

Research Article

Range and Precision of Formant Movement in Pediatric Dysarthria

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Purpose: This study aimed to improve understanding of speech characteristics associated with dysarthria in children with cerebral palsy by analyzing segmental and global formant measures in single-word and sentence contexts.

Method: Ten 5-year-old children with cerebral palsy and dysarthria and 10 age-matched, typically developing children participated in this study. Vowel space area and second formant interquartile range were measured from children's elicited productions of single words and sentences.

Results: Results showed that the children with dysarthria had significantly smaller vowel space areas than typically

developing children in both word and sentence contexts; however, overall ranges of second formant movement did not differ between groups in word or sentence contexts. Additional analysis of single words revealed that, compared to typical children, children with dysarthria had smaller second formant interquartile ranges in single words with phonetic contexts requiring large changes in vocal tract configuration, but not in single words with monophthongs.

Conclusions: Results of this study suggest that children with dysarthria may not have globally reduced ranges of articulatory movement compared to typically developing peers; however, they do exhibit reduced precision in producing phonetic targets.

Articulatory imprecision is a hallmark characteristic of dysarthria (Darley, Aronson, & Brown, 1969) and a primary contributor to intelligibility deficits associated with this disorder (De Bodt, Hernandez-Diaz, & Van De Heyning, 2002; J. Lee, Hustad, & Weismer, 2014; Weismer, Jeng, Laures, Kent, & Kent, 2001). For children with cerebral palsy (CP), articulatory imprecision is a common perceptual feature of dysarthria (Hustad, Gorton, & Lee, 2010; Nip, 2013, 2017; Workinger & Kent, 1991). Prior research has identified acoustic correlates of reduced intelligibility in children with CP (Higgins & Hodge, 2002; Hsu, Chen, & Cheng, 2013; Hustad et al., 2010; J. Lee et al., 2014); however, little is known empirically about the movement characteristics underlying this imprecision in children with CP. Such information is essential for understanding the articulatory basis of intelligibility deficits in children with dysarthria and developing improved intervention strategies.

Acoustic Indicators of Articulatory Imprecision

Formant measures have been used extensively as a noninvasive method for studying speech motor patterns in both typical speakers and disordered populations (R. D. Kent, Weismer, Kent, Vorperian, & Duffy, 1999; Weismer & Martin, 1992). Although formants do not directly measure articulatory movement, many studies have demonstrated strong correspondence between acoustic measurements and articulatory movements (Fant, 1960; Mefferd & Green, 2010; Rong, Loucks, Kim, & Hasegawa-Johnson, 2012; Stevens & House, 1961; Wang, Green, Samal, & Yunusova, 2013). In speakers with dysarthria, various formant measures have been used to quantify vowel distinctiveness as an indicator of the precision of vowel articulation. Studies have shown that reductions in multiple measures of vowel distinctiveness in speakers with dysarthria are related to reduced intelligibility and degraded vowel perception by listeners (Lansford & Liss, 2014; Neel, 2008). Reduced acoustic distinctiveness of phonemes in speakers with dysarthria is assumed to be due to imprecise articulation associated with impaired speech motor control. Thus, acoustic metrics of vowel production can be interpreted as an index of articulatory precision in speakers with dysarthria; however, formant measures of individual speech segments do not, alone, provide adequate information to make inferences about the movement characteristics underlying articulatory imprecision.

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Utterance-level formant measures, such as second formant (F2) range, provide complementary information that can be interpreted to reflect a speaker's more global articulatory movement characteristics. Together, segmental and utterance-level formant measures may be able to provide information about children's speech movements better than segmental measures alone.

One of the most widely studied segmental acoustic measures in both adult and pediatric populations is acoustic vowel space area. Across studies, findings have shown that speakers with dysarthria have reduced vowel space areas compared to normal speakers, and that vowel space area explains a significant amount of variance in intelligibility. In adults, these findings have been replicated in studies of speakers with amyotrophic lateral sclerosis (ALS), Parkinson's disease, multiple sclerosis, stroke (Turner, Tjaden, & Weismer, 1995; Weismer et al., 2001), and young adults with CP (Liu, Tsao, & Kuhl, 2005). Reduced vowel space area in adults with dysarthria has been found in single-word contexts (Liu et al., 2005), as well as in connected speech (Tjaden, Lam, & Wilding, 2013; Turner et al., 1995; Weismer et al., 2001). Studies of children have consistently found that reduced vowel space area is associated with dysarthria and correlated with reduced intelligibility in pediatric populations (Higgins & Hodge, 2002; Hustad et al., 2010; J. Lee et al., 2014); however, to date, studies of vowel space area in children with CP have exclusively examined single-word productions, and it is currently unknown whether findings indicating reduced vowel space area also apply to connected speech.

Reduced vowel space area is commonly interpreted as an indication that speakers with dysarthria tend to undershoot acoustic targets and use smaller acoustic working spaces than healthy controls, suggesting that a reduction in range of articulatory movement underlies imprecise production of corner vowels (R. D. Kent & Kim, 2003). However, vowel space areas are based on static measurements of first and second formant frequencies (F1 and F2) taken at the temporal midpoint of corner vowel productions (Higgins & Hodge, 2002; J. Lee & Hustad, 2013; Liu et al., 2005; Tsao, Weismer, & Iqbal, 2006). Although it is assumed to reflect the range of horizontal and vertical movement used by speakers between extreme articulatory positions, this measure provides a very limited sampling of the frequencies used by speakers over the course of an entire production, and may be too sparse to accurately characterize the range of formant frequencies used by speakers.

In contrast, measures of F2 range may provide a more accurate reflection of the range of articulatory movement used by speakers than vowel space area, and can be measured at an utterance level or segmental level. At an utterance level, measures of F2 range are derived from time histories of F2 traces across all vocalic segments in an utterance, and thus take into account the full range of F2 frequencies used by a speaker. Thus, one way to interpret F2 range is as a reflection of a speaker's range of articulatory movement. If speakers with dysarthria have restricted ranges of articulatory movement, this should be reflected by a reduction in F2 range at an utterance level.

F2 range can also be measured for specific phonemes. Many phonetic contexts, including consonant–vowel transitions and diphthongs require large changes in vocal tract configuration and, thus, large F2 transitions. Prior research has suggested that such phonetic contexts may be more sensitive to dysarthria than overall measures of F2 range in adult speakers with mild dysarthria (Rosen, Goozee & Murdoch, 2008), as phonemes requiring larger vocal tract excursions have greater speech motor demands and thus may be more likely to be affected by speech motor impairment (SMI). F2 range of segments requiring large changes in vocal tract configuration can be interpreted to reflect precision of executing these phonemes, and may or may not be associated with a global reduction in F2 range. If speakers with dysarthria have overall restricted ranges of articulatory movement, we would expect F2 range to be reduced at both a segmental and utterance level; however, if articulatory imprecision is not due to global reductions in articulatory movement, F2 range may be reduced in certain phonetic contexts, but not at an utterance level.

