Research Article

Influence of Language Load on Speech Motor Skill in Children With Specific Language Impairment

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Purpose: Children with specific language impairment (SLI) show particular deficits in the generation of sequenced action: the quintessential procedural task. Practiced imitation of a sequence may become rote and require reduced procedural memory. This study explored whether speech motor deficits in children with SLI occur generally or only in conditions of high linguistic load, whether speech motor deficits diminish with practice, and whether it is beneficial to incorporate conditions of high load to understand speech production.

Method: Children with SLI and typical development participated in a syntactic priming task during which they generated sentences (high linguistic load) and, then, practiced repeating a sentence (low load) across 3 sessions. We

assessed phonetic accuracy, speech movement variability, and duration.

Results: Children with SLI produced more variable articulatory movements than peers with typical development in the high load condition. The groups converged in the low load condition. Children with SLI continued to show increased articulatory stability over 3 practice sessions. Both groups produced generated sentences with increased duration and variability compared with repeated sentences.

Conclusions: Linguistic demands influence speech motor production. Children with SLI show reduced speech motor performance in tasks that require language generation but not when task demands are reduced in rote practice.

Specific language impairment (SLI) has classically been defined as a disorder that is constrained to language, particularly to morphosyntax (Leonard, 2014). However, over the last several years, it has become evident that children diagnosed with SLI experience other deficits related to nonlinguistic cognitive processing (Ellis Weismer, Plante, Jones, & Tomblin, 2005; Miller et al., 2006) and to action (Bishop, 2002; Hill, 2001; Vuolo, Goffman, & Zelaznik, 2017). In the speech motor domain, children with SLI show difficulties with the production of multiword phrases (Brumbach & Goffman, 2014) and weak–strong stress patterns (Goffman, 1999, 2004). Motor and

speech motor deficits may be broadly distributed and general or may be specific to particular aspects of performance. The latter option may involve demands related to sequential movement (Goffman, 1999; Hsu & Bishop, 2014; Lum, Gelgic, & Conti-Ramsden, 2010; Tomblin, Mainela-Arnold, & Zhang, 2007) or cognitive–linguistic processing (Goffman, 2004; Heisler, Goffman, & Younger, 2010; Maner, Smith, & Grayson, 2000). Furthermore, although children with SLI do not always have overt speech motor deficits, previous research has shown that they commonly demonstrate more variable articulation across multiple productions of a sentence (Brumbach & Goffman, 2014). It is the objective of the present work to determine whether children with SLI demonstrate a deficit in speech motor skill that broadly influences performance or that is constrained to particular components. For example, higher linguistic load tasks may be impaired, and lower linguistic load or practiced tasks may be unaffected. In the context of the current study, we define *linguistic load* on a continuum, with tasks with increased formulation demands (such as word and sentence generation) as relatively high load and those with lower formulation demands (such as word and sentence imitation) as relatively low load.

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Analytic Approaches to the Assessment of Speech Motor Skill

Articulatory Variability

Speech motor skill may be measured via articulatory kinematics. Kinematic measures provide a direct assessment of the movements of the articulatory structures that are used for speech production. One central measure is articulatory variability. The spatiotemporal index (STI) is one measure that has been used to analyze articulatory variability across repeated utterances (Smith, Goffman, Zelaznik, Ying, & McGillem, 1995). Younger children demonstrate more variable oral speech movements than adults (Goffman & Smith, 1999; Green, Moore, Higashikawa, & Steeve, 2000; Nip & Green, 2013; Smith & Goffman, 1998), and adults who stutter or who have Parkinson's disease demonstrate more variable oral speech movements than healthy adults (Kleinow & Smith, 2000; Walsh & Smith, 2011). Most relevant to the current study, children with SLI demonstrate more variable oral speech movements than children with typical development (TD; Brumbach & Goffman, 2014; Goffman, 1999). However, there is a dual nature of high variability. For example, Green and Nip (2010) discuss how young children may demonstrate transient episodes of increased variability during times of rapid development or the emergence of new speech skills, presumably because the child is in a period of reorganization in pursuit of the best coordinative approach. In these cases, increased variability in development may actually be a positive or adaptive strategy.

Speech Duration

Analyses of duration have also been used to infer articulatory skills in young children (classically studied by Eguchi & Hirsch, 1969). In the acoustic domain, utterance durations are often used as a proxy for motor skill or processing load. By measuring duration, researchers can determine whether it takes longer for a particular age group or population to produce given nonwords, words, or sentences, with duration differences used to infer processing load. Sevald and Dell (1994) provide a model for the ways in which processing and planning affect utterance duration. Previous findings have demonstrated that children are slower than adults (Grigos & Patel, 2007; Smith & Goffman, 1998; Smith & Zelaznik, 2004; Walsh & Smith, 2002) and that individuals with speech and/or language disorders are slower than those with typical speech and language (Strand & McNeil, 1996). Durations may change when task demands, such as those related to syntactic complexity or length, increase (Brumbach & Goffman, 2014; Dromey & Benson, 2003; Maner, Smith, & Grayson, 2000; Sadagopan & Smith, 2008). However, duration and articulatory variability are not necessarily correlated and thus may reveal different underlying production processes (Brumbach & Goffman, 2014; Goffman & Smith, 1998; Maner, Smith, & Grayson, 2000). Most relevant to the current study, children with SLI are slower at speech production, at least in some tasks, compared with children with TD (Goffman,

1999). Quantifying utterance duration can provide insight into the influence of processing load on speech production but, perhaps, in a different way from those revealed by direct assessment of articulatory movement stability.

Influence of Load on Articulatory Variability and Duration

In both adults and children, imitation and repetition paradigms have been used to assess how relatively high levels of language processing may influence the lower level components of speech production. Findings on the basis of imitation paradigms have provided evidence that multiple linguistic levels influence speech production.

Articulatory Variability

In the production of sentences, Maner, Smith, and Grayson (2000) showed that young children used increased articulatory variability when imitating utterances that were embedded in longer and more complex sentence frames, as compared with imitating the same phrase in isolation. Kleinow and Smith (2000) asked adults who stutter to produce phrases in isolation and then the same phrases embedded in sentences with low and high syntactic complexity (defined as conjoined compared with embedded clauses that were matched for length). In their study, adults who stutter produced utterances with higher variability than normally fluent adults and were particularly susceptible to increases in syntactic complexity.

