = -0.978, *p* = 0.328; *Z* = -1.245, *p* = 0.213) respectively for the dysarthria-only group.

		PRE		POST		FUP		Time Main Effect	
				mean formant values (Hz)					
		24%	64%	24%	64%	24%	64%	χ^2	p
				/ɑ/ - phrases					
F1 – full (n = 12)		761	827	860	888	778	833	2.667	0.264
	ΔF	66		28		55			
F1 – dys (n = 10)		767	846	855	897	771	840	3.200	0.202
	ΔF	79		42		69			
F2 – full (n = 13)		1360	1398	1373	1457	1316	1373	7.538*	0.023*
	ΔF	38		84		57			
F2 – dys (n = 11)		1322	1347	1305	1391	1263	1325	7.818*	0.020*
	ΔF	25		86		62			
				/ɑ/ - single words					
F1 (n = 10)		851	899	845	914	856	868	3.800	0.150
	ΔF	48		69		12			
F2 (n = 11)		1461	1348	1459	1354	1420	1293	0.545	0.761
	ΔF	-113		-105		-127			
				/i/ - phrases					
F1 – full (n = 17)		396	389	407	395	389	381	0.118	0.943
	ΔF	-7		-12		-8			
F1 – dys (n = 14)		395	388	408	399	382	372	0.143	0.931
	ΔF	-7		-9		-10			
F2 – full (n = 17)		2828	2829	2805	2794	2695	2792	0.353	0.838
	ΔF	1		-11		97			
F2 – dys (n = 14)		2870	2874	2882	2843	2745	2768	0.143	0.931
	ΔF	4		-39		23			
				/i/ - single words					
F1 (n = 10)		383	375	373	387	394	351	3.200	0.202
	ΔF	-8		14		-43			
F2 (n = 10)		2799	2876	2788	2830	2774	2813	1.400	0.497
	ΔF	77		42		39			
				/u/ - phrases					
F1 – full (n = 16)		430	468	456	491	430	461	1.125	0.570
	ΔF	38		35		31			
F1 – dys (n = 13)		424	468	463	511	439	487	1.077	0.584
	ΔF	44		48		48			
F2 – full (n = 16)		1635	1518	1531	1518	1579	1560	3.375	0.185
	ΔF	-117		-13		-19			
F2 – dys (n = 13)		1588	1519	1551	1518	1511	1575	1.846	0.397
	ΔF	-69		-33		64			
				/u/ - single words					
F1 (n = 9)		498	486	504	479	493	457	1.556	0.459
	ΔF	-12		-25		-36			
F2 (n = 9)		1879	1447	1792	1395	1899	1348	0.667	0.717
	ΔF	-432		-397		-551			

Table 9. Children with cerebral palsy, vowel inherent spectral change – differences [VISCd]. "Full" refers to the full cerebral palsy (CP) group; "dys" refers to the dysarthria-only CP subgroup, "FUP" refers to follow-up. F1 and F2 values were measured at 24% and 64% of the duration of each vowel. Measures were transformed into $\log_{10}$Hz before calculating VISCd, the difference between $\log_{10}$Hz F2 values at 64% and 24% of the duration of each vowel. The χ^2 and p values reported are for the VISCd averages for individual speakers. Means were calculated using $\log_{10}$Hz formant values, and then converted back to Hz using exponentiation (i.e., they are geometric means). ΔF rows report the differences between pairs of geometric means. *Statistically significant.

