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An Exploratory Study of the Influence of Load and Practice on Segmental and Articulatory Variability in Children with Speech Sound Disorders

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Abstract

This exploratory treatment study used phonetic transcription and speech kinematics to examine changes in segmental and articulatory variability. Nine children, ages 4- to 8-years-old, served as participants, including two with childhood apraxia of speech (CAS), five with speech sound disorder (SSD), and two who were typically developing (TD). Children practised producing agent + action phrases in an imitation task (low linguistic load) and a retrieval task (high linguistic load) over five sessions. In the imitation task in session one, both participants with CAS showed high degrees of segmental and articulatory variability. After five sessions, imitation practice resulted in increased articulatory variability for five participants. Retrieval practice resulted in decreased articulatory variability in three participants with SSD. These results suggest that short-term speech production practice in rote imitation disrupts articulatory control in children with and without CAS. In contrast, tasks that require linguistic processing may scaffold learning for children with SSD but not CAS.

Keywords

segmental variability; speech sound disorders; childhood apraxia of speech; linguistic load; speech production practice; speech motor control

The purpose of this study was to explore how, over the course of learning in a short-term quasi-treatment design, linguistic load and speech production practice affect segmental and articulatory variability in children with childhood apraxia of speech (CAS), speech sound disorder (SSD), and who are typically developing (TD). The core impairment in CAS is presumably at the level of planning/programming the spatiotemporal parameters of speech movements (ASHA, 2007). CAS is often characterized by inconsistent errors, coarticulation difficulties, and inappropriate prosody (ASHA, 2007). However, the diagnostic criteria have not been validated. In contrast to CAS, SSD is a speech disorder characterized by articulation and/or phonological difficulties, without accompanying motor speech deficits

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Statement of Interest

The authors report no conflicts of interest.

(Bradford & Dodd, 1996). Elucidating factors that influence segmental and articulatory variability can inform theoretical accounts of language and speech motor processing as well as intervention approaches for children with CAS and SSD.

Variability in development and disorders

Variability is observed across multiple behaviors in typical development (e.g., walking, kicking, and speech production) and may be viewed as a positive indicator of change, or of learning (e.g., Corbetta & Thelen, 1996; Gershkoff-Stowe & Thelen, 2004; Thelen, 1985). Regarding speech production variability, some researchers make a distinction between variability, which indicates learning, and inconsistency, which indicates a disorder (Dodd & Bradford, 2000). A child who produces both a developmentally appropriate phonological process and the correct production (e.g. ‘wabbit’ and ‘rabbit’) is said to exhibit variability that signals the transition toward a more stable and mature pattern. In typically developing children, segmental variability decreases with age (Holm, Crosbie, & Dodd, 2007; Sosa, 2015) as children become more systematic in their application of phonological regularities.

In contrast, inconsistency (referred to henceforth as segmental variability) is characterised by multiple different error types (e.g. ‘wabbit’, ‘abbi’, ‘yabbit’, and ‘zabbit’ for *rabbit*) that occur over a protracted developmental time course. Inconsistency is associated with decreased intelligibility (Holm, Crosbie, & Dodd, 2005) and poor learning and generalization of treated sounds (Crosbie, Holm, & Dodd, 2005; Dodd & Bradford, 2000; Forrest, Elbert, & Dinnsen, 2000). Inconsistent errors are considered a hallmark of CAS (ASHA, 2007). Children with CAS exhibit a large number of unpredictable and unsystematic errors that are qualitatively and quantitatively different from those observed in typical development (McIntosh & Dodd, 2009).

Speech motor development follows a protracted time course, with adult-like levels of stability not achieved until late adolescence (Smith & Zelaznik, 2004; Walsh & Smith, 2002). The most direct way to capture articulatory variability is by recording the speech movements associated with multiple productions of a syllable, word, phrase, or sentence. The spatial and temporal variability that is associated with these movements is calculated, and the degree to which multiple productions converge onto a single pattern provides an index of articulatory variability (Smith, Goffman, Zelaznik, Ying, & McGillem, 1995). This index provides a metric of learning at a different level than phonetic transcription (Goffman, 2010), and is independent from segmental accuracy (Goffman, Gerken, & Lucchesi, 2007). Centrally for the present research, articulatory variability measures provide crucial insights into how speech motor control processes interact with linguistic demands.

Researchers consider the source of speech difficulties in CAS to be in planning/programming the spatiotemporal parameters of movement sequences (ASHA, 2007), yet until recently there was no empirical evidence to support this claim. Three studies have investigated articulatory variability in children with CAS compared to children without speech motor planning impairments (Grigos & Kolenda, 2010; Grigos, Moss, & Lu, 2015; Terband, Maassen, van Lieshout, & Nijland, 2011), and all found higher spatiotemporal movement variability in children with CAS relative to peers. These studies all include

relatively small numbers of participants; a common limitation in CAS research. Furthermore, how articulatory variability is affected by language demands remains unclear. The role of language variables in articulatory stability is especially important to consider because children with specific language impairment also show higher levels of articulatory variability than their typical peers (Goffman, 1999; Brumbach & Goffman, 2014).

Influence of linguistic load on articulatory variability

Imitating concrete high frequency words is a relatively easy task for unimpaired talkers. Imitation minimizes short-term memory, language formulation, and phonological retrieval demands (Dell, Martin, & Schwartz, 2007; Dodd & McCormack, 1995). Thus, imitation necessitates articulatory motor practice but only shallow language practice. Imitation is used widely in both research and therapy. Speech motor control research has relied almost exclusively on imitation paradigms to investigate how development, aging, and speech and language disorders influence speech motor control processes. Typically, the goal of these studies is to understand the underlying neural organization or movement patterning of speech, and linguistic processes are not a primary area of inquiry.

