Research Article

Oral Articulatory Control in Childhood Apraxia of Speech

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Purpose: The purpose of this research was to examine spatial and temporal aspects of articulatory control in children with childhood apraxia of speech (CAS), children with speech delay characterized by an articulation/phonological impairment (SD), and controls with typical development (TD) during speech tasks that increased in word length.
Method: The participants included 33 children (11 CAS, 11 SD, and 11 TD) between 3 and 7 years of age. A motion capture system was used to track jaw, lower lip, and upper lip movement during a naming task. Movement duration, velocity, displacement, and variability were measured from accurate word productions.

Results: Movement variability was significantly higher in the children with CAS compared with participants in the SD and TD groups. Differences in temporal control were seen between both groups of children with speech impairment and the controls with TD during accurate word productions. As word length increased, movement duration and variability differed between the children with CAS and those with SD.
Conclusions: These findings provide evidence that movement variability distinguishes children with CAS from speakers with SD. Kinematic differences between the participants with CAS and those with SD suggest that these groups respond differently to linguistic challenges.

Childhood apraxia of speech (CAS) is a complex disorder involving a core impairment in the planning and/or programming of speech movements (American Speech-Language-Hearing Association [ASHA], 2007). ASHA's (2007) position statement on CAS highlights three features that are consistent with deficits in speech motor control: inconsistent errors on repeated syllable or word productions, impaired coarticulation patterns, and prosodic errors. Although these differentiating features implicate a deficit in articulatory control, questions remain about the specific aspects of movement that are deficient in CAS. To address this knowledge gap, the current study examined oral articulator movement in children with idiopathic CAS, children with delayed speech development characterized by articulation and/or phonological errors (SD), and controls with typical development (TD). We examined spatial and temporal parameters of articulator movement in an effort to identify whether movement characteristics distinguish these two groups of children with speech impairment from one another as well as from children with age-appropriate speech production skills.

One approach to studying speech motor control in CAS aims to isolate a particular level of processing deficit (e.g., motor planning, programming, execution). The challenge in doing so, however, is that the connection between different levels of processing is difficult to tease apart in a developing system where impairment at one level may affect the development of other levels of processing (Maassen, Nijland, & Terband, 2010). Therefore, it has been proposed that research should shift focus away from locating the core etiology of CAS and should place greater emphasis on the interactional nature of development (see Maassen et al., 2010, for a review). One approach to exploring the complex interaction between different levels of processing is to study speech production in the context of varied task demands. Thus, an additional goal of the present work was to compare articulatory control between children with speech impairment and children with TD as they produced words that increased in length.

Speech Motor Control in CAS

Researchers have used acoustic or kinematic methods to examine speech motor control in CAS (Bahr, 2005; Grigos & Kolenda, 2010; Moss & Grigos, 2012; Nijland et al., 2002; Nijland, Maassen, & van der Meulen, 2003; Nijland, Maassen, van der Meulen, Gabreels, et al., 2003; Shriberg, Campbell, et al., 2003; Shriberg, Green, Campbell,

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McSweeny, & Scheer, 2003; Skinder, Strand, & Mignerey, 1999; Terband, Maassen, Van Lieshout, & Nijland, 2011; Terband, Zaalen, & Maassen, 2012). Results from several studies have provided evidence of deviant coarticulation patterns in children with CAS (Nijland et al., 2002; Nijland, Maassen, & van der Meulen, 2003; Nijland, Maassen, van der Meulen, Gabreels, et al., 2003). Nijland et al. (2002) investigated coarticulation in 4- to 6-year-old children with CAS, children with TD, and adults during production of nonwords embedded in a carrier phrase. They reported that second formant (F2) values were higher and more variable in the CAS group than in the TD group. In addition, children with CAS produced lower F2 ratios than controls and had higher within-group and within-subject variability for F2 ratios. The authors concluded that both intrasyllabic and intersyllabic coarticulation differed in CAS, suggesting a deficit in syllabic planning. In a subsequent study, Nijland, Maassen, van der Meulen, Gabreels, et al. (2003) examined anticipatory coarticulation during repetition of phrases that consisted of identical phonetic contexts yet differed by syllable structure. Across syllable structures, intrasyllabic coarticulation and within-subject variability were higher in the CAS group than in the controls.

In addition to differences in coarticulation in CAS, there is acoustic evidence consistent with deficits in temporal control of speech. Children with CAS have been reported to produce longer acoustic durations of segments (Nijland, Maassen, van der Meulen, Gabreels, et al., 2003) and words (Bahr, 2005) than controls with TD. Past research has also shown that the degree of variability in the duration of pause and speech events may differentiate children with CAS from children with other speech impairments (Shriberg, Green, et al., 2003). In relation to lexical stress production, differences in the use of acoustic cues (i.e., frequency, amplitude, and duration) to mark either lexical or sentential stress have been reported between children with CAS and controls with TD (Skinder et al., 1999) as well as children with other speech sound disorders (Shriberg, Campbell, et al., 2003). Together, these works provide support from acoustic analyses that CAS involves deficient speech motor processing.

Kinematic research has aimed to delineate patterns of articulatory control in children with CAS. Grigos and Kolenda (2010) used movement tracking to investigate longitudinal changes in jaw movement during a period of phonemic acquisition in a 3-year-old child with CAS and a TD control group. The child with CAS was studied every 2 weeks over an 8-month period until he began accurately and consistently producing the bilabial phonemes /p/, /b/, and /m/ in consonant–vowel–consonant word structures (i.e., *bob, mom, pop*). Changes in articulator movement over time included decreased variability (measured by the spatiotemporal index [STI]; A. Smith, Goffman, Zelaznik, Ying, & McGillem, 1995) and increased jaw velocity. By the final session, both velocity and variability fell within a 95% confidence interval established for the controls with TD. There was a significant positive correlation between movement stability and consonant accuracy. The authors

suggested that increased phoneme accuracy and consistency may have been facilitated by more refined articulatory control. This relationship between speech motor processes and perceptual indices of speech intelligibility was further explored in the present work in a larger cohort of children with CAS. We examined the hypothesis that children demonstrating the poorest segmental accuracy would show atypical speech motor performance during accurate speech production.

To date, few studies have compared articulatory control between children with CAS and children with other speech sound disorders (Moss & Grigos, 2012; Terband et al., 2011, 2012). Terband et al. (2011) used electromagnetic midsagittal articulography to examine lip, jaw, and tongue tip movement in five children with a speech sound disorder (SSD) characterized by phonological deficits, five children with subtype CAS, and six children with TD, all of whom were between the ages of 6 and 9 years. Tongue, lower lip, and jaw movement displacement were measured during a reiterative speech task (i.e., repeated productions of /pa:s/ and /spa:/). The results showed larger lower lip amplitude in both the CAS and speech sound disorder groups in the absence of any differences in stability. This finding suggests the use of an adaptive strategy in which both groups increased movement amplitude to obtain stability equal to that of the controls. A direct relationship between amplitude and stability has been described in previous studies (Van Lieshout, Bose, Square, & Steele, 2007; Van Lieshout, Rutjens, & Spauwen, 2002) and is thought to reflect a control strategy in which amplitude changes result in greater stability by providing more precise afferent feedback. In a later study, Terband et al. (2012) investigated jaw movement in the coronal plane in 16 children with TD, 18 young adults, and five children with developmental speech disorders between 4 and 7 years of age during the same reiterative speech task. Results showed that all children in the speech sound disorder group (which included participants with CAS) had greater lateral jaw movement and variability relative to normative data for at least one of the stimuli. The authors highlighted that lateral jaw movement of the child with a phonological disorder may have deviated from controls in average angle but was not characterized by higher instability. For the child with CAS, a deviant average movement angle was accompanied by greater instability. Taken together, these studies provide evidence that children with a range of speech sound disorders may demonstrate deviant speech motor control relative to children with TD. What may differentiate children with CAS from children with other speech impairments is the degree of instability across articulators and speech tasks, potentially indicating that children with CAS do not use the same strategies as children with other subtypes of speech sound disorders to minimize instability when articulatory and linguistic demands increase.