	PRE	POST	FUP	Time Main Effect	
	median (lower quartile, upper quartile)			χ^2	p
/ɑ/ - phrases (full, n = 13)	0.264 (-0.080, 0.421)	0.304 (0.129, 0.465)	0.189 (-0.027, 0.515)	2.000	0.368
/ɑ/ - phrases (dys, n = 11)	0.264 (-0.194, 0.407)	0.304 (0.119, 0.451)	0.200 (-070, 0.551)	2.364	0.307
/ɑ/ - single words (n = 11)	-0.235 (-0.600, -0.063)	-0.153 (-0.498, -0.015)	-0.392 (-0.438,-0.267)	0.545	0.761
/i/ - phrases (full, n = 17)	0.014 (-0.096, 0.158)	0.037 (-0.068, 0.090)	0.036 (-0.032, 0.108)	0.000	1.000
/i/ - phrases (dys, n = 14)	0.012 (-0.076, 0.168)	0.022 (-0.113, 0.071)	0.035 (-0.064, 0.073)	1.714	0.424
/i/ - single words (n = 10)	0.024 (-0.060, 0.181)	0.038 (-0.004, 0.120)	0.032 (-0.033, 0.088)	1.400	0.497
/u/ - phrases (full, n = 16)	-0.029 (-0.539, 0.149)	0.011 (-0.489, 0.411)	0.001 (-0.272,0.418)	1.625	0.444
/u/ - phrases (dys, n = 13)	0.007 (-0.430, 0.160)	-0.007 (-0.485, 0.341)	0.003 (-0.233, 0.416)	0.462	0.794
/u/ - single words (n = 9)	-0.612 (-1.055, -0.216)	-0.716 (-0.928, -0.296)	-0.949 (1.190, -0.406)	1.556	0.459

Table 10. Children with cerebral palsy, vowel inherent spectral change – slopes (VISCs). "Full" refers to the full cerebral palsy (CP) group; "dys" refers to the dysarthria-only CP subgroup, "FUP" refers to follow-up. VISCs was calculated as the difference between $\log_{10}$Hz F2 values at 64% and 24% of the duration of each vowel, divided by vowel duration. Medians and quartiles are reported in $\log_{10}$Hz/s. For mean vowel durations see Table A3.

DS Group. Table 11 reports results for all VISCd variables, with the exception of the VISCd1/u/ and VISCd2/u/ in the phrases condition, and includes mean formant values at 24% and 64% of vowel durations, and results of statistical tests for both the phrases and single words conditions. Table 12 reports VISCs medians, upper and lower quartiles, and results of statistical tests for both the phrases and single words conditions, with the exception of VISCs/u/ in the phrases condition. All VISC results for /u/ in the phrases condition are reported in Table 13 and are descriptive only due to the small sample size (*n* = 4). There were no statistically significant results in this group, however the failure to find significance should be interpreted with caution, as it may be due to the small sample size.

	PRE			POST			PRE-POST Comparison	
	mean formant values (Hz)							
	24%	64%	ΔF	24%	64%	ΔF	*Z*	*p*
			/ɑ/ - phrases					
F1 (n = 7)	941	1021	80	1014	1094	80	-0.338	0.735
F2 (n = 7)	1677	1703	26	1644	1694	50	-1.352	0.176
			/ɑ/ - single words					
F1 (n = 8)	797	990	193	758	978	220	-0.280	0.779
F2 (n = 8)	1493	1730	237	1387	1667	280	-0.840	0.401
			/i/ - phrases					
F1 (n = 7)	428	417	-11	428	427	-1	-1.352	0.176
F2 (n = 7)	2889	2798	-91	3283	3298	15	-0.676	0.499
			/i/ - single words					
F1 (n = 6)	556	464	-92	464	431	-33	-0.524	0.600
F2 (n = 6)	2757	3181	424	2544	3157	610	-1.153	0.249
			/u/ - single words					
F1 (n = 6)	477	501	24	568	574	6	-0.338	0.735
F2 (n = 8)	2105	1944	-161	2190	1904	-286	-0.420	0.674

Table 11. Children with Down syndrome, vowel inherent spectral change – differences (VISCd). F1 and F2 values were measured at 24% and 64% of the duration of each vowel. Measures were transformed into $\log_{10}$Hz before calculating VISCd, the difference between $\log_{10}$Hz F2 values at 64% and 24% of the duration of each vowel. The χ^2 and *p* values reported are for the VISCd averages for individual speakers. Means were calculated using $\log_{10}$Hz formant values, and then converted back to Hz using exponentiation (i.e., they are geometric means). ΔF columns report the differences between pairs of geometric means.