Imitation is also a primary cueing technique in intervention for individuals with SSD and CAS. However, for children with CAS multiple authors describe reduced segmental accuracy in imitation as a feature of the disorder (Davis, Jakielski, & Marquardt, 1998; Forrest, 2003; McCabe, Rosenthal, & McLeod, 1998; Snowling & Stackhouse, 1993). Two groups of investigators showed that imitation cues did not increase speech production accuracy in children with CAS (Bradford & Dodd, 1996; Bradford-Heit & Dodd, 1998). This may be because imitative speech is especially voluntary (Halperen, 1986), and thus challenging in the face of a speech motor planning disorder.

Researchers rarely use retrieval or confrontation naming paradigms to study speech motor control processes, yet the increased demands associated with retrieval may also provide crucial insights into how linguistic and articulatory levels of processing interact in persons with and without communication disorders. Compared to imitation, retrieval incorporates greater cognitive demands, including integration of perceptual, semantic, and phonological processing, lexical retrieval, and planning, execution, and monitoring of speech production (Kurland, Reber, & Stokes, 2014). Standard intervention hierarchies such as dynamic temporal and tactile cueing (Strand, Stoeckel, & Baas, 2006) typically rely first on imitation cues then fade to retrieval as the client becomes more accurate. Therefore, understanding the relationship between linguistic demands and articulatory control has direct application to intervention approaches.

Speech production practice

To date, little work has focused on how speech production practice influences articulatory control in typically developing children or children with speech impairments. Walsh, Smith, and Weber-Fox (2006) and Gladfelter and Goffman (2013) showed that, in typically developing children, articulatory variability decreased as a result of short-term speech production practice. This line of investigation in children with speech disorders can

contribute to a better understanding of how CAS is distinct from SSD. Children with CAS show especially slow gains in therapy (Forrest, 2003; Lewis, Freebairn, Hansen, Iyengar, & Taylor, 2004), and a reasonable hypothesis is that for children with CAS, because of their core deficit in speech motor planning/programming, articulatory control is resistant to change over the course of a short term intervention.

A major goal of CAS research has been to determine whether linguistic-based (Iuzzini & Forrest, 2010; McNeill, Gillon, & Dodd, 2009) or motor-based (Edeal & Gildersleeve-Neumann, 2011; Maas, Butalla, & Farinella, 2012; Maas & Farinella, 2012) approaches best facilitate learning. No study to date has investigated how the linguistic demands associated with a speech production task influence variability measures in children with CAS compared to those with SSD. The current study seeks to determine whether different cues (i.e., imitation or retrieval) are effective for learning in children with CAS compared with those with SSD.

Relationship between segmental and articulatory variability

Investigators presume that movement variability underlies speech production variability in children with CAS, yet the relationship between variability at these two levels of language production is not well understood in typical or speech disordered learners. Thus far, the relationship between segmental and articulatory variability has been largely speculative (Green, 2003) and the few studies that have examined this association have reported mixed findings. Goffman, Gerken, and Lucchesi (2007) found few correlations between segmental and kinematic measures in typically developing children and children with specific language impairment. Grigos and Kolenda (2010) found, in a case study of a three-year-old male with CAS, that the child's articulatory movements became less variable as his speech accuracy improved. However, the post-test movement variability measures were collected when the child was able to produce the target phonemes /p/, /b/, and /m/ with 90% accuracy over two consecutive sessions. The results of these two studies do not allow us to conclude that segmental accuracy or variability measures improve as a direct function of the articulatory system becoming more stable. This theoretical question remains open to investigation.

Current study

The current study falls in the tradition of small case studies, and simulates a short-term intervention. Children first imitate (low linguistic load task) then retrieve (high linguistic load task) agent + action phrases (e.g. 'mommy beeps') over five sessions. Half of the phrases are withheld from treatment (i.e. only practised in the first and last session) to assess generalization of learning. This design allows us to examine how both linguistic load in session one (imitation versus retrieval) as well as speech production practice over five sessions influence segmental and articulatory variability.

We investigate the influence of linguistic load by comparing performance in the imitation task to performance in the retrieval task in session one. We expect that participants with CAS, because of their underlying speech motor deficit, will produce phrases with high levels of segmental and articulatory variability in the imitation task compared to participants with

SSD and TD (Grigos & Kolenda, 2010; Grigos et al., 2015). In the retrieval task, we predict that all children, regardless of diagnostic category, will produce phrases with higher articulatory variability compared to the imitation task because of the increased linguistic load. Children with SSD and TD should show low levels of segmental variability in both tasks (e.g., Iuzzini-Seigel, Hogan, & Green, in press).

Regarding the influence of practice over five sessions, in the imitation task we anticipate that children with CAS will exhibit high levels of segmental and articulatory variability across all five sessions. In contrast, we predict that children with SSD and TD will initially exhibit relatively low levels of articulatory variability and perhaps become even less variable over the course of five practice sessions. In the retrieval task, articulatory variability will decrease for children with SSD and TD as they become familiar with the target phrases and linguistic demands diminish. It is possible that this will be the case for children with CAS as well, if speech production practice in active retrieval is more facilitative than practice in direct imitation.

Finally, we ask how segmental and articulatory variability align in children from different diagnostic categories. Because children with CAS are presumed to have motor planning deficits, we predict that articulatory variability and segmental variability measures will be highly correlated in the participants with CAS. However, based on prior work from children with typical development and those with specific language impairment (Goffman et al., 2007), we expect that these two sources of variability will not correlate in children with SSD and TD.