Articulatory Imprecision in Children With Dysarthria

In studies of adults with acquired dysarthria, converging evidence from acoustic and kinematic studies supports the hypothesis that speakers with dysarthria have reductions in articulatory range of movement manifested in both reduced precision in reaching corner vowel acoustic targets and in reduced overall F2 range. Acoustic studies have shown that speakers with dysarthria due to Parkinson's disease and ALS have reduced vowel space areas (Turner et al., 1995; Weismer et al., 2001) and smaller F2 ranges than healthy controls in connected speech (Rosen, Kent, Delaney, & Duffy, 2006; Yunusova, Weismer, Kent, & Rusche, 2005), and that F2 interquartile range (F2 IQR) was significantly correlated with intelligibility (Yunusova et al., 2005). In addition, kinematic studies have also indicated reductions in range and speed of tongue movement in speakers with dysarthria due to ALS (Green et al., 2013).

Far less is known about articulatory imprecision in children with dysarthria, and the findings from adult literature on dysarthria may not be generalizable. In children, abnormal speech movements are occurring within the context of substantial shifts in vocal tract size and geometry, as well as in articulatory control and coordination. Growth of the vocal tract lowers formant frequencies, whereas refinement of speech motor control with age results in improved accuracy in producing acoustic targets (Vorperian & Kent, 2007). Speech movement variability is known to be greater in children than adults (Smith & Zelaznik, 2004; Walsh & Smith, 2002), and coordination of articulatory movements changes dramatically over the first 6 years of life (Green, Moore, Higashikawa, & Steeve, 2000). For children with CP, both developmental factors and neurological factors influence speech movements. The neurological basis of dysarthria in CP is variable, but is most frequently related to damage to cortical sensorimotor pathways, which

differs from the progressive upper and lower motor neuron involvement in ALS and the basal ganglia involvement in Parkinson's disease.

Prior research has yielded conflicting evidence regarding how articulatory movement in children with CP is restricted relative to typically developing (TD) children. One study found that children with CP and dysarthria had shallower F2 slopes and shorter F2 extents than TD children in production of diphthongs (J. Lee et al., 2014). In contrast, kinematic studies have found that children with CP tend to use larger jaw excursions than typical children, possibly reflecting inefficient motor control or compensatory movement (R. Kent & Netsell, 1978; Nip, 2013). Thus it is unclear from extant research whether or not global restrictions in articulatory movement contribute to imprecise articulation in children with dysarthria secondary to CP. In addition, it is unknown which acoustic measures of articulation most strongly relate to speech intelligibility in children with CP. Identifying speech characteristics that contribute most to intelligibility impairment is important for understanding which aspects of speech performance are having the most detrimental impact on communication function and identifying potential treatment targets.

Moreover, CP is a very heterogeneous disorder, and thus there is wide individual variability in speech characteristics among children with the diagnosis. Variability can result from individual differences in speech motor patterns (Allison & Hustad, 2014) as well as severity of speech motor involvement (J. Lee et al., 2014). Few studies have investigated these factors directly; however, larger standard deviations in F2 slope and vowel space area among children with CP and dysarthria compared to children without dysarthria have been reported (J. Lee et al., 2014). One recent study investigated how severity of speech motor involvement influenced change in vowel space area longitudinally in children with CP (J. Lee & Hustad, 2013). Results showed that change in vowel space area between the ages of 4 and 6 years differed depending on dysarthria severity. To be specific, children with severe dysarthria showed decreased vowel space area over the 2-year time span, whereas children with mild and moderate dysarthria did not show significant changes in vowel space area. Children at all severity levels showed increased intelligibility over time; however, this was only statistically significant for the mild and severe dysarthria groups (J. Lee & Hustad, 2013).

Acoustic studies of vowel space area and range of formant movement collectively provide complementary information that can be used to more fully characterize the speech patterns of children with dysarthria. To our knowledge, no previous studies have examined vowel space area or F2 range in connected speech of children with dysarthria. Examining global formant movement characteristics in conjunction with segmental formant measures, such as vowel space area, will enhance understanding of the underlying basis of articulatory imprecision in children with CP. In addition, determining how these acoustic measures relate to intelligibility will provide important information about the relative contribution of global and segmental

speech characteristics to intelligibility impairment in children with CP. This has important clinical implications, as improved characterization of speech movement patterns in children with dysarthria has the potential to inform development of more effective intervention methods.

In the current study, we aimed to expand our understanding of formant movement characteristics in children with dysarthria secondary to CP by investigating vowel space area and F2 range in both single-word and sentence contexts. To be specific, we sought to investigate the following questions: (a) Do children with dysarthria due to CP show differences in vowel space area compared to TD children in both single-word and sentence contexts? (b) Do children with dysarthria due to CP show differences in F2 range compared to TD children in both single words and sentences, and are these differences influenced by phonetic context? (c) How do acoustic measures (vowel space and F2 IQR) relate to overall intelligibility for children with CP and dysarthria? If children with dysarthria secondary to CP have an overall reduction in range of articulatory movement, we would expect them to demonstrate reductions in vowel space area and F2 range in both single-word and sentence contexts, compared to TD peers. We would also expect that a measure of F2 range in sentences would be most related to intelligibility, as it most comprehensively reflects range of articulatory movement in sentences. In contrast, if children with CP have impairments in precision of articulatory movements but not an overall reduction in range of movement, we would expect reduced vowel space area in words and sentences and reduced F2 range in words with large F2 transitions, but no reduction in overall F2 range in sentences. We would also expect segmental measures to show stronger relations to intelligibility than overall F2 range in sentences.

Method

Participants

Children With CP and Dysarthria

Ten children with CP participated as speakers in this study. These children were all enrolled in a larger longitudinal study of communication development in children with CP. Previous work from this longitudinal study has described a communication classification scheme for children with CP based on the presence of speech motor impairment (SMI) with or without co-occurring language impairment (Hustad et al., 2010). Following this classification scheme, children with CP and dysarthria in this study will be subsequently referred to as the SMI group. Data from one of these children have been included in previous publications (J. Lee & Hustad, 2013; J. Lee et al., 2014). Inclusion criteria required that children: (a) Have a medical diagnosis of CP and (b) have hearing abilities within normal limits as documented by either formal audiological evaluation or distortion product otoacoustic emission screening. For the present study, the following additional criteria were imposed: (c) Be able to produce five-word sentences in a repetition format, (d) be 5 years of

age, and (e) have clinical evidence of SMI. SMI was judged by two experienced speech-language pathologists on the basis of the presence of any obvious audible signs of dysarthria in one or more speech subsystems (i.e., articulation, phonation, resonance, or respiration), as well as visual evidence of abnormal orofacial and/or respiratory movements during speech associated with abnormal tone or weakness. Language abilities were not explicitly controlled in this study, as we were interested in characterizing the speech motor patterns of children with CP who were representative of the larger population. Seven of the 10 children in the SMI group had language scores in the average range on the Test of Auditory Comprehension of Language–Fourth Edition (Carrow-Woolfolk, 2014), and three children had standard scores in the below average range (68, 72, and 74). The mean age of children in the SMI group was 64.7 months ($SD = 3.62$), and included five boys (mean age 67.4 months, $SD = 3.05$) and five girls (mean age 62 months, $SD = 1.41$). Children in the sample primarily had moderate-to-severe dysarthria, with intelligibility ranging from 31%–71%. For the purposes of this study, intelligibility was used as an index of severity. Children with a range of intelligibility levels were deliberately included, in order to examine how acoustic measures varied with severity of SMI. Demographic characteristics of the children in the SMI group, including medical diagnoses and Gross Motor Function Classification System level (Palisano et al., 1997), are listed in Table 1.

