Research Article

Articulatory Control in Childhood Apraxia of Speech in a Novel Word–Learning Task

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Purpose: Articulatory control and speech production accuracy were examined in children with childhood apraxia of speech (CAS) and typically developing (TD) controls within a novel word–learning task to better understand the influence of planning and programming deficits in the production of unfamiliar words.

Method: Participants included 16 children between the ages of 5 and 6 years (8 CAS, 8 TD). Short- and long-term changes in lip and jaw movement, consonant and vowel accuracy, and token-to-token consistency were measured for 2 novel words that differed in articulatory complexity.

Results: Children with CAS displayed short- and long-term changes in consonant accuracy and consistency. Lip and

jaw movements did not change over time. Jaw movement duration was longer in children with CAS than in TD controls. Movement stability differed between low- and high-complexity words in both groups.

Conclusions: Children with CAS displayed a learning effect for consonant accuracy and consistency. Lack of change in movement stability may indicate that children with CAS require additional practice to demonstrate changes in speech motor control, even within production of novel word targets with greater consonant and vowel accuracy and consistency. The longer movement duration observed in children with CAS is believed to give children additional time to plan and program movements within a novel skill.

Childhood apraxia of speech (CAS) is a pediatric motor speech disorder that often results in unintelligible verbal output and slow progress in treatment (American Speech-Language-Hearing Association [ASHA], 2007; Davis, Jakielski, & Marquardt, 1998; Forrest, 2003; Shriberg, Aram, & Kwiatkowski, 1997a). CAS is characterized by (a) impaired coarticulatory transitions between sounds and syllables; (b) inconsistent errors within repeated productions of the same word; and (c) inappropriate prosody, particularly with respect to lexical and phrasal stress patterning (ASHA, 2007). Past research has demonstrated that children with CAS display deficits in the planning and/or programming of speech movements (Grigos & Kolenda, 2010; Grigos, Moss, & Lu, 2015; Grigos, Moss, & Tampakis, 2011; Moss & Grigos, 2012; Nijland, Maassen, & Van der Meulen, 2003; Nijland, Maassen, Van der Meulen, Gabreels, et al., 2003; Terband & Maassen, 2010; Terband, Maassen, Van Lieshout, & Nijland, 2011; Van der Merwe, 2009). Although several studies have investigated treatment strategies to target speech motor deficits in CAS

(Ballard, Robin, McCabe, & McDonald, 2010; Edeal & Gildersleeve-Neumann, 2011; Iuzzini & Forrest, 2010; Maas, Butalla, & Farinella, 2012; Maas & Farinella, 2012; Murray, McCabe, & Ballard, 2015; Strand & Debertine, 2000; Strand, Stoeckel, & Baas, 2006), it remains unknown how children with CAS respond to the motor demands intrinsic to learning novel speech targets. To further explore this process, this work investigated speech motor learning within a novel word–learning task to examine how children with CAS produce unfamiliar words and the impact of this task on speech motor control.

Levels of Speech Processing

Spoken communication involves both linguistic and speech motor processes (Goffman, 2010; Kent, 2004; Levelt, 1989; Van der Merwe, 2009). When learning a new word, an individual acquires information about the semantic, lexical, and phonological properties of a word (Gupta & MacWhinney, 1997). The phonological information is used to create a motor plan that specifies spatial and temporal aspects of speech movements for each phoneme of that word (Van der Merwe, 2009). Once the core motor plan is retrieved, a motor program is created according to movement specifications determined by the context (Van der Merwe, 2009). The final stage involves the execution of the motor plan, during which the target word is produced.

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Research has shown that children with CAS exhibit deficits across all levels of speech production, including lexical representation (Marquardt, Sussman, Snow, & Jacks, 2002; Shriberg, Aram, & Kwiatkowski, 1997b), phonological encoding (Thoonen, Maassen, Gabreels, & Schreuder, 1994), speech motor planning (Nijland, Maassen, Van der Meulen, Gabreels, et al., 2003), and speech motor programming (Nijland, Maassen, & Van der Meulen, 2003). Conflicting findings have emerged from these works, as they claim that different processing levels are the core deficit for children with CAS. However, greater consensus recently has been achieved in acknowledging motor planning and programming to be the primary deficit for children with CAS (ASHA, 2007; Grigos & Kolenda, 2010; Grigos et al., 2011, 2015; Moss & Grigos, 2012; Nijland, Maassen, & Van der Meulen, 2003; Nijland, Maassen, Van der Meulen, Gabreels, et al., 2003; Terband & Maassen, 2010; Terband et al., 2011; Van der Merwe, 2009). The current research aims to understand whether and how these speech motor deficits impede a speaker's ability to produce novel words for which there would be no preexisting linguistic or motoric representation.

Articulatory Control in CAS

Researchers have studied articulatory control as one approach to examining speech motor planning and programming. This line of research provides information about kinematic parameters of speech production (e.g., duration, displacement, or velocity of articulator movement) that would be specified at the planning and/or programming levels of speech production. Studies on speech motor development have revealed that young children produce lip and jaw movements that are longer in duration, slower in velocity, and greater in variability than those produced by adults (Green, Moore, Higashikawa, & Steeve, 2000; Grigos, Saxman, & Gordon, 2005; Sadagopan & Smith, 2008; Smith & Zelaznik, 2004). There is mounting evidence that children with speech sound disorders (including CAS) exhibit less mature speech motor patterns compared with their typically developing (TD) peers (Grigos, Hayden, & Eigen, 2010; Grigos & Kolenda, 2010; Grigos et al., 2011, 2015; Moss & Grigos, 2012; Terband et al., 2011). Grigos and colleagues have used facial tracking technology to measure oral articulator movement in children with CAS, speech sound disorders secondary to impaired articulation or phonological skills (SD), and typical speech-language development. In a longitudinal study of a child with CAS, Grigos and Kolenda (2010) reported decreased jaw movement variability, decreased duration, and increased jaw speed over an 8-month period compared with TD controls. As consonant and vowel accuracy increased in the child with CAS, articulator movement became more similar to that in TD controls. Moss and Grigos (2012) and Grigos et al. (2015) compared articulator movement during accurate word production in children with CAS and SD and in TD children. Results from these works revealed more variable spatial and temporal coupling in children with

CAS than in children with SD (Moss & Grigos, 2012), as well as higher jaw movement variability in children with CAS compared with both TD children and children with SD (Grigos et al., 2015).

Terband et al. (2011) also examined differences in articulatory control between TD children and children with CAS and SD using electromagnetic midsagittal articulography to analyze lip, jaw, and tongue tip movements. Different movement patterns were observed between the groups of children. Children with CAS displayed greater variability in tongue tip and jaw movement trajectories and higher lower lip amplitude than TD children. These results also support the notion that articulatory control differs between children with CAS and TD controls.

Speech Motor Control in Novel Word Learning

Several investigators have examined changes in oral articulator movement in TD children (Heisler, Goffman, & Younger, 2010; Sasisekaran, Smith, Sadagopan, & Weber-Fox, 2010; Walsh, Smith, & Weber-Fox, 2006) and children with specific language impairment (Heisler et al., 2010) in nonword-learning tasks. Walsh et al. (2006) and Sasisekaran et al. (2010) investigated changes in kinematic parameters as a function of practice within the production of one- to four-syllable nonwords of increasing complexity (e.g., /mæb/, /mæbjaɪb/, /mæbfaɪeɪb/, /mæbjeɪtaɪdɔɪb/) by 9- and 10-year-olds and adults. Walsh et al. (2006) reported shorter movement durations and increased movement consistency following multiple repetitions of nonwords in children but not in adults. Sasisekaran et al. (2010) included more complex nonwords (i.e., nonwords with clusters containing two to three constituents—/mæbspoukwɪfleɪb/, /mæbskɪsploɪstrub/) and investigated longer term changes 1 day following the initial session. Similar to Walsh et al. (2006), children exhibited shorter total movement durations and decreased variability in nonwords secondary to practice. Adults also exhibited short-term within-session changes, though predominantly in the production of the more complex tokens. Furthermore, both adults and children demonstrated long-term retention of the observed changes, as evidenced by shorter durations and increased movement consistency on the following day. To examine language and speech motor interactions in younger children, Heisler et al. (2010) investigated how 4-year-olds (TD and those with specific language impairment) produced nonwords in which a subset of words was assigned a lexical referent (e.g., “fushpim,” “pafkub,” “bapkfif,” “mofpum”). Decreased movement variability was reported for all participants in words assigned a lexical referent compared with those that remained a novel phonetic string. This finding was interpreted as evidence of an interaction between lexical and phonetic levels of speech processing in both groups of children.