Another window into speech motor development in CAS is the study of movement coordination. Moss and Grigos (2012) examined the relationship between lip and jaw movements in 3- to 6-year-old children identified as

having CAS, a speech delay characterized by articulation and/or phonological deficits (SD), or typical speech and language development (TD; six participants per group). The peak correlation coefficient was obtained for each articulator pair (i.e., jaw and upper lip; jaw and lower lip; upper lip and lower lip) per production and was used as an index of spatial coupling, whereas the lag, or time required to achieve peak spatial coupling, was used as a measure of temporal coupling (Green, Moore, Higashikawa, & Steeve, 2000). There were no significant differences in the peak coefficient and lag between articulator pairs in the children with CAS, SD, and TD. There were group differences, however, in the variability of spatial–temporal coupling, as measured by the coefficient of variation of the peak coefficient and lag values. Both spatial and temporal coupling were shown to be more variable in the children with CAS compared with the participants with SD. In addition, lip aperture STIs (A. Smith, Goffman, Zelaznik, et al., 1995) were significantly higher in the CAS group than in the SD group. These findings provide further evidence that children with CAS achieve accurate speech using a motor plan that is less stable than that used by their peers with other speech impairments. Based on these results and others described above, we predicted that children with CAS would be differentiated from children with other speech sound disorders by articulator movements that are longer in duration, smaller in displacement, slower in velocity, and greater in variability.

Effects of Word Length on Articulatory Control in Children

Task effects on articulator movement have been shown in young children with TD producing different orofacial behaviors (Nip, Green, & Marx, 2009). The influence of task complexity on speech output is particularly interesting to explore in children with CAS because they commonly display difficulties sequencing articulator movements, such that phonemes are often produced with greater accuracy in isolation than when embedded in longer sequences. This suggests that task demands, such as increased utterance length, may have specific effects on articulator movement in CAS. There is evidence that children and adolescents with TD display increases in movement variability as utterance length increases (Sadagopan & Smith, 2008; Walsh, Smith, & Weber-Fox, 2006). For instance, Sadagopan and Smith (2008) showed that, in children and adolescents, lip aperture variability was higher when "Buy Bobby a puppy" was embedded in a longer utterance than when produced in isolation; however, the young adults studied did not display differences in STI related to utterance length. Walsh et al. (2006) reported that children's speech movements were of greater duration than those of the adults when producing nonwords that increased in length. Lip aperture and lower lip–jaw variability increased with word length in all speakers, although to a greater extent in the children than the adults.

Findings from Moss and Grigos (2012) suggested that word length may affect articulator movement to a

greater extent in children with CAS than children with SD and TD. Significant group differences in lip aperture stability were found as the children produced one-, two-, and three-syllable words. Although the interaction between group and length was not significant, the CAS group demonstrated much larger effect sizes between one- and two-syllable words, as well as between one- and three-syllable words, compared with the SD and TD groups. This result highlights the need for additional research to determine whether increases in speaking demands, such as changes in word length, have a greater effect on movement sequencing for children with CAS compared with children with other speech sound disorders. As a means to further explore the relationship between speech motor and linguistic processes in CAS, the current work examined the production of stimuli that varied in word length. We hypothesized that manipulating word length itself—thus directly taxing the level of syllabic planning—would affect children with CAS to a greater extent than their peers.

Research Questions

Many studies of speech motor control in CAS are limited by small sample sizes or the absence of a comparison group including children with other speech sound impairments. Moreover, studies involving children with CAS have not adequately examined the effect of increasing linguistic complexity on speech motor control or studied the relationship between speech motor processes and perceptual measures of speech intelligibility. The current study addressed these issues by investigating spatial and temporal aspects of articulatory control in a larger cohort of children with CAS, children with SD, and controls with TD during speech tasks that increased in linguistic complexity through changes in word length. The following research questions were explored:

1. Do characteristics of oral articulator movement (duration, displacement, velocity, and variability) differ in children with CAS relative to participants with SD and TD?

2. Do increases in word length influence oral articulator movement to a greater extent in children with CAS relative to participants with SD and TD?

3. Is there a relationship between measures of articulatory control and indices of speech intelligibility in children in the CAS, SD, and TD groups?

Method
Participants

The participants were 33 children (11 children with CAS, 11 children with SD, and 11 children with TD) between the ages of 3 years 1 month and 7 years 7 months. Eleven participants with TD were selected from a larger cohort of 24 children with TD, matching for chronological age as closely as possible. The mean (standard deviation) age per group was 4.7 years (1.2) for CAS, 5.2 years (1.4)

for SD, and 5.2 years (1.2) for TD. In light of the age discrepancy between the children in the CAS group and children in the SD and TD groups (on average 7 months), all children displayed age-appropriate receptive language and cognitive skills (discussed in detail below). Data were collected from five additional children, who after careful analysis were identified as having characteristics of both CAS and dysarthria. The inclusion criteria specified that children in the CAS group could not display characteristics of dysarthria. As a result, these children were excluded from group comparisons. All participants were monolingual speakers of American English.

Standardized testing of speech, language, cognition, and oral motor skills and a hearing screening were conducted. Table 1 displays standardized testing results. To ensure that language comprehension and cognition did not influence performance on the experimental protocol, inclusion in the study for all participants was dependent on the

following criteria: normal receptive language (> −1 standard deviation from mean) as measured by the Test of Early Language Development (TELD-3; Hresko, Reid, & Hammill, 2007) and normal cognition (> −1 standard deviation from mean) as measured by the Columbia Mental Maturity Scale (Burgmeister, Blum, & Lorge, 1972). This measure of cognitive functioning was chosen because it is a nonverbal test and performance was not influenced by speech production difficulties. The mean (standard deviation) receptive language quotient on the TELD-3 per group was 109 (16) for CAS, 110 (12) for SD, and 120 (9) for TD. The mean (standard deviation) standard score on the Columbia Mental Maturity Scale per group was 118 (18) for CAS, 111 (11) for SD, and 121 (16) for TD. All participants passed a hearing screening at 25 dB SPL at 500, 1000, 2000, and 4000 Hz.

Expressive language was evaluated through the Expressive Language subtest of the TELD-3. Children in the TD group were required to score no lower than 1 standard

Table 1. Formal and informal testing results.

Participant	Age (months)	Gender	TELD		CMMS ADS	GFTA		VMPAC			Speech sample		
			RLQ	ELQ		Percentile	SS	GMC	FOMC	SEQ	PCC	PVC	WWC
CAS1	37	M	122	101	93	8	73	100	63	35	47	72	28
CAS2	43	M	134	77	111	29	95	95	83	54	54	85	25
CAS3	44	F	83	94	101	5	63	100	44	20	46	79	19
CAS4	45	M	116	115	150	5	64	95	77	57	54	81	27
CAS5	51	M	122	91	106	56	104	80	66	48	75	87	49
CAS6	53	M	90	88	118	13	82	100	85	76	66	78	38
CAS7	62	M	113	115	150	19	88	85	84	72	55	52	47
CAS8	64	M	110	88	120	13	82	85	93	87	87	92	59
CAS9	68	M	110	105	122	<1	47	100	91	70	80	85	55
CAS10	69	M	85	91	113	2	55	100	97	76	66	76	54
CAS11	86	M	115	115	116	30	100	100	98	98	83	83	61
SD1	38	F	113	105	104	32	90	100	77	65	90	99	62
SD2	49	M	125	124	103	2	53	85	83	61	65	88	43
SD3	44	F	137	120	124	78	113	100	100	100	93	97	63
SD4	58	F	95	102	105	66	110	100	74	100	90	93	68
SD5	56	M	108	115	118	43	99	100	97	80	88	93	75
SD6	63	M	110	112	130	79	112	100	99	100	90	95	73
SD7	64	M	110	94	106	14	83	100	94	100	79	86	56
SD8	72	M	110	97	106	27	98	100	95	98	83	99	67
SD9	78	M	105	102	94	8	74	95	99	78	84	87	60
SD10	79	M	100	97	118	9	77	100	100	100	74	89	62
SD11	92	F	96	107	109	3	78	90	99	100	87	88	77
TD1	37	M	119	115	128	98	127	100	100	100	94	98	91
TD2	49	M	122	112	108	41	99	100	100	100	80	87	84
TD3	48	F	128	118	133	91	118	100	99	100	99	100	97
TD4	58	F	119	112	128	>87	117	100	99	83	92	89	95
TD5	56	M	131	115	105	72	110	100	98	96	94	98	91
TD6	66	M	130	118	128	>83	113	100	100	100	98	99	98
TD7	68	M	121	97	150	>79	112	100	100	100	100	100	100
TD8	69	M	118	94	130	>79	112	100	99	100	99	100	99
TD9	73	M	118	112	115	54	107	100	97	98	97	100	91
TD10	82	M	110	102	107	>64	110	100	99	100	100	99	98
TD11	84	M	100	115	94	>64	109	100	100	94	93	95	94

Note.   TELD = Test of Early Language Development–3 (RLQ = receptive language quotient; ELQ = expressive language quotient); CMMS ADS = Columbia Mental Maturity Scale age deviation score; GFTA = Goldman-Fristoe Test of Articulation–2 (SS = standard score); VMPAC = Verbal Motor Production Assessment for Children (GMC = global motor control; FOMC = focal oral motor control; SEQ = sequencing); Speech sample: PCC = percentage of consonants correct; PVC = percentage of vowels correct; WWC = percentage of whole words correct. CAS = childhood apraxia of speech; M = male; F = female; SD = speech delay characterized by an articulation/phonological impairment; TD = typical development.

deviation below the mean on the Expressive Language subtest. As speech production skills may affect expressive language skills, this same criterion did not apply to performance on the Expressive Language subtest of the TELD-3 for children in the CAS and SD groups. The Verbal Motor Production Assessment for Children (VMPAC; Hayden & Square, 1999) was used to assess oral motor skills.

