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Research Article

Interaction of Language Processing and Motor Skill in Children With Specific Language Impairment

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Purpose: To examine how language production interacts with speech motor and gross and fine motor skill in children with specific language impairment (SLI).
Method: Eleven children with SLI and 12 age-matched peers (4–6 years) produced structurally primed sentences containing particles and prepositions. Utterances were analyzed for errors and for articulatory duration and variability. Standard measures of motor, language, and articulation skill were also obtained.
Results: Sentences containing particles, as compared with prepositions, were less likely to be produced in a priming task and were longer in duration, suggesting increased difficulty with this syntactic structure. Children with SLI demonstrated higher articulatory variability and poorer gross and fine motor skills compared with aged-matched controls. Articulatory variability was correlated with generalized gross and fine motor performance.
Conclusions: Children with SLI show co-occurring speech motor and generalized motor deficits. Current theories do not fully account for the present findings, though the procedural deficit hypothesis provides a framework for interpreting overlap among language and motor domains.

Key Words: children, language, language disorders, specific language impairment, speech motor control, speech production, syntax

Over the past several years, it has been suggested that complex and hierarchical language production interacts in specific ways with motor skill (e.g., Greenfield, 1991; Iverson, 2010; Thelen & Smith, 1994). Because children with specific language impairment (SLI), by definition, show dissociations among aspects of cognitive and language development, they provide a particularly strong test of whether and how domain general mechanisms may interact with language. Some theoreticians propose a common mechanism underlying language and motor processing in SLI (e.g., Tomblin, Maniela-Arnold, & Zhang, 2007; Ullman & Pierpont, 2005), whereas others suggest a comorbidity, with independent deficits associated with language and motor components (e.g., Locke, 1997). It is our objective to begin to assess how grammatical aspects of language production cohere with speech motor and gross and fine motor performance in children diagnosed with SLI.

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Evidence for a Motor Deficit in SLI

SLI is explicitly defined on the basis of language deficits; children with SLI show impairments in expressive and possibly receptive language that cannot be explained by hearing, neurological, or gross and fine motor deficits (Leonard, 1998; Stark & Tallal, 1981). Yet as a group, children with SLI perform poorly on a range of motor tasks and have been identified as having soft neurological signs, such as minor abnormalities in behavior and coordination (Bishop & Edmundson, 1987; Hill, 2001; Powell & Bishop, 1992). Further, children diagnosed with SLI tend to be motorically clumsy (Powell & Bishop, 1992; Zelaznik & Goffman, 2010) and to demonstrate poor motor skill and haptic object recognition (Müürsepp, Aibast, Gapeyeva, & Pääsuke, 2012; Müürsepp, Aibast, & Pääsuke, 2011). In a review of 29 studies, Hill (2001, p. 166) concluded that there is a "substantial co-morbidity between SLI and poor motor skills." These children show deficits in fine motor hand, limb, and finger movements (Hill, 1998; Marton, 2009; Noterdaeme, Amorosa, Ploog, & Scheimann, 1998); peg moving, bead threading, and buttoning (Owen & McKinlay, 1997); representational gestures (Hill, Bishop, & Nimmo-Smith, 1998); as well as a weak hand preference (Hill & Bishop,

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1998). It is now well known that deficits observed in children with SLI are not confined purely to the linguistic domain.

On the basis of neuroanatomical evidence, it is not surprising that children with SLI show co-occurring deficits in language and motor domains. Broca's area, which is implicated in syntactic language functions (Caplan, Alpert, Waters, & Olivieri, 2000; Nishitani & Hari, 2000), also coordinates the mirror neuron system (Rizzolatti & Craighero, 2004), which supports the notion of a specific relationship between syntactic and motor abilities. Consistent with this view, neuroanatomical studies suggest an interaction between language and motor systems in SLI. Jancke, Siegenthaler, Preis, and Steinmetz (2007) showed that children with developmental language disorder had decreased white matter volume in motor areas of the left hemisphere and also corresponding behavioral deficits in a complex manual coordination task.