To our knowledge, there is no published research that has explored articulatory control in children with CAS during novel word learning. This area is of particular interest in CAS because slow treatment progress and poor

generalization and maintenance of speech skills are commonly reported in this population (Ballard et al., 2010; Davis et al., 1998; Forrest, 2003; Grigos & Kolenda, 2010; Maas et al., 2012; Strand & Debertine, 2000; Strand et al., 2006). The use of nonword targets provides the opportunity to capture the learning process and provide insight into the motor processes that may facilitate or hinder accurate word production in children with CAS.

Speech Motor Learning

This work addresses novel word learning within a framework that integrates principles of motor learning. Principles of motor learning describe the practice conditions that best facilitate and enhance learning of a novel skill, including intensity and frequency of practice sessions (Edeal & Gildersleeve-Neumann, 2011), order of stimulus presentation (Maas & Farinella, 2012), type and degree of feedback (Ballard et al., 2012), and task complexity (Ballard et al., 2010; Maas, Barlow, Robin, & Shapiro, 2002; Schneider & Frens, 2005). Several works in the CAS literature have applied principles of motor learning to their procedural design (Ballard et al., 2010; Edeal & Gildersleeve-Neumann, 2011; Iuzzini & Forrest, 2010; Maas & Farinella, 2012; Maas et al., 2012; Strand & Debertine, 2000; Strand et al., 2006). Specific elements include frequent and intensive practice (Edeal & Gildersleeve-Neumann, 2011), a faded feedback schedule (Maas et al., 2012), and more complex targets to facilitate generalization of learned skills (Ballard et al., 2010).

The influence of task complexity on speech output has been reported in studies of TD children (Sasisekaran et al., 2010; Walsh et al., 2006), children with phonological impairment (Gierut, 2001; Gierut, Morrisette, & Ziemer, 2010), children with CAS (Ballard et al., 2010; Grigos et al., 2015), and adults with acquired apraxia of speech (Maas et al., 2002; Schneider & Frens, 2005; Van der Merwe, 2011). Few studies have analyzed the impact of complexity on speech production in children with CAS. Grigos et al. (2015) reported that children with CAS displayed higher spatiotemporal indices (STIs) in longer words compared with children with other speech sound disorders, suggesting that these groups are affected to different extents by task demands (i.e., increase in word length). Ballard et al. (2010) investigated a treatment paradigm that targeted prosody in three children with CAS. They examined generalization of treatment gains to less and more complex stimuli. Greater generalization was evidenced in more complex stimuli compared with less complex stimuli, supporting the notion that complexity plays a role in speech motor learning.

Although there are a number of ways to approach task complexity (Maas, Gildersleeve-Neumann, Jakielski, & Stoeckel, 2014), studies have examined complexity with regard to the number of different consonant and vowel combinations in a token (Ballard et al., 2010; Schneider & Frens, 2005). This view of articulatory complexity is of particular interest for disorders of motor planning and/or programming because more complex targets would require

a greater degree of articulatory adjustments and coordination along the vocal tract (Browman & Goldstein, 1992), which would pose greater motoric challenges to children with CAS.

Research Questions and Hypotheses

The current study examined short- and long-term changes (i.e., following a 3-day interval) in articulator movement and speech production accuracy in children with CAS and TD controls using a novel word-learning task that integrated motor learning principles. The following research questions and hypotheses were addressed:

1. Do speech production accuracy (i.e., consonant and vowel accuracy) and token-to-token consistency improve over time when children with CAS and TD controls learn a novel word? It was hypothesized that both groups would display short-term improvements in consonant and vowel accuracy and token-to-token consistency. We anticipated that a long-term learning effect would be seen only in the TD group.
2. Does articulator movement (i.e., lip and jaw movement duration and variability) change over time when children with CAS and TD controls learn a novel word? We predicted that the TD group would exhibit shorter movement durations and decreased variability following practice. We did not anticipate short- or long-term changes in movement duration or variability in the CAS group.
3. What is the impact of increased articulatory complexity on speech sound production and articulator movement when children with CAS and TD controls learn a novel word? Greater articulatory complexity was predicted to affect consonant and vowel accuracy, token-to-token consistency, and articulator movement to a greater degree in the children with CAS than in the TD children due to increased motoric demands posed by more complex targets.

Method

Participants

Sixteen children between the ages of 5;0 and 6;10 years (12 male participants, 4 female participants) participated in the study (see Table 1 for participant characteristics). Eight participants were children with typical speech and language development, and eight participants were children who met criteria for the diagnosis of CAS (described below). Beyond these 16 participants, three children were seen but not included in the study because they did not meet the criteria for CAS and displayed characteristics of both articulation and phonological impairments. All participants were monolingual speakers of English who lived in the United States. The mean age (standard deviation) was 5;8 years (6 months) for children with CAS and 5;8 years (8 months) for TD children. Pairwise matching was conducted between the groups for

Table 1. Participant characteristics.

TELD-3																							VMPAC									
ID	Age	Receptive		Expressive		CMMS		GMC		FOMC		Sequencing		Connected speech		Speech characteristics		GFTA		Speech sample												
		Q	Percentile	Q	Percentile	ADS	Percentile	%	Rating	%	Rating	%	Rating	%	Rating	%	Rating	SS	Percentile	PCC	PVC	PWC										
CAS																																
CAS1	5;4	110	74	88	21	120	89	85	Sev	93.0	WNL	87.0	WNL	87.0	Mod	71.0	Sev	82	13	88.8	92.0	86.5										
CAS2	5;0	110	74	102	55	93	33	95	WNL	83.0	Mod	74.0	WNL	87.0	Mod	71.0	Sev	93	27	94.9	97.7	84.3										
CAS3	6;9	97	42	94	34	89	25	90	Sev	70.2	Sev	73.9	Mild	80.0	Sev	57.1	Sev	44	<1	45.0	76.4	63.3										
CAS4	5;11	110	74	94	34	106	65	90	Sev	73.0	Sev	50.0	Sev	71.0	Sev	71.0	Sev	<40	<1	45.1	64.4	42.9										
CAS5	6;4	89	24	88	21	89	25	75	Sev	72.0	Sev	69.6	Mod	88.9	Mild	71.4	Sev	100	24	89.4	98.4	78.5										
CAS6	5;11	118	88	118	88	116	84	100	WNL	91.0	WNL	84.8	WNL	86.7	Mild	71.4	Sev	75	9	67.5	84.9	46.6										
CAS7	5;8	118	88	100	50	113	79	95	Mod	75.0	Sev	69.5	Mild	87.0	Mod	86.0	Mod	67	5	68.8	93.4	83.8										
CAS8	5;7	118	88	82	12	109	71	100	WNL	85.1	Mod	78.3	WNL	57.8	Sev	57.1	Sev	<40	<1	58.1	82.0	61.6										
M	5;8	108.8	69.0	95.75	39.38	104.4	58.9	91.3		80.3		73.4		80.6		69.6		76.8	15.6	69.7	86.2	68.4										
SD	6	10.60	23.60	11.13	24.51	12.50	27.00	8.40		8.90		11.40		10.90		9.20		20.00	9.50	19.80	11.70	17.10										
TD																																
TD1	5;0	109	73	94	34	103	57	100	WNL	97.0	WNL	87.0	WNL	100.0	WNL	100.0	WNL	112	68	100.0	100.0	100.0										
TD2	6;10	105	63	118	88	96	40	100	WNL	98.5	WNL	97.8	WNL	100.0	WNL	100.0	WNL	108	56	100.0	100.0	100.0										
TD3	6;0	121	92	115	84	111	75	100	WNL	99.2	WNL	91.3	WNL	100.0	WNL	100.0	WNL	112	>75	99.4	98.3	97.1										
TD4	5;4	130	98	115	84	128	96	100	WNL	100.0	WNL	100.0	WNL	100.0	WNL	86.0	Mod	113	>83	97.8	99.2	94.0										
TD5	5;7	121	92	100	50	133	98	100	WNL	99.2	WNL	91.3	WNL	100.0	WNL	100.0	WNL	113	78	99.5	100.0	100.0										
TD6	5;3	124	95	112	79	144	99+	100	WNL	96.6	WNL	84.8	WNL	93.3	WNL	100.0	WNL	101	31	88.1	99.2	95.0										
TD7	6;10	121	92	112	79	150+	99+	100	WNL	99.6	WNL	95.6	WNL	100.0	WNL	100.0	WNL	108	56	91.2	98.4	96.7										
TD8	5;7	118	88	115	84	142	99+	100	WNL	100.0	WNL	80.4	WNL	100.0	WNL	100.0	WNL	111	76	100.0	99.3	100.0										
M	5;8	118.6	86.6	110.5	73.3	122.4	73.2	100.0		98.8		91.0		99.3		98.4		109.8	60.8	97.0	99.3	97.9										
SD	8	8.05	12.10	8.80	20.10	19.10	25.00	0.00		1.30		6.70		2.40		5.00		4.10	17.40	4.70	0.70	2.50										