Method

Participants

Nine children ranging in age from 4;8 to 8;9 (years; months) participated. The Institutional Review Board at Purdue University approved all tasks and procedures, and parental consent and child assent were obtained prior to participation. All participants were monolingual speakers of English, had normal or corrected-to-normal vision, passed a bilateral hearing screening (20 dB HL at 500, 1000, 2000, and 4000-Hz), scored within one standard deviation of the mean on the structural component of the Robbins and Klee (1987) oral motor protocol, and per parent report had no history of neurological dysfunction or autism spectrum disorder. Each participant completed either the Columbia Mental Maturity Scale – Third Edition (Burgemeister, Blum, & Lorge, 1972), Primary Test of Nonverbal Intelligence (Ehrler & McGhee, 2008), or Wechsler Preschool and Primary Scale of Intelligence – Third Edition (administered by a licensed school psychologist; Wechsler, 1991) to assess cognitive abilities. See table 1 for detailed participant information. The Test of Auditory Comprehension of Language – Third Edition (TACL-3; Carrow-Woolfolk, 1999) was also administered as a measure of receptive language ability.

Participants were classified as CAS ($n = 2$), SSD ($n = 5$), or TD ($n = 2$). Both participants with CAS were enrolled in speech therapy and had previously received a diagnosis of CAS from a licensed Speech Language Pathologist in a local hospital or outpatient clinic and were receiving speech-language therapy. They also met inclusionary criteria for CAS

classification in the current study. This included performance greater than one standard deviation below the mean on the Bankson-Bernthal Test of Phonology (BB-ToP; Bankson & Bernthal, 1990), the Diagnostic Evaluation of Articulation and Phonology (DEAP; Dodd, Hua, Crosbie, Holm, & Ozanne, 2006) Articulation subtest, the functional component of the Robbins and Klee (1987) oral motor protocol, and a DEAP Word Inconsistency (DEAP WI) or Single-Word Inconsistency score greater than 40%. A cut-off of 40% on the DEAP WI, in conjunction with impaired oral motor skills, is used by some research groups to classify CAS (e.g. Dodd, 1996; McNeill et al., 2009).

The five participants with SSD were all currently enrolled in speech therapy. They all scored greater than one standard deviation below the mean on the BB-ToP and the DEAP Articulation subtest and achieved a DEAP WI score less than 40%. The participants in the SSD group also scored within the average range on the TACL-3. One participant with SSD, SSD 2, received a total functional score that was one standard deviation below the mean on the oral motor protocol.

The two children with TD had no history of speech or language difficulties. Both children scored within the normal range on the BB-ToP and the TACL-3. They also scored less than 40% inconsistent on the DEAP WI. TD 2 scored in the average range on the DEAP Articulation subtest. TD 1, however, received a standard score of 80 on the DEAP Articulation subtest, and a total functional score more than one and a half standard deviations below the mean on the oral motor protocol.

To provide further support of CAS classification, on table 2 we include additional information regarding the number of CAS characteristics each participant showed on the 10-point CAS checklist (Shriberg, Potter, & Strand, 2011). In table 2 we list each of the characteristics and the tasks in which they occurred. Both children with CAS showed four or more features, and all other children showed fewer than four features.

Recall that all of the children with CAS and SSD were receiving speech therapy. Treatment goals were uncontrolled and often unreported. However, all of the target consonants included in the experimental tasks were relatively early developing (Shriberg, 1993) and determined to be in the inventories of all of the children. Therefore, speech targets selected for therapy should not interfere with performance within the experimental tasks.

General procedure

Participants attended five individual sessions, each lasting approximately 60 minutes. Sessions were scheduled based on family preference and availability with the requirement that sessions occur on separate days but no more than one week apart. The participants in the TD and CAS groups completed the study over an average of six and a half weeks (range: TD = 4–9 weeks; CAS = 6–7), and children in the SSD group completed the study over an average of three weeks (range = 1–4). Each session began with the experimental tasks (the imitation and retrieval tasks, described in more detail below), which lasted 15–30 minutes. Standardized testing (see table 1) was conducted for the remainder of each session (30–45 minutes). The first author, a certified Speech-Language Pathologist, administered all of the experimental tasks and standardized assessments. We provided rest breaks and

reinforcement as necessary to keep the children engaged and to avoid fatigue. We also used a sticker schedule or checklist, depending on the age and preference of the child, during the experimental tasks to indicate how long the task would take. CAS 1 did not complete the experimental tasks in session 4 due to equipment failure, and CAS 2 did not attend session 4 due to a scheduling conflict.

Signals recorded

The 3D Investigator (Northern Digital Inc., Waterloo, Ontario, Canada) was used to record lip and jaw movements while children produced target phrases in the imitation and retrieval tasks. Three infrared light emitting diodes collected the kinematic data analysed in this study; one placed at midline on the vermilion border of the upper lip, one at midline on the lower lip, and one on a small splint attached underneath the jaw with medical adhesive. Five additional diodes were used to account for head movement; one on the forehead at midline and four placed on a pair of sports goggles worn by each child. Kinematic data were collected at a sampling rate of 250 samples/second. A time-locked acoustic signal was also collected at a sampling rate of 16000 Hz. High quality audio and video recordings were also obtained. A Shure SM58 microphone, placed 12 inches in front of and to the right of the participant on a 29-inch high table (at approximately mouth level), was connected to a Marantz PMD 660 digital recorder to obtain a high quality recording of the child's productions.