Perhaps the most detailed hypothesis to emerge to date is Ullman and Pierpont's (2005) procedural deficit hypothesis. In this view, the grammatical deficits associated with SLI are part of a larger unified deficit in the brain systems underlying procedural learning. Procedural learning is implicit and is required for the acquisition of new sequential skills, such as riding a bicycle, tying shoes, or producing a sentence. Among other capacities, both motor sequencing and grammar are explicitly implicated in the procedural deficit hypothesis.

As motivated by the neuroanatomical evidence and by the procedural deficit hypothesis, our objective is to contribute to understanding the documented relationship between grammatical aspects of language production, articulatory sequencing, and motor skill. In the following sections, we first describe the syntactic constructions we examine and the standard analyses used to evaluate children's performance. We then turn to articulatory sequencing and finally relate both language and speech motor performance to measures of generalized gross and fine motor skill.

Syntactic Constructions

In the first component of the present study, we investigated error patterns in children's productions of syntactic structures that varied in difficulty. Children with SLI show particular deficits in their production of grammatical inflections (Rice, Wexler, & Hershberger, 1998). Specifically, children with SLI have difficulty with morphemes that connect to a verb (Miller & Leonard, 1998). Unstressed function words pose problems for English-speaking children with SLI, particularly verb inflections such as third-person singular *–s*, auxiliary and copula *–s*, and regular past tense *–d* (Bedore & Leonard, 1998; Rice et al., 1998). The particle, which shares many of these syntactic and prosodic characteristics, is also prone to difficulty in children with SLI. Watkins and Rice (1991) found that 4- and 5-year-old children with SLI tended to omit particles more frequently compared with their age-matched peers. Particles and prepositions are similar phonologically and lexically but differ in their syntactic organization, which meets the methodological constraints of the current study.

Critically, verb particles are syntactically distinct from prepositions (Cappelle, 2004), because verb particles form a unit with a verb, whereas prepositions operate independently of the verb (Watkins & Rice, 1991). English verb particles can either be split (1) or joined (2) in phrases with a full noun phrase.

1. Mary [kicked over (the chair)].
2. Mary [kicked (the chair) over].

In sentences with full noun phrases, the placement of the particle is influenced by characteristics of the sentence structure. These factors include the length of the noun phrase and the focus of the sentence. In sentences with a pronominal noun phrase, the particle must follow the pronoun.

3. She kicked it over.
4. *She kicked over it.

The prepositional phrase, in contrast, is fixed in its syntactic position. The preposition that heads a noun phrase must always come before the noun.

5. She jumped [over the chair].
6. She jumped [over it].
7. *She jumped the chair over.
8. *She jumped it over.

Because the verb particle and the preposition can be phonetically similar but differ syntactically, the present study used these constructions to assess influences of syntax on language production abilities in children with SLI.

Relationship of Speech Motor Skill and Language Complexity

The production of sentences containing verb particles and prepositions also incorporates complex articulatory sequencing goals. These particular language targets were selected because they are difficult for children with SLI and are also amenable to speech motor analysis. An approach to assess language and motor relations is to directly record the movement of the articulators while children and adults produce different linguistic structures. In this way, it can be shown how movements of the articulators interact with higher levels of representation.

Articulatory movements during speech may be affected by complex language. Maner, Smith, and Grayson (2000) found that normally developing (ND) 5-year-old children and adults showed increased articulatory variability for a phrase spoken in longer and more complex sentences compared with the same sentence spoken in isolation. Length and linguistic complexity influence speech motor performance in ND children. Kleinow and Smith (2006) controlled for utterance length when manipulating syntactic complexity. They found that ND 9-year-old children showed more articulatory variability when imitating a sentence containing a more complex relative clause than a syntactically simpler conjunction.