In the production of lexical stress, Goffman (1999, 2004) explored children's variability and modulation of articulatory movement (i.e., whether weak syllables are produced with relatively short and small amplitude and/or variable articulatory movements), both in content (Goffman, 1999; Goffman & Malin, 1999) and function (Goffman, 2004) words. Articulatory movement measures revealed production differences as a function of linguistic context (or load), with content words produced differently from function words and iambs produced differently from trochees. Surprisingly, iambs were produced with more articulatory stability than trochees, suggesting that increased load may lead to increased rather than decreased stability. Finally, when considering lexical-semantic load, Heisler, Goffman, and Younger (2010) and Heisler and Goffman (2016) demonstrated that adding a lexical representation (visual or functional) in a novel word-learning task resulted in decreased articulatory variability in children with TD and children with SLI.

Duration

Utterance durations are often used as a proxy for processing load. In young children, Goffman (2004) found that function words were produced with shorter durations than weak syllables of content words. Children also use duration to distinguish between declaratives and interrogatives (Grigos & Patel, 2007). Adults, but not children, reduce durations when producing sentences that are

embedded in a longer utterance rather than in isolation (Maner, Smith, & Grayson, 2000). Interestingly, in these cases, durations were shorter when complexity was higher.

In adults, movement durations are longer for bilingual talkers who are less proficient in their second language (Chakraborty, Goffman, & Smith, 2008). Strand and McNeil (1996) reported longer segment durations in long utterances compared with short utterances in speakers with apraxia. Dromey and Benson (2003) demonstrated that conditions of cognitive distraction also influence participants' speaking durations. The common theme across these studies is that utterance durations may vary in response to conditions of different linguistic load. It is important to note that these data were all obtained in the context of imitation or repetition paradigms.

Nonimitated Tasks

A small group of studies have relied on elicited or spontaneous speech and language production to investigate early development. To assess the development of the voicing contrast, Grigos, Saxman, and Gordon (2005) elicited spontaneous productions by training 20-month-old children to say "papa" when viewing a male puppet and "baba" when viewing a toy sheep. Similarly, Grigos and Patel (2007) examined temporal and spatial changes in prosodic control using contextual scenarios with puppets representing the target words, "Bob," "Pop," "bot" (short form of *robot*), and "pot." Children had opportunities to tell the experimenter "Show Bob a bot" and "Show Pop a pot" or ask her to "Show Bob a bot?" or "Show Pop a pot?" These studies reveal that nonimitative tasks that require increased load may be used to elicit speech in young children.

Nip and Green (2013) explored the speaking rate and articulatory kinematics of children and young adults producing speech tasks that varied in demand. These included narrative retell, sentence repetition, and a diadochokinetic task. Their findings indicate that task demands influenced speaking rate (a faster rate for tasks with lower language demands) and that speaking rate increased gradually between 4 and 13 years of age. Nip and Green's results are consistent with the hypothesis that older children experience a decrease in the time needed to formulate an utterance and that motor practice may decrease planning time.

Finally, Brumbach and Goffman (2014) introduced a unique paradigm involving structurally primed sentences. Children with SLI or TD listened to a talker describe a video using either a preposition or a particle (e.g., "jump over the box" while watching a girl jump over a box). They then had to generate a sentence using the same structure but different lexical items (e.g., "tip over the block"). Speech movement variability and production duration were measured in this priming task, and children with SLI showed more articulatory variability than their typical peers. However, both groups showed similar utterance durations in this task.

In summary, in both adults and children, imitation paradigms have predominantly been used to assess how relatively high levels of language processing may influence the lower level components of speech production. Findings on the basis of imitation paradigms have provided evidence that multiple linguistic levels influence speech production. A few studies have incorporated language production tasks that require increased processing but have not generally applied these nonimitative tasks to studies of speech motor control. One next step in this line of research is to include procedures that involve sentence generation as opposed to strictly imitation, in order to assess how language processing load influences speech movement variability and duration.

The Roles of Procedural and Declarative Processing in Speech Motor Production

In 2005, Ullman and Pierpont proposed the procedural deficit hypothesis (PDH). They suggested that the pattern of speech and nonspeech impairments found in children with SLI can be captured by strengths in declarative learning and deficits in procedural learning (Ullman & Pierpont, 2005; Ullman & Pullman, 2015).

These individuals' relatively robust abilities in declarative processing translate into strengths in producing linguistic forms that are chunked. It is suggested that vocabulary is less affected in children with SLI and that they also tend to make fewer errors when producing the irregular past tense because, in English, these verbs rely on rote memorization, which is more heavily weighted on declarative mechanisms (Ullman & Pierpont, 2005). Tasks involving repeated imitations allow for chunking and may therefore tap into declarative learning.

In contrast, children with SLI demonstrate impairments in producing the hierarchically related sequences related to procedural learning. This type of processing is associated with the learning of new skills involving motor learning or cognition and the control of established motor and cognitive skills. Acquiring a skill via implicit learning mechanisms invokes the rule-governed aspects of language (phonology, morphology, and syntax; Nicolson & Fawcett, 2007). Tasks involving this type of production include generating implicit sequences (including linguistic sequences) or organizing grammatical structures, which require more implicit and procedural weighting rather than repeated, memorized chunking. Procedural memory is implicit because the learning that occurs is not available for intentional access and is also gradual in that it occurs over multiple trials. Procedural learning deficits are also related to nonspeech motor impairments (gross and fine motor) in individuals with SLI, particularly in those tasks requiring hierarchical and sequential demands, active formulation, and/or complex sequences of movement (Tomblin, Mainela-Arnold, & Zhang, 2007).

Thus, overall, the PDH differentiates rote learning from new language generation. The learning, which is present in the practiced recitation of a nursery rhyme, involves

relatively declarative elements, in contrast to the learning that is present in the reorganization and sequencing of new language production and that involves relatively procedural elements.