	PRE	POST	PRE-POST Comparison	
	median (lower quartile, upper quartile)		*Z*	*p*
		/ɑ/		
Phrases (n = 7)	0.189 (-0.127, 0.286)	0.149 (0.093, 0.365)	-1.014	0.310
Single words (n = 8)	0.483 (0.375, 0.707)	0.566 (0.162, 1.199)	-1.120	0.263
		/i/		
Phrases (n = 7)	-0.035 (-0.150, 0.365)	0.067 (-0.088, 0.125)	-1.352	0.176
Single words (n = 6)	0.521 (-0.089, 1.382)	0.660 (0.351, 1.587)	-0.943	0.345
		/u/		
Single words (n = 8)	-0.220 (-0.609, 0.196)	-0.198(-0.534, -0.028)	-0.140	0.889

Table 12. Children with Down syndrome, vowel inherent spectral change – slopes (VISCs). VISCs was calculated as the difference between $\log_{10}$Hz F2 values at 64% and 24% of the duration of each vowel, divided by vowel duration. Medians and quartiles are reported in $\log_{10}$Hz/s.

	PRE			POST			VISCd		VISCs	
	Mean Formant Values									
participant	24%	64%	ΔF	24%	64%	ΔF	PRE	POST	PRE	POST
S25 F1	448	457	9	529	569	40	0.005	0.034		
S25 F2	1502	1630	128	1400	1494	94	0.033	0.029	0.151	0.259
S26 F1	487	474	-13	388	424	36	-0.012	0.039		
S26 F2	1703	1682	-21	1670	1681	11	-0.031	0.010	-0.266	0.096
S28 F1	517	557	40	471	546	75	0.031	0.069		
S28 F2	2322	2278	-44	2118	2330	212	-0.011	0.042	-0.045	0.393
S29 F1	461	473	12	441	499	58	0.012	0.058		
S29 F2	1854	2143	289	1596	1825	229	0.067	0.059	0.293	0.622

Table 13. Children with Down syndrome, vowel inherent spectral change (VISC): individual means (/u/ in phrases). Means were calculated using $\log_{10}$Hz formant values, and then converted back to Hz using exponentiation (i.e., they are geometric means). ΔF columns report the differences between pairs of geometric means. VISC differences (VISCd) were calculated as the difference between $\log_{10}$Hz F2 values at 64% and 24% of the duration of each vowel. VISC slopes (VISCs) were calculated as VISCd divided by vowel duration.

Intelligibility

CP Group. Group averaged intelligibility data are reported separately for two cohorts of participants: LSVT I (F601, F801, F802, F1001, F1201, F1202, M901 and

M1001), and LSVT II (F1, M2, F3, M4, M5, M6, F7, M8, M9) in Table 14, and indicate significant PRE to POST and PRE to FUP gains for both cohorts, using a liberal α of 0.10, consistent with Phase I research (Robey, 2004).

	PRE-POST Comparison				PRE-FUP Comparison			
% Whole Word correct	Mean differences (SD)	*t*-value	*p*-value	Cohen's *d*	Mean differences (SD)	*t*-value	*p*-value	Cohen's *d*
LSVT I – single words (TOCS+)	7.28% (6.36%)	3.02	0.01	0.35	4.71% (7.22%)	1.69	0.09	0.42
LSVT II – single words (TOCS+)	1.37% (6.77%)	0.61	0.56	0.05	4.48% (7.-7.03%)	1.91	0.09	0.18
LSVT II – phrases (TOCS+ sentences)	9.61% (7.06%)	4.08	0.004	0.31	6.76% (7.88%)	2.57	0.03	0.22

Table 14. Children with cerebral palsy, intelligibility data: percent whole world correct. FUP refers to "follow-up"; "TOCS+" refers to the *Test of Children's Speech Plus*.