Speech production skills were examined using the Goldman-Fristoe Test of Articulation (GFTA-2; Goldman & Fristoe, 2000), a 100-word conversational speech sample, and the Sequencing subtest of the VMPAC. Information obtained from these speaking contexts was used to describe phonetic inventory, syllable structure, lexical stress, consonant and vowel accuracy, whole-word accuracy, occurrence of phonological processes, and error consistency. A phonetic inventory was judged to be reduced if a child did not produce phonemes acquired by 90% of children their age as reported by Smit, Hand, Freilinger, Bernthal, and Bird (1990). The presence of a phonological process was confirmed using criteria from McReynolds and Elbert (1981), where a process needs to occur in at least 20% of the possible opportunities and have at least four opportunities to occur. Percentage of consonants correct (PCC), percentage of vowels correct (PVC; Shriberg, Austin, Lewis, McSweeny, & Wilson, 1997), and whole-word accuracy were calculated from speech samples. Accuracy of whole-word productions was examined by modifying published measures (i.e., Ingram & Ingram, 2001; Schmitt, Howard, & Schmitt, 1983), which identified only segmental errors, to also include suprasegmental errors (i.e., inaccurate and equal lexical stress). The percentage of whole words correct (WWC) was determined by dividing the number of words produced without segmental or suprasegmental errors by the total number of intelligible words in the sample and then multiplying by 100. This whole-word measure captures the broad effect of segmental and suprasegmental errors on word accuracy. PCC, PVC, and WWC scores are shown in Table 1.

Differential Diagnosis

There is no definitive list of characteristics that distinguish children with CAS from those with other speech sound disorders (ASHA, 2007). Another challenge in the diagnosis of CAS is that characteristics seen in children with CAS may also be seen in children with other speech sound disorders. The diagnoses of CAS and SD in the present work were based on careful analysis of each participant's speech production skills across three different speaking contexts: single-word productions (GFTA-2), connected speech (conversational speech sample), and sound/syllable sequencing tasks (VMPAC). These analyses were separately performed by two ASHA-certified speech-language pathologists with expertise in pediatric motor speech disorders (the first and second authors). Assessing the presence of speech characteristics across different speaking contexts (e.g., single words, conversation, and syllable sequencing tasks) is an essential component of a comprehensive examination, as poor performance

on single-word testing alone is not sufficient for diagnosis of a motor speech impairment, such as CAS. Further, results from single-word articulation tests can be misleading when scoring is not based on all phonemes included in the words and when difficulties seen during connected speech may not be evident during the production of isolated words. Our analyses identified whether children produced in more than one speaking context speech errors that were not age appropriate according to normative data from Smit et al. (1990) and Hodson and Paden (1981). Participants who were later diagnosed with CAS or SD met one or more of the following criteria: (a) GFTA-2 standard scores below 85, (b) PCC below 85%, and (c) WWC below 65% for children between the ages of 36 and 48 months and below 80% for children older than 48 months. Previous research on children with age-appropriate articulation skills reported increases in whole-word accuracy from 69% to 80% from 36 to 48 months and to 92% by 72 months (Schmitt et al., 1983). Diagnostic distinction between CAS and SD is specified below.

CAS Group

Diagnostic classification for CAS was determined according to the presence of the three core features identified in the ASHA (2007) position statement: (a) inconsistent consonant and vowel errors, (b) difficulties forming articulatory transitions between sounds and syllables, and (c) prosodic errors. Children diagnosed with CAS displayed these features in more than one speaking context and within at least three different words (or sounds/syllables in the sequencing task). Inconsistent errors were defined as consonant and vowel errors that differed across repeated productions of the same word (e.g., *hot* /hat/ produced as /ha/, /at/, or /ta/ by the same speaker).[1] Difficulties forming articulatory transitions were characterized by poor sequencing of adjacent sounds and/or syllables, particularly when they included phonemes that were present in the child's repertoire (e.g., difficulty combining the phoneme /b/ with different vowels, even though /b/ and the vowels are accurately produced in other contexts). Prosodic errors were identified as incorrect lexical and/or phrasal stress (e.g., producing a strong–weak structure as strong–strong or weak–strong). In addition to the three core features, children with CAS demonstrated at least four of the following characteristics: metathesis, vowel errors, timing errors (e.g., difficulty differentiating between voiced and voiceless cognates), phoneme distortions, articulatory groping (e.g., visual struggle accompanying phoneme production), impaired volitional oral movement (e.g., excessive oral opening during an open/close sequence), reduced phonetic inventory, and poorer expressive than receptive language skills. A participant was identified as using metathesis, vowel errors, timing errors, distortions, and articulatory

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[1]Inconsistent errors were identified in two speaking contexts—connected speech and the sequencing task—as repeated word productions were not obtained from the GFTA-2.

groping when such patterns were seen across two different speaking contexts and within at least three different words (or sounds/syllables in the sequencing task). Children in the CAS group exhibited normal structure of the oral–peripheral mechanism as determined by the VMPAC. The examiners were 100% reliable in identifying the presence of characteristics in the children with CAS.

SD Group

All participants in the SD group were diagnosed with an articulation and/or phonological impairment. The diagnosis was based on measures of accuracy and intelligibility during single-word testing, the connected speech sample, and the sequencing task. Deviant speech patterns seen in the SD group primarily included consonant or vowel substitutions, omissions, additions, and distortions associated with an articulation impairment (e.g., interdental lisp, r-distortion) as well as systematic use of phonological processes (e.g., velar fronting, gliding) as seen in a phonological impairment. Several children displayed prosodic errors. A participant was identified as using substitutions, omissions, additions, distortions, and prosodic errors when such patterns were seen across two different speaking contexts and within at least three different words (or sound/syllables in the sequencing task). None of the children included in the SD group displayed all three of the core features identified in the ASHA (2007) position statement associated with CAS (i.e., inconsistent errors, poor articulatory transitions, and prosodic errors). Results of the VMPAC were analyzed to rule out motor speech and sequencing deficits as well as to confirm that children in the SD group exhibited normal structure of the oral–peripheral mechanism. Speech characteristics displayed by children in the CAS and SD groups in each of the three speaking contexts are shown in Table 2. The examiners were 96% reliable in identifying the presence of characteristics in the children with SD.

TD Group

The participants with typically developing speech and language skills had no reported histories of speech, language, or hearing problems and/or neurological disorders. The children with TD met the inclusionary criteria described above regarding cognition, receptive language, and hearing. In addition, they demonstrated (a) normal structure and functioning of the oral mechanism as determined by the VMPAC (Hayden & Square, 1999), (b) age-appropriate articulation skills as measured by the conversational speech sample and GFTA-2, and (c) age-appropriate expressive language skills as measured by the TELD-3. The lower limit for performance on the GFTA-2 and the TELD-3 for the children with TD was 1 standard deviation below the mean. We used normative data provided in Smit et al. (1990) and Hodson and Paden (1981) to determine whether articulation skills were age appropriate. Children with age-appropriate articulation and/or phonological errors, according to these criteria, were included in the TD group.