Note. TELD-3 = Test of Early Language Development—Third Edition; Q = quotient; CMMS = Columbia Mental Maturity Scale; ADS = age deviation score; VMPAC = Verbal Motor Production Assessment for Children; GMC = Gross Motor Control subtest; FOMC = Focal Oromotor Control subtest; SEQ = Sequencing; Conn Speech = Connected Speech; Speech Char = Speech Characteristics; % = percentage; WNL = within normal limits; Mod = moderate; Sev = severe; GFTA = Goldman-Fristoe Test of Articulation—Second Edition; SS = standard score; PCC = percentage of consonants correct; PVC = percentage of vowels correct; PWC = percentage of whole-word consistency.

age (± 3 months) and gender. The children demonstrated age-appropriate receptive language skills according to the receptive language component of the Test of Early Language Development—Third Edition (TELD-3; Hresko, Reid, & Hammill, 2007) and normal cognitive skills on the Columbia Mental Maturity Scale (CMMS; Burgmeister, Blum, & Lorge, 1972). Participants passed a hearing screening at 20 dB SPL at 500, 1000, 2000, and 4000 Hz.

To establish whether participants met criteria for the TD or CAS groups, a comprehensive assessment of oromotor function, articulation skills, movement transitions in speech and nonspeech tasks, and prosody was conducted. Differential diagnosis (ASHA, 2007; Davis et al., 1998) was used to rule out children who presented with articulation or phonological disorders, dysarthria, or fluency disorders.

The diagnosis of CAS was made independently by both authors, who are ASHA-certified speech-language pathologists with extensive experience in the evaluation of CAS. Speech production was assessed during three speaking contexts: single words, connected speech, and repeated productions of varied syllables and words. Single-word production was assessed using the Goldman–Fristoe Test of Articulation—Second Edition (GFTA-2; Goldman & Fristoe, 2000). Connected speech was examined using a 100-word speech sample elicited by a story retell narrative of the wordless picture book *Pancakes for Breakfast* (DePaola, 1978). Repeated productions of varied syllables (e.g., /a-i/, /pʌtʌkʌ/) and words (e.g., *pea*, *tea*, *key*) were examined using the Verbal Motor Production Assessment for Children (VMPAC; Hayden & Square, 1999). These tasks were administered to assess coarticulatory transitions within speech movements. The VMPAC was also used to evaluate oromotor structure and function. Single-word and connected speech samples were examined to describe each participant's phonetic inventory and token-to-token consistency as well as the presence of additions, omissions, distortions, and substitutions.

Children With CAS

The eight children in the CAS group were recruited by contacting pediatric speech-language pathologists and families of children with CAS from New York University's Speech, Language and Hearing Clinic, hospitals, schools, and private practices in New York and New Jersey. Diagnostic classification for CAS was determined according to the presence of the three core features identified in ASHA (2007)—inconsistent errors, inappropriate prosody, and coarticulatory deficits—in more than one speaking context. The presence of the following characteristics associated with CAS was also identified: vowel errors, timing errors related to voicing and nasality, speech sound distortions, articulatory groping, increased errors with increased utterance length and complexity, atypical errors, and a reduced phonetic inventory (see Table 2 for CAS diagnostic features). In addition, performance on the Sequencing subtest of the VMPAC was examined for evidence of speech and nonspeech movement sequencing difficulties. The Connected Speech and Language Control and Speech Characteristics subtests of the

VMPAC were also analyzed to assess the impact of speech motor deficits on connected speech and the overall quality of speech. Although children ranged in severity according to standard scores, speech production accuracy, and error patterns (see Tables 1 and 2), all displayed the three core features described by ASHA (2007) in more than one speaking context. Further, all participants in the CAS group displayed timing errors, vowel errors, and distortions. Children included in the CAS group met the criteria above and exhibited normal structure of the oral peripheral mechanism as determined by the VMPAC.

TD Children

The children in the TD group were recruited from local community centers, preschools, and elementary schools in the New York City area. TD children had no reported histories of speech, language, or hearing problems and/or developmental or neurological disorders. In addition to demonstrating age-appropriate receptive language and cognition, participants in the TD group demonstrated (a) normal structure and functioning of the oral mechanism on the VMPAC, (b) age-appropriate articulation skills as measured by the GFTA-2 and a conversational speech sample, and (c) age-appropriate expressive language skills on the TELD-3. Age-appropriate performance on the GFTA-2 and the TELD-3 for the TD children was determined by standardized results greater than 1 *SD* below the mean (i.e., ≥ 85). The normative data provided in Smit, Hand, Freilinger, Bernthal, and Bird (1990) were used to determine the age appropriateness of articulation skills observed within the connected speech sample.

Procedure

Instruments

A motion-capture system (Vicon 460; Vicon Motion Systems, Los Angeles, CA) was used to track articulator movement in three dimensions. Twelve reflective markers (each 3 mm in diameter) were placed on the face and were used to track lip and jaw movement and to account for head movement. The system tracked the reflective markers at a sampling rate of 120 frames per second. Video and audio recordings were made using a digital video camera (Model DSC-T1; Sony, Tokyo, Japan) and a digital minidisc recorder (HHB50). Testing and data collection took place at the Department of Communicative Sciences and Disorders at New York University. Recordings were made in a sound-attenuated audiometric booth at New York University. Kinematic data were analyzed using MATLAB (MathWorks Inc., 2013).

Stimuli

To examine the impact of complexity on speech motor learning, the experimental tokens consisted of two novel words that differed in articulatory complexity with respect to the number of place, manner, and voicing differences in consonants and vowels between syllables (Ballard et al.,

Table 2. Diagnostic criteria met by children with childhood apraxia of speech (CAS).

Criterion	CAS1	CAS2	CAS3	CAS4	CAS5	CAS6	CAS7	CAS8
ASHA (2007)								
Impaired coarticulatory transitions	X	X	X	X	X	X	X	X
Inappropriate prosody	X	X	X	X	X	X	X	X
Inconsistent errors	X	X	X	X	X	X	X	X
Additional features								
Vowel errors	X	X	X	X	X	X	X	X
Timing errors	X	X	X	X	X	X	X	X
Speech sound distortions	X	X	X	X	X	X	X	X
Articulatory groping			X	X	X	X		X
Errors increase with length and complexity	X	X	X	X	X	X	X	X
Atypical errors	X	X	X	X	X	X	X	X
Reduced phonetic inventory		X	X	X		X	X	X

2012; Schneider & Frens, 2005). All phonemes were early-developing sounds and were present in participants' phonetic repertoires. The low-complexity stimulus contained similar vowels with different consonants (i.e., *badabap*; /'ba.rə.bap/), and the high-complexity stimulus contained different consonants and vowels (i.e., *madeepoom*; /'ma.ri.pum/). The following hierarchies were applied: (a) low complexity (*badabap*)—vowel harmony + consonant disharmony with different place of articulation (i.e., labial and alveolar), same manner class (i.e., stop plosives), and all voiced consonants except for the final /p/; (b) high complexity (*madeepoom*)—vowel disharmony + consonant disharmony with variations in manner class (i.e., nasals and stop plosives) and a within-word voiceless consonant. The low-complexity word would be less taxing to the motoric system because the vowels were similar and there was a lesser degree of change in place, manner, and voicing across this token. The high-complexity token would require increased articulatory effort due to alternations in place, manner, and voicing in both consonants and vowels. Primary stress was placed on the first syllable, secondary stress was placed on the third syllable, and the second syllable was unstressed.