DS Group. Intelligibility data for the DS group are reported in Table 15, and indicate significant PRE to POST gains, using a liberal α of 0.10, consistent with Phase I research (Robey, 2004).

% Whole Word correct	Mean differences (SD)	*t*-value	*p*-value	Cohen's *d*
Single words - GFTA	4.44% (8.62%)	1.55	0.08	0.27

Table 15. Children with Down syndrome, intelligibility data: percent whole word correct, pre- to post-treatment comparison; "GFTA" refers to the *Goldman-Fristoe Test of Articulation* 2.

Discussion and Conclusions

The purpose of this Phase I treatment study was to test for acoustic changes, specifically to vowel working space, and vowel inherent spectral change (VISC), in the speech of two groups of children with dysarthria and cerebral palsy (CP) or Down syndrome (DS), who received full doses of LSVT LOUD, and who had previously shown indications of improved speech intelligibility following treatment. Statistically significant PRE to POST (CP and DS groups) and PRE to 12 weeks follow up (FUP) (CP group only) gains in percent whole word correct, one measure of speech intelligibility, have previously been observed in the same participants. In the CP group, statistically significant results from the acoustic measures tested in the present study were: 1) PRE to

FUP decrease in vowel triangle area (VTA) – phrases condition; 2) PRE to FUP increase in VTA – single words condition; and 3) PRE to POST increase in VISC for F2 of /ɑ/, measured as the difference between formant values at onset and offset, in the phrases condition only. Both results in the phrases condition retained their significance when retested in a sub-group excluding those with moderate or greater comorbid dysfluency or apraxia of speech. There were no statistically significant results in the DS group, possibly as a result of the small sample size, however all four participants in the phrases condition showed PRE to POST gains in VTA, which were reported descriptively.

Vowel Space Area

The CP group results for VTA were surprising because the direction of change in the phrases condition was a decrease in VTA, which suggests a smaller vowel working space, and because this finding conflicted with that in the single word condition, which did show an increase in VTA as predicted. As described above, previous dysarthria research has correlated reduced vowel working space with lower speech intelligibility (see, e.g., Higgins & Hodge, 2002; Liu et al., 2005), yet the participants in this study showed speech intelligibility increases both PRE to POST and PRE to FUP. One possibility, especially given the heterogeneity of the group's ages, neurological and dysarthria diagnoses, and dysarthria severity ratings, is that individual participants responded very differently to the therapy, and that the group study design obscures some treatment effects by aggregating results from strong responders, weak responders, and non-responders (see, e.g., discussions in Nip, 2017; Wenke, Cornwell, & Theodoros, 2010; and Youssef, Anter, & Hassen, 2015). A second possibility is that the VTA metric using the three corner vowels /ɑ/, /i/, and /u/, is not a sensitive enough measure of vowel working space; measures that incorporate formants from more vowels might provide more accurate representations of articulatory function (see, e.g., Lansford & Liss, 2014b; Sandoval, Berisha, Utianski, Liss, & Spanias, 2013).

It also is possible that for some participants in the phrases condition, the treatment resulted in changes to speech physiology that, while they reduced vowel working space, were compensated for by greater articulatory precision. For example, Kim et al., (2010) describe a trading relationship between F1 precision and vowel space size in one of their control participants: despite a smaller vowel space, the participant maintained vowel distinctiveness because of relatively little F1 variability. The conflicting findings in the single words condition could be related to task differences (i.e., repeating a phrase, which would have had increased breath support and/or cognitive demands, as compared with repeating a single word), to differences in which participants' data was included in each of the two conditions, to the reliance on single tokens for most vowels in the single word condition (compared with up to three tokens at each time in the phrases condition), and/or to differences in the coarticulatory contexts for the target vowels. It is possible that, due to task demands, vowel duration was shorter in the phrases condition than in the single words condition, particularly since two of the three tokens used in the phrases condition ("key" and "pot") were at the end of the utterances when breath support may have been taxed. If so, longer vowel durations in the single words condition might have allowed participants additional time to reach more distinctive articulatory targets, which would result in increased VTA. It is interesting that although the results from the single words condition correspond to the prediction that treatment would produce a larger VTA, the intelligibility results for one cohort (LSVTII) were better in the phrases condition than in the single words condition. This suggests the possibility that, as for the participant in Kim et al.’s (2010) study, a strategy of greater articulatory consistency might be more effective in running speech for at least some speakers with dysarthria and CP than a strategy of producing more distinctive vowels that also reduces speaking rate.