TD Children

Ten typically developing (TD) 5-year-old children also participated as speakers (TD group). Inclusion criteria

required that children: (a) Have typically developing speech, (b) have typically developing language, (c) have no history of developmental delay per parent report, and (d) have hearing abilities within normal limits as documented by either formal audiological evaluation or distortion product otoacoustic emission screening. All TD children participated in standardized speech and language screening measures to ensure they met inclusion criteria. The Arizona Articulatory Proficiency Scale–Third Edition (Fudala, 2000) was used for screening speech skills, and the Preschool Language Scale–Fourth Edition Screening Test (Zimmerman, Steiner, & Pond, 2005) was used for language screening. All children in this group earned standard scores above 85 on the Arizona Articulatory Proficient Scale and passed the Preschool Language Scale Screener. The mean age of children in the TD group was 62.2 months ($SD = 2.53$), and included five boys (mean age 62.6 months, $SD = 3.29$) and five girls (mean age 61.8 months, $SD = 1.79$). All children from both groups were from the upper Midwest. Demographic characteristics are listed in Table 1.

Listeners

One hundred healthy adults participated as listeners. Listeners were recruited from the university community via public postings and were primarily undergraduate students. Five different listeners were randomly assigned to each child, and each listener heard only one child producing all stimulus material. Inclusion criteria required that listeners: (a) Pass pure-tone hearing screening at 25 dB HL for 250, 500, 1000, 4000, and 8000 Hz bilaterally, (b) be between 18 and 45 years of age, (d) have no more than incidental experience listening to or communicating with

Table 1. Demographic characteristics of children with cerebral palsy and dysarthria (CP) and typically developing children (TD).

Child	Age (months)	Sex	Medical diagnosis	GMFCS ^a	Overall intelligibility (%)
CP01	62	F	Spastic diplegia	IV	59.88
CP02	64	F	Spastic quadriplegia	III	31.91
CP03	62	F	Spastic diplegia	IV	35.70
CP04	62	F	NR	II	40.24
CP05	60	F	Spastic diplegia	IV	64.84
CP06	63	M	Spastic quadriplegia	IV	71.87
CP07	68	M	Right-sided hemiplegia	IV	31.66
CP08	69	M	NR	IV	59.88
CP09	71	M	Right-sided hemiplegia	III	71.56
CP10	66	M	Right-sided hemiplegia	I	38.62
TD01	60	F			95.72
TD02	60	F			89.22
TD03	62	F			84.67
TD04	63	F			88.33
TD05	64	F			93.64
TD06	60	M			85.00
TD07	60	M			91.46
TD08	62	M			91.23
TD09	63	M			91.59
TD10	68	M			94.24

Note. GMFCS = Gross Motor Function Classification System; NR = not reported; I = mild or no impairment; V = severe impairment.

persons having communication disorders, (e) be a native speaker of American English, and (f) have no self-identified language, learning, or cognitive disabilities. Participants included 24 men and 77 women. The mean age of listeners was 21.7 years ($SD = 2.8$).

Acquisition of Speech Samples

Child speakers were audio-recorded while repeating a list of 42 different single words and 60 sentences between two and seven words in length (10 sentences of each length) from the Test of Children's Speech (TOCS+; Hodge & Daniels, 2007) following a prerecorded adult model. Single words were elicited one time each, with the exception of eight single words containing corner vowels (see Table 2), which were elicited four times each, interspersed within the list of single words. Sentences were all elicited one time each.

The research protocol was administered by a speech-language pathologist in a sound-attenuating room. Speech samples from children were recorded using a digital audio recorder (Marantz PMD570, Marantz, Kawasaki, Japan) at a 44.1 kHz sampling rate (16-bit quantization). A condenser studio microphone (Audio-Technica AT4040, Audio Technica, Tokyo, Japan) was positioned next to each child using a floor stand, and was located approximately 18 in. from the child's mouth. The level of the signal was monitored and adjusted on a mixer (Mackie 1202 VLZ, Mackie Designs, Inc., Woodinville, WA) to obtain optimized recordings and to avoid peak clipping.

Acquisition of Intelligibility Data

Recorded speech samples were edited to create individual files for each stimulus utterance produced by each child. Audio samples were peak amplitude normalized (using Sony Sound Forge, Version 10.0, Sony Creative Software, Inc., Middleton, WI) to ensure that maximum loudness levels were consistent across children and utterances, while preserving the amplitude contours of the original productions.

During the experiment, listeners were seated in a sound-attenuating suite. Speech stimuli were presented via

in-house software, with the average audio output level calibrated to approximately 65 dB SPL. Each listener was presented with all recorded utterances produced by one child (102 total utterances), and asked to transcribe orthographically what they thought the child said following each stimulus item. Listeners heard each utterance one time. They were instructed that the children were producing real words and to take their best guess if they were unsure what the child said. The order of presentation for stimulus items was randomized for each listener.

Intelligibility scores for each child and each listener were obtained by dividing the number of words transcribed correctly by the total number of words possible across all stimulus items. Per child intelligibility scores were obtained by averaging scores from each of the five listeners.

Acoustic Analysis

A subset of each child's recorded utterances were selected for acoustic analysis: eight single words containing corner vowels (/i/, /ae/, /a/, and /u/), and eight 4–5-word sentences containing words with corner vowels were used as a basis for vowel space measurements. Productions were included in acoustic analysis as long as they contained clear approximations of the word containing the target corner vowel. During data collection sessions, a research assistant monitored the audio recordings online to ensure that children's productions did not overlap with the recorded examples or contain linguistic errors (i.e., substituting or omitting words), and asked children to repeat utterances when these criteria were not met. The final analyzed data set was complete, and included 32 single-word productions (8 Corner Vowel Words \times 4 Productions) and eight sentences (8 Sentences \times 1 Production) for each child.

For vowel space measurements, TF32 (Milenkovic, 2002) was used to measure F1 and F2 values from a 30-ms window centered at the temporal midpoint of each corner vowel, following the protocol previously described by Hustad et al. (2010). Linear predictive coding (LPC) was used to generate formant tracks, which were visually inspected and hand-corrected as needed. Approximately 50% of LPC tracks required hand correction.