These results support a more tightly connected language and articulatory system than has previously been considered.

The specific interaction between syntactic complexity and articulatory abilities found by Kleinow and Smith (2006) suggests that general motor capacities could relate to language abilities. Children with SLI demonstrate poorer articulatory movement skills compared with age-matched peers. Specifically, they show increased variability in the patterning of oral movements during repetitions of a specific word or sentence (Goffman, 1999, 2004). Further, in their production of varying prosodic sequences, they have difficulty producing the small and short movements associated with weak syllables (Goffman, 1999). It is not known whether these language and speech motor deficits relate to those frequently cited in the gross and fine motor domains (Bishop & Edmundson, 1987; Hill, 2001).

Syntactic Priming Compared With Sentence Imitation

Previous studies that have investigated speech motor control have used imitations to elicit target utterances. This line of research has used word and sentence repetitions because it requires highly specified targets and has focused on investigating speech motor skill, such as variability, amplitude, and duration of articulatory movements (Goffman, 1999; Goffman, Gerken, & Lucchesi, 2007; Smith & Goffman, 2004). In the present study, we aimed to tax children's language and motor systems during language formulation and to evaluate the effects on both grammatical and articulatory sequencing.

A major obstacle to increasing formulation demands in speech motor control research has been the requirement to elicit target utterances through imitation. Although imitations presumably incorporate many components of language processing, it could be beneficial to elicit sentences that demand additional syntactic processing. Structural priming techniques may provide an ideal approach for assessing motor aspects of sentence production. Huttenlocher (2004) found that ND children were more likely to produce a target syntactic form if it had been modeled with different lexical items (e.g., prime: "the girl is throwing the ball to the boy": target: "the man is handing the book to the girl"). In addition, the use of syntactic priming has been useful for eliciting particular grammatical structures in children with SLI (Leonard et al., 2000). A priming paradigm could be applied to studies of speech motor control to increase the speaker's processing load.

Current Study

There were three major and interrelated hypotheses in the present study:

1. Children with SLI would have more overt errors in the relatively difficult particle compared with the less difficult preposition structure, replicating Watkins and Rice (1991).
2. Children with SLI would show increased articulatory variability and longer duration than their ND peers (Goffman, 1999, 2004). Further, the sentences containing the particle would show increased motor variability and longer duration compared with the prepositions, consistent with earlier findings that syntactic difficulty influences articulatory aspects of production (Kleinow & Smith, 2006).
3. Children with SLI would, as a group, demonstrate impairments in gross and fine motor skill, similar to that reported by Hill (2001), Bishop and Edmundson (1987), Zelaznik and Goffman (2010), and others.

Together, the findings from this study will provide a window into how generalized motor, speech motor, and language deficits hang together in children with SLI and thus into the nature of the well-documented co-occurrence of language and motor deficits.

Method

Participants

A total of 23 individuals participated, including 11 four- to six-year-old children diagnosed with SLI (6 girls) and 12 age-matched ND children (6 girls). Parents showed similar levels of education across groups (SLI, M = 16.18 years, SD = 2.42; ND, M = 17.55 years, SD = 2.13).

All children's nonverbal cognitive skills were within the normal range (SLI, M = 106, SD = 14.89; ND, M = 121.2, SD = 8.93) as measured by the Columbia Mental Maturity Scale (Burgemeister, Blum, & Lorge, 1972). In addition, all children had normal hearing as indicated by responses to pure tones presented at 25 dB for the frequencies 0.5 kHz, 1 kHz, 2 kHz, 4 kHz, and 6 kHz. All participants also had normal structural and functional oral motor skills as measured by the Clinical Assessment of Oropharyngeal Motor Development (St. Louis & Ruscello, 1987). Children were given a standardized test of articulation, the Bankson Bernthal Test of Phonology (Bankson & Bernthal, 1990). As shown in Table 1, all of the children with SLI performed at least one standard deviation below expected levels on this single word articulation test.