Our paradigm in the current study aligns with elements of the PDH. We set task demands such that the first task involved relatively difficult reorganization, sequencing, and higher formulation demands. In this condition, children with SLI generated aspects of sentences via scaffolded priming: a task that aligns with components of procedural processing. Next, we manipulated those task demands such that the second task involved easier rote recitation and lower formulation demands: a task that aligns with components of declarative processing. Children practiced sentence imitation over time, presumably increasing rote components of the task. Through this manipulation, we can assess whether children with SLI show a broad and general speech motor deficit or one that diminishes with rote and relatively declarative learning that occurs with practice and over time.

Our goal in this study is to examine the group differences in articulatory variability and utterance duration between children with SLI and their typical peers as they transitioned between these two tasks. Although these tasks are not the same as those aspects of processing described in the PDH, they were constructed to mirror those differences. To better understand this phenomenon, we need to compare tasks composed of sentence imitation paradigms (as reported in most of the studies cited above) to parallel tasks composed of sentence generation paradigms. To assess the role of practice, it is important to study production over time.

Hypotheses

The primary prediction of this study is that children with SLI will show higher degrees of speech motor variability and longer speech movement durations than their typical peers, with differences even greater when linguistic load is increased. That is, children with SLI will be especially vulnerable to a condition of increased linguistic load in which they generate rather than imitate or repeat a sentence. A second prediction is that imitation practice will reduce differences in articulatory variability and duration in both children with TD and children with SLI (with group differences diminishing), suggesting that practice facilitates motor learning and that learning more closely associated with declarative mechanisms is not affected in children with SLI.

Method

Participants

Two groups of children, matched for age, participated: 18 children with SLI (10 boys, eight girls), ages 4;0–7;1 (years;months), and 18 children with TD (seven boys, 11 girls), ages 4;4–6;2. All participants were monolingual English speakers and passed a hearing screening and a

structural oral motor screening (Robbins & Klee, 1987). Children were recruited via advertisements and referrals from the general community of a small city in the midwest United States. The children with SLI participated in a 4-week summer program that included both speech/language intervention and participation in research protocols, including the one that informed the current study.

Children participated in standardized cognitive, language, speech, and motor testing. All children were required to have normal nonverbal intelligence as measured by the Columbia Mental Maturity Scale–Third Edition (Burgemeister, Blum, & Lorge, 1972), which was designed to screen young children's general nonverbal cognition. Additionally, all children were required to score in the minimal-to-no symptoms of autism spectrum disorder range on the Childhood Autism Rating Scale–Second Edition (Schopler, Reichler, & Renner, 2002; a measure designed to identify children with autism on the basis of direct observation) and per parent report have no history of neurological dysfunction (such as epilepsy or head injury).

The children with SLI met exclusionary criteria based on Leonard (2014). Children who met these criteria demonstrated significantly impaired language abilities, as indicated by a standard score of 87 or below (Greenslade, Plante, & Vance, 2009) on the Structured Photographic Expressive Language Test–Preschool 2, or Third Edition (Dawson et al., 2003; Dawson et al., 2005): a measure of children's production of morphology and syntax in a picture description task. This score was inclusionary for the children with SLI; all other measures were free to vary. The average Structured Photographic Expressive Language Test scores are quite low, consistent with a diagnosis of SLI (Greenslade, Plante, & Vance, 2009).

Receptive vocabulary was measured by the Peabody Picture Vocabulary Test–Fourth Edition (Dunn & Dunn, 2007), and expressive vocabulary was measured by the Expressive Vocabulary Test–Second Edition (Williams, 2007). Segmental accuracy, including consonants correctly produced, was measured by the Bankson-Bernthal Test of Phonology (Bankson & Bernthal, 1990). The two groups differed in their performance on all of the standardized language tests. Receptive scores from the Clinical Evaluation of Language Fundamentals Preschool–Second Edition (Semel, Wiig, & Secord, 2004) were also available for the children with SLI.

In addition, fine and gross motor skills were measured by the Movement Assessment Battery for Children–Second Edition (Henderson, Sugden, & Barnett, 2007). This test assesses three areas: manual dexterity, ball skills (aiming and catching), and static and dynamic balance, and may be used to identify children who demonstrate impairments in motor function. The two groups did not differ in their performance on the Movement Assessment Battery for Children–Second Edition total score or any of the three subtests. See Table 1 for a summary of these behavioral measures. Because of family schedules, not every child completed every measure.

Table 1. Scores on the measures of standardized testing.

Measure	SLI, <i>M (SD)</i>	TD, <i>M (SD)</i>	Significance
Age	5.58 (0.90)	5.16 (0.47)	$t(34) = 1.74, p = .09$
Father's SES	5.38 (1.12)	6.28 (0.89)	$t(29) = 2.47, p = .02$
Mother's SES	4.94 (1.14)	6.11 (1.13)	$t(33) = 3.04, p = .005$
CMMS	106.44 (10.91)	116.78 (9.75)	$t(32) = 2.91, p = .006$
SPELT	78.50 (8.36)	113.22 (10.29)	$t(34) = 11.11, p < .001$
PPVT	100.56 (11.73)	118.44 (10.92)	$t(34) = 4.74, p < .001$
EVT	97.82 (17.61)	116.67 (11.14)	$t(33) = 3.81, p < .001$
BBTOP consonant	70.67 (9.04)	100.94 (8.38)	$t(34) = 10.42, p < .001$
BBTOP word	69.13 (9.03)	100.28 (10.80)	$t(31) = 8.87, p < .001$
MABC total score	9.88 (3.57)	10.67 (2.40)	$t(33) = .77, p = .45$
MABC manual dexterity	9.12 (2.20)	9.94 (2.34)	$t(33) = 1.07, p = .29$
MABC aiming and catching	11.59 (2.62)	9.83 (2.87)	$t(33) = 1.88, p = .07$
MABC balance	10.00 (3.76)	11.94 (2.92)	$t(33) = 1.71, p = .10$
CELF Preschool-2 receptive	91.71 (12.45)	Not administered	N/A

Note. SLI = specific language impairment; TD = typical development; SES = socioeconomic status; CMMS = Columbia Mental Maturity Scale; SPELT = Structured Photographic Expressive Language Test; PPVT = Peabody Picture Vocabulary Test; EVT = Expressive Vocabulary Test; BBTOP = Bankson-Bernthal Test of Phonology; MABC = Movement Assessment Battery for Children; CELF Preschool-2 = Clinical Evaluation of Language Fundamentals Preschool–Second Edition.