Instruments

A motion capture system (Vicon 460; Vicon Motion Systems, 2001) was used to track articulator movement in three dimensions. Twelve 3-mm reflective markers were placed on the face to track lip and jaw movement and to account for head movement. Three markers were placed on the jaw and four markers were placed on the lips to measure oral articulator movement. Five markers were placed on the nose, nasion, and forehead to account for head movement and rotation. Lip markers were placed in the midline of the vermilion border of the upper lip, in the midline of the vermilion border of the lower lip, and on the corners of the mouth. Vertical lip movement was tracked using the markers on the upper lip and lower lip. The system tracked reflective markers at a sampling rate of 120 frames/s. Video and audio recordings were made using a Sony digital video camera (Model DSC-T1) and a digital minidisc recorder (HHB50; Sony, Tokyo, Japan). Recordings were made in a sound-attenuated audiometric booth. Testing and data collection were performed in the Motor Speech Laboratory in the Department of Communicative Sciences and Disorders at New York University.

Data Collection and Procedures

The children were seated in a chair in a sound-attenuated booth. During the familiarization phase, the children were introduced to the characters *Pop* (an elderly male puppet), *puppet* (a dragon puppet), and *puppypop* (a puppy shaped as a lollipop). These particular words were chosen as they included the bilabial plosive /p/, which allowed for visualization of lip and jaw movement. A brief training session was used to familiarize the children with the characters and items and to model appropriate responses. The experimenter elicited token productions while following a protocol, which specified the sequence to follow and the cues that could be used. Character names were embedded in a story retell game in which the children were asked to complete a sentence or respond to a question using one of the target words. For example, to elicit the utterance *Pop* the child was presented with a scenario in which *Pop* was hungry and had to select a food choice, such as a banana. The clinician asked the child, "Who will eat the banana?" with the correct response being *Pop.* This approach was taken to elicit naturalistic productions of the target words. Model responses were provided if a child did not remember a character name; however, direct imitations were not included in the analyses. Each token was elicited between 10 and 15 times in a randomized order.

Analyses

Data analyses were performed in several ways. Transcription measures were computed from correct and incorrect production of tokens (*Pop, puppet, puppypop*). Kinematic measures were based only on accurate word productions to ensure that any observed kinematic

Table 2. Speech characteristics of participants diagnosed with childhood apraxia of speech (CAS) and speech delay characterized by an articulation/phonological impairment (SD).

	Age (months)	Incon. errors	Mvt. seq. deficits	Prosodic errors	Timing errors	Groping	Reduced inventory	Phon. process.	Vowel errors^	Consonant Errors			
										DIST*	SUB	ADD	OMM
CAS1	37	+[2,3]	+[1,2,3]	+[1,2,3]	—	—	+[1,2]	+[1,2,3]	+[1,2,3]	—	+[1,2,3]	+[1,2,3]	+[1,2,3]
CAS2	43	+[2,3]	+[1,2,3]	+[1,2,3]	+[1,2,3]	+[2,3]	+[1,2]	+[1,2,3]	+[1,2,3]	—	+[1,2,3]	—	+[1,2]
CAS3	44	+[2,3]	+[1,2,3]	+[1,2,3]	+[1,2,3]	+[2,3]	+[1,2]	+[1,2,3]	+[1,2,3]	+[1,2,3]	+[1,2,3]	+[2,3]	+[1,2,3]
CAS4	45	+[2,3]	+[1,2,3]	+[1,2,3]	+[1,2]	+[2,3]	+[1,2]	+[1,2,3]	+[1,2,3]	+[1,2,3]	+[1,2,3]	+[2,3]	+[1,2,3]
CAS5	51	+[2,3]	+[1,2,3]	+[1,2,3]	+[1,2]	—	+[1,2]	+[1,2]	+[1,2,3]	+[1,2,3]	+[1,2,3]	—	+[1,2,3]
CAS6	53	+[2,3]	+[1,2,3]	+[1,2,3]	+[1,2]	+[1,2,3]	+[1,2]	+[1,2]	+[1,2,3]	+[1,2]	+[1,2,3]	+[2,3]	+[1,2,3]
CAS7	62	+[2,3]	+[1,2,3]	+[1,2,3]	—	—	+[1,2]	+[1,2]	+[1,2,3]	—	+[1,2,3]	+[2,3]	+[1,2,3]
CAS8	64	+[2,3]	+[1,2,3]	+[1,2,3]	—	+[1,2,3]	+[1,2]	—	+[1,2,3]	+[2,3]	+[1,2,3]	+[1,2,3]	+[1,2,3]
CAS9	68	+[2,3]	+[1,2,3]	+[1,2,3]	—	+[2,3]	+[1,2]	+[1,2]	+[1,2,3]	—	+[1,2,3]	+[1,2]	+[1,2]
CAS10	69	+[2,3]	+[1,2,3]	+[1,2,3]	+[2,3]	+[1,2,3]	—	+[1,2]	+[1,2,3]	+[1,2,3]	+[1,2,3]	+[2,3]	+[1,2]
CAS11	86	+[2,3]	+[1,2]	+[1,2,3]	+[1,2,3]	+[1,2,3]	—	—	+[1,2]	+[1,2,3]	+[1,2]	+[1,2]	+[1,2]
SD1	38	+[2,3]	—	+[1,2]	—	—	+[1,2]	+[1,2,3]	—	+[1,2,3]	—	+[1,2]	+[1,2]
SD2	49	+[2,3]	+[2,3]	—	—	—	+[1,2]	+[1,2]	+[1,2]	—	+[1,2,3]	+[1,2,3]	+[1,2]
SD3	44	—	—	+[1,2]	—	—	—	—	—	+[1,2]	+[1,2]	+[1,2]	+[1,2]
SD4	58	—	—	—	+[1,2]	—	—	—	+[1,2]	—	+[1,2]	—	+[1,2]
SD5	56	—	—	—	—	—	+[1,2]	+[1,2]	+[1,2]	—	+[1,2]	—	+[1,2]
SD6	63	—	—	—	—	—	—	—	+[1,2]	+[1,2]	+[1,2]	—	+[1,2]
SD7	64	—	—	—	+[1,2]	—	—	—	+[1,2]	—	+[1,2]	+[1,2]	+[1,2]
SD8	72	—	—	—	+[1,2]	—	—	—	—	—	+[1,2]	+[1,2]	+[1,2]
SD9	78	—	—	+[1,2]	—	—	—	+[1,2,3]	+[1,2]	—	+[1,2,3]	—	+[1,2]
SD10	79	—	—	—	+[1,2]	—	—	—	+[1,2]	+[1,2]	+[1,2]	+[1,2]	+[1,2]
SD11	92	—	—	—	+[1,2]	—	—	—	+[1,2]	+[1,2]	+[1,2]	+[1,2]	+[1,2]

Note. Incon. Errors = inconsistent errors; Mvt. seq. deficits = movement sequencing deficits; phon. process. = phonological processes; DIST = distortions; SUB = substitutions; ADD = additions; OMM = omissions; + = characteristic present; — = characteristic absent; ^ = including vocalic /r/ errors; * = including /s/ lateralizations, interdentalizations, and consonantal /r/ distortions.
[1]Single words. [2]Conversational speech sample. [3]Syllable sequencing task.

differences were due to underlying changes in speech motor control that were independent from articulation errors.

Transcription Analysis

Two listeners transcribed all productions of *Pop, puppet,* and *puppypop* using narrow transcription. The percentage agreement between listeners was 93%. Productions were eliminated if the listeners identified segmental or suprasegmental errors or identified unusual voice or fluency patterns and if all reflective markers were not visible for the entire utterance. The original data pool consisted of 902 productions, which included trials in which reflective markers were visible for the entire utterance (CAS = 312, SD = 301, TD = 289). These productions were analyzed for consonant (PCC) and vowel (PVC) accuracy. In addition, consistency across repeated productions of the same word were examined using percentage word consistency (PWC). The PWC was calculated by comparing the number of different forms of the word produced by a participant (which included both correct and incorrect forms of the word) with the total number of productions of that particular token. This whole-word measure examined the entire word form rather than individual segmental errors. Preliminary findings showed that PWC differentiated error consistency in children with CAS and SD compared with calculations that examined only erred productions or those that focused only on segmental accuracy (Case, Moss,

& Grigos, 2012). The following formula was utilized for this calculation:

$$PWC = 1 - \frac{\text{\# of different forms of the word}}{\text{total \# of productions of the word}} \times 100.$$

If a participant produced a token accurately more than eight times, the first eight accurate productions were selected for further analysis. Thus, a maximum of 264 productions could be obtained from each experimental group (8 productions × 11 participants × 3 tokens). The resulting number of productions per group (*Pop, puppet,* and *puppypop,* respectively, in parentheses) was 190 (76, 64, 50) for CAS, 231 (82, 73, 76) for SD, and 227 (81, 79, 67) for TD. The number of productions varied (ranging from five to eight) per child. One participant with CAS did not achieve any accurate productions of *puppet.* Several participants did not achieve any accurate productions of *puppypop* (3 CAS, 2 SD, and 1 TD). Data for those tokens were then analyzed for the remaining participants in each group. Further, lip movement data were not obtained from three of the children with CAS who displayed hypersensitivity to placement of reflective markers on the upper and lower lips. The number of participants per group for each comparison is noted in the Results and on all related figures.