Vowel space area in words was based on measurement of 32 single-word productions per child (4 Corner Vowels \times 2 Words Per Corner Vowel \times 4 Productions Per Word). Children produced each corner vowel eight times across two different single-word contexts (see Table 2). For each child, F1 and F2 values were averaged across the eight productions, to yield an average F1 and F2 value for each corner vowel (e.g., /u/ coordinates were based on average formant values of four repetitions of *boot* and four repetitions of *hoot*). Vowel space area in sentences was based on measurement of eight sentence productions per child (4 Corner Vowels \times 2 Sentences Per Corner Vowel \times 1 Production Per Sentence). Children produced each corner vowel in two different sentence contexts (see Table 2). For each child, F1 and F2 values were averaged across the two productions to yield an average F1 and F2 value for each corner vowel (e.g., /u/ coordinates were based on average

Table 2. Word and sentence stimuli used for acoustic analyses.

Vowel	Word stimuli	Sentence stimuli
Corner vowel words		
/u/	<u>B</u> oot	Cut <u>two</u> small pieces.
	H <u>oo</u> t	Water sh <u>oo</u> ts from that gun.
/ae/	<u>Ba</u> d	They are singing <u>happy</u> birthday.
	H <u>a</u> t	Both faces are <u>happy</u> .
/a/	H <u>o</u> t	Jump over the <u>box</u> .
	<u>T</u> op	They'll eat those hot <u>d</u> ogs soon.
/i/	Sh <u>ee</u> t	This <u>chee</u> se doesn't smell good.
	S <u>ea</u> t	The sign says, " <u>keep</u> out."
Large F2 transition words		
	Boy	
	Pipe	
	Toys	
	Wait	
	Whip	

formant values of one repetition of *two* in “Cut two small pieces,” and one repetition of *shoots* in “Water shoots from that gun”).

The analyzed words and sentences were selected from the set of Test of Children’s Speech stimuli, which were developed to be linguistically appropriate for young children as part of an intelligibility test (Hodge & Daniels, 2007), and thus the phonetic and phonotactic context of corner vowels varied between the word and sentence stimuli. As the aim of this analysis was to examine vowel space area differences between children in the SMI and TD groups within single-word and sentence contexts, but not to directly compare single-word vowel space area to sentence vowel space area within groups, potential effects of coarticulation on formant frequencies were controlled by having all children repeat the same list of stimuli. The variation in phonetic and phonotactic context across stimuli was desirable for the purpose of this study, as it reflects the context variation inherent in children’s spontaneous speech and lends ecologic validity to the findings. A complete list of the stimuli used for acoustic analysis is included in Table 2. Vowel space area was calculated using the following formula for the area of a quadrilateral in the F1/F2 plane (Johnson, Flemming, & Wright, 2004):

$$\begin{aligned} & \frac{1}{2}(F1/i/ \times F2/u/ - F1/u/ \times F2/i/) + \frac{1}{2}(F1/u/ \times F2/a/ - F1/a/ \times F2/u/) \\ & + \frac{1}{2}(F1/a/ \times F2/\text{æ}/ - F1/\text{æ}/ \times F2/a/) + \frac{1}{2}(F1/\text{æ}/ \times F2/i/ - F1/i/ \times F2/\text{æ}/). \end{aligned} \quad (1)$$

Second formant interquartile range (F2 IQR) was used as a measure of the range of F2 frequencies used by children across an utterance. F2 IQR measurements were obtained for each of the words and sentences in the subset defined above for calculating vowel space area. In order to examine the effect of phonetic context on F2 IQR, five additional single words were also selected for this analysis: *boy*, *pipe*, *toys*, *wait*, and *whip*, which children produced one time each as part of the single-word repetition task. These words were chosen because their production requires large, rapid changes in vocal tract configuration (i.e., containing diphthongs or /w/ + vowel combinations) and, thus, large F2 excursions. Due to their increased articulatory movement demands, F2 IQR of these “large F2 transition words” may be more affected by dysarthria than corner vowel words with monophthongs, which are steady state vowels and involve minimal F2 variation. For each child, F2 IQR was calculated for a total of 37 single words (32 monophthong words with corner vowels + 5 large F2 transition words) and eight sentences.

To measure F2 IQR, F2 trajectories for all vocalic segments in each utterance were generated using LPC analysis in TF32, then visually examined and hand-corrected as needed. Approximately 90% of LPC traces required hand correction. Words with nasal consonants were omitted from F2 tracing, as nasal consonants introduce an extra formant in the F1/F2 region and make it difficult to accurately isolate F2. Descriptive statistics from F2

histories, listing F2 frequencies at each sampling point, were used to determine the first and third quartiles and calculate F2 IQR for each utterance, following the protocol from Yunusova et al. (2005). For sentences, F2 IQR was calculated for each sentence and then averaged across the set of eight sentences for each child. For single words, F2 IQR was calculated for each word, an average F2 IQR was obtained for each corner vowel word by averaging F2 IQRs across the four productions, and then F2 IQRs were averaged across the 13 words (8 corner vowel words + 5 large F2 transition words) to obtain an average single-word F2 IQR for each child.

Interjudge Reliability

Interjudge reliability involved having a second researcher, trained in acoustic analysis, independently re-measure productions from six randomly selected children (30% of the sample, three children from the SMI group and three children from the TD group). Pearson’s product moment correlations between the first and second set of measurements ranged from 91%–99%, and were within an acceptable range (R. D. Kent et al., 1999). For single-word vowel space, Pearson’s $r = .99$, and the mean difference in F1 and F2 measurements between judges was 49 and 78 Hz, respectively. For sentence vowel space, Pearson’s $r = .99$, and the mean difference in F1 and F2 measurements between judges was 46 and 44 Hz, respectively. For single-word F2 IQR measurements, Pearson’s $r = .99$, and the mean difference between judges’ measurements was 68 Hz. For sentence F2 IQR, Pearson’s $r = .91$ and the mean difference between judges’ measurements was 112 Hz.

Experimental Design and Statistical Procedures

Given the small sample size, nonparametric tests were used to address research questions. To determine whether the SMI and TD groups differed in vowel space area in single-word and sentence contexts, we conducted two Mann–Whitney U tests to compare groups on vowel space area in words and vowel space area in sentences. In order to preserve a family-wise alpha of .05, we partitioned our alpha equally across the two tests, resulting in a significance criterion of $p \leq .025$ for each of these tests. To determine whether the SMI and TD groups differed in F2 IQR in single-word and sentence contexts, a series of four Mann–Whitney U tests were conducted. First, two Mann–Whitney U tests were conducted to analyze group differences in F2 IQR of words and F2 IQR of sentences; then to determine whether phonetic context affected differences between groups, two additional Mann–Whitney U tests were conducted to examine whether F2 IQR significantly differed between TD and SMI groups for words containing monophthongs and large F2 transition words. In order to preserve a family-wise alpha of .05, we partitioned our alpha equally across the four tests, resulting in a significance criterion of $p \leq .0125$ for each of these tests. Effect sizes are reported. To determine how well acoustic measures relate

to overall intelligibility within the SMI group, Spearman's rank-order correlations were conducted.