Stimuli and procedure

The stimuli used to elicit the target phrases included six animated video clips (approximately 2 seconds long) of puppets producing various actions. An agent + action phrase corresponded with each video. The six phrases were *mommy beeps*, *mommy bumps*, *baby pops*, *baby puffs*, *puppy wipes*, and *puppy mops*. Audio stimuli were recorded in a sound booth by an adult native English female talker, and equated for intensity in Praat (Boersma & Weenink, 2013). For the imitation task, the audio stimuli were paired with the corresponding video clip in PowerPoint. For the retrieval task, the children watched the video clips and generated the target phrases. The six phrases were constructed so that all consonants (except the third person singular -s) were labial sounds, and therefore could be subjected to kinematic analyses. In addition, these six phrases were composed of relatively early developing sounds (Shriberg, 1993) that were specifically in the inventories of the children with CAS and SSD.

Children sat in a wooden Rifton chair with an attachable tray table approximately eight feet in front of a thirty-inch Dell computer monitor. The 3D investigator was mounted above the monitor. The examiner presented the stimuli via PowerPoint at a comfortable pace and loudness level. Participants always completed the imitation task first to allow them to practise and become familiar with the target phrases before they completed the retrieval task. For the imitation task, the examiner instructed participants to repeat exactly what they heard. In the retrieval task, the examiner instructed the participant to retrieve that phrase after viewing the target video clip.

In each task, if the child omitted a labial or substituted a non-labial sound, the examiner provided up to three gestural phonemic prompts to attempt to elicit the correct sound. The examiner provided these prompts only during the first three trials; if the participant continued to omit a labial or substitute a non-labial sound after the third trial, these productions were excluded from the kinematic analyses. In addition, the production of third person singular *-s* was not required, and */s/* was not incorporated into the kinematic or transcription analyses. An additional prompting hierarchy was used for the retrieval task if the participant forgot a target word or used an incorrect word. In this hierarchy, if one of the words in the target phrase was incorrect or forgotten, the examiner provided the correct word and asked the participant to produce the phrase again (e.g. for ‘Doggy mops’, the examiner responded, ‘That’s a puppy. Tell me that again’). If both words were incorrect, the examiner played the audio clip used in the imitation task and asked the participant to imitate the phrase. Imitated phrases were discarded; only phrases that were actively retrieved were incorporated in the kinematic analyses.

In sessions one and five, participants imitated then retrieved all six phrases. In sessions two, three, and four, participants practised imitating then retrieving just three of the phrases, referred to as the ‘practised’ phrases. The three phrases that were only practised in sessions one and five are referred to as the ‘generalization’ phrases. The three practised and three generalization phrases were counterbalanced across participants within each diagnostic category. Participants either practised *mommy bumps*, *baby pops*, and *puppy wipes* (randomization A: TD 2, SSD 1, SSD 3, SSD 4, CAS 1), or *mommy beeps*, *baby puffs*, and *puppy mops* (randomization B: TD 1, SSD 2, SSD 5, CAS 2). Eight productions of each phrase were elicited in each task. Within each task, the phrases were presented in a quasi-random order, with no phrase occurring more than two times in a row.

Extraction of movement sequences

Custom Matlab (Mathworks, 2009) routines were used for all articulatory kinematic analyses. The lower lip signal was used to extract all usable productions of the movement sequences associated with each target phrase from the long data files (Smith et al., 1995). The opening movement out of the initial labial consonant and the closing movement into the final labial consonant were selected by visually examining the displacement records and confirmed by playing back the synchronized acoustic signal. As shown in figure 1, an algorithm determined the minimum peak velocity value within a 25-point (100 ms) window of the point chosen by the experimenter. A minimum of five and a maximum of eight repetitions were included in the kinematic analyses. Productions that contained missing signals from the lip or jaw diodes, laughter, or disfluencies were excluded from analyses. In addition, phrases were not included from the imitation task if they were not produced in direct imitation to the audio clip, and not included from the retrieval task if the audio clip was played. Therefore, the retrieval task only included actively retrieved and no imitated productions.

Calculation of articulatory variability

To calculate articulatory variability, lip aperture was initially derived as the difference between the upper lip and the lower lip displacement records. The extracted lip aperture

movement sequences were linearly amplitude- and time-normalized to eliminate absolute differences in loudness and speech rate, respectively. Amplitude normalization was performed by setting the mean to zero and the standard deviation to one. Time normalization was accomplished using a spline function (Mathworks, 2009) to interpolate each lip aperture record onto a common time base of 1000 points (see Smith et al., 1995; Smith & Zelaznik, 2004). The multiple lip aperture records associated with a specific speech target were assessed for patterning variability using the spatiotemporal index (STI; Goffman, 1999; Smith, Goffman, Zelaznik, Ying, & McGillem, 1995; Walsh & Smith, 2002). To calculate the STI, standard deviations were computed at 2% intervals across all of the time- and amplitude-normalized records associated with a specific phrase, and these 50 standard deviations were summed. A higher STI value reflects greater articulatory patterning variability.

Transcription analyses

The first author, a certified Speech-Language Pathologist, transcribed all productions using broad transcription and the International Phonetic Alphabet (IPA). All vowels and consonants were transcribed, except for third person singular /s/. Transcription was based on the video recording, and the audio recording was used to confirm any transcriptions that were in question. Segmental accuracy and segmental variability were calculated separately for each phrase in each task (imitation and retrieval) in session one and session five. Segmental accuracy was calculated as the percent phonemes correct (PPC), quantified as the number of consonants and vowels produced correctly, divided by the total number of consonants and vowels, multiplied by 100. A trained graduate student, blind to group assignment, completed transcription reliability on 33% of the transcription data. Reliability was completed on session one and session five transcripts from one participant randomly selected from each diagnostic category with 99% inter-rater agreement.