Kinematic Analysis

The nasion and forehead markers were used to determine the orientation and to account for vertical head movement and rotation. Upper lip and jaw movements were calculated by subtracting their y coordinates from stationary forehead points (i.e., upper lip – forehead; jaw – forehead). Lower lip displacement was measured as the vertical lower lip movement subtracted from the jaw (i.e., lower lip – jaw). Lip aperture was calculated as the vertical distance between the upper and lower lips. The jaw signal was subtracted from the mean jaw value, creating an origin. The same subtraction method was applied to the lower and upper lip signals. The right jaw marker was used to track jaw movement to reduce the error associated with chin surface tracking (Green, Wilson, Wang, & Moore, 2007). The acoustic signal was aligned with the kinematic trajectory for each production. Movement kinematics were examined using custom MATLAB algorithms (Version 7.5; Math Works, 2007).

The jaw displacement trajectory was used to identify the onset and offset of movement for each trial. The threshold for movement onset was taken as the point 10 frames (0.083 s) prior to the initial peak closing displacement for the first consonant in each token. Movement offset was selected as the point 10 frames (0.083 s) following the final opening displacement associated with the vowel in *Pop* and the final vowels in *puppet* and *puppypop* (see Figure 1). The offset was chosen in this manner to be consistent across tokens because lip and jaw movement associated with

Figure 1. Kinematic traces of jaw displacement, jaw velocity, and lip aperture corresponding to the utterance *Pop.* Point A indicates the onset of movement in the jaw displacement trajectory, and point B marks the movement offset.
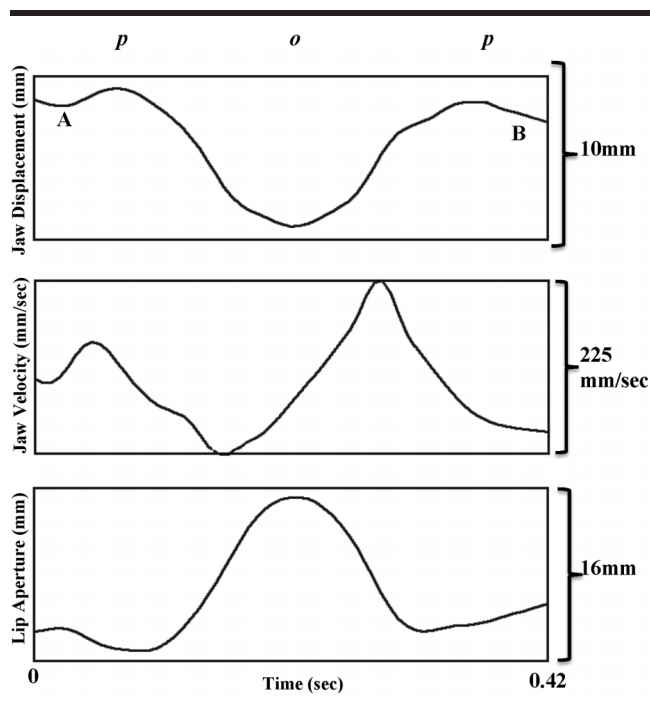
/t/ in *puppet* cannot be measured using facial tracking technology. These onset and offset criteria were used to mark duration, displacement, and velocity across the entire word. Total movement duration was measured as the time between the onset and offset points. Average jaw displacement was calculated as the mean peak-to-peak displacement of each open and closing movement across the utterance, excluding the final consonant. Average jaw velocity was calculated as the mean velocity across the utterance. Lip aperture was measured as the distance between the upper and lower lips.

Spatiotemporal stability of jaw movement (jaw STI) was calculated using the STI (A. Smith, Goffman, Zelaznik, et al., 1995). To compute the STI, segmented displacement traces were normalized for amplitude and time. For each displacement trace, amplitude normalization was achieved by subtracting the mean of the displacement record and dividing by its standard deviation. Time normalization was achieved by using a cubic spline procedure to interpolate each waveform onto a time base of 1,000 points. The STI was then calculated to examine the stability of movement trajectories across repeated productions of target utterances. The STI was computed by calculating standard deviations at 2% intervals across repetitions of the time- and amplitude-normalized displacement traces. The STI is the cumulative sum of these 50 standard deviations and indicates the degree to which the set of trajectories converges onto one fundamental movement pattern (A. Smith, Johnson, McGillem, & Goffman, 2000). Figure 2 displays normalized movement trajectories and STIs for a participant in each of the experimental groups.
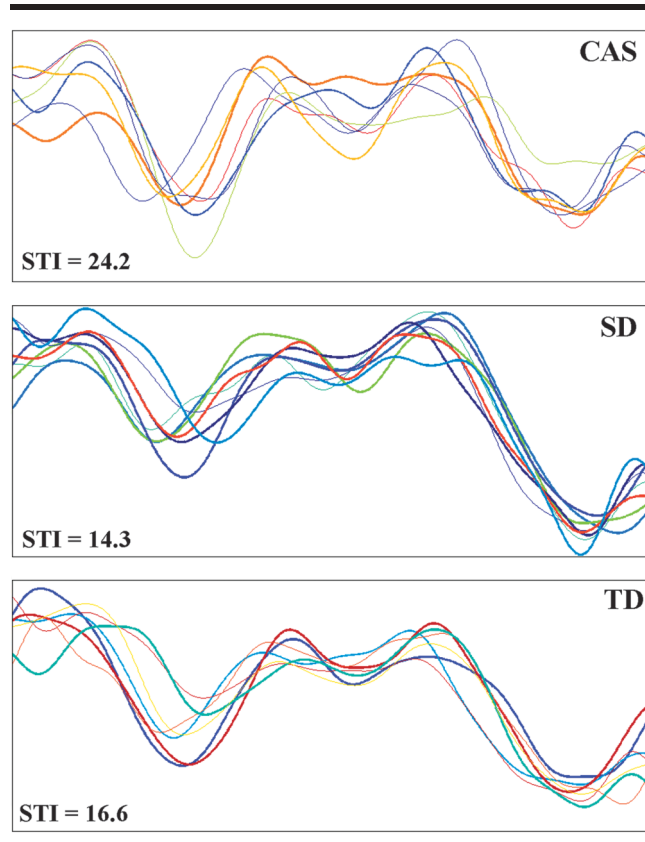
Statistical Analysis

To measure the extent to which each of the outcome variables of interest differed across three groups (CAS, SD, and TD) and different word lengths (one, two, and three syllables), controlling for age effect, analysis of covariance with repeated measures was performed. The main effect of group was treated as a between-subjects effect, and the main effect of word length was treated as a within-subject effect in this model. To control type I error due to multiple pairwise comparisons, a post hoc p value adjustment (Tukey's method) was conducted whenever applicable. Partial correlation analysis was used to quantify the correlation between various kinematic and transcription measures. The significance level of statistical tests is 5% unless otherwise mentioned. All statistical analyses were performed using SPSS Version 20.

Results

Transcription measures were computed on 902 productions (CAS = 312, SD = 301, TD = 289), which included both correct and incorrect productions of *Pop, puppet,* and *puppypop.* Kinematic measures were based only on accurate productions, which reduced the data pool to 648 utterances (CAS = 190, SD = 231, TD = 227). As a result,

Figure 2. Normalized jaw movement trajectories and corresponding spatiotemporal indices (STI) associated with the utterance *puppypop* produced by one participant each in the childhood apraxia of speech (CAS), speech delay characterized by an articulation/phonological impairment (SD), and typical development (TD) groups.

STI = 24.2

STI = 14.3

STI = 16.6

Table 3. Mean (standard deviation) of percentage of consonants correct (PCC), percentage of vowels correct (PVC), and percentage of word consistency (PWC).