Equipment

Three-dimensional kinematic data were collected at 250 samples/second. A three-camera motion capture system (Optotrak 3020 or 3D Investigator, both Northern Digital Inc.) was used. Small infrared light-emitting diodes (IREDs) were attached to each participant's upper lip, lower lip, and a lightweight splint under the chin at midline (used to approximate jaw movement). In addition, five other IREDs were used to create a three-dimensional head coordinate system in order to subtract head motion artifact (Smith, Johnson, McGillem, & Goffman, 2000). A time-locked acoustic signal was collected at 16,000 samples/second in order to confirm that movement records aligned with target productions. High-quality audio and video recordings were also obtained for analyses of production accuracy.

Procedure and Session Structure

Children participated in three experimental sessions on three different days. Sessions included the collection of kinematic data followed by behavioral assessments. The first session contained a highly scaffolded syntactic priming task that was designed to increase processing load. At the end of the first session and then over two sessions that followed, children engaged in a sentence repetition task. See Figure 1 for a representation of the structure of these sessions. Of these two tasks, the priming task carried a higher processing load because it required the child to generate a variety of sentences in response to picture cues. In comparison, the repetition task carried a lower processing load because it required only that the child repeat a single sentence multiple times rather than generate multiple different sentences. In this way, the task manipulations were designed to mirror elements of procedural versus declarative processing. The generation task required more

active formulation, indicating that it is more heavily weighted on the hierarchical demands associated with procedural learning, whereas the repetition task is more heavily weighted on what are often viewed as declarative mechanisms. The sentences in these tasks were constructed using words that are familiar to young children, as indicated by their inclusion in the MacArthur–Bates Communicative Development Inventories (Fenson et al., 2007). An additional constraint was that the sentences needed to be heavily loaded with labial consonants to facilitate the analysis of lip movement.

Structured Syntactic Priming Task

Children viewed 32 pairs of photographs, each depicting an actor, a verb, and a patient. For the first item in each pair, the children listened to a female voice describing the picture. Their task was then to generate a sentence that included the same syntactic structure but different lexical items to describe the second photograph in each pair. For example, the primed sentence may be “Mouse washes the baby,” and the child's target sentence may be “Mom pats the puppy” or “Monkey pushes the cow.” Two of the target sentences, “Mom pats the puppy” and “Mom pats the baby,” were elicited 10 times over the course of the experiment; these two sentences were subjected to analysis. An additional eight filler sentences with the same syntactic structure (such as “Mouse washes the baby” and “Monkey pushes the cow”) were quasirandomly (no consecutive presentation of the same sentence) distributed throughout the experimental block. These fillers served to increase the processing load. See Table 2 for the lists of target and filler sentences. It is important to note that the children heard and produced both the analyzed target sentences and the fillers.

Initially, to verify that the child knew the target verb, he or she was exposed to the verb “pat” in the children's book

Figure 1. Session structure.

“Pat the Bunny” (Kunhardt, 2001). Next, to assure familiarity with the subjects and objects included in the experimental sentences, photographs of these were presented and labeled. Finally, the child completed three practice trials demonstrating his or her understanding of the priming paradigm before beginning the experimental task. The sentences and their accompanying illustrations were presented via PowerPoint at a comfortable loudness level. If a child produced errors in target sentences (such as substituting “dog” for “puppy” or producing a syntactic error), the examiner would remind the child of the correct production and encourage him or her to reattempt the sentence. During the first experimental session, the children engaged in the scaffolded priming task. Imitated sentences were not analyzed.

Sentence Repetition Task

At the end of the first and during the second and third sessions, the child was instructed to repeat the target

sentence “Mom pats the puppy” 10 times consecutively. This is similar to prior tasks used to assess speech motor variability in children (Smith & Goffman, 1998; Smith & Zelaznik, 2004).

Data Processing

The kinematic data from the target sentences “Mom pats the puppy” and “Mom pats the baby” were processed in customized MATLAB routines (The Mathworks, 2009). When processing the kinematic data, some productions could not be used, including those that contained extra or missing syllables or phonemes, interruptions in the speech signal, extra opening and closing of the lips, or IREDs missing from the cameras’ view. Incorrect but consistent productions were analyzed if they outnumbered correct productions, that is, if the child said “Mom petted the puppy” eight times and “Mom pats the puppy” twice, the eight consistent productions were used.

Calculating Articulatory Variability

The STI for lip aperture was used to measure variability of articulatory movements across multiple productions of a sentence. In this case, the STI quantifies the movement of three effectors (upper lip, lower lip, and jaw) as they interact to control the opening and closing of the mouth during speech (Smith & Zelaznik, 2004). To calculate the STI, the onsets and offsets of each target sentence (e.g., the opening movement following the first [m] in “mom” and the opening movement following the second [p]

Table 2. Target and filler sentences.

Target sentences	Filler sentences
Mom pats the puppy.	Mom pushes the bunny.
Mom pats the baby.	Mom washes the plate.
	Mouse pushes the puppy.
	Mouse washes the bird.
	Mouse pats the flower.
	Monkey pats the cat.
	Monkey washes the baby.
	Monkey pushes the cow.