Design

Children were seen over 3 days. Day 1 was dedicated to administration of the testing battery; Days 2 and 3 were designated for the experimental task, a practice session, and completion of testing, if needed. The experimental task consisted of three separate data-collection sessions: Time 1 (T1), Time 2 (T2), and Time 3 (T3). Details regarding each day and the respective tasks are provided in the following sections (also see Table 3).

Day 1

Standardized testing and speech sampling were conducted on Day 1. This testing and sampling assessed oro-motor function, articulation skills, speech and nonspeech movement sequencing skills, and prosody.

Day 2

Familiarization. A brief familiarization session was conducted prior to T1. Participants were shown two puppets

named *Badabap* and *Madeepoom*. When the stimuli were presented, children were instructed to listen and remain quiet while the investigator introduced each word and provided an accompanying narrative containing five repetitions of that particular token.

T1 (baseline). Kinematic data collection began following the familiarization phase. Participants first produced the tokens during T1 in order to obtain a baseline measure of oral articulator movement within initial attempts of articulating novel words. Productions were elicited during a story retell game in which children were asked to respond to a question or complete a sentence using names of the puppets that represented each of the novel words (e.g., "Madeepoom went for a walk. Who went for a walk? It was..."). Multiple models of novel word tokens (i.e., puppet names) were presented throughout data collection to reduce the cognitive demand associated with memorization of tokens. If children displayed difficulty retrieving the target name, the examiner would restate the name of the target word in a natural manner and re-elicited production (e.g., "Yes, Madeepoom took a walk. Tell me again. Who took a walk?"). The examiner followed a protocol in which tokens were produced up to 20 times each and elicited in a random order that followed a randomization sequence. No feedback related to accuracy was given, although children were provided with encouragement and motivational feedback (e.g., "Great job!").

Practice session. Following T1, children were brought to a clinic treatment room and participated in a structured, play-based practice session to facilitate learning of novel word tokens. The practice session integrated motor learning

Table 3. Outline of procedure.

Day	Tasks
1	Speech-language and nonverbal cognitive testing Collection of speech sample Auditory screening
2	Familiarization period Baseline Practice session Short-term change
3	Familiarization period Long-term retention (3 days later)

principles with regard to the structure of the practice session and feedback. Tokens were first practiced within a blocked design to facilitate initial learning, followed by randomized presentation of the stimuli. Because the learning of novel words was predicted to be particularly challenging for children with CAS, the current work incorporated blocked practice to facilitate initial learning followed by randomized practice to enhance long-term retention of practice gains (Hall & Magill, 1995). A reduced knowledge of results (KR) feedback schedule was implemented to facilitate long-term retention of practice gains (Maas et al., 2008; Schmidt, 2003). Tokens were practiced 30 times each, resulting in a total of 60 productions during the practice session.

Stimulus presentation was divided into thirds (i.e., 10 productions of each novel word per third), with a faded amount of feedback provided for each portion of the practice session. In the initial third of the session, targets were presented in a blocked design in which participants practiced one target at a time. KR and knowledge of performance (KP) feedback was provided on 100% of the first 10 productions of each word to promote initial learning. KR feedback indicated whether the child produced the token accurately. KP feedback consisted of visual, verbal, or tactile cues and provided children with direct information about how a token was produced (e.g., “Your lips are not closing at the end of the word. Watch my lips close. Be sure to close your lips too.”). During the second third of the practice session, stimuli were presented in a randomized order with both KP and KR feedback provided on 50% of productions of the second 10 productions of each word. In the final third of the practice sessions, tokens continued to be presented randomly, and KP and KR feedback was offered on 20% of the words produced. Despite findings that KP feedback does not facilitate long-term retention (Ballard et al., 2012), KP feedback was offered throughout the practice session and given at gradually reduced intervals. Continued KP feedback was necessary for children with CAS because this group of children required feedback that offered specific details to facilitate accurate production of targets.

T2 (short-term change). Following practice, a second kinematic session was conducted to assess short-term practice effects. Short-term changes are representative of skill acquisition and do not necessarily suggest that the targeted skill was learned. Rather, these changes reflect within-session practice effects. The data were collected in the same manner as during the baseline session.

Day 3

Refamiliarization. Three days later, participants returned for a third data collection session to assess maintenance of short-term change. This time period was selected to parallel the amount of time that would lapse between treatment sessions that occurred twice per week. Prior to kinematic data collection, participants completed the same familiarization protocol as at the beginning of Day 2.

T3 (long-term retention). The third kinematic session occurred immediately following refamiliarization. Retention of changes from T1 to T3 and from T2 to T3 was

measured to assess long-term maintenance of practice gains. No verbal productions of tokens were elicited between T2 and T3. Elicitation of the tokens followed the same format as T1 and T2.

Analyses

Transcription Analysis

Each utterance was transcribed from a recording using narrow phonetic transcription. Productions were compared to the intended target to identify (a) percentage of consonants correct (PCC; Shriberg & Kwiatkowski, 1982), (b) percentage of vowels correct (PVC), and (c) percentage of whole-word consistency (PWC). A maximum of 20 productions of each token were obtained from each participant. Productions were not included if (a) the child did not use his or her habitual speaking pattern in terms of perceived rate, fluency, and vocal quality; (b) the child and experimenter spoke simultaneously; and/or (c) there was background noise. To ensure an equal number of utterances between children, only the first 13 productions were included in the transcription analysis.

PCC and PVC represented the percentage of accurately produced consonants and vowels, calculated as (number of consonants correct / total number of consonants) $\times$ 100. Accurate productions were defined as consonant and vowel productions that were free of errors, such as distortions, omissions, substitutions, or additions. PWC was calculated as the number of different variations of a token that a child produced and included both incorrect and correct productions (Case, Moss, & Grigos, 2012). For instance, if a child produced *badabap* as “badabap,” “badeebap,” “babeebap,” and “badeebap,” there would be three variants of that word. This number was then divided by the total number of productions of the same word (e.g., four total productions in the above example). As this was a measure of consistency, this number was subtracted from 1 and then multiplied by 100. The following formula was used for this measure: $[1 - (\text{number of different word forms} / \text{total number of productions of that word})] \times 100$. Using the previous example of *badabap*, a PWC of 25% would be obtained: $[(1 - (3 / 4)) \times 100 = 25\%$.

Reliability of transcriptions was conducted on 10% of the tokens by two ASHA-certified speech-language pathologists to judge interrater agreement. An interrater reliability of 93.75% was achieved. Disagreements were resolved by a third listener. Consensus was achieved across all discrepancies, and no trials were eliminated due to lack of agreement.

Kinematic Analysis

Kinematic analyses were performed on accurately produced tokens using MATLAB (MathWorks Inc., 2013). Analyses on accurate productions is common in studies of articulator movement to ensure that kinematic differences are due to changes in speech motor control that were independent from articulation errors (e.g., Green et al., 2000, Green, Moore, & Reilly, 2002; Moss & Grigos, 2012;

Sasisekaran et al., 2010). Production of targets in the current work was particularly challenging for children with CAS, and a limited number of error-free tokens were produced across all three time periods. As a result, our criteria for accurate productions were modified to maximize the number of productions that could be incorporated in the kinematic analyses. Productions containing timing errors affecting nasality and voicing (e.g., prevocalic voicing, denasalization, nasalization) and final consonant errors were included. These productions were included for several reasons: (a) timing errors did not alter place of articulation, (b) manner and/or voicing were not entirely changed following the timing errors, and (c) the kinematic analyses did not include the word-final consonant because participants did not consistently release the final phoneme.