Measure	Group	*Pop*	*puppet*	*puppypop*
PCC	CAS	82.5 (15.9)	88.3 (22.8)	78.4 (33.1)
	SD	96.5 (4.2)	97.6 (3.7)	96.1 (7.7)
	TD	98.9 (3.8)	100.0 (0.0)	98.5 (5.0)
PVC	CAS	89.3 (18.1)	82.8 (27.9)	86.0 (23.1)
	SD	94.4 (12.3)	96.2 (7.3)	97.7 (3.9)
	TD	100.0 (0.0)	100.0 (0.0)	95.6 (9.9)
PWC	CAS	74.3 (15.4)	76.5 (18.8)	64.8 (23.8)
	SD	85.8 (14.0)	82.8 (20.1)	81.7 (21.7)
	TD	97.7 (7.5)	100.0 (0.0)	88.6 (13.4)

Note. CAS = childhood apraxia of speech; SD = speech delay characterized by an articulation/phonological impairment; TD = typical development.

the number of participants included in duration, jaw displacement, velocity, and movement stability comparisons for *Pop, puppet,* and *puppypop,* respectively, was as follows: CAS = 11, 10, and 8; SD = 11, 11, and 9; TD = 11, 11, and 10. The number of participants included in lip aperture comparisons was further reduced in the CAS group to 8 participants per token.

Transcription

PCC, PVC, and PWC were calculated for each participant from repeated productions of *Pop, puppet,* and *puppypop.* Mean PCC, PVC, and PWC scores are shown in Table 3. High PCC, PVC, and PWC scores reflect a greater percentage of consonant and vowel accuracy and consistency. As expected, consonant and vowel accuracy was lowest in the CAS group and highest in the TD group for all three tokens, with a significant between-subjects effect of group on PCC, $F(2, 28) = 3.82$, $p = .034$, $\eta^2 = .214$, and PVC, $F(2, 28) = 4.71$, $p = .017$, $\eta^2 = .252$. Post hoc tests revealed that PCC of the CAS group was significantly lower than that of the SD (mean difference = −12.14, $p = .039$) and TD (mean difference = −14.58, $p = .015$) groups. Likewise, PVC was significantly lower in the CAS

group than in the SD (mean difference = −7.97, $p = .032$) and TD (mean difference = −10.43, $p = .006$) groups. In contrast, PCC and PVC scores were not significantly different between the TD and SD groups. There was no significant within-subject effect of word length or group by word length interaction for PCC and PVC. Further, there was no significant effect of age on PCC or PVC.

The participants with CAS demonstrated the lowest PWC scores for all three tokens, indicating that they produced a greater number of inconsistent errors than children in the other experimental groups. These observations were supported by a significant between-subjects effect of group on PWC, $F(2, 28) = 11.45$, $p < .001$, $\eta^2 = .45$. Again, post hoc comparisons showed that PWC was significantly lower in the CAS group than in the SD (mean difference = −10.38, $p = .036$) and TD (mean difference = −22.42, $p < .001$) groups as well as lower in the SD group than in the TD group (mean difference = −12.04, $p = .013$). Similar to PCC and PVC, there was no significant within-subject effect of word length or group by word length interaction. Last, there was no significant effect of age on PWC.

Movement Kinematics

Movement Duration

Total movement duration, measured as the timing of jaw movement across the entire utterance, is displayed in Figure 3. As expected, duration increased with word length for all three experimental groups, resulting in a significant within-subject effect of word length on duration, $F(2, 50) = 6.75$, $p < .01$, $\eta^2 = .21$. The effect of group on movement duration was not significant, $F(2, 25) = 3.06$, $p = .065$, $\eta^2 = .197$. Movement duration was longer for three-syllable words than for one- and two-syllable words; the difference in duration was particularly prominent among the CAS and SD groups in comparison with the TD group. Movement duration associated with *Pop* and *puppet* was longest for the participants with SD, followed by the participants with CAS and then the participants with TD. In contrast, duration of *puppypop* was longer for the CAS

Figure 3. Mean total jaw movement duration and standard error associated with the production of *Pop, puppet,* and *puppypop* by participants in the childhood apraxia of speech (CAS), speech delay characterized by an articulation/phonological impairment (SD), and typical development (TD) groups. Number of participants included for the tokens *Pop, puppet,* and *puppypop,* respectively: CAS = 11, 10, and 8; SD = 11, 11, and 9; TD = 11, 11, and 10.

Figure 4. (a) Mean average jaw displacement and standard error associated with the production of *Pop, puppet,* and *puppypop* by participants in the childhood apraxia of speech (CAS), speech delay characterized by an articulation/phonological impairment (SD), and typical development (TD) groups. Number of participants included for the tokens *Pop, puppet,* and *puppypop,* respectively: CAS = 11, 10, and 8; SD = 11, 11, and 9; TD = 11, 11, and 10. (b) Mean average lip aperture and standard error associated with the production of *Pop, puppet,* and *puppypop* by participants in the CAS, SD, and TD groups. Number of participants included for the tokens *Pop, puppet,* and *puppypop,* respectively: CAS = 8, 8, and 8; SD = 11, 11, and 9; TD = 11, 11, and 10.
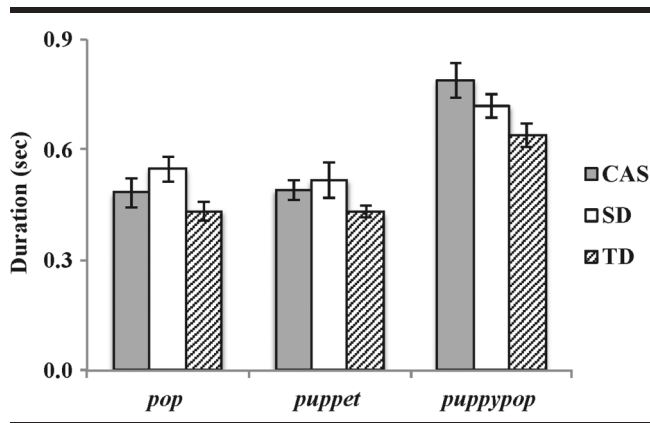
group than the SD and TD groups. These observations were supported by a significant interaction between group and word length, $F(4, 50) = 2.875$, $p = .034$, $\eta^2 = .19$. The effect of age on movement duration was not significant.

Movement Displacement

Average jaw displacement and lip aperture were calculated to examine the excursion of jaw and lip movement during the production of each word. Overall, jaw displacement and lip aperture were similar among the CAS, SD, and TD groups. There was, however, a significant main effect of word length on jaw displacement, $F(2, 50) = 3.541$, $p = .05$, $\eta^2 = .101$, and lip aperture, $F(2, 48) = 3.567$, $p = .036$, $\eta^2 = .129$. The interaction between group and word length was not significant. Across all three groups, when syllable number increased, movement excursion decreased. Post hoc testing showed that participants in all groups produced the shorter, single-syllable token *Pop* with larger jaw and lip excursions compared with the longer, two- and three-syllable words *puppet* (mean difference in displacement = 6.21, $p < .001$; mean difference in lip aperture = 7.648, $p < .001$) and *puppypop* (mean difference in displacement = 6.88, $p < .001$; mean difference in lip aperture = 10.024, $p < .001$). Last, there was no significant effect of age on movement displacement or lip aperture. Figures 4a and 4b illustrate the findings for jaw displacement and lip aperture, respectively.