in “puppy”) were extracted from lower lip movement on the basis of peak velocity. We then took the lower lip signals and subtracted them point-by-point from the upper lip signals, giving us the lip aperture values. Movement onsets and offsets were selected by visually inspecting the velocity record for local minima. An algorithm then established the minimum value, determining the point at which velocity crossed 0 within a 100-ms window of the point selected by the experimenter. We measured the movement within that entire time window. The movement trajectories were then linearly time normalized by setting each extracted record to a time base of 1,000 points and using a cubic spline algorithm to interpolate between points. They were amplitude normalized by setting the mean to 0 and the *SD* to 1. The rationale for time and amplitude normalization was to rule out differences in rate and loudness; the goal was to assess spatiotemporal patterning. After normalizing the data, standard deviations were computed at 2% intervals in relative time across the 10 records and then summed. The sum of the 50 *SD*s is the STI; a higher value reflects greater movement variability (Goffman, 1999; Goffman, Gerken, & Lucchesi, 2007; Goffman & Smith, 1999; Smith & Goffman, 1998; Smith et al., 1995; Smith & Zelaznik, 2004). A maximum of 10 productions were analyzed, but if errors were present, a minimum of five consistent productions were used to calculate the STI. An example of the STI calculation is presented in Figure 2. It is important

to note that increased articulatory variability may index flexibility in learning and thus may be viewed as a positive. Increased articulatory pattern stability also suggests that a motor pattern has been acquired (e.g., the acquisition of a tennis swing). Both components of variability are relevant for this study: Higher variability may indicate flexibility and learning, and lower variability, reliance on an established motor pattern.

Calculating Duration

In addition to the STI, we measured the mean durations of each production. Duration was assessed from the same kinematic records as those used to calculate the STI.

Statistical Analyses

The research questions were answered using linear mixed-effects models via the *lmer* function requiring the *lme4*, *lmerTest*, and *lsmeans* packages in R (Bates, Maechler, Bolker, & Walker, 2015; Kuznetsova, Brockhoff, & Christensen, 2016; Lenth, 2016). We examined the outcome variables of speech stability and duration separately. Fixed effects in the model were group (SLI, TD) and task (primed/*puppy*, primed/*baby*, first repetition, second repetition, and third repetition). A random intercept was included in the model to account for within-subject

Figure 2. Extracted movement sequences from a child with SLI’s productions of the sentence, “Mom pats the puppy.” The left column represents productions elicited by priming; the right column represents repeated productions. The top two panels represent the raw movement records. The middle two panels represent the same records, now time normalized and amplitude normalized. The bottom two panels represent the standard deviations of the normalized records, the sums of which compose the spatiotemporal index (STI) values for lip aperture, or the lip aperture index (LA index). SLI = specific language impairment.

correlation arising from the within-subject task factor. The model for duration included different variances by task. The covariance structure used in each model was chosen based on the smallest Akaike information criterion value. The mixed-effects model allows us to test for overall group effect, overall task effect, the interaction between group and task, and test for pairwise differences of interest between the two primed conditions and the three repetitions, while appropriately controlling for repeated observations and unequal group variances all within one unifying model. A follow-up analysis was performed to find the relationship between STI and duration, after adjusting for group and task, using a similar mixed-effects model. Our primary tests of interest are the pairwise comparisons between the two primed conditions and the three repetitions. To control overall Type I error resulting from performing multiple tests, we use the false discovery rate (FDR; Benjamini & Hochberg, 1995). FDR-adjusted p values control the number of false discoveries (Type I errors) so that .05 implies that 5% of significant tests will result in false positives. The FDR-adjusted p value is less conservative than a Bonferroni adjustment. The alpha level was set to .05.

Results

Analysis 1. Errors in Sentence Production

In the structured syntactic priming task, children in both groups produced errors that we divided into two types: word selection errors (e.g., substituting “mommy” for “mom”) and syntactic errors (e.g., substituting “pat” for “pats”). The majority of the word choice errors were appropriate; however, children were corrected because, for the kinematic analysis, it is necessary that labial consonants and a consistent number of syllables be included. Syntactic errors were generally true errors, as in omitting the regular third-person singular morpheme. These data are presented in Table 3. Results indicate that the children with SLI produced more syntactic errors but that both groups produced a similar number of word choice errors. As expected on the basis of their diagnosis, children with SLI demonstrated significant difficulty with accurately producing the third-person singular form. The numerous syntactic errors or nonerrorful substitutions made by both groups (and by the SLI group in particular) suggest that the task was sufficiently challenging and successfully indexed components of procedural learning.

Analysis 2. Articulatory Variability as an Index of Speech Motor Control

Effects of Group and Task

Tests for the main effects and interactions from the linear mixed-effects regression model were completed using Type III F tests with a Satterthwaite approximation for degrees of freedom. Model results for STI show that there was not a significant interaction between group and task, $F(4, 136) = 0.907$, $p = .46$, but there was a significant main effect of group, $F(1, 34) = 6.159$, $p = .02$. This indicates that children with SLI produced more variable articulatory movements than their peers with TD in both a condition of relatively high formulation demands and a condition of relatively low formulation demands. Because the priming task has an additional sentence that was not given to the children during the repetition sessions, to compare the effect of task, we must look at the pairwise comparisons of primed/puppy versus the three repeated puppy sentences. Because there was not a significant interaction between group and task, we can analyze the differences between the tasks by averaging over the two groups. The effect of task is highly significant in all three comparisons, $p < .0001$ and FDR $< .0001$ (see Table 4). This is convincing evidence that the higher processing load obligated by the priming condition led to increased articulatory variability for all children, regardless of group (see Figure 3).

Priming Task

In order to incorporate both primed sentences and to evaluate the influence of SLI on sentence production that requires higher formulation demands, we examined the pairwise comparisons between group and sentence (puppy vs. baby; see Table 4). The effect of group was significant only for puppy, $p = .01$, FDR = .05, meaning that there is evidence that children with SLI were more variable than children with TD when asked to produce the sentence “Mom pats the puppy.” There was no statistically significant effect of sentence for either group, $p = .42$, FDR = .61, and $p = .12$, FDR = .21, for children with TD and SLI, respectively.

Repetition Task

We were also interested in whether children with SLI differed from their peers with TD in a task with lower formulation demands that was practiced over time. To do

Table 3. Children’s word choice errors and syntactic errors while completing the priming task.

Group	Puppy: nontarget word choice	Puppy: syntactic error	Baby: nontarget word choice	Baby: syntactic error
SLI	47.93% (34.38)	70.48% (36.44)	42.34% (41.56)	73.24% (39.81)
TD	56.95% (37.65)	16.77% (31.44)	49.10% (42.65)	15.85% (32.14)
	$F(1, 47) = 0.76$, $p = .39$	$F(1, 47) = 28.62$, $p < .001$	$F(1, 47) = 0.31$, $p = .58$	$F(1, 47) = 28.64$, $p < .001$

Note. SLI = specific language impairment; TD = typical development.