While the comparisons between formant values for participants in this study in the phrases condition and the norms illustrated in Figures 2 and 3 should be treated with caution due to differences in age, dialect, speech context, and other factors, the most apparent difference is the decreased F1/ɑ/ in the CP group compared with norms for healthy speakers at PRE, POST and FUP. The vowel /ɑ/ typically features a relatively high F1 and a relatively small gap between F1 and F2 (see, e.g., the values reported in Lee et al., 1999). A lower F1 would be expected to correspond to a higher tongue position (see, e.g., Hixon et al., 2014) and reduced distinctiveness of /ɑ/ from central and mid-back vowels. The lower F1/ɑ/ values observed in the present study are inconsistent with Higgins and Hodge’s (2002) finding of higher F1/ɑ/ values in children with dysarthria compared with controls, but are consistent with Levy et al.’s (2016) finding of a trend of /ɑ/ as having the lowest intelligibility of vowels in children with CP and dysarthria. Examination of Figures 2 and 3 suggests that the statistically significant PRE to FUP change in VTA was primarily a manifestation of decreased F1 and F2 values for /ɑ/ at FUP and, to a lesser extent, increased F1 values for /u/, with little change in the /i/ formants. The direction of movement in F1/ɑ/ from PRE to FUP is unexpected as it suggests a further reduction in vowel distinctiveness, and is inconsistent with Youssef et al.’s (2015) finding of higher F1/ɑ/ values post LSVT LOUD, however the lower F2/ɑ/ and higher F1/u/ are both consistent with the results of that study. The decrease in F2/ɑ/

would be consistent with increased tongue movement toward the back of the oral cavity (see, e.g., Hixon et al., 2014), and might help to offset the low F1 values by narrowing the gap between the two formants, which could explain some of the improvement in intelligibility. This combination of formant changes might be consistent with a wider opening of the jaw, without a corresponding lowering of the tongue. Finally, the finding of significant changes PRE to FUP but not PRE to POST might be explained as the result of some treatment effects taking longer to manifest than others, perhaps as some participants continued to practice skills learned in therapy, or perhaps as slow phase learning of motor skills (Boliek & Fox, 2016). This result differs from the results of both Youssef et al. (2015) and Wenke et al. (2010), who found significant PRE to POST changes that were maintained at FUP only in the latter study. This inconsistency between the findings of the present study and those of Youssef et al. and Wenke et al. could reflect differences in how LSVT LOUD treatment effects occur in children and adults, and/or in participants with different types of dysarthrias.

In the DS group, VTA did increase PRE to POST as predicted in all four of the participants in the phrases condition. The single-word condition did not produce a statistically significant result, however four of eight participants also showed increased VTAs, including three of the four participants in the phrases condition. The similarity of results occurred despite differences between the tokens used in the datasets, namely the single-word tokens were nearly all spontaneously produced (i.e., without the benefit of modeling) in contrast with the phrases, which were directly imitated by participants; and in the single word condition the token “watch” was used for /ɑ/, which might have influenced VTA values through coarticulatory effects of the linguolabial glide persisting at mid-vowel where the formant measurements used in the calculations were taken. An examination of Figures 4-7 shows striking variance in magnitude and direction of vowel space increase among the four participants in the phrase condition. Only one participant (S26 – see Figure 5) showed significant movement for the vowel /i/. In one of the three pre-treatment speech samples taken, this participant presented with exceptionally poor voice quality, which produced F2 values around 1300 Hz. As results were averaged across the three samples, the initial low value of F2 for /i/ illustrated in Figure 5 is likely not representative of S26's typical performance. Three of four participants show noticeably higher F1 values for /ɑ/ at POST, and all four participants show lower F2 values for /u/, although these vary in magnitude. These results are consistent with previous findings with respect to F1/ɑ/ and F2/u/ post LSVT LOUD treatment (Wenke et al., 2010; Youssef et al., 2015), as well as Moura's (2008) observations in children with DS of 1) lower F1/ɑ/ values, which the author attributed to more limited jaw movement and mouth opening, and 2) smaller f2i/f2u ratios, which the author attributed to higher F2/u/ values due to restricted tongue movement in the high back position. As noted above, the higher F1 /ɑ/ value would be consistent with a lower tongue position and possibly a more open jaw, and a lower F2 /u/ value would be consistent with a less forward tongue position (see, e.g., Hixon et al., 2014). Both of these changes would be consistent with less centralization and more distinctive productions of the two vowels.