Kinematic tracings of the upper lip, lower lip, and jaw were analyzed to study the temporal and spatial features of lip and jaw movements. The acoustic signal for each token was compared with each kinematic trajectory. Kinematic measures of total jaw movement duration and stability of jaw movement and lip aperture were obtained. The jaw displacement trajectory was used to define movement onset and offset for each token. Movement onset was the point 10 frames (0.083 s) before the initial peak closing displacement. Movement offset was taken as the point 10 frames after the final peak opening displacement (0.083 s). Total jaw movement duration was calculated for each word and measured as the duration of time (seconds) between the onset and offset of jaw movement.

To examine the stability of movement patterns, trajectories were time and amplitude normalized. The STI was then calculated (Smith, Goffman, Zelaznik, Ying, & McGillem, 1995) and used as an index of movement stability for both jaw movement and lip aperture. 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 computed by calculating standard deviations at 2% intervals across the repetitions of the time- and amplitude-normalized displacement traces. The STI is the cumulative sum of these 50 standard deviations (Smith et al., 1995) and indicates the degree to which the set of trajectories converges onto one fundamental movement pattern (Smith, Johnson, McGillem, & Goffman, 2000).

Jaw STI (jSTI) and lip aperture STI (laSTI) were computed. jSTI reflected the distance between the lower lip and the jaw, whereas laSTI was the distance between the upper and lower lips. Both measures of stability were used because each measure represents differing levels of speech motor control (Smith & Zelaznik, 2004). In their study of speech motor development from 4 years of age through early adulthood, Smith and Zelaznik (2004) described lip aperture as a higher order synergy representative of oral opening within speech and lower lip–jaw movement as a lower order synergy subordinate to lip aperture. Thus, the analysis of both laSTI and jSTI could reveal differences in speech motor control within the present task.

Statistical Analysis

A repeated measures analysis of variance (ANOVA) was performed. Conditions of normality and homogeneity for the repeated measures ANOVA were met for all dependent variables. The assumption of sphericity was met for all variables except PCC, PWC, and lip aperture stability. In these cases, the degrees of freedom were corrected using Greenhouse–Geisser estimates. We examined the effect of time (T1, T2, and T3, or baseline, short-term change, and long-term retention, respectively), word complexity (low vs. high), and group (CAS or TD) on movement duration, stability, consonant and vowel accuracy, and consistency. The variables time and complexity were entered as repeated measures variables, whereas group was a between-subjects variable. When the overall main effect of repeated measures variables was significant, pairwise comparisons were examined to determine specific differences between variables. When there was a significant interaction, simple effects of the variables involved in the interaction were analyzed. If the simple effect was significant, pairwise comparisons were examined to identify which variables differed. When multiple pairwise comparisons of simple effects were conducted, Bonferroni adjustments were made to the *p* value to control for Type I error.

Results

A total of 1,282 word productions were obtained from the participants. This included 595 productions from the CAS group (313 low complexity, 282 high complexity) and 687 productions from the TD group (364 low complexity, 323 high complexity). The analyses were performed in two ways. First, transcription analyses were conducted on the first 13 productions from each participant (both correct and incorrect). This reduced the data set to 1,248 productions for the transcription analyses—16 participants $\times$ 2 novel words $\times$ 13 productions $\times$ 3 time periods (T1, T2, T3). Consonant (PCC) and vowel (PVC) accuracy and consistency (PWC) were then calculated for each participant. The first 13 productions were selected from each child to ensure an equal number of productions per child. Second, kinematic analyses were completed using accurately produced tokens and those tokens that contained previously defined acceptable errors (i.e., final consonant errors, voicing errors, denasalization or nasalization errors). Participants were required to have at least three correct productions to be included in the kinematic analyses. Two participants with CAS were eliminated from the kinematic analyses due to failure to meet these criteria. As expected, the TD group produced a greater number of accurate productions compared with the CAS group. To reduce the number of productions included from the TD group, a maximum of eight correct productions were included for each of the two tokens at each of the three time periods. A total of 640 productions were included in the kinematic analyses: 265 for the CAS group (127 low complexity, 138 high complexity)

and 375 for the TD group (183 low complexity, 192 high complexity). In the CAS group, 63% of tokens contained predefined acceptable errors, compared with 0.2% of tokens in the TD group. Transcription and kinematic results are described below.

Transcription Analysis

PCC

Children with CAS displayed lower PCC values than did TD children at T1, T2, and T3 (see Table 4). This observation was supported by a significant main effect of time on PCC, $F(1.392, 19.493) = 23.461, p < .001, \eta^2 = .626$, in addition to a significant Time $\times$ Group interaction, $F(1.392, 19.493) = 14.205, p < .001, \eta^2 = .504$. There was no observed main effect of complexity on PCC, $F(1, 14) = 2.977, p = .106$. There was also a significant main effect of group, $F(1, 14) = 17.05, p = .001, \eta^2 = .549$, which supports the observation of lower levels of consonant accuracy in the CAS group compared with the TD group.

Simple main effects were examined to explore the Time $\times$ Group interaction in the production of both non-words. Analyses included the combined PCC values for both the low- and high-complexity words because there was no main effect of complexity. A main effect of time on PCC was found for the CAS group, $F(2, 13) = 20.718, p < .001, \eta^2 = .761$, but not the TD group, $F(2, 13) = 0.434, p = .657$. Post hoc pairwise analyses were conducted for the CAS group. The p value was adjusted to $p = .008$ to account for multiple comparisons. Significant increases in PCC were observed between T1 and T2 (mean difference = $-16.405, p < .001$) and between T1 and T3 (mean difference = $-17.970, p < .001$). There were no significant differences between T2 and T3 (mean difference = $-1.564, p = .270$). These findings indicate that children with CAS displayed significant short- and long-term improvements in consonant accuracy at T2 and T3. Furthermore, practice gains were maintained when children returned 3 days later, as there were no significant differences between T2 and T3. TD children did not

exhibit significant differences in consonant accuracy over time. The lack of an effect on the TD children is due to highly accurate performance across all sessions.

PVC

In the production of novel words, children with CAS displayed lower vowel accuracy than TD children at T1, T2, and T3 (see Table 4). Significant main effects of time, $F(2, 28) = 6.459, p = .005, \eta^2 = .316$, complexity, $F(1, 14) = 27.909, p < .001, \eta^2 = .666$, and group, $F(1, 14) = 15.592, p = .001, \eta^2 = .527$, were found. Significant interactions were also found for Time $\times$ Group, $F(2, 28) = 3.329, p = .050, \eta^2 = .192$; Complexity $\times$ Group, $F(1, 14) = 4.67, p = .049, \eta^2 = .250$; Time $\times$ Complexity, $F(2, 28) = 5.707, p = .008, \eta^2 = .290$; and Time $\times$ Complexity $\times$ Group, $F(2, 28) = 4.100, p = .027, \eta^2 = .227$.

Simple main effects for the three-way Time $\times$ Complexity $\times$ Group interaction were analyzed. Children with CAS displayed a significant increase in vowel accuracy for both the less complex tokens, $F(2, 13) = 11.389, p = .001, \eta^2 = .637$, and the more complex tokens, $F(2, 13) = 8.613, p = .004, \eta^2 = .570$. The TD children did not exhibit significant differences in vowel accuracy across the three sessions for either the less complex or the more complex tokens, although lack of change is attributed to high levels of initial accuracy. Post hoc pairwise comparisons were conducted to determine where significant changes in vowel accuracy occurred in the CAS group for each token. To account for multiple pairwise comparisons, the p value was adjusted to $p = .004$. In the production of the low-complexity word, there were no significant changes between T1 and T2 (mean difference = $-11.552, p = .029$) or T2 and T3 (mean difference = $-6.429, p = .154$), though vowel accuracy significantly increased from T1 to T3 (mean difference = $-17.981, p < .001$). When producing the high-complexity word, there was a significant increase in vowel accuracy from T1 to T2 (mean difference = $-12.18, p = .001$) followed by a significant decrease in vowel accuracy from T2 to T3 (mean difference = $9.936, p = .004$). There was no significant change

Table 4. Mean (standard deviation) values for percentage of consonants correct (PCC), percentage of vowels correct (PVC), and percentage of whole-word consistency (PWC) for the first 13 productions at Time 1 (T1; baseline), Time 2 (T2; short-term change), and Time 3 (T3; long-term retention) in children with childhood apraxia of speech (CAS) and in typically developing (TD) children.