Results

Acoustic Vowel Space

Descriptive data showing group medians and ranges for vowel space areas are presented in Figure 1a. In single-word and sentence contexts, children in the SMI group had smaller vowel space areas than the TD children. Results of Mann–Whitney U tests revealed significant differences in vowel space area between the SMI and TD groups both for single-word productions, $U = 20$, $p = .023$, and sentences, $U = 14$, $p = .007$. Effect sizes were large for both contrasts (single words, $r = .51$; sentences, $r = .61$). The magnitude of the difference between the SMI and TD groups was similar in both word and sentence contexts.

The average vowel quadrilaterals for each group and the individual data for each corner vowel production are presented in Figure 2. In single-word productions, the shape of the vowel quadrilaterals was similar for the TD

Figure 1. Differences between speech motor impaired (SMI) and typically developing (TD) groups on (a) acoustic vowel area in words and sentences, (b) second formant interquartile range (F2 IQR) in words and sentences, and (c) F2 IQR for single words with monophthongs and single words with large F2 transitions. Circles denote outliers.

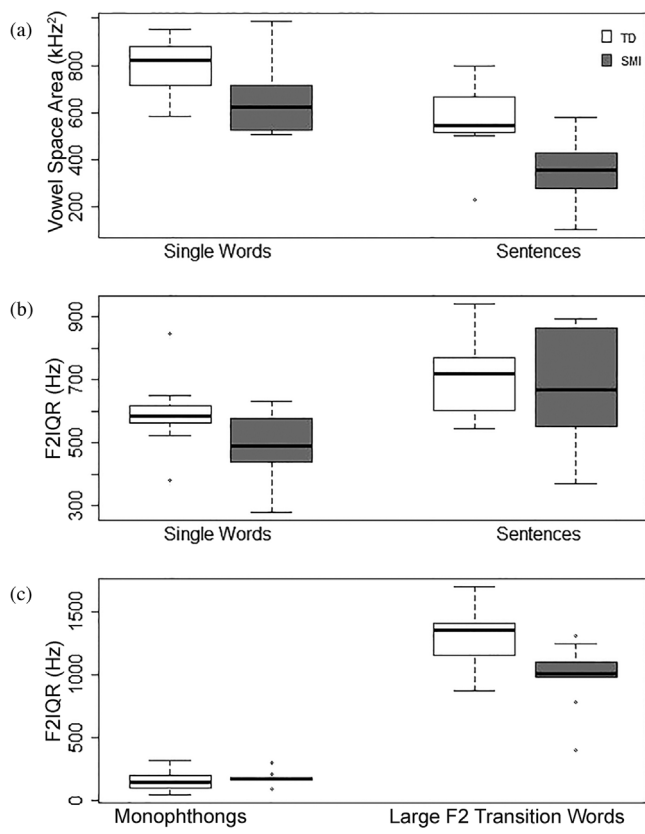
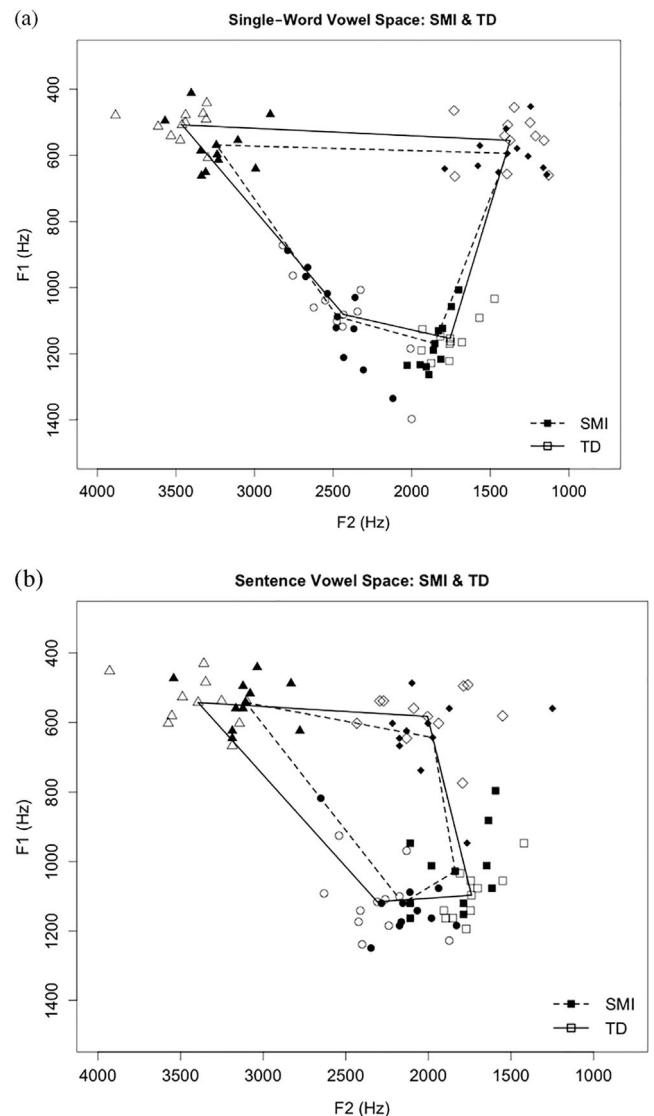


Figure 2. Vowel quadrilaterals for children in the speech motor impaired (SMI) and typically developing (TD) groups in (a) single words and (b) sentences. F1 = first formant; F2 = second formant.