Average Velocity

Average jaw movement velocity was calculated to examine the speed of jaw movement across word production. Similar velocity patterns were observed among children in the CAS, SD, and TD groups for the three tokens. Thus, there were no significant main effects or interactions of group or word length on average jaw velocity. The effect of age on velocity was not significant.
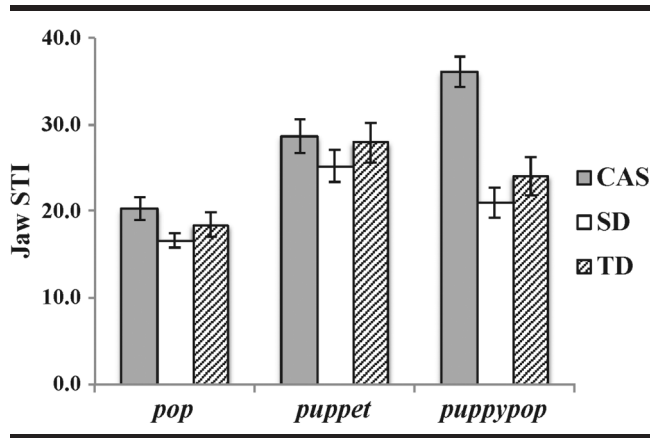
Movement Stability

The STI was calculated to examine the stability of jaw movement trajectories across repeated productions of words. Mean STIs are shown in Figure 5. High STIs indicate greater spatiotemporal variability, and low STIs represent more stability across movement trajectories. Jaw STIs were higher in the CAS group compared with the SD and TD groups. This observation was supported by a significant between-subjects effect of group on jaw STI, $F(2, 23) = 4.676$, $p < .05$, $\eta^2 = .289$. These findings indicate poorer spatiotemporal stability in the children with CAS than in the children with SD and the controls with TD. Post hoc comparisons revealed significantly higher jaw STIs in the CAS group compared with the SD group (mean difference = 6.68, $p = .006$) and the TD group (mean difference = 3.85, $p = .03$). There were no significant differences in jaw STIs

Figure 5. Mean jaw spatiotemporal index (STI) and standard error associated with the production of *Pop, puppet,* and *puppypop* by participants in the childhood apraxia of speech (CAS), speech delay characterized by an articulation/phonological impairment (SD), and typical development (TD) groups. Number of participants included for the tokens *Pop, puppet,* and *puppypop,* respectively: CAS = 11, 10, and 8; SD = 11, 11, and 9; TD = 11, 11, and 10.

between the SD and TD groups. The effect of age on movement stability was not significant.

There was an influence of word length on movement stability because STIs were lower for productions of *Pop* compared with *puppet* and *puppypop.* This finding was supported by a significant main effect of word length on STI, $F(2, 46) = 5.424$, $p = .008$, $\eta^2 = .191$. Post hoc comparisons revealed significantly lower STIs for *Pop* compared with both *puppet* and *puppypop* (mean difference = −9.1 and −8.98, respectively; $p < .001$), but there was no significant difference between *puppet* and *puppypop.* As Figure 5 illustrates, STI values increased consistently from *Pop* to *puppet* and to *puppypop* in the CAS group, suggesting a pattern of greater movement stability for shorter than for longer words in the children with CAS. In contrast, STIs were higher in *puppet* than in *puppypop* in the participants with SD and TD. These findings were supported by a statistically significant interaction between group and word length, $F(4, 46) = 6.852$, $p < .001$, $\eta^2 = .373$.

Relationship Between Transcription and Kinematic Measures

The relationship between indices of articulatory control (i.e., duration, stability) and measures reflective of speech intelligibility (i.e., PCC, PVC, PWC) were examined by computing Pearson partial correlations between these kinematic and transcription parameters while controlling for participants' age. Seven pairwise comparisons were made for each experimental group: PCC and STI, PVC and STI, PWC and STI, PCC and duration, PVC and duration, PWC and duration, and duration and STI (which adjusted the alpha level to .01). A significant positive correlation was found between PCC and duration ($r = .54$, $p < .01$) among the children with CAS but not the children

with SD or TD. Correlations between PCC, PVC, and STI were not significant in the CAS, SD, or TD groups. There were no significant correlations between PWC and STI or duration. Last, a significant positive correlation was found between duration and STI in the children with CAS ($r = .53$, $p < .01$) but not the children with SD or TD.

Discussion

Temporal and Spatial Control in Children With Speech Impairment

The current study investigated articulatory control in children with CAS and SD, as well as children with TD, during the production of words that increased in length. We hypothesized that movement duration, displacement, velocity, and variability would distinguish groups during accurate speech production. Our results partially supported these predictions and revealed that children in the CAS, SD, and TD groups were differentiated by movement duration and variability. Regarding duration, both groups of children with speech impairment (CAS and SD) produced longer jaw movement durations than children in the TD group across all three tokens. This result is consistent with research reporting longer acoustic durations in children with CAS than in controls with TD (Bahr, 2005; Nijland, Maassen, van der Meulen, Gabreels, et al., 2003). In addition, past work conducted in our laboratory (Grigos & Kolenda, 2010) revealed decreases in movement duration as a child with CAS produced words accurately and consistently over an 8-month period. The authors proposed that longer movement durations may have facilitated improved speech output. Although speaking rate was not directly measured in our present or past work, the movement duration findings from these experiments suggest that children with speech sound disorders may be reducing speaking rate as they achieve accurate speech. Reducing speech rate may allow these speakers to glean information derived from auditory feedback more easily (Terband & Maassen, 2010). It is interesting to note that longer movement durations have also been reported for children with specific language impairment compared with controls with TD (Goffman, 1999, 2004); this result leaves us questioning whether increased duration represents a characteristic of children with speech and language impairment in general. Taken together, the findings above illustrate the need for additional research to examine whether differences in acoustic and kinematic timing between children with TD and children with speech and language impairment reflect poor speech motor control or are adaptive strategies that support improved communication.

To further explore temporal patterns displayed by the children with CAS and SD, we examined the relationship between transcription and kinematic measures. PCCs (obtained from correct and incorrect productions) were significantly correlated with movement duration (obtained from correct productions) in the CAS group but not in the SD group, suggesting that increased duration facilitated

segmental accuracy in the children with CAS. Severity of impairment and task demands are two factors that may have affected these results. Formal and informal assessment revealed more speech errors in the children with CAS than in the children with SD. Likewise, the transcription findings from the experimental task showed that the children with CAS and SD were challenged to varying degrees. The children with CAS displayed lower PCCs on *Pop, puppet,* and *puppypop* than the children with SD, who performed close to ceiling (mean PCCs > 95), as shown in Table 3. Further, the number and range of segmental errors produced by children in the CAS group were particularly striking given that all phonemes included in the tokens were early developing, were within each participant's phonetic repertoire, and were embedded within simple syllable structures. Thus, longer movement durations may have aided the children with CAS, who displayed more severe speech deficits than the children with SD. It is possible that the relationship between duration and PCC would have been stronger in the SD group if the tokens included a wider range of phonemes within more complex syllable structures.

Interpretation of the temporal findings would not be complete without consideration of developmental changes in duration. Speech motor development in children with TD is characterized by decreased movement duration with age (Goffman & Smith, 1999; Grigos & Patel, 2007, 2010; A. Smith & Goffman, 1998). Given the participant age range in the present work (i.e., the controls with TD were on average 7 months older than the children with CAS), we considered the possibility that duration differences between the CAS and TD groups reflected this age difference. We do not believe that this is the case for several reasons. First, the SD group also produced longer movement durations compared with the TD group, and these groups (SD and TD) were more similar in mean age compared with the CAS group. Second, there was no statistically significant effect of age on movement duration. Still, although age may not have contributed to group differences, it is possible that children with CAS represent a subset of less mature speakers. These children may not have had the same practice and feedback exposure as children of similar ages. To further investigate whether children with CAS display speech motor patterns that mirror those of less mature speakers, future studies should include a comparison group of younger children with TD.

In contrast to the results for temporal control, there were no group differences in movement displacement. A significant length effect was found where all children produced the single-syllable word *Pop* with greater jaw and lip excursion than the longer words *puppet* and *puppypop.* These displacement findings appear to be confounded by vowel height, where larger displacements associated with *Pop* reflect the larger jaw openings required to produce the low-back vowel /a/. Although our data set cannot rule out the vowel height effect on our displacement results (as measures of average displacement across the word were obtained), the fact that the relationship between displacement and stability changed with the articulatory challenges

presented by the stimuli (whether vowel height or length) supports earlier research linking stability and displacement. The SD and TD groups produced *puppypop* with smaller displacements and a similar degree of movement stability relative to *Pop.* Displacement decreased with word length in the CAS group as movement stability also decreased (i.e., higher STIs). Several researchers have suggested that increased amplitude may result in greater movement stability (Terband et al., 2011; Van Lieshout et al., 2002, 2007). Terband et al. (2011) proposed that amplitude adjustments helped children with CAS achieve STIs that were similar to those of the control participants. Although we did not find group differences in displacement similar to those reported by Terband et al. (2011), this may be a result of task differences. We examined the production of real words that increased in length where the longer words included vowels that varied in height and backness. In contrast, Terband et al. (2011) studied speech production within a reiterative speech task, where the stimuli included one vowel type. In relation to the present work, it is plausible that children with CAS may not have the refined motor skill necessary to modify displacement during challenging speaking tasks. In contrast, children with more mature speech motor skills, such as the participants in the TD and SD groups, may not need to increase movement displacement when producing multisyllabic words or words that include vowels of various heights. Given the task-specific nature of speech motor control, understanding how task demands influence articulatory control is essential to unveiling deviant speech motor processes in CAS. This is discussed in greater detail below.