Calculation of segmental variability

Segmental variability was calculated using the inconsistency severity percentage (ISP; Iuzzini & Forrest, 2010), defined as the number of productions of a phrase that differed by at least one segment, divided by the total number of productions, multiplied by 100. Note that the ISP is independent of accuracy. To avoid penalizing a child for producing the phrase the same way each time (i.e. one divided by eight yields an ISP of 12.5%), we set the occurrence of no variability to zero by subtracting one divided by the denominator from each ISP score. For example, a child who produces the phrase '*mommy bumps*' as [mabi bʌp] eight times would receive an ISP of 0. However, if the child produced three different forms of this phrase (e.g., [mabi bʌp], [mami bʌp], and [mabi bʌmp]), the ISP would be 25 (i.e. three divided by eight minus one divided by eight). PPC and ISP were calculated only for the phrases included in the kinematic analyses. In addition to the raw PCC and ISP scores, difference scores (calculated as score at session five – session one) were computed to more directly examine change over the course of learning.

Statistical analyses

As is a standard approach in small n treatment designs (e.g. Edeal & Gildersleeve-Neumann, 2011; Gierut & Morissette, 2011; Maas et al., 2012; Maas & Farinella, 2012), to test within-

participant changes in articulatory variability from session one to session five we computed effect sizes (ES) from the STI values. ES were computed separately for the imitation and retrieval tasks, and for the three practised phrases and the three generalization phrases. The ES was calculated as the session five mean STI minus the session one mean STI, divided by the session one STI standard deviation. Following Maas and Farinella (2012), we operationally defined an ES as significant when $ES = > 1$ or < -1 . An ES greater than 1 indicates that articulatory variability increased in session 5, and an ES less than -1 indicates that articulatory variability decreased in session 5. From a clinical standpoint, an ES greater than 1 or less than -1 indicates change over baseline levels that exceeds the baseline variance.

Pearson correlations between STI and ISP values were also calculated to determine the relationship between segmental and articulatory variability. These were calculated separately for the CAS participants and the SSD and TD participants in the imitation and retrieval tasks. All productions over all five sessions that had an ISP score greater than zero were included.

Results

Linguistic load in session one

Articulatory variability—As shown in figure 2, the two participants with CAS exhibited the highest levels of articulatory variability in the imitation task, along with the youngest TD participant. All nine participants demonstrated higher STI mean values in the retrieval task compared to the imitation task in session one. A paired t-test comparing the raw STI scores for all six phrases across all participants revealed a significant difference between the imitation ($M = 17.70$, $SD = 4.89$) and retrieval task ($M = 25.08$, $SD = 8.68$) in session 1, $t = -6.21$, $p < 0.001$.

Segmental variability—Tables 4 and 5 present the segmental accuracy, segmental variability, and difference score data for the imitation and retrieval task. For the two participants with CAS, mean segmental accuracy improved slightly in the retrieval task (CAS 1 $MPPC = 89\%$; CAS 2 $MPPC = 99\%$) compared to the imitation task (CAS 1 $MPPC = 83\%$; CAS 2 $MPPC = 96\%$). Consistent with a CAS classification, the two participants with CAS exhibited relatively high levels of segmental variability. CAS 1 showed high levels of segmental variability in both the imitation ($MISP = 30.33\%$) and retrieval ($MISP = 24.50\%$) task. CAS 2 also showed high segmental variability in imitation ($MISP = 14.58\%$), but in retrieval his segmental variability was similar to the participants with SSD and TD ($MISP = 4.17\%$).

Mean segmental accuracy was near ceiling for participants with TD and SSD in both the imitation ($MPPC$ range = 99–100%) and retrieval task ($MPPC$ range = 97–100%), which was not surprising considering the stimuli were selected to be well within their language and speech production capacities. Correspondingly, segmental variability was low in both imitation ($MISP$ range = 0–6.25%) and retrieval ($MISP$ range = 0–11.64%).

In summary, as predicted, the two children with CAS showed the highest levels of articulatory variability, but the younger child who was TD did as well. Further, articulatory variability was higher in retrieval than imitation for all children, regardless of diagnostic category. Both participants with CAS showed high levels of segmental variability. Linguistic load did not affect segmental accuracy or segmental variability in session one for any of the participants with SSD or TD.

Effects of speech production practice across five sessions

Imitation

Articulatory variability: The left side of figure 3 shows the mean STI for session 1 and 5 by condition (practiced/generalization phrases) and the left side of table 3 presents the mean STI effect sizes for the imitation task. Five participants had positive effect sizes, indicating that articulatory variability increased in the practised phrases from session one to session five. These five participants included TD 1 (ES = 11.96), SSD 3 (ES = 1.44), SSD 4 (ES = 1.11), CAS 1 (ES = 4.56), and CAS 2 (ES = 2.32). There were no significant effect sizes in the generalization phrases.

Segmental variability: Speech production practice did not affect segmental accuracy for the participants classified as TD and SSD. Accuracy was close to ceiling in both session one and five (*MPCC* range = 98.64–100%), and segmental variability was low (*MISP* range = 0–6.25%). The two participants with CAS, in comparison, exhibited different profiles of performance, which are detailed below.

CAS 1—Difference scores are used to show the direction of change from session one to session five. In the imitation task, CAS 1 demonstrated increased segmental accuracy in the practised phrases, shown by a difference score of 4.77. Decreased segmental accuracy was observed in the generalization phrases, shown by a difference score of –3.77. In line with this, segmental variability decreased in the practised phrases, shown by a difference score of –14.23, and increased in the generalization phrases, shown by a difference score of 12.50.