Vowel Inherent Spectral Change (VISC)

The data from phrase repetition in the CP group showed statistically significant PRE to POST increases in VISC for the F2 of /ɑ/, in onset-offset difference. The mechanisms through which VISC affects speech perception are not yet well understood, and it is known that age, dialect and coarticulatory context may all contribute to variability in VISC (see, e.g. Assmann, Nearey, & Bharadwaj, 2013; Nearey, 2013). As an example of how context may affect VISC, values reported by Nearey (2013) for Alberta English show mean F2 differences between 20% and 70% of vowel duration of 32.9 Hz for [pɑ], and 175.5 Hz for [pɑt]. The token used in the CP group was "pot", which was pronounced by some participants as [pɑt], and by others as [pɑ]. It is therefore difficult to compare the values measured in this study's participants with those of typical speakers reported in the literature. As described above, decreased speech intelligibility has previously been correlated with shallower F2 slopes, (see, e.g., Lee et al., 2014), though not specifically for /ɑ/, and not in terms of onset-offset difference alone (as opposed to rate of change). The present results must therefore be interpreted with caution, as there are limited comparators available in the literature. The change to the VISC (difference) for the F2 of /ɑ/ in the CP group does suggest increased forward movement of the tongue (see, e.g. Hixon et al., 2014) over the vowel duration. One possibility is that this increase in F2 change represents a gain in acoustic cues that help listeners to identify the vowel. Another is that participants' articulatory coordination has improved so that they have a better tongue placement toward the back of the oral cavity at vowel onset, resulting in an initial lower F2, but are unable to maintain this placement through the course of the vowel.

Treatment Effects

The combined findings with respect to vowel space and VISCd2 /ɑ/ suggest within participant changes in jaw and tongue movement, particularly in the context of low vowels, and, to a lesser extent, high back vowels, in both the CP and DS groups following LSVT LOUD treatment. The evidence for changes in production of the vowel /ɑ/ is especially interesting in light of the emphasis on repetitions of “ah” in the treatment protocol, and previous findings that /ɑ/ may be particularly difficult to distinguish in dysarthric speakers (e.g. Levy, 2016). Repeated practice producing “ah” at various pitches, a task initially designed to target the laryngeal system, may also have the effect of improving coordination and extent of jaw opening. In dysarthric speakers with DS, the tongue may lower with the jaw, resulting in higher F1 /ɑ/ values closer to canonical targets, and overall increased vowel working space. In dysarthric speakers with CP, the tongue might initially retract rather than lower with the jaw, resulting in lower F2 /ɑ/ values closer to canonical targets. The finding of increased VISCd2 /ɑ/ in the CP group suggests those speakers may have difficulty maintaining that initial retracted tongue position over the course of the vowel. While the exact physiological changes behind the acoustic changes, and the exact mechanisms by which these changes might account for improved intelligibility, are not entirely clear, the present findings do together provide strong evidence of treatment spreading effects on the articulatory system, adding to the body of similar findings in the literature on LSVT LOUD (Sapir et al., 2007; Sauvageau et al., 2015; Wenke, Cornwell, & Theodoros, 2010; Youssef et al., 2015).