Variable	CAS			TD		
	T1	T2	T3	T1	T2	T3
Low complexity (<i>badabap</i>)						
PCC	74.46 (12.78)	92.06 (6.12)	95.19 (8.41)	94.47 (7.15)	98.08 (2.52)	98.32 (2.17)
PVC	68.56 (12.98)	80.11 (9.93)	86.54 (13.34)	92.63 (4.43)	96.16 (5.13)	95.51 (7.09)
PWC	30.77 (13.00)	55.77 (15.25)	67.31 (19.61)	73.08 (19.72)	79.81 (17.42)	83.66 (13.29)
High complexity (<i>madeepoom</i>)						
PCC	70.13 (20.52)	85.34 (11.07)	85.34 (11.26)	96.16 (4.71)	95.91 (2.99)	97.36 (3.24)
PVC	84.30 (16.81)	96.48 (6.12)	86.54 (13.83)	99.04 (1.91)	99.68 (0.91)	99.04 (1.91)
PWC	38.46 (24.33)	68.27 (15.07)	59.62 (10.68)	82.69 (16.32)	80.77 (10.88)	86.54 (9.86)
Nonwords combined						
PCC	72.30 (16.66)	88.70 (9.31)	90.26 (10.87)	95.31 (4.67)	97.00 (2.89)	97.84 (2.71)
PVC	76.43 (16.63)	88.29 (11.61)	86.54 (13.12)	95.83 (4.67)	97.92 (3.99)	97.28 (5.33)
PWC	34.62 (19.26)	62.02 (16.01)	63.46 (15.76)	77.88 (18.18)	80.29 (14.04)	85.10 (11.40)

in vowel accuracy for the more complex token from T1 to T3 (mean difference = -2.244 , $p = .428$). When producing the more complex token, children with CAS did not maintain improvements in vowel accuracy following a 3-day interval.

PWC

Similar to other transcription analyses, children with CAS demonstrated poorer consistency (i.e., lower PWC) than did TD children at all three time points (see Table 4). A significant main effect of time on PWC was found, $F(1.459, 20.427) = 20.929$, $p < .001$, $\eta^2 = .599$, in addition to a Time $\times$ Group interaction, $F(1.459, 20.427) = 10.373$, $p = .002$, $\eta^2 = .426$. There was no significant main effect of complexity, $F(1, 14) = -1.816$, $p = .199$. Significant between-groups differences were also observed, $F(1, 14) = 31.651$, $p < .001$, $\eta^2 = .693$, with higher levels of consistency in the TD group than in the CAS group.

Due to the significant Time $\times$ Group interaction, simple main effects of each variable were analyzed. Because there were no findings for complexity, these analyses considered change in consistency for both the low- and high-complexity tokens. Simple effects analyses revealed that consistency significantly increased across the three time periods for the CAS group, $F(2, 13) = 19.104$, $p < .001$, $\eta^2 = .746$, but not the TD group, $F(2, 13) = 1.458$, $p = .268$. Post hoc pairwise comparisons, at an adjusted significance value of $p = .008$, revealed that children with CAS significantly increased consistency from T1 to T2 (mean difference = -27.403 , $p < .001$) and from T1 to T3 (mean difference = -28.847 , $p < .001$). There were no significant differences between T2 and T3 (mean difference = -1.443 , $p = .620$). These findings indicate that children with CAS displayed short- and long-term improvements in consistency at T2 and T3. Practice gains were maintained 3 days later, as there were no significant differences between T2 and T3.

Articulator Movement Analyses

Total jaw movement duration, jaw movement stability (jSTI), and lip aperture stability (laSTI) were measured for each word. As mentioned previously, analyses were performed on accurately produced tokens and those with previously defined acceptable error patterns.

Total Jaw Duration

Mean total jaw movement duration tended to be longer in the CAS group than in the TD group at T1, T2, and T3 (see Table 5). Despite this observation, between-groups differences in duration did not reach significance, $F(1, 12) = 3.595$, $p = .082$, $\eta^2 = .231$. There was a main effect of complexity on duration, $F(1, 12) = 5.023$, $p = .045$, $\eta^2 = .295$, as movement duration was longer in the high-complexity token than in the low-complexity token. There was no main effect of time, $F(2, 24) = 0.202$, $p = .819$.

Examination of individual data revealed that children tended to follow the group trend at all three time points

for both tokens, except for one child with CAS (CAS1) who exhibited shorter movement duration than all other participants (see Figure 1). Further examination of this child's speech characteristics also revealed a fast rate of speech in connected speech and in production of nonword tokens. Interval estimation therefore was used to compare movement duration for CAS1 with the mean duration values for the TD and CAS groups. A 95% confidence interval was calculated from the between-subjects variance of movement duration for all participants, and upper and lower bound limits were established (McCall, 1994). Comparisons of mean duration between CAS1 and the group mean indicated that this participant did not fall within a 95% confidence interval of the mean at any time point when producing both tokens. Due to these findings, the repeated measures ANOVA was performed excluding CAS1. Significant between-groups differences were observed with longer durations in children with CAS than in TD children, $F(1, 11) = 11.657$, $p = .006$, $\eta^2 = .514$. There was no main effect of time on duration, $F(2, 22) = 0.277$, $p = .761$. Complexity did not reach significance, $F(1, 11) = 4.228$, $p = .064$, although movement durations tended to be longer in the high-complexity token than in the low-complexity token.

Jaw Stability

The STI was calculated to examine patterns of jaw movement stability (jSTI) over time (see Table 6). Higher STI values indicate greater levels of instability, whereas lower values reflect greater levels of stability. Examination of individual data (see range values in Table 6) indicated that children in both groups displayed notable within-group variability with regard to jaw movement stability at all time points and in both tokens. There were no between-groups differences between children with CAS and TD controls, $F(1, 12) = 0.965$, $p = .345$. Further, there was no main effect of time on jSTI, $F(2, 24) = 0.202$, $p = .819$, though the main effect of complexity was significant, $F(1, 12) = 9.401$, $p = .010$, $\eta^2 = .439$, as jSTI values were lower in the less complex token than in the more complex token. There were no significant interactions between variables for jaw stability. jSTI results did not differ when excluding CAS1 (as was noted for measures of movement duration).

Lip Aperture Stability

Lip aperture stability (laSTI) was analyzed to determine change over time in the production of low- and high-complexity tokens by the CAS and TD groups (see Table 7). Similar to measures of jSTI, a high degree of within-group variability (see range values in Table 7) was observed for both groups of children at all sessions and when producing both tokens. Differences in laSTI between the CAS and TD groups were not significant, $F(1, 11) = 1.352$, $p = .270$. There was no main effect of time on laSTI, $F(1.293, 14.219) = 0.042$, $p = .895$. The main effect of complexity on laSTI was significant, $F(1, 11) = 13.297$, $p = .004$, $\eta^2 = .547$, as laSTI was greater in the more complex word than in the less

Table 5. Mean (standard deviation) values for total duration in seconds for all children with childhood apraxia of speech (CAS all), children with childhood apraxia of speech without outlying data (CAS adjusted), and typically developing (TD) children at Time 1 (T1; baseline), Time 2 (T2; short-term change), and Time 3 (T3; long-term retention).