The children were diagnosed with SLI on the basis of their performance on the Structured Photographic Expressive Language Test (Dawson, Stout, & Eyer, 2003); all children with SLI performed below the 4th percentile on this test. Their age-matched ND peers scored within the normal range (between the 46th and 99th percentile). Because nonword repetition (NWR) and the finite verb morphology composite (FVMC) have been found to be especially sensitive markers of SLI (Dollaghan & Campbell, 1998; Leonard, Miller, & Gerber, 1999), these two measures were used to further verify the group status of the children with SLI. The FVMC (Leonard et al., 1999) was calculated as a percent correct of grammatical morphemes marking tense and agreement (i.e., past tense *–ed*, third-person singular *–s*, the copula and auxiliary forms of *is, are,* and *am*). For a summary of findings from the FVMC and NWR tasks, see Table 1.

As a standardized measure of gross and fine motor skill, children below the age of 6;0 (years;months; SLI, n = 10; ND,

Table 1. Individual results of tests.

Subject	Comprehension		SPELT	CMMS	BBTOP	NWR	FVM
	Particle	Preposition					
			SLI				
SLI-1[a]	no data	no data	<1	100	71	0.46	0.47
SLI-2[a]	83%	100%	<1	99	71	0.71	0.78
SLI-3[a]	83%	100%	<1	111	75	0.57	0.76
SLI-4[a]	67%	71%	<1	107	72	0.63	0.95
SLI-5[a]	83%	86%	4	85	68	0.78	0.91
SLI-6[a]	33%	86%	<1	125	82	0.64	0.77
SLI-7	no data	no data	<1	85	76	0.64	0.64
SLI-8	no data	no data	<1	109	78	0.66	0.57
SLI-9	83%	71%	<1	135	72	0.63	0.82
SLI-10	83%	86%	<1	103	72	0.62	0.93
SLI-11	83%	86%	<1	108	72	0.61	0.82
M	0.75	0.86	1.27	106.09	73.545	0.63	0.76
SD	0.18	0.11	0.90	14.89	3.908	0.08	0.15
			ND				
ND-1	67%	100%	71	111	98	no data	no data
ND-2	100%	86%	84	140	101	no data	no data
ND-3	100%	100%	46	116	100	no data	no data
ND-4	83%	100%	62	131	105	no data	no data
ND-5	100%	100%	90	122	104	no data	no data
ND-6	100%	86%	93	126	95	no data	no data
ND-7	83%	100%	80	119	105	no data	no data
ND-8	100%	100%	94	115	98	no data	no data
ND-9	100%	100%	99	125	105	no data	no data
ND-10	100%	100%	79	110	80	no data	no data
ND-11	100%	100%	70	118	89	no data	no data
M	0.94	0.97	78.91	121.18	98.18		
SD	0.11	0.06	15.78	8.93	7.81		

Note. SPELT = Structured Photographic Expressive Language Test (percentiles reported); CMMS = Columbia Mental Maturity Scale (standard scores reported); BBTOP = Bankson Bernthal Test of Phonology Consonant Inventory (standard scores reported); NWR= nonword repetition; FVM = finite verb morphology; SLI = specific language impairment; ND = normally developing.

[a]Performance greater than 1 standard deviation below mean on motor test.

n = 11) were assessed using the Peabody Developmental Motor Scales (PDMS; Folio & Fewell, 2000). One child with SLI and one age-matched control were 6;0 and did not meet the standardization age requirement of the PDMS and thus were administered the Bruininks-Oseretsky Test of Motor Integration (Bruininks, 1978). These two older children were not included in the analyses comparing groups on the basis of gross and fine motor performance on the PDMS; however, they were included in all other analyses. Typical gross and fine motor skill was considered inclusionary for the children who were ND. Because of the complex and poorly understood relationship between SLI and developmental coordination disorder (e.g., Hill, 2001), we felt that typical performance on tests of both language and motor skill would result in more interpretable results. On the basis of these inclusionary criteria, one child who was ND was excluded as the result of scoring greater than one standard deviation below the mean on the PDMS. Gross and fine motor descriptive data are shown in Table 2.