Poor Movement Stability in CAS

We hypothesized that children with CAS would produce more variable articulator movements than participants in the SD and TD groups during accurate word productions. Our findings supported this prediction as children with CAS produced targets with higher jaw STIs than children in the SD and TD groups, which is consistent with the notion that CAS is characterized by a higher degree of movement variability relative to children with an articulation and phonological impairment. The observation that children in the SD group had significantly lower STIs than participants in the CAS group suggests that they have more stable motor plans.

STI differences related to word length were observed only in the CAS group. As word length increased, jaw STIs increased in the CAS group. Although the children with CAS accurately produced the longer three-syllable target, they did so with more variable articulator movements, reflecting poor movement stability. This result supports our previous findings, which showed that coordinative consistency differed between children with CAS and SD as measured by lip aperture STI (Moss & Grigos, 2012), and is consistent with research that has associated increased variability with CAS. Such studies involving children with CAS have identified high within-subject variability of

second formant values (Nijland, Maassen, van der Meulen, Gabreels, et al., 2003), decreased jaw movement variability as speech accuracy increased (Grigos & Kolenda, 2010), and high tongue tip movement variability (Terband et al., 2011). We also considered the average age difference (7 months) between the children with CAS and the children with SD and TD in our interpretation of the current STI findings. Although it is well documented that movement stability increases with age in children (Green, Moore, & Reilly, 2002; Grigos, 2009; Grigos, Saxman, & Gordon, 2005; Sharkey & Folkins, 1985; A. Smith, Goffman, & Stark, 1995; B. L. Smith & McLean-Muse, 1986; Watkin & Fromm, 1984), there was no statistically significant effect of age on STI in the current study. As mentioned above in regards to duration, future studies examining speech motor control in CAS should add a control group of younger children with TD to investigate the importance of speaker experience and maturation. Given that the behavioral symptoms characteristic of CAS (e.g., articulatory groping, inconsistent productions of the same word, prosodic errors) are not typical of less mature speakers, we would antici-pate that children with CAS would display different speech motor patterns than younger children with TD. Additional research is warranted to examine this prediction in a larger cohort of children with CAS compared with age-matched and younger controls with TD.

Last, within-group differences and the potential effect of missing data should be acknowledged when interpreting STI and duration findings. As noted above, data from three children with CAS (CAS2, CAS3, and CAS6) were not included in all kinematic analyses because they did not achieve accurate productions of *puppet* (CAS 2) and/or *puppypop* (CAS2, CAS3, and CAS6). Their speech profiles (Tables 1 and 2) showed that they were among the more impaired children with CAS: They performed either at the midpoint or in the bottom half of the CAS group in terms of the number of speech characteristics they displayed as well as on indices of connected speech accuracy (i.e., PCC and WWC). These participants were also in the younger half of their cohort (under 5 years of age). In contrast, speech profiles from the two participants with SD with missing kinematic data for *puppypop* (SD1 and SD11) differed in severity, and these children were the youngest (SD1) and oldest (SD11) participants in the SD group. These results highlight some of the challenges researchers contend with when studying speech motor control in children with speech impairment. It can be difficult to account for severity of impairment, the characteristics displayed by participants within the same diagnostic category, and overlap in the diagnostic profiles of children who may clearly classify as CAS or SD. Further, researchers interested in examining speech motor control during accurate speech in children are faced with the task of collecting an adequate amount of interpretable data from experiments that tax the motor and linguistic systems. Although we are cautious in over-interpreting the effect that these missing data may have had on our findings, we are left speculating whether group differences for duration and STI may have been even more

distinct if the participants with CAS who were more severely impaired were included in all analyses.

Influence of Task Demands on Speech Motor Control in CAS

We predicted that increasing linguistic complexity, by increasing word length, would differentially affect artic-ulator movement across groups. Our results for duration and movement stability lend support to this hypothesis, illustrating that the motor commands that underlie speech are shaped by task demands. As expected, increasing word length resulted in increased duration across all groups. This finding illustrates the challenge in producing a longer word, as has been documented in the literature (Sadagopan & Smith, 2008; Sasisekaran, Smith, Sadagopan, & Weber-Fox, 2010; Walsh et al., 2006), as well as the increased time required to produce two- and three-syllable tokens. It is interesting to note that the groups altered duration in different ways in response to task demands. The children with SD displayed longer durations for one- and two-syllable words compared with the children with CAS and TD. Children with CAS exhibited longer durations for three-syllable words than the participants with SD and TD. These findings may reflect a point of breakdown for the children with CAS between the production of two- and three-syllable words. Likewise, a significant increase in jaw STI between two- and three-syllable words was observed in the children with CAS but not in the SD and TD groups. The positive relationship between STI and duration in the CAS group suggests that strategies, such as increasing move-ment duration, may help children with less stable speech motor skills achieve accurate speech. From a clinical stand-point, the high degree of movement variability, seen during accurate productions of longer words by children with CAS in the present work, may be related to the inconsis-tent errors that are characteristic of this population. We are also left wondering whether reduced stability of articu-latory control may underlie the difficulties children with CAS have in maintaining treatment gains and in general-izing phonemes across speaking contexts. Longitudinal studies of speech motor control in children with CAS are needed to reveal whether mature speech motor patterns emerge over time and to determine whether increased sta-bility of articulatory control precedes maintenance of accu-rate speech.

Just as utterance length may affect performance and lead to speech breakdowns, children with CAS may utilize simple word structures to compensate for their motor deficits. Likewise, children with cleft palate were shown to avoid words that begin with phonemes that are difficult to produce, a strategy that also affected their lexical devel-opment (Estrem & Broen, 1989; Willadsen, 2013). If chil-dren with CAS avoid more difficult productions, the consequences would be seen in their expressive output and potentially in their expressive competence. Consistent with this notion, the children with CAS in the present work demonstrated poorer performance on the expressive language

portion of the TELD-2 compared with children in the SD and TD groups. Although the children with CAS were also determined to have age-appropriate receptive language skills on the basis of assessment with the TELD-2, this tool is a broad-based language assessment and may not capture specific language deficits. Without a more comprehensive analysis of language performance, it is difficult to establish whether language factors may have contributed to speech motor performance in the children with CAS. In light of the evidence that children with specific language impairment display deficits in articulatory control that are similar to those seen in the children with CAS in the present work (Goffman, 1999, 2004), future studies are needed to elucidate the complex relationship between speech and language in children with communication impairments.

Taken together, our findings illustrate the challenges in isolating a level of breakdown in speech motor processing in CAS. For instance, differences in temporal control between the children with speech impairment (CAS and SD) and children with TD suggest problems at the motor programming level of speech processing in CAS and SD. Thus, the children with CAS and SD may both have difficulty specifying temporal movement parameters. When these findings are viewed in relation to task demands, the children with CAS may also have difficulty adapting the motor plan to adjust to contextual factors. All groups were influenced by the demands placed on them as word length increased; however, the children with CAS displayed more deviant speech motor patterns when they produced three-syllable words. Our findings support the claim that movement variability distinguishes children with CAS from speakers with SD, particularly as task demands increase. There are additional challenges placed on the speech production mechanism by anatomical and physiological maturation as well as cognitive and linguistic development; the contribution of these factors to speech motor development in CAS warrants further exploration. In sum, these results support the shift toward exploring the interactional nature of development to fully understand speech motor processing in children with speech sound disorders (Maassen et al., 2010).

Conclusions

Although the nature of motor control deficits in CAS continues to be debated, a profile of the speech motor skills in CAS, which is characterized most notably by increased variability, has begun to emerge. Our study also provides evidence that children with CAS and SD are affected by task demands to different extents. This was most apparent in the high STIs seen in the CAS group in the production of longer words. Although the children with CAS produced these words accurately, they used a less consistent motor plan to do so. We interpret this finding to suggest that speech motor deficits may underlie the speech production difficulties characteristic of CAS and may play a role in the challenges children with CAS display in achieving and maintaining accurate speech. Future research is warranted

to develop an understanding of the source of such variability and to explore whether speech motor processes are refined in response to intervention. The interaction between linguistic and motor factors in CAS also warrants further investigation in which semantic, syntactic, and phonologic complexity are modified. Additional work in this area can further quantify speech motor performance in CAS, which can contribute to the classification of speech production impairments overall.

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