CAS 2—In the imitation task, CAS 2 demonstrated segmental accuracy that was similar to the participants with TD and SSD in both session one and five ($M = 96.53$ –100%). His segmental variability, however, decreased in the practised phrases, shown by a difference score of –20.83, and in the generalization phrases, shown by a difference score of –4.16, so that by session five his ISP values were similar to those of the other participants.

In summary, for both participants with CAS, and somewhat surprisingly for two participants with SSD and one participant with TD, articulatory variability increased with imitation practice. Even though movement variability increased, segmental variability decreased after practice for both participants with CAS. Participants with SSD and TD did not show changes in segmental variability in the practised or generalization phrases.

Retrieval

Articulatory variability: The right side of figure 3 shows the mean STI for session 1 and 5 by condition (practiced/generalization phrases) and the right side of table 3 shows the mean

STI effect sizes for the retrieval task. Seven out of the nine participants had significant effect sizes in the retrieval task, which occurred in both the practised and generalization phrases.

In the practised phrases, three participants with SSD exhibited decreased articulatory variability, including SSD 2 (ES = -2.77), SSD 3 (ES = -10.21) and SSD 5 (ES = -1.92). Three other participants showed increased articulatory variability, including CAS 2 (ES = 2.00), SSD 1 (ES = 1.44), and TD 1 (ES = 13.81).

Mixed results were also seen in the generalization phrases. Three participants exhibited decreased articulatory variability in the generalization phrases, including SSD 1 (ES = -1.17), SSD 3 (ES = -1.72), and TD 2 (ES = -3.70). However, CAS 2 (ES = 1.71) and TD 1 (ES = 14.65) showed increased articulatory variability in the generalization phrases.

Segmental variability: Segmental accuracy was also very high in the retrieval task for the participants classified as TD and SSD in sessions one and five ($MPCC = 97.96\text{--}100\%$), and segmental variability was generally low ($MISP = 0\text{--}11.01\%$). The two participants with CAS showed more errors and are discussed in detail below.

CAS 1—In the retrieval task, CAS 1 demonstrated increased segmental accuracy in the practised phrases, shown by a difference score of 3.31, and a relatively large decrease in segmental accuracy in the generalization phrases, shown by a difference score of -15.72. Segmental variability, however, decreased in both the practised, shown by a difference score of -16.67, and the generalization, shown by a difference score of -7.50, phrases.

CAS 2—In the retrieval task, CAS 2's segmental accuracy and segmental variability were similar to that of other participants in both session one and session five ($MPCC = 98\text{--}100\%$, $MISP = 0\text{--}4.17\%$).

In summary, in the retrieval task, patterns of articulatory change were heterogeneous. All participants showed low levels of segmental variability over all five sessions, except CAS 1, who showed large decreases in segmental variability in both the practised and generalization phrases from session 1 to session 5.

Relationship between segmental and articulatory variability

No significant correlations emerged between segmental and articulatory variability for participants with CAS (imitation $r = 0.07$; retrieval $r = 0.11$) or those with SSD/TD (imitation $r = 0.47$; retrieval $r = 0.19$), suggesting that these two types of variability may be dissociated.

Discussion

The goal of this study was to examine the influence of linguistic load and speech production practice on segmental and articulatory variability in children with CAS, SSD, and TD. CAS is thought to be a disorder in speech motor planning, and should therefore be characterized by relatively high levels of articulatory variability. In addition, children with CAS make slow or limited progress over the course of intervention (Forrest, 2003; Hall et al., 2007). The

objective of this work was to assess whether articulatory variability truly characterizes children with CAS and, more centrally, how segmental and articulatory variability change over time in response to tasks with different linguistic demands in children with CAS, SSD, and typical speech and language learning. In general, the results of this study contribute to an understanding of how segmental and articulatory variability measures and task demands may differentiate children with CAS from those with SSD and TD.

Role of linguistic load in speech production

In the imitation task, we found that the two participants with CAS exhibited high levels of articulatory variability, along with the youngest TD participant (TD 1). This finding contributes to a small number of studies that have documented impaired spatiotemporal planning/programming in children with CAS (Grigos & Kolenda, 2010; Grigos et al., 2015; Terband et al., 2011).

Researchers have increasingly acknowledged interactivity across semantic, lexical, phonological, and articulatory levels (e.g. Goffman, 2010; Hickok, 2014; Tourville & Guenther, 2011). In the current study, we included a retrieval task to examine how linguistic processing demands affect articulatory control. All participants implemented articulatory movements with higher spatiotemporal variability in the retrieval task compared to the imitation task in session one. Linguistic load disrupted articulatory movement patterning regardless of diagnostic category.

Role of practice in speech production

Several studies have shown that short-term speech production practice can lead to reductions in articulatory variability in typically developing children (Gladfelter & Goffman, 2013; Heisler, Goffman, & Younger, 2010; Walsh et al., 2006). For children with CAS, however, if motor planning/programming deficits are really the basis of the disorder, articulatory variability may not be as amenable to change. Surprisingly, imitation practice resulted in increased articulatory variability in both participants with CAS, two with SSD, and one with TD. We suggest that, at least for young children, imitation practice over multiple sessions may result in a reduction of meaningful linguistic processing, and rote motor practice without a linguistic or pragmatically relevant goal may actually disrupt articulatory planning in children with and without motor speech deficits. However, an alternative perspective proposes that increased variability indicates that the system is flexible and able to reorganize (Gershkoff-Stowe & Thelen, 2004). It is possible that five sessions of practice only allowed us to observe part of a U-shaped learning trajectory (Gershkoff-Stowe & Thelen, 2004), and a longer course of intervention would have revealed a stabilisation or reduction in articulatory variability, at least for children with SSD and TD.