Table 4. Pairwise comparisons of interest for speech stability.

Contrast	Estimate	SE	df	t ratio	p value	FDR
PrimePuppy – Rep1	8.9278	1.0045	136	8.888	< .0001	< .0001
PrimePuppy – Rep2	10.7400	1.0045	136	10.692	< .0001	< .0001
PrimePuppy – Rep3	11.1486	1.0045	136	11.099	< .0001	< .0001
TD, PrimeBaby – SLI, PrimeBaby	–3.1811	1.6822	128	–1.891	0.0609	0.1218
TD, PrimePuppy – SLI, PrimePuppy	–4.2722	1.6822	128	–2.540	0.0123	0.0492
TD, PrimeBaby – TD, PrimePuppy	–1.1522	1.4205	136	–0.811	0.4187	0.6090
SLI, PrimeBaby – SLI, PrimePuppy	–2.2433	1.4205	136	–1.579	0.1166	0.2073
TD, Rep1 – SLI, Rep1	–3.5767	1.6822	128	–2.126	0.0354	0.0944
TD, Rep2 – SLI, Rep2	–1.5133	1.6822	128	–0.900	0.3700	0.5920
TD, Rep3 – SLI, Rep3	–1.1361	1.6822	128	–0.675	0.5007	0.6162
TD, Rep1 – TD, Rep2	0.7806	1.4205	136	0.549	0.5836	0.6669
SLI, Rep1 – SLI, Rep2	2.8439	1.4205	136	2.002	0.0473	0.1081
TD, Rep1 – TD, Rep3	1.0006	1.4205	136	0.704	0.4824	0.6162
SLI, Rep1 – TD, Rep3	3.4411	1.4205	136	2.422	0.0167	0.0536
TD, Rep2 – TD, Rep3	0.2200	1.4205	136	0.155	0.8772	0.8772
SLI, Rep2 – SLI, Rep3	0.5972	1.4205	136	0.420	0.6748	0.7198

Note. FDR = false discovery rate; SLI = specific language impairment; TD = typical development.

this, we again observed the pairwise comparisons between group and repetition session (see Table 4). There was not a significant effect of group for any of the three repetitions, $p = .04, .37, .50$, and $FDR = .09, .59, .62$, for Sessions 1–3, respectively. The effect of session was significant only for

children with SLI between the first and third sessions, although the size is small, $p = .02$, $FDR = .05$. This indicates that, in conditions of low formulation demands, children with SLI show similar articulatory variability to their peers with TD. Importantly, with imitation practice,

Figure 3. Speech stability by group and task. SLI = specific language impairment; STI = spatiotemporal index; TD = typical development.

children with SLI demonstrate a decrease in articulatory variability.

Analysis 3. Movement Duration as an Index of Language Processing

Effects of Group and Task

The model results for duration show that there was not a significant interaction between group and task, $F(4, 136) = 2.15$, $p = .08$, or a significant main effect of group, $F(1, 34) = 0.51$, $p = .48$. Because there was not a significant interaction between group and task, we can analyze the differences in duration between the tasks by averaging over the two groups. The difference between tasks was significant at all three sessions; $p < .0001$ and $FDR < .0001$ for all three comparisons (see Table 5). This is convincing evidence that the higher formulation demands obligated by the priming condition led to increased sentence duration for all children, regardless of group (see Figure 4).

Priming Task

To investigate how children with SLI differed from their peers with TD in sentence production in a context with high formulation demands, we analyzed the pairwise comparisons between group and sentence (see Table 5). There was no statistically significant effect of group for either sentence, $p = .84$, $FDR = .92$, and $p = .18$, $FDR = .37$, for primed/baby and primed/puppy, respectively. There was also no statistically significant effect of sentence for either group, $p = .74$, $FDR = .92$, and $p = .08$, $FDR = .21$, for children with TD and SLI, respectively. This indicates that neither children with SLI nor TD had a difference in speech duration when primed for different sentences.

Repetition Task

The differences in children with SLI and their peers with TD in the task with lower formulation demands of

repeating a target sentence can also be analyzed by looking at the pairwise comparisons between group and repetition session (see Table 5). There was not a significant effect of group for any of the three repetitions, $p = .87$, $.82$, $.45$, and $FDR = .92$, $.92$, $.79$, for Sessions 1–3, respectively. There were statistically significant differences in speech duration between the first and third sessions and between the second and third sessions, only for children with SLI, $p = .002$, $FDR = .01$, and $p = .01$, $FDR = .04$, respectively. This indicates that, with practice, children with SLI produce sentences with shorter durations.

Analysis 4. Relationship Between STI and Duration

The mixed model shows that duration is highly significant in the model for STI, $F(1, 166.88) = 29.53$, $p < .0001$. The slope estimate indicates that, after adjusting for relationship with group and task, an increase in duration of 1-s increases the STI by 6.57, on average.

Discussion

In this study, we examined the impact of manipulating language load on the speech production of two groups of children. Children with SLI or TD produced the same sentence (“*Mom pats the puppy*”) in two tasks. In one task, they generated two target sentences 10 times in the context of highly scaffolded priming (higher formulation demands, aligning with elements of procedural processing). In the second task, they repeated one of the sentences 10 times sequentially (lower formulation demands, aligning with elements of declarative processing) across three practice sessions. The goal was to evaluate whether there is a generalized and global speech motor deficit in children with SLI or one that is associated with specific task demands (Goffman, 1999; Heisler, Goffman, & Younger, 2010; Hsu & Bishop, 2014; Lum, Gelgic, & Conti-Ramsden, 2010; Tomblin, Mainela-Arnold, & Zhang, 2007). We also

Table 5. Pairwise comparisons of interest for speech duration.