To assess comprehension of the particle and preposition structures used in the experimental task, we asked children to demonstrate their knowledge by pointing to pictures and manipulating objects. For example, using a doll and small objects, participants were asked to show the clinician actions associated with the following commands: “Jump over the bucket,” “tip over the bucket,” “lift up the bucket,” “climb up the bucket,” “turn on the flashlight,” “turn the flashlight,” “take off the shoe,” and “take the shoe.” For results of the comprehension task, see Table 1. The comprehension probe was incorporated into the project after three participants completed the study; therefore, data from these children were unavailable.

Stimuli and Procedure

Each child participated in two 30-min experimental sessions in addition to standardized testing. During the experimental sessions, movements of the lips and the jaw were tracked using the Northern Digital Optotrak 3020 three-camera system, a system designed for recording human movement in three dimensions, at a sampling rate of 250 samples per second. The kinematic data were low-pass filtered with a cutoff of 10 Hz. Three infrared light emitting diodes (IREDs) recorded articulatory movement and were placed on the upper lip, the lower lip, and a small splint on the jaw. Four other IREDs were used as a reference frame for the

Table 2. Individual scores on the Peabody Developmental Motor Scales.

Subject	Stationary	Locomotion	Object manip.	Grasping	Visual motor	GMQ	FMQ	TMQ
				SLI				
SLI-1	7	9	6	5	8	83	79	79
SLI-3	7	9	7	3	8	85	73	78
SLI-4	9	9	10	2	7	96	67	82
SLI-5	6	8	11	6	9	89	85	86
SLI-6	8	10	7	5	7	89	76	82
SLI-7	9	9	7	8	10	89	94	90
SLI-8	10	10	9	10	12	98	106	101
SLI-9	7	12	8	11	12	94	109	100
SLI-10	7	8	10	10	8	89	94	90
SLI-11	12	10	10	9	9	104	94	100
				ND				
ND-2	12	4	7	11	13	85	112	96
ND-3	11	13	10	11	9	109	100	105
ND-4	10	10	9	9	12	119	103	100
ND-5	8	10	8	12	8	91	100	94
ND-6	11	9	7	6	12	94	94	93
ND-7	11	10	7	11	10	96	103	98
ND-8	9	10	7	11	11	91	106	97
ND-9	8	13	8	12	9	98	103	100
ND-10	9	11	8	9	12	96	103	98
ND-11	10	8	9	11	11	94	121	98

Note. manip. = manipulation; GMQ = Gross Motor Quotient; FMQ = Fine Motor Quotient; TMQ = Total Motor Quotient.

subtraction of head movement and were placed on modified sports goggles and on the forehead. An acoustic signal that was time locked to the movement signal was also recorded. Finally, a video recording was used to identify production errors.

Children produced target phrases (particle or preposition) that were matched for word length and differed only in whether the phrase contained a particle or a preposition. The target sentence frames were as follows:

Session A:
Preposition: Jump over the block.
Particle: Tip over the block.

Session B:
Preposition: Climb up the boxes.
Particle: Lift up the boxes.

In each experimental session, in addition to the target utterances, there were 12 particle foils (e.g., "knock over the box") and 12 preposition foils (e.g., "run up the hill"). See the Appendix for a sample block within an experimental session.