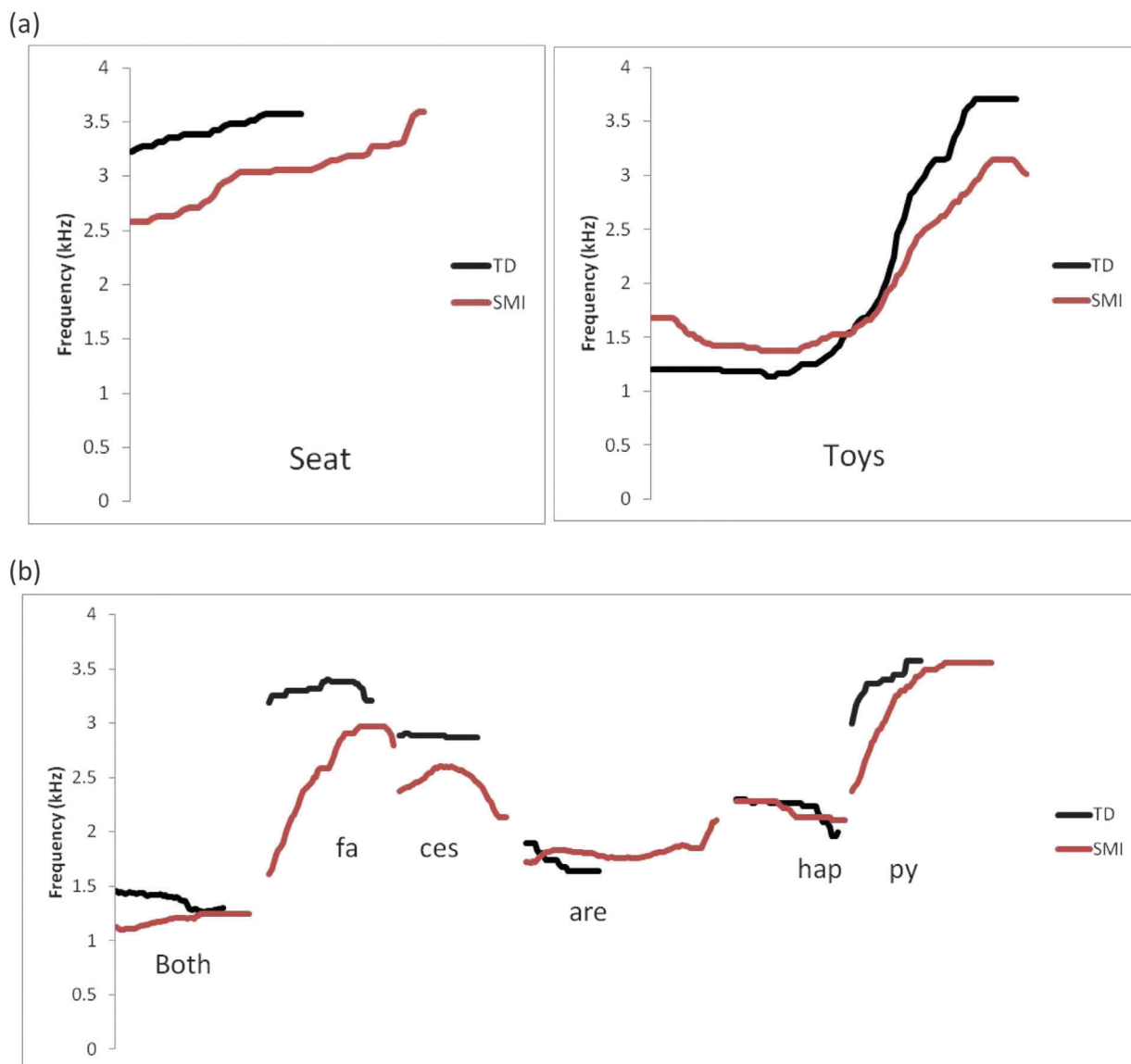


and SMI groups (Figure 2a). The shape of the vowel quadrilaterals derived from sentence productions differed from those based on single words; however, again the shape was similar between TD and SMI groups (Figure 2b). Within-group differences in vowel space area between word and sentence contexts were not statistically tested because the phonetic context of the corner vowels differed between word and sentence stimuli, potentially confounding interpretation of direct comparison.

F2 IQR

Descriptive data showing group medians and ranges for F2 interquartile range of words and sentences are

Figure 3. Example F2 trajectories from one child in the SMI group and one child in the TD group for (a) productions of a monophthong word (*seat*) and a large F2 transition word (*toys*), and (b) production of the sentence “Both faces are happy.”



presented in Figure 1b and c. Example F2 traces of one representative child from the TD and SMI groups are shown in Figure 3. In the combined set of single words, children in the SMI group had descriptively smaller F2 IQRs than children in the TD group, and in sentences, the SMI and TD groups had very similar F2 IQRs. Results of Mann–Whitney U tests revealed that differences in F2 IQR between the SMI and TD groups were not statistically significant for the combined set of single words, $U = 25$, $p = .059$, $r = .42$, or sentences, $U = 46$, $p = .762$, $r = .06$.

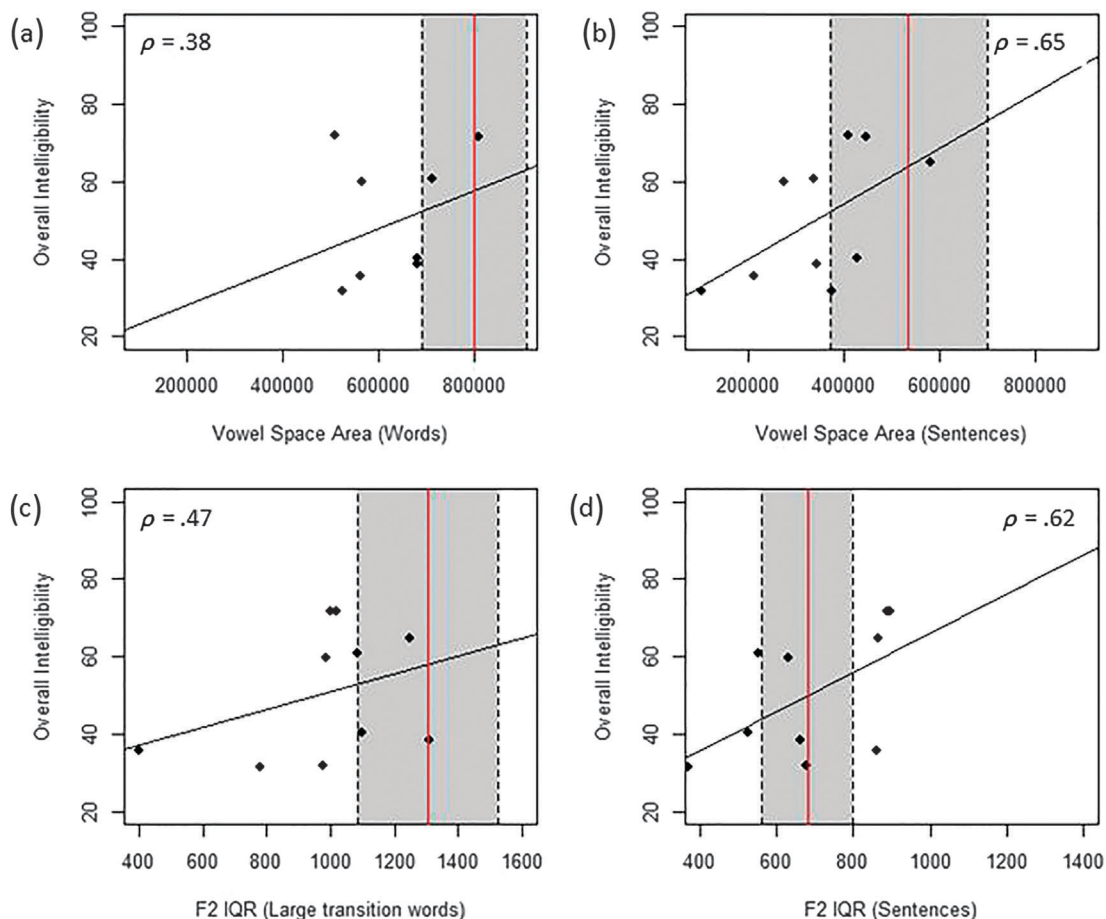
When single words were separated by phonetic context (i.e., monophthongs vs. large F2 transition words), children in the SMI group had descriptively smaller F2 IQRs for large transition words than children in the TD

group, but F2 IQRs for the monophthong words were very similar between groups (see Figure 1c). Results of Mann–Whitney U tests showed that F2 IQRs of large F2 transition words were significantly different between groups, $U = -2.797$, $p = .005$, $r = .63$, but F2 IQRs of words with monophthongs did not significantly differ between TD and SMI groups, $U = 34$, $p = .23$, $r = .27$.