In contrast to the imitation task, practice in the retrieval task resulted in decreased articulatory variability in three out of five participants with SSD, indicating that tasks which invoke higher linguistic demands may scaffold motor learning for some children with SSD. All children completed the imitation task first, which allowed them to become familiar with the agent + action phrases before we asked them to retrieve those phrases independently. Over the course of the following sessions, the children likely became more familiar with the

phrases and their linguistic structure and were able to retrieve them with fewer linguistic processing demands, which facilitated a decrease in articulatory variability. Speech production practice in a task requiring active retrieval of meaningful lexical items may improve articulatory movement stability for children without motor planning deficits. Further research on retrieval practice in children with CAS is warranted, as only one of the CAS participants showed decreased articulatory variability in retrieval practice in the current study

Relationship between segmental and articulatory variability

Finally, we predicted that segmental and articulatory variability would correspond differently in the participants with CAS compared to participants with SSD and TD. The participants with CAS did show high levels of variability in both measures, particularly in the imitation task in session one. However, a correlation analysis showed that segmental and articulatory variability measures within individual productions did not align. This is consistent with findings from Goffman, Gerken, and Lucchesi (2007) in children with specific language impairment and typically developing children. Our results provide preliminary empirical data showing that there is not a strict relationship between segmental and articulatory variability in children with CAS. Kinematic and transcription measures both index learning, but these two measures capture different processes; articulatory movement patterning can change independent of segmental accuracy. Knowledge of a child's segmental system should not be used to infer characteristics of their articulatory system.

Limitations and future directions

An obvious limitation to this study is that only a small, heterogeneous group of children participated. Future studies should include a larger number of children in each group. Although we deliberately selected sounds within the phonetic inventories of all of our participants, it is perhaps also important to include stimuli that contain more complex sound sequences to challenge children's speech production accuracy. The relationship between segmental and articulatory variability could be further elucidated if the stimuli were sufficiently difficult to elicit more segmental errors. Additionally, in the current study only eight productions of each phrase were elicited in each task, and we only included five practice sessions. This may not have been enough trials to facilitate motor learning, particularly in the participants with CAS. Therefore, future studies should consider including a larger number of trials and perhaps a larger number of sessions. CAS treatment studies continue to shed light on the theoretical underpinnings of the disorder as well as best intervention practices for these children.

Conclusion

The core impairment in CAS is considered to reside at the level of motor planning/programming, and these children are frequently perceived as having a severe communication disorder that is difficult to treat. In the current study, we asked whether children with CAS exhibited disrupted articulatory movements relative to peers with SSD and with typical speech and language development, how task demands influenced articulatory and segmental variability, and if these two measures of variability aligned. This study adds to the small but growing body of literature demonstrating that spatiotemporal variability is

disrupted in children with CAS. It also provides preliminary support for therapy approaches that target higher linguistic processing rather than rote imitation of words and phrases in children with SSD. Finally, our results show that speech motor control processes can not fully account for high levels of segmental variability.

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Figure 1.
Example of algorithm to extract movement sequences. This is lower lip movement from TD 1 producing 'mommy beeps'.

Figure 2.
Mean STI in the imitation versus retrieval task in session 1 for each participant.

Figure 3. Mean STI for session 1 and session 5 by task (imitation/retrieval) and condition (practised/generalization) for each participant.

Table 1

Summary of test scores by participant

P	Age/Sex	NVBL	BB-ToP CI	DEAP Artic	DEAP WI	Structural Oral	Functional Oral	LANG
TD 1	4;8 F	100 ^a	90	80	20% ^f	Pass	>-1.5 SD	117 ^g
TD 2	7;4 M	106 ^a	93	95	0% ^e	Pass	Pass	119 ^g
SSD 1	5;0 M	112 ^a	76	70	28%		Pass	113 ^g
SSD 2						Pass	-1 SD	
SSD 3	6;7 M	101 ^a	77	55	30%		Pass	115 ^g
SSD 4						Pass	Pass	
SSD 5	7;11 M	108 ^a	82	55	8%		Pass	109 ^g
CAS 1						Pass	>-3 SD	
CAS 2	8;3 F	116 ^a	81	55	4%		>-3 SD	112 ^h
						Pass		
	8;9 M	105 ^a	79	55	32%			111 ^g
						Pass		
	5;10 M	52 ^b	66 ^d	55	60% ^f			66/50 ⁱ
						Pass		
	5;10 M	86 ^c	<55 ^e	55	56%			84 ^j
						Pass		

Note. P = Participant; NVBL = Nonverbal Intelligence Score; BB-ToP CI = Bankson-Bernthal Test of Phonology Consonant Inventory; DEAP Artic = Diagnostic Evaluation of Articulation and Phonology Articulation subtest; DEAP WI = Diagnostic Evaluation of Articulation and Phonology Word Inconsistency subtest; Structural Oral = Total Structural Score, Robbins & Klee (1987); Functional Oral = Total Functional Score, Robbins & Klee (1987); LANG = Language Score.

^a = Columbia Mental Maturity Scale – Third Edition;

^b = Wechsler Preschool and Primary Scale of Intelligence – Third Edition;

^c = Primary Test of Nonverbal Intelligence;

^d = Structured Photographic Articulation Test – Second Edition;

^e = Clinical Assessment of Articulation and Phonology;

^f = DEAP Single-Word Inconsistency subtest,

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g = TACL-3 = Test of Auditory Comprehension of Language – Third Edition;
 h = Clinical Evaluation of Language Fundamentals – Fourth Edition;
 i = Preschool Language Scales –Fifth Edition Auditory Comprehension/Expressive Communication Subtests;
 j = TACL-3 grammatical morphemes subtest.