Contrast	Estimate	SE	df	t ratio	p value	FDR
PrimePuppy – Rep1	0.4572	0.0690	136	6.629	< .0001	< .0001
PrimePuppy – Rep2	0.4861	0.0733	136	6.636	< .0001	< .0001
PrimePuppy – Rep3	0.5117	0.0725	136	7.061	< .0001	< .0001
TD, PrimeBaby – SLI, PrimeBaby	–0.0339	0.1620	34	–0.209	.8356	.9244
TD, PrimePuppy – SLI, PrimePuppy	–0.2456	0.1805	34	–1.361	.1826	.3651
TD, PrimeBaby – TD, PrimePuppy	0.0333	0.1003	136	0.332	.7402	.9244
SLI, PrimeBaby – SLI, PrimePuppy	–0.1783	0.1003	136	–1.777	.0778	.2073
TD, Rep1 – SLI, Rep1	–0.0167	0.0985	34	–0.169	.8666	.9244
TD, Rep2 – SLI, Rep2	0.0200	0.0881	34	0.227	.8219	.9244
TD, Rep3 – SLI, Rep3	0.0689	0.0894	34	0.771	.4463	.7933
TD, Rep1 – TD, Rep2	0.0106	0.0304	136	0.348	.7286	.9244
SLI, Rep1 – SLI, Rep2	0.0472	0.0304	136	1.555	.1222	.2792
TD, Rep1 – TD, Rep3	0.0117	0.0304	136	0.384	.7015	.9244
SLI, Rep1 – SLI, Rep3	0.0972	0.0304	136	3.201	.0017	.0068
TD, Rep2 – TD, Rep3	0.0011	0.0194	136	0.057	.9545	.9545
SLI, Rep2 – SLI, Rep3	0.0500	0.0194	136	2.575	.0111	.0355

Note. FDR = false discovery rate; SLI = specific language impairment; TD = typical development.

Figure 4. Speech duration by group and task. SLI = specific language impairment; TD = typical development.

inquired whether practice in imitating the sentence (that is, as the task transitions between an emphasis on high formulation demands to a task comprising lower formulation demands) would cause the two groups to converge. We address each of our predictions below.

The Speech Motor Deficit in Children With SLI

First, we predicted that children with SLI would demonstrate higher speech movement variability and longer utterance durations. Our findings indicate that the SLI group produced more variable speech movements in both tasks, but that there were no group differences in duration. We also found that both groups had more variable movements and longer utterance durations in the condition of high formulation demands than in the condition of low formulation demands. This indicated that the reduced demands associated with imitation facilitated stable and relatively fast articulatory movements in both groups.

Second, we predicted that group differences would be higher when formulation demands were higher, in that children with SLI would be especially susceptible to this manipulation. Specifically, both groups would demonstrate higher variability in the condition of high formulation demands, but with motor practice and lower formulation demands, group differences would diminish. Even though

the interaction term was not statistically significant because planned analyses of interest were the pairwise comparisons, we evaluated all of the pairwise comparisons while adjusting the p value with a suitable Type I error adjustment, FDR. As predicted, the mean variability score was significantly different between SLI and TD in the priming condition, but the group means were not significantly different in the repetition condition. In addition, practice facilitated motor learning in children with SLI.

Our findings indicate that articulatory variability and utterance duration decreased by Session 3 of practice for children with SLI, indicating motor learning with practice even in children with potential deficiencies in speech motor learning. The TD group did not show this difference. This indicates that, as the demands of the experimental task diminished, the two groups converged, and children with SLI no longer showed differences from their peers with TD.

These discoveries contribute to characterization of the motor deficit in children with SLI. Our comparison of speech production in conditions of high formulation demands versus conditions of motor practice/rote recitation revealed that children with SLI do not have a generalized speech motor deficit. Actually, the differences between speech motor production in children with SLI versus children with TD appeared predominately in the condition

of high linguistic load. Our findings here are novel, as they are the first to show that motor skills are more variable under generation demands versus repetition demands.

Third, we found that speech movement stability showed group effects, whereas utterance duration did not, in that there were group differences for stability but not duration. It therefore appears that duration captures different components of processing from articulatory variability. These findings suggest that motor learning is not always the same as other aspects of processing. Rather, these two speech production processes differ: The first is related to movement implementation, and the second is related to broader dimensions of language processing. Yet, the mixed model showed that these two measures were correlated, in that more stable STI values corresponded to shorter utterance durations. In sum, both children with SLI and their peers with TD produce longer and more variable movements in a high load retrieval condition. However, only speech motor stability shows group differences, with children with SLI more variable than their peers in the high retrieval condition. Motor aspects of speech production appear to be implicated in SLI, but only as related to the stability of movement implementation in a relatively high load task.

The Change in Processing Demands Impacts Speech Production

In previous studies, children with SLI were hypothesized to show relative strengths in declarative learning and relative difficulties in procedural learning (Ullman & Pierpont, 2005; Ullman & Pullman, 2015). This inherent deficit can be observed via tasks demanding generation of sentences with correct English syntax and morphology. In the current study, the task that we propose aligned most closely with procedural processing was our priming task, requiring understanding of English underlying grammar, online production of a grammatical structure, the creative variable lexical items, and the correct organization and sequencing of elements within the sentence. In contrast, individuals with SLI experience relative strengths in the use of declarative processing: the type of learning that can be consciously and explicitly recalled and that involves remembering idiosyncratic representations and linguistic mappings memorized in the “mental lexicon.” As a compensatory strategy, individuals with SLI may memorize complex sequences and forms rather than attempt to generate them anew during each attempt. When a word or concept becomes learned in a way that is rote, as in the memorization of verbs with irregular past tense marking, the word or concept switches from procedural awareness to declarative awareness. In the current study, the task that we propose aligned most closely to declarative learning was our repetition task.

Therefore, our second major finding in this study was that the change in processing demands impacts speech production in children with SLI. Following our priming task with our repetition task changed the demands from

being weighted toward processing associated with procedural learning (organizing and sequencing) to processing associated with declarative learning (rote recitation or memorization). This discovery is consistent with previous studies exploring multiple repetitions of the sentence, “Buy Bobby a puppy” (Smith & Goffman, 1998; Walsh & Smith, 2002). A production task that is normally associated with procedural learning becomes more associated with declarative learning as the utterance is repeated again and again over time. These results speak to the clinical observation that a child with SLI may be able to recite a nursery rhyme from memory even though he or she is unable to construct a sentence containing those same words. It also may imply that increased articulatory stability may reflect less generative and flexible learning, in that children with SLI converge to the variability level of their peers in a task that is rote, rather than language-like.