Limitations and Future Directions

As suggested above, one limitation of the present study is that the heterogeneity of the CP group in particular may have masked some treatment effects; future studies might use sub-groups chosen for common characteristics (e.g., severity of dysarthria diagnosis) with the aim of identifying factors that might predict strength of response to LSVT LOUD therapy (Boliek & Fox, 2014). Larger sample sizes also would be desirable to increase statistical power. The data used in this study was not originally collected for the purposes of analysis of formants, and future studies designed for this purpose might control vowel contexts more carefully (e.g., by excluding tokens with glides and liquids preceding or following the vowel), exclude tokens which children are likely to make articulation errors on (e.g., consonant blends such as in the word “tree”, which was pronounced in several different ways by participants in the Down syndrome group, including [tri], [twi], [ti], [tʃi], and [fi]), and ensure more repetitions by participants at each time. Tokens could also be chosen to allow for calculation of acoustic vowel space using an expanded set of vowels (e.g., Sandoval et al., 2013), which might be more sensitive to treatment effects. Analyses of different types of speech tasks, for example, conversational speech and read speech (for participants who have that capacity) would also be beneficial. Future research also could consider whether and how the current LSVT LOUD treatment protocol (e.g., intensity and program length), which was developed for individuals with PD, might be modified to maximize results for pediatric populations with dysarthria secondary to CP or DS (e.g., dose, maintenance), and whether or not treatment effects are similar to those of other therapies targeting multiple speech sub-systems (e.g., Pennington et al., 2010).

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APPENDIX A: Supplementary Tables

Participant	F1 ɑ PRE	F1 ɑ POST	F1 ɑ FUP	F2 ɑ PRE	F2 ɑ POST	F2 ɑ FUP	F1 i PRE	F1 i POST	F1 i FUP	F2 i PRE	F2 i POST	F2 i FUP	F1 u PRE	F1 u POST	F1 u FUP	F2 u PRE	F2 u POST	F2 u FUP
Single Words																		
F1001	983	1044	932	1396	1647	1544	334	304	287	2950	3088	3237	491	431	531	2187	2086	1476
F1201	1013	984	975	1118	1230	1166	453	554	543	2772	2564	2720	420	599	547	1486	1797	1280
F3	844	968	978	1323	1333	1487	404	494	434	3175	2900	2981	533	532	494	1601	1702	1632
F601	1110	1127		1447	1196		334	398		2982	2967		596	652		2130	2489	
F7	1007	999	990	1644	1768	1821	323	275	318	2792	2978	2813	467	506	491	1833	1792	1739
F802	948	1015	960	1307	1378	1288	326	385	364	3279	3400	3415	509	561	600	2609	2125	1693
M1001	881	955	802	1863	1940	1713	420	405	488	2416	2827	2497	844	519	506	1672	2906	2017
M2	827	962	867	1077	1044	1166	431	474	401	2711	2537	2495	469	487	459	1416	1294	1357
M4	735	676	729	1465	1310	1205	286	277	282	3050	2605	2617	311	339	297	1346	1137	1498
M6	955	817	998	1341	1070	1351	403	349	303	3024	3025	2946	377	387	337	2297	2637	1445
M8	990	889	1007	1569	1549	1605	364	412	452	3275	3274	3299	702	481	565	1524	1286	1543
M901	851	810	915	1264	1088	1217	431	354	291	1948	2257	2565	527	532	478	1595	1397	1911
Phrases																		
F1	938	996	941	1336	1380	1282	392	455	402	3132	3209	3098	374	364	404	1344	1281	1296
F1001	929	860	719	1458	1277	1511	347	345	305	3256	2733	2753	414	454	476	1465	1690	1625
F1201	849	905	908	1235	1510	1238	479	492	452	2761	2569	2787	535	639	657	2255	2163	1947
F1202	611	627	516	1631	1642	1040	438	459	424	2535	2160	2157	395	320	385	1321	1445	1525
F3	857	881	837	1410	1308	1216	393	400	382	3021	3008	2984	513	503	500	1869	1884	1844
F601	1128	1092	-	1978	1785	-	453	549	-	3056	2792	-	639	965	-	1998	1992	-
F7	1025	1080	1040	1782	1792	1815	416	436	427	2762	2745	2785	488	492	495	1472	1490	1658
F801	1025	1001	906	1309	1407	1573	444	419	371	3255	3377	3013	494	553	740	2163	2019	2097
F802	971	1030	978	1375	1512	1357	330	408	514	3453	3634	3561	500	633	614	1749	1672	2013
M1001	764	666	768	1668	1691	1592	449	444	461	2414	2302	2317	561	537	529	2024	1865	1862
M2	832	885	816	1243	1152	1168	412	416	390	2543	2565	2462	486	533	474	1412	1635	1535
M4	725	599	685	1277	1534	1138	264	271	276	2743	2551	2638	353	358	362	1394	1140	1397
M5	998	969	833	1483	1269	1462	426	474	497	2817	3057	3282	519	622	599	1387	1658	1402
M6	617	845	692	1455	1337	1290	357	343	390	2439	3111	2550	519	468	380	2079	1943	1919
M8	856	850	923	1235	1190	1276	327	384	316	2836	2747	2678	383	546	539	1637	1986	1602
M9	677	849	735	998	1151	1075	423	389	289	2629	2859	2615	472	563	517	1345	1620	1544
M901	938	996	941	1336	1380	1282	392	455	402	3132	3209	3098	478	364	404	1344	1281	1296