Table 2

CAS speech characteristics by participant.

	TD 1	TD 2	SSD 1	SSD 2	SSD 3	SSD 4	SSD 5	CAS 1	CAS 2
1. Vowel distortions								<i>b</i>	<i>c</i>
2. Difficulty achieving articulatory configurations/Transitional movements								<i>d e</i>	<i>b</i>
3. Equal stress/Lexical stress errors									
4. Distorted substitutions	<i>a, b, c</i>			<i>a</i>					
5. Syllable segregation									
6. Groping					<i>d</i>			<i>d e</i>	<i>e</i>
7. Intrusive schwa									
8. Voicing errors	<i>b, c</i>							<i>b</i>	<i>b, c</i>
9. Slow rate									
10. Increased difficulty with multisyllabic words								<i>b</i>	<i>c</i>
Total Number of Characteristics	2	0	0	1	1	0	0	5	5

Note.

a = BBToP CI;

b = DEAP Artic;

c = DEAP WI;

d = DEAP oral motor screen;

e = Robbins & Klee (1987) oral motor protocol. See table 1 for test abbreviation key.

Table 3

Mean STI effect size calculations by task (imitation/retrieval) and condition (practiced/generalization) for each participant

P	Imitation		Retrieval	
	Prac	Gen	Prac	Gen
TD 1	11.96	0.38	13.81	14.65
TD 2	0.29	-0.21	-0.83	-3.70
SSD 1	0.23	-0.16	1.44	-1.17
SSD 2	0.42	0.13	-2.77	-0.58
SSD 3	1.44	0.12	-10.21	-1.72
SSD 4	1.11	-0.98	0.30	-0.65
SSD 5	-0.33	-0.12	-1.92	-0.44
CAS 1	4.56	-0.42	-0.88	-0.68
CAS 2	2.32	-0.12	2.00	1.71

Note. P = Participant; Prac = Practised phrases; Gen = Generalization phrases. Significant effect sizes (>1 or <-1) are bolded. Positive ESs indicate spatiotemporal variability increased from session 1 to session 5; negative ESs indicate spatiotemporal variability decreased.

Table 4

Mean percent phonemes correct (PPC), mean inconsistency severity percentage (ISP), and difference scores (Diff) for the practised and generalization phrases in the Imitation task.

		Imitation											
		Practised			ISP			PPC			Generalization		
P	Age, Sex	PPC S1	PPC S5	Diff S1	ISP S1	ISP S5	Diff S1	PPC S1	PPC S5	Diff S1	ISP S1	ISP S5	Diff S1
TD 1	4;8, F	100.00	100.00	0	0	0	0	100.00	100.00	0	0	0	0
TD 2	7;4, M	100.00	100.00	0	0	0	0	100.00	100.00	0	0	0	0
SSD 1	5;0, M	100.00	100.00	0	0	0	0	98.81	99.40	0.59	4.17	8.33	4.16
SSD 2	6;7, M	100.00	100.00	0	0	0	0	99.40	100.00	0.60	4.17	0	-4.17
SSD 3	7;11, M	99.48	100.00	0.52	4.17	0	-4.17	98.64	100.00	1.36	8.33	0	-8.33
SSD 4	8;3, F	100.00	100.00	0	0	0	0	100.00	100.00	0	0	0	0
SSD 5	8;9, M	100.00	100.00	0	0	0	0	100.00	100.00	0	0	0	0
CAS 1	5;10, M	83.33	88.10	4.77	39.83	25.60	-14.23	86.31	82.54	-3.77	20.83	33.33	12.50
CAS 2	5;10, M	96.53	100.00	3.47	20.83	0	-20.83	98.61	99.40	0.79	8.33	4.17	-4.16

Note. S1 = session 1, S5 = session 5.

Table 5

Mean percent phonemes correct (PPC), mean inconsistency severity percentage (ISP), and difference scores (Diff) for the practised and generalization phrases in the Retrieval task.

Retrieval														
Practised										Generalization				
		PPC			ISP			PPC			ISP			
P	Age, Sex	PPC S1	PPC S5	Diff	ISP S1	ISP S5	Diff	PPC S1	PPC S5	Diff	ISP S1	ISP S5	Diff	
TD 1	4;8, F	100.00	99.40	-0.60	0	4.17	4.17	98.88	98.96	0.08	8.33	8.33	0	
TD 2	7;4, M	100.00	100.00	0	0	0	0	100.00	100.00	0	0	0	0	
SSD 1	5;0, M	97.96	99.40	1.44	8.33	4.17	-4.16	98.21	99.40	1.19	13.69	4.17	-9.52	
SSD 2	6;7, M	100.00	100.00	0	0	0	0	100.00	100.00	0	0	0	0	
SSD 3	7;11, M	100.00	100.00	0	0	0	0	100.00	100.00	0	0	0	0	
SSD 4	8;3, F	100.00	100.00	0	0	0	0	100.00	100.00	0	0	0	0	
SSD 5	8;9, M	100.00	100.00	0	0	0	0	100.00	100.00	0	0	0	0	
CAS 1	5;10, M	89.14	92.45	3.31	25.00	8.33	-16.67	88.93	73.21	-15.72	24.17	16.67	-7.50	
CAS 2	5;10, M	99.31	100.00	0.69	4.17	0	-4.17	98.61	100.00	1.39	4.17	0	-4.17	