Variable	CAS all			CAS adjusted			TD		
	T1	T2	T3	T1	T2	T3	T1	T2	T3
Low complexity (<i>badabap</i>)									
Duration	0.73 (0.22)	0.77 (0.22)	0.74 (0.18)	0.79 (0.20)	0.84 (0.16)	0.80 (0.10)	0.63 (0.09)	0.59 (0.11)	0.64 (0.10)
Range	0.44–1.06	0.45–0.99	0.42–0.91	0.57–1.06	0.65–0.99	0.67–0.91	0.47–0.78	0.47–0.78	0.52–0.84
High complexity (<i>madeepoom</i>)									
Duration	0.83 (0.23)	0.89 (0.44)	0.80 (0.15)	0.89 (0.18)	0.97 (0.43)	0.84 (0.11)	0.66 (0.10)	0.67 (0.09)	0.69 (0.10)
Range	0.51–1.07	0.47–1.74	0.58–0.96	0.64–1.07	0.67–1.74	0.69–0.96	0.55–0.80	0.56–0.84	0.54–0.85
Nonwords combined									
Duration	0.78 (0.22)	0.83 (0.34)	0.77 (0.16)	0.84 (0.19)	0.91 (0.31)	0.82 (0.10)	0.64 (0.09)	0.63 (0.11)	0.67 (0.10)
Range	0.44–1.07	0.45–1.74	0.42–0.96	0.57–1.07	0.65–1.74	0.67–0.96	0.47–0.80	0.47–0.84	0.52–0.85

complex word for both groups. There were no significant interactions between variables for lip aperture. The laSTI results did not differ when excluding CAS1.

Discussion

Children with CAS and TD controls were engaged in a novel word-learning task in which they practiced two novel words of differing articulatory complexity. With practice, children with CAS displayed improved consonant and vowel accuracy and token-to-token consistency, which is evidence of a learning effect. They did not exhibit changes in articulator movement over time. Significant differences in temporal control (i.e., movement duration) were found between the CAS and TD groups (when excluding CAS1). In addition,

Figure 1. Movement duration in participant CAS1 compared with group performance. Mean duration and standard error of measure are displayed for the childhood apraxia of speech (CAS) group (black line) and the typically developing (TD) group (gray line) for the low- and high-complexity tokens at Time 1 (T1; baseline), Time 2 (T2; short-term change), and Time 3 (T3; long-term retention). Mean duration and standard error for CAS1 (dotted line) at each time point are also shown.

both groups of children displayed significantly more variable lip and jaw movements when producing the more complex token compared with the less complex token. These findings are discussed below in relation to learning effects in a word-learning task, factors that influence speech motor learning, and implications for treatment.

Learning Effects

Children with CAS displayed improved speech production accuracy and consistency within a task that integrated mass practice, random practice, and faded feedback. This statement is consistent with past research that has shown improved speech production patterns when principles of motor learning were incorporated into treatment (Ballard et al., 2010; Edeal & Gildersleeve-Neumann, 2011; Iuzzini & Forrest, 2010; Maas & Farinella, 2012; Maas et al., 2012; Strand & Debertine, 2000; Strand et al., 2006). Children in the TD group did not display changes in accuracy or consistency over time, though lack of change was due to a high number of correct productions. These findings partially supported our hypothesis that short-term improvements in speech production accuracy and word consistency would be seen in both groups of children, whereas long-term improvements would be observed only in the TD group.

Vowel accuracy displayed a different pattern of change than did consonant accuracy, as PVC varied according to the complexity of the token. In the production of the low-complexity token, children with CAS had greater vowel accuracy by the final data collection session (T3). When producing the more complex token, children with CAS displayed improved vowel accuracy when short-term change was measured (T2), yet did not maintain these changes at T3, as vowel accuracy had returned to baseline levels following a 3-day interval. The vowels in the high-complexity token differed in lingual height and degree of labial retraction or protrusion (V1 = /a/; V2 = /i/; V3 = /u/), whereas the low-complexity token included similar vowels (V1 = /a/; V2 = /æ/; V3 = /a/). Different vowels in the high-complexity target required a greater degree of movement transitioning between syllables compared with the vowels in the low-complexity token. Articulatory placement differences

Table 6. Mean (standard deviation) values for jaw spatiotemporal index (jSTI) and range at Time 1 (T1; baseline), Time 2 (T2; short-term change), and Time 3 (T3; long-term retention) in children with childhood apraxia of speech (CAS) and in typically developing (TD) children.

Variable	CAS			TD		
	T1	T2	T3	T1	T2	T3
Low complexity (<i>badabap</i>)						
jSTI	28.86 (9.01)	27.79 (4.68)	29.24 (7.21)	23.23 (7.49)	25.30 (6.07)	24.50 (4.47)
Range	19.41–38.31	22.13–34.02	19.59–39.95	11.26–33.11	17.02–35.93	16.50–30.59
High complexity (<i>madeepoom</i>)						
jSTI	29.75 (6.28)	30.92 (8.76)	30.18 (9.92)	28.90 (7.49)	30.50 (5.60)	27.66 (4.99)
Range	21.10–34.14	20.13–41.17	11.35–38.37	13.27–36.51	24.44–41.10	21.62–33.75
Nonwords combined						
jSTI	29.30 (7.42)	29.36 (6.89)	29.71 (8.28)	26.07 (7.78)	27.90 (6.25)	26.08 (4.86)
Range	19.41–38.31	20.13–41.17	11.35–39.95	11.26–36.51	17.02–41.10	16.50–33.75

between vowels across this sequence in the high-complexity token thus posed a greater motoric challenge to children with CAS compared with the low-complexity target. These findings suggest that children with CAS may not be able to improve consonant and vowel accuracy simultaneously at varying degrees of articulatory complexity in the absence of ongoing, intensive practice. This observation is attributed to impaired coarticulatory transitions between segments and syllables in children with CAS—a core feature of CAS (ASHA, 2007).

Lack of articulator movement change over time can be interpreted differently for the two groups. Although children with CAS demonstrated improvements in speech production accuracy and consistency within the complete data set, long-term changes in the speech motor system may be seen only following more intense practice over a longer time period. In two longitudinal case studies of children with impaired speech by Grigos and colleagues, change in oral articulator movement was reported following an 8-week period (Grigos et al., 2010) and an 8-month period (Grigos & Kolenda, 2010). Observed differences in articulatory control in the former study were facilitated by the child's participation in an intensive treatment program for 8 weeks. The 3-day interval in the current work may not be an adequate time period to capture changes in speech motor control in young children with CAS. Thus, these findings

support our hypothesis that children with CAS would not demonstrate short- or long-term changes in duration or movement stability. It is unknown whether articulator movement would be modified following longer and more intensive practice.

An additional consideration is that improved speech production accuracy and consistency in children with CAS is secondary to phonological learning rather than speech motor learning. One could argue that the phonological representation of these targets (phonological learning) has been strengthened across this learning paradigm, whereas the underlying movement sequence (speech motor learning) was not yet modified due to motor planning and/or programming deficits characteristic of CAS. Although many of the surface features observed in CAS could be consistent with a range of communication disorders and described as either motor or linguistic errors (see Murray, McCabe, Heard, & Ballard, 2015), we posit that motor planning and/or programming processes involved in novel word production play a more dominant role in children with CAS due to the core deficit of this disorder. As discussed at length in other works (Buchwald & Miozzo, 2012; Goffman, 2004; Heisler et al., 2010; Kent, 2004), it is extremely challenging to isolate purely motor or linguistic contributions to speech production. It is also acknowledged that linguistic and motoric processes mutually influence one another (Van der Merwe,

Table 7. Mean (standard deviation) values for lip aperture spatiotemporal index (laSTI) and range at Time 1 (T1; baseline), Time 2 (T2; short-term change), and Time 3 (T3; long-term retention) in children with childhood apraxia of speech (CAS) and in typically developing (TD) children.