Relationships Between Acoustic Measures and Intelligibility

For the children in the SMI group, Spearman’s rank-order correlations were used to examine the association between each acoustic variable and overall intelligibility.

Figure 4. Scatterplots showing the correlation between overall intelligibility and acoustic variables for children in the SMI group. For each acoustic measure, red lines denote the average value of children in the TD group, and the shaded regions indicate 1 SD above and below the TD mean. Graphs show the relationship between overall intelligibility and (a) single-word vowel space, (b) sentence vowel space, (c) second formant interquartile range (F2 IQR) of large transition words, and (d) F2 IQR of sentences.



Scatterplots showing the relationships between acoustic measures and intelligibility are presented in Figure 4. Results showed weak-to-moderate correlations between single-word acoustic measures and overall intelligibility, none of which were statistically significant (single-word vowel space, $\rho = .38$, $p = .28$; single-word F2 IQR, $\rho = .31$, $p = .39$; F2 IQR of large transition words, $\rho = .47$, $p = .17$). Correlations between sentence-based acoustic measures and intelligibility were stronger than correlations between single-word acoustic measures and intelligibility, and were statistically significant (sentence vowel space, $\rho = .65$, $p = .04$; F2 IQR of sentences, $\rho = .62$, $p = .05$).

Discussion

This study examined differences between children with SMI secondary to CP and TD children on vowel space area and F2 IQR in single-word and sentence contexts. In addition, relations between acoustic measurements

from word and sentence contexts and overall intelligibility were analyzed for children in the SMI group. There were two key findings from the present study. First, vowel space areas of children in the SMI group were significantly smaller than those of TD children in both single-word and sentence contexts, although only vowel space area in sentences was significantly correlated with intelligibility. Second, F2 IQR did not differ between children in the SMI and TD groups in single words or sentences; however, when single words were separated by phonetic context, group differences emerged. To be specific, children in the SMI group had significantly reduced F2 IQRs in production of large F2 transition words compared to TD children, but F2 IQR did not significantly differ between groups in production of single words with monophthongs. Despite the lack of group differences, F2 IQR of sentences was significantly correlated with intelligibility for children in the SMI group. Each of these findings and their relation to extant literature are discussed in detail below.

Vowel Space in Words and Sentences

Within both single-word and sentence contexts, children with dysarthria had smaller vowel space areas than TD children. Single-word vowel space area was not significantly correlated with overall intelligibility for children in the SMI group in this small sample; however, sentence vowel space area was significantly correlated with intelligibility. These group differences are consistent with findings of previous research on single-word vowel space area in children with dysarthria secondary to CP (Higgins & Hodge, 2002; Hustad et al., 2010; J. Lee et al., 2014). In addition, results demonstrate that group differences in vowel space area are also present in connected speech. This is consistent with results of adult studies, which have shown that vowel space derived from corner vowel productions in sentence contexts is reduced in speakers with dysarthria compared to typical controls (Tjaden et al., 2013; Turner et al., 1995). Although expected, these findings provide further evidence that vowel space area is sensitive to dysarthria across linguistic contexts in children with CP, and lends support to its use as a measure of articulatory precision.

The magnitude of the difference between groups in single-word vowel space area was commensurate with findings of previous studies of children with CP (J. Lee et al., 2014). For children in the SMI group, the F1 and F2 frequencies for the corner vowels were consistent with average formant frequencies previously reported in studies of children with CP (J. Lee & Hustad, 2013). For TD children, the F1 and F2 frequencies for the corner vowels were generally consistent with the average formant frequencies previously reported for 5-year-old children (S. Lee, Potamianos, & Narayanan, 1999). In the present study, TD children had somewhat higher average F2 values for /i/, and somewhat lower average F2 values for /u/, than reported in Lee et al. (1999). These differences may be due to dialectal differences between participants in the current study (from the Upper Midwest) and participants in Lee et al. (1999; from Missouri and southern Illinois).

For both groups of children, vowel space areas in sentence productions were descriptively smaller than the vowel space areas in single-word productions. These differences were not statistically tested, as the word and sentence stimuli differed in phonetic and phonotactic characteristics that precluded direct comparison. However, the descriptive data warrant a brief discussion, as they highlight important factors that can affect vowel space area within speakers. First, the shape of vowel quadrilaterals differed substantially between word and sentence contexts. This was largely driven by higher F2 values for /u/ in sentences, which can be accounted for by the alveolar consonants preceding the /u/ in sentences (i.e., words *two* and *shoots*) as they are associated with higher F2 values in the following vowel, relative to the neutral consonants /b/ and /h/ that preceded /u/ in single words (i.e., words *boot* and *hoot*; see Table 2 for stimuli). As shown in Figure 2, these phonetic context differences appeared to affect both groups similarly, as vowel quadrilateral shapes were similar between TD and SMI

groups in both single-word and sentence contexts. Second, differences in the motor demands of producing sentences as compared to single words may also have contributed to the contraction in vowel space area between single words and sentences. Sentences are more motorically complex to produce, and speech motor performance tends to deteriorate in longer utterances, including decreases in intelligibility at long utterance lengths (Allison & Hustad, 2014; Hustad, Schueler, Schultz, & DuHadway, 2012). Thus, it is possible that increased motor demands associated with sentence production contributed to smaller vowel space areas in sentences, particularly for children in the SMI group. Third, factors related to speaking style are known to be associated with expanded vowel space area, such as slower rate, increased stress, and use of clear speech (Fourakis, 1991; Ferguson & Kewley-Port, 2007). Thus, differences in how children produced vowels in single-word and sentence contexts may also have contributed to differences in vowel space area. Additional research with controlled phonetic contexts is needed to determine the effect of sentence length on vowel space area for children with and without dysarthria.