Table A1: Children with cerebral palsy individual average formant values at 30 ms mid-section of vowels (Hz). “FUP” refers to follow-up.

	F1	F1	F2	F2	F1	F1	F2	F2	F1	F1	F2	F2
Participant	ɑ	ɑ	ɑ	ɑ	i	i	i	i	u	u	u	u
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST
Single Words												
S21	1465	1088	1799	1583	529	573	3894	3357	616	572	2296	
S22	777	716	1581	1391	460	451	2570	3180	493	427	2595	2406
S23	1142	893	1817	1760	499	404	3071	3095	449	714	1966	2337
S24	998	789	2074	1237	545	513	3378	3497	552	774	1893	2781
S25	987	921	1544	1526	354	400	3019	2888	419	352	1797	1614
S26	1163	1211	2050	1928	419	401	3395	3565	562	638	2608	2715
S28	739	798	1281	1231	546	552	2789	3047	577	704	2546	2332
S29	848	1039	1464	1593	484	428	2972	3014	508	551	1791	1885
Phrases												
S25	912	1134	1554	1490	358	371	2798	2793	462	553	1543	1482
S26	1111	1100	1783	1563	459	492	2664	3737	492	380	1846	1423
S28	988	903	1502	1651	407	399	3225	3236	558	528	2313	2267
S29	879	1008	1583	1443	426	382	3147	3272	487	489	1990	1704

Table A2: Children with Down syndrome individual average formant values at 30 ms mid-section of vowels (Hz). “FUP” refers to follow-up.

	PRE			POST			FUP		
	ɑ	i	u	ɑ	i	u	ɑ	i	u
CP Group (full) - Phrases	0.288	0.305	0.403	0.274	0.386	0.435	0.281	0.424	0.507
CP Group (dysarthria only) - Phrases	0.203	0.289	0.389	0.266	0.349	0.447	0.272	0.329	0.454
CP Group – Single Words	0.383	0.536	0.639	0.379	0.538	0.569	0.400	0.535	0.676
DS Group – Phrases	0.218	0.256		0.228	0.298				
DS Group – Single Words	0.314	0.281	0.353	0.267	0.288	0.414			

Table A3: Average vowel durations (s) for children with cerebral palsy (CP) and children with Down syndrome (DS). “FUP” refers to follow-up.