The Importance of Including Higher Level Tasks in Speech Production Studies

Our third significant discovery in this study relates to the ways in which children’s language production is studied, in that there may be substantial differences between requiring imitation and requiring generation. Most previous studies of speech motor control have not tapped into these types of language demands because the methods used to investigate language in children with SLI were based on imitation tasks. Researchers have found that these imitation paradigms reveal how language influences speech production (operationalized by measuring articulatory stability and duration). However, in the current study, we have discovered that imitation paradigms do not fully capture the influences of language load. Both groups of children were highly sensitive to these differences in task demands, and the higher linguistic load was associated with increased speech motor variability and longer utterance duration. We therefore conclude that increasing linguistic load via sentence generation demands, rather than relying solely on imitation paradigms, may provide important and innovative information regarding speech production. Furthermore, the inferences that can be made based on imitation are limited. Requiring children to generate an utterance leads to substantial increases in spatio-temporal variability. The inclusion of increased sentence generation influences speech production and may be important to incorporate into the study of SLI. Indeed, articulatory variability likely indexes increased flexibility in the generation of an utterance. Clearly, manipulation of linguistic and motoric difficulty can make an important difference in the results of a given study.

Clinical Implications

There are two significant clinical implications for our findings: It is crucial to incorporate both higher formulation demands and motor practice in therapy designs.

First, it may be important for clinicians to include increased linguistic load in their therapy because that is actually where the child's difficulty may lie. This is in contrast to traditional therapy, which usually begins with the child imitating the production of the clinician. Speech-language pathologists (SLPs) classically utilize a hierarchy of difficulty that begins with imitation. That is, children with language impairments are instructed to imitate utterances produced by the SLP or instructor as the first component of therapy. They then go on to use procedures, such as script fading, in which the SLP gradually encourages the child to produce sentences with an increasing number of empty spaces (i.e., beginning with "I like to play video __," then proceeding to "I like to play __" and then "I like __," and so forth, until the client can produce the script independently; Paul & Norbury, 2012). However, it may be the case that scaffolded retrieval tasks are more effective at tapping into the deficit, which is specific to children with SLI. This concept is consistent with the works of Karpicke and Blunt (2011) and Karpicke and Roediger (2008) who have explored the role of retrieval in learning. Similarly, our findings suggest that eliciting productions via conditions of higher linguistic load may actually facilitate deeper learning, and the increased articulatory variability observed reflects this learning.

This idea has been confirmed by studies indicating that increased complexity in teaching facilitates learning and generalization. For example, Guo, Van Horne, and Tomblin (2011) discuss how sentence complexity interacts with children's knowledge of grammar. Returning to the current study, requiring the child to either generate or repeat an utterance may have a large impact on his or her performance and, most importantly, the success of his or her learning. It is therefore crucial to focus more carefully on the demands of the task that the child is asked to perform and to make sure that this variable is controlled across the therapy program.

The incorporation of motor practice (generally speaking, consisting of a variety of motor exercises) is also a crucial element of speech and language therapy. Specifically, motor-based treatment approaches elicit target speech behaviors from the client by teaching the correct production of an individual sound; in this process, repetition is crucial (Bernthal, Bankson, & Flipsen, 2013). Typical speech sound production involves both accurate and efficient sound production at the motor level and the use of speech sounds in accordance with language rules (Bernthal et al., 2013). Similarly, grammatical intervention often relies upon repetitions and recasts or imitations of a given structure (Fey, Long, & Finestack, 2003). Clearly, therefore, motor practice coupled with language training should be an important component of speech and language intervention. Despite the fact that children with SLI do not always have speech motor, gross motor, or fine motor deficits, our results indicate that motor practice still has relevance in a clinical setting because it may impact language processing. This is a novel conclusion that we can draw from our data.

Limitations and Future Directions

One consideration is how the findings of increased articulatory variability should be interpreted. Traditionally, gross-motor or fine-motor variability is seen to be indicative of an adaptive process that actually facilitates learning. For example, in infants' reaching trajectories, early variability in the body's posture, reach positions and speeds, and the freedom of the other arm actually support learning (Thelen & Spencer, 1998). However, this concept has not been addressed in studies of speech motor processes, even though it is generally assumed that greater stability is more positive than greater variability (Saletta, 2015). Future work should address this question directly.

Additionally, this study is limited by the deficiency of external validity. That is, repeated motor practice is not an element of natural language learning (except in, e.g., the use of music and poetry), and sentences are not repeated verbatim over and over in the course of typical development. Future works should increase the clinical feasibility of this paradigm by incorporating activities that more closely mirror natural development and learning. Another important next step in this line of work is to conduct an additional priming/high linguistic load task after the three repetition/low linguistic load tasks. This will speak to the issue of whether the priming exercise changes as a result of previous exposure to the repetition exercise. Also, further work is necessary to ascertain how imitation paradigms tap into language processing. Finally, future research in child language intervention should continue to explore the role of sentence generation/production tasks rather than relying exclusively on activities involving direct imitation or repetition.

Conclusions

In conclusion, our data indicate that, when investigating the connection between speech and language, it is essential to include tasks that tap into high levels of linguistic processing. All children, with TD or SLI, show high levels of movement variability and long durations in sentence production tasks of relatively high load. However, group differences only emerge in a high load condition that presumably requires active retrieval. It is in this task that children with SLI show a distinct pattern of speech motor learning, as they demonstrate great variability (but not utterance duration) compared with their peers with TD. In the articulatory kinematic domain, in which speech motor deficits are explicitly assessed, children with SLI become closer to the performance of their peers with TD in imitation conditions of lower linguistic load. These data extend upon the theoretical account of the PDH and the nature of the (speech) motor deficit in SLI and speak to important methodological considerations for future studies.

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