F2 IQR

Children in the SMI and TD groups did not use significantly different F2 interquartile ranges in either sentences or the combined set of single words. This contrasts with findings from previous studies demonstrating reduced F2 ranges in adults with dysarthria compared to healthy speakers (Rosen et al., 2006; Yunusova et al., 2005), and suggests that children with dysarthria may not use globally reduced ranges of articulatory movement when producing speech. If children in the SMI group had overall restricted ranges of articulatory movement, F2 IQR would have been expected to differentiate children in the SMI group from the TD group in both sentence and single-word contexts. Instead, our findings suggest that some phonetic contexts are more likely to show reductions in the F2 range than others. When single words were separated by phonetic context, results indicated children in the SMI group had significantly smaller F2 IQRs than TD children for large F2 transition words (i.e., *boy*, *pipe*, *toys*, *wait*, and *whip*), though there was no group difference in F2 IQR for words with monophthongs.

One possible explanation of this finding is that articulatory imprecision in children with CP and dysarthria may result from deficits in coordination and timing of speech movements, resulting in impaired production of phonetic targets despite overall similar ranges of movement. Precise execution of monophthongs requires achieving and maintaining steady-state formant frequencies during the vowel. In contrast, precise execution of diphthongs and some consonant-vowel transitions require large changes in F2 frequency within the rapid timing demands of the phoneme or syllable. At the sentence level, F2 range does not reflect precision of individual phonemes, but rather indexes the variation in F2 frequencies used, regardless of how the timing of F2 fluctuations corresponds with phonemic targets.

A deficit in precise timing of speech gestures could account for group differences in vowel space areas and F2 range for large F2 transition words, as well as the similarity between groups in overall range of F2 movement across utterances. Observation of example data in Figure 3 demonstrates how this could be possible; the child with SMI showed more fluctuation in F2 frequency within each vocalic segment than the TD child, though the overall F2 range used by the children was similar. Such formant instability within vocalic segments containing corner vowels could affect vowel space area measurements for children with SMI, as the vowel midpoints may not reflect the ultimate endpoint of the formant trajectory for that phoneme. This hypothesis is also supported by kinematic research, which has demonstrated that children with CP have decreased spatial and temporal coupling between articulators (Nip, 2017) and use larger lip and jaw excursions than TD children in some contexts (Nip, 2013).

Alternatively, it is also possible that individual differences among children in the SMI group may have masked group differences in F2 IQR between children with SMI and TD children. Children in the SMI group spanned a wide severity range. It is interesting to note that F2 IQR of sentences was significantly correlated with intelligibility among children in the SMI group, although this variable did not differentiate groups. Furthermore, observation of individual data points in Figure 4d shows that four children in the SMI group had F2 IQRs more than 1 *SD* above the mean of the TD group. Three of those four children were the children with the highest intelligibility in the SMI group, whereas those with more severely reduced intelligibility tended to have reduced F2 IQRs in sentences compared to TD children. This suggests that dysarthria severity may influence the range of articulatory movement used by children with SMI in connected speech. It is possible that children with mild-moderate dysarthria may use exaggerated articulatory excursions, similar to those reported by Nip (2013), whereas children with more severe dysarthria may exhibit global reductions in range of articulatory movement. In addition to severity, individual differences in children's pattern of SMI may also contribute to the variation in formant range. Prior research has demonstrated individual differences in factors contributing to intelligibility in children with SMI secondary to CP, which may relate to different patterns of speech subsystem involvement (Allison & Hustad, 2014). Future research is needed to investigate factors contributing to individual differences in speech patterns among children with SMI due to CP.

There are several reasons why our results may differ from previous studies of adults with dysarthria due to Parkinson's disease and ALS, which have shown overall reductions in F2 range in connected speech (Rosen et al., 2006; Yunusova et al., 2005). First, there are key neurological differences between children with CP and adults with Parkinson's disease and ALS, including the brain regions affected, the course of disease progression, and immaturity of children's neurological systems (Morgan & Liegeois,

2010). Furthermore, for children with CP, all speech development occurs in the context of a neuromotor impairment, in contrast to adults for whom dysarthria affects a previously intact speech system. Thus, the discrepancy between results of the present study and prior adult studies may suggest a difference in how dysarthria affects speech movements in a developing system compared to an adult system with mature neurology and stable motor representations for phoneme productions.

Results of the current study also suggest that segmental measures (i.e., vowel space area and F2 range of large transition words) may not provide adequate information to make inferences about the overall range of articulatory movement used by children with dysarthria, at least to the degree that F2 range is an accurate reflection of range of articulatory movement. Although segmental measures provide important information about articulatory precision, utterance-level formant measures may be needed to fully characterize a speaker's global speech movement patterns. Thus, for children with CP, reduced vowel space area may not necessarily indicate that a child has reduced range of articulatory movement in connected speech. This is important, as it suggests that articulatory imprecision in children with dysarthria secondary to CP may not be due to restricted range of movement, and that more research is needed to better understand the motor basis of articulatory imprecision in this population.

Limitations and Future Directions

Results of this study are preliminary, and would be strengthened by replication in a larger sample of children. In addition, the current study focused specifically on children at 5 years of age; however, it is possible that findings may differ across age groups, as anatomical growth and speech motor development may affect formant patterns and speech movement characteristics over time. Children with CP in the present study also spanned a wide range of dysarthria severity, as indexed by intelligibility scores. Future research is needed to understand how severity of dysarthria in children relates to range of formant movement. Research using more direct measures, such as articulatory kinematics, would help further characterize the differences between children with dysarthria and TD children in the range and precision of speech movements across different linguistic and phonetic contexts. In addition, our findings suggest that speech movement characteristics of children with congenital dysarthria differ from those of adults with acquired dysarthria. Thus, there is a need for additional acoustic studies using ecologically valid stimuli to more fully understand how dysarthria affects speech patterns in connected speech of children with CP.

Conclusion and Clinical Implications

In this study, a global measure of range of F2 movement was not sensitive to SMIs in 5-year-old children with dysarthria; however, segmental measures reflecting

precision of phoneme production did reveal differences between groups. Although preliminary, results of the present study have important clinical implications. Findings suggest that reduction in overall range of articulatory movement may not be a primary concern, at least for some children with SMI secondary to CP. For children with SMI who use articulatory movement ranges equivalent to or greater than TD children, it is possible that interventions targeting timing and coordination of speech movements rather than overall range of articulatory movement may provide greater benefit to speech function. Thus, evaluating both articulatory precision and articulatory range of movement during a motor speech assessment may be helpful for clinical decision-making. Given the variability among children with CP, additional research is needed to characterize individual differences in speech motor patterns and identify children who would be optimal candidates for different intervention techniques. Although studies of adult dysarthria have suggested that intervention focused on global speech characteristics, including loudness, rate, and prosody, can positively affect speech function (Yorkston, Hakel, Beukelman, & Fager, 2007), limited data exist on the efficacy of speech interventions for children with dysarthria (Pennington, Goldbart, & Marshall, 2005; Yorkston et al., 2007). Results of the present study suggest speech movement characteristics associated with dysarthria in children with CP differ from those of adults with acquired dysarthria, and highlight the need for future research focused on the efficacy of dysarthria intervention in pediatric populations.

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