Variable	CAS			TD		
	T1	T2	T3	T1	T2	T3
Low complexity (<i>badabap</i>)						
laSTI	29.77 (10.72)	26.59 (6.39)	29.27 (8.86)	22.32 (7.70)	25.01 (6.98)	24.20 (6.36)
Range	14.43–42.22	16.56–32.34	18.25–42.82	10.76–31.89	17.60–36.37	18.37–35.17
High complexity (<i>madeepoom</i>)						
laSTI	31.62 (6.54)	29.80 (10.60)	31.93 (10.86)	29.48 (8.16)	29.58 (4.99)	25.99 (5.32)
Range	22.21–39.64	14.05–42.17	12.63–38.20	13.26–41.39	24.61–38.21	18.43–34.07
Nonwords combined						
laSTI	29.53 (8.87)	28.20 (7.69)	30.35 (9.00)	25.90 (8.51)	27.30 (6.32)	25.09 (5.74)
Range	14.43–42.22	14.05–42.17	12.63–42.82	10.76–41.39	17.60–38.21	18.37–35.17

2009). Additional research is needed to understand this complex relationship between levels of speech production processes—particularly in CAS, a disorder of motor planning and programming.

Our results did not support predictions for the TD group, in which we anticipated a decrease in movement duration and an increase in stability, as reported in studies of speech motor control for novel word learning (i.e., Heisler et al., 2010; Sasisekaran et al., 2010; Walsh et al., 2006). Lack of change over time in the TD group could be explained by the challenge point framework (Guadagnoli & Lee, 2004), which states that learning can occur only when an individual is sufficiently challenged by a task. The stimuli may not have been complex enough to elicit change in the TD group, as has also been reported for adult productions of less phonetically complex stimuli (Sasisekaran et al., 2010; Walsh et al., 2006). Although there were movement stability differences between the high- and low-complexity tokens (see the discussion below), both tokens contained early-developing phonemes and simple syllable shapes. As a result, TD children may have already established a motor program for the simple syllable shapes in the novel words tested in this study, and articulator movement may not change following practice in a speaker with typical speech motor skills.

Our findings reflect a challenge in the design of the study, as we aimed to develop stimuli that could tax both groups of participants without being overly difficult for the children with CAS. As a result, the experimental tokens consisted of early-developing singleton consonants (i.e., /b, p, m, d/) and monophthongs (i.e., /a, ə, i, u/). In contrast, tokens presented in other works (Heisler et al., 2010; Sasisekaran et al., 2010; Walsh et al., 2006) included clusters and consonant or vowel combinations not frequently used in English (e.g., “fushpim,” “pafkub”). Taken together, these findings highlight the importance of considering articulatory complexity and how to sufficiently challenge all participants when designing studies of speech motor learning.

Influences on Speech Motor Learning

The current findings provide insight into spatial and temporal control as children with CAS learn novel words. All children with CAS (with the exception of CAS1) displayed longer movement duration than did TD children, which is consistent with existing evidence of motor deficits in CAS (Grigos & Kolenda, 2010; Grigos et al., 2010, 2011, 2015; Moss & Grigos, 2012). Because we did not include an experimental group of children with other speech sound disorders, we cannot determine whether longer movement duration is specific to children with CAS or whether it represents a broader characteristic of speech motor skill in children with speech and language impairment. Longer duration may allow more time for children to process feedback in the midst of producing speech targets (Schmidt, 2003) and to plan and/or program speech movement sequences. This notion warrants further study in a larger group of children with a range of speech and language impairments to

determine precisely whether and how temporal control for speech differs by diagnostic category during novel word learning.

The influence of articulatory complexity on speech motor learning was evident when comparing articulator movement between the high- and low-complexity tokens. Thus, although speech motor performance did not change over time, jSTI and laSTI were significantly higher when both CAS and TD children produced the high-complexity target compared with the less complex target at all time points. Longer duration was also observed for the more complex token, although differences did not achieve statistical significance ($p = .064$). Observed differences in articulator movement support our initial hypothesis that speech motor control would be influenced by a higher degree of articulatory complexity. Furthermore, these findings are consistent with past research that has reported poorer movement stability (Sasisekaran et al., 2010; Walsh et al., 2006) and longer duration in TD children within tokens of greater phonemic complexity (Walsh et al., 2006) and in children with CAS when producing a three-syllable word compared with one- and two-syllable words (Grigos et al., 2015). However, the absence of a Group $\times$ Complexity interaction demonstrated that articulatory complexity did not have a greater impact on children with CAS than on TD controls as initially predicted.

Given that children with CAS have been reported to demonstrate more variable articulatory control than children with SD and TD controls (Grigos et al., 2015), we were surprised that there were no significant group differences in either the higher order (laSTI) or lower order (jSTI) movement synergies. There are different interpretations of variability in speech production that may explain these results (Goffman, 2010; Green et al., 2002; Sharkey & Folkins, 1985; Smith, 2010; Smith & Goffman, 1998). For the TD group, high levels of movement variability were observed in combination with an overall high degree of sound production accuracy and consistency. Therefore, variability in this group could represent inherent plasticity and flexibility in the motor system that supports accurate production of novel targets (Sharkey & Folkins, 1985; Thelen & Smith, 1994).

In contrast, for children with CAS, we argue that variability represents speech motor planning and/or programming deficits (Grigos et al., 2015). Recall that measures of lip and jaw stability were made only on productions that met specific accuracy criteria. As a result, a smaller set of tokens was used for children with CAS (256 tokens) than for TD controls (365 tokens). Despite significant gains in accuracy and consistency, children with CAS were still significantly less accurate and consistent than the TD group by the final session (T3). These observations lead us to speculate that high movement variability, in combination with longer movement durations, may be hindering novel word production across the entire data set. Furthermore, evidence that movement duration is also longer in the CAS group supports this notion of a motor speech deficit rather than flexibility in the motor system.

Implications for Treatment

The current findings suggest that although children with CAS display improvements in speech production accuracy (PCC, PVC) and consistency (PWC), they may require more intensive practice over time to facilitate articulator movement changes. Children with CAS may be using less efficient movement patterning to achieve accurate novel word production (i.e., longer movement duration), which may explain why children with CAS experience difficulty retaining newly acquired speech targets and generalizing learning to untreated contexts. Increased practice of newly acquired tokens may promote change in speech movement patterns or the development of a more efficient motor program, which in turn could facilitate generalization of skills acquired in treatment. At this time, it remains unknown what degree of practice is needed or how much time is required to refine speech motor control for a novel target.

Findings related to the articulatory complexity of tokens highlight the need to incorporate treatment targets that challenge children in a variety of ways. Treatment studies of children and adults with motor speech disorders support this claim, as individuals have been found to demonstrate varying degrees of generalization and progress in treatment according to the complexity of therapeutic targets. Several studies have found greater treatment gains and/or generalization to untreated targets when more complex targets were used in treatment (Ballard et al., 2010; Iuzzini & Forrest, 2010; Maas et al., 2002; Schneider & Frens, 2005). There is also some evidence of greater improvement when simple sounds were targeted in treatment from a single-subject case study of an adult with apraxia of speech (Van der Merwe, 2011). A low-complexity target may not adequately tax the system or evoke widespread change to speech production skills, whereas a high-complexity token could result in greater generalization to untreated targets that would more efficiently promote systemwide change, as shown by Ballard et al. (2010). It is interesting to note that children with CAS in the current work did not consistently maintain practice gains in vowel accuracy for the more complex token when continued practice was not provided. This result highlights the need to further explore how clinicians can appropriately challenge clients by adjusting target complexity while balancing the degree of practice and feedback necessary to facilitate and maintain accurate sound production.

Future Research

There is a strong need for additional research to determine the degree of practice needed to elicit change in speech motor control processes of children with CAS. As intensive therapy is recommended for treatment of CAS (ASHA, 2007), studies incorporating more frequent practice sessions could shed light on the impact of intensity on articulatory control and whether changes in speech motor control would facilitate long-term retention and generalization of skills. Future research should also consider the

relationship between treatment intensity and task complexity on speech motor performance. Last, a comprehensive understanding of motor learning skills in children with CAS warrants a comparison with children with other speech sound disorders as well as younger TD children. Such evidence will reveal whether children with CAS display speech motor deficits that are specific to CAS and/or are more similar to a less mature motor system, as seen in younger TD children.

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