A highly structured priming paradigm in the form of a game used foils to elicit target phrases. The participants were first exposed to the paradigm during an instructional phase of the experiment. During the experimental priming task, participants watched a video and listened to a priming sentence composed of a specific syntactic form (i.e., preposition or particle). The syntactic prime was produced by a female Midwestern accented talker (e.g., cue: "What did the teacher tell the girl to do?"; prime: "Step over the book"). After the participant was exposed to the priming sentence, he or she was immediately presented with a video that was semantically unrelated to the priming sentence (e.g., a video of a girl jumping over a block). A cue was then given to prompt the participant to produce the target phase ("Now it's your turn, what did you tell the girl to do?"). Following the structural priming, it was expected that participants would describe the video with the same syntactic form as the preceding priming sentence and thus produce the correct target utterances. If a child did not produce the target utterance, there were a series of prompts designed to elicit a fluent target utterance that was captured by the Optotrak system. These prompts began with asking the child to "say that again" and proceeded to include increased support until the child could produce the target form (e.g., imitation: "Say, 'Tip over the block'").

Each experimental session consisted of three blocks of stimuli (the Appendix shows an example of one block), presented in a quasi-random order. The stimulus blocks included five tokens of each target with no more than three particles or prepositions in a row, and the same prime was not used twice in a row. The target utterance occurred as a prime only once in each block and did not prime itself. Across the three blocks, there were opportunities to elicit each target utterance 15 times. The particle and preposition foils in Session A and B, respectively, used the lexical entries "over" and "up." The order of administration of the two experimental sessions was counterbalanced.

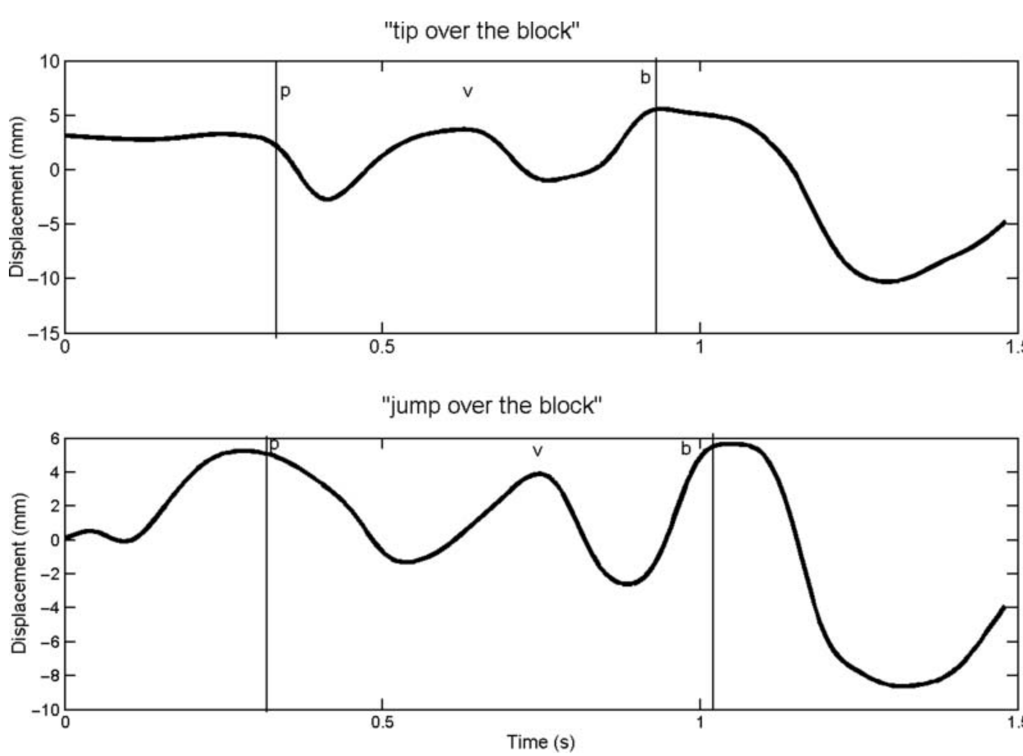
Analyses

Perceptual analysis. Videos of all experimental sessions were observed by two trained transcribers. The first author orthographically transcribed the utterances, and a research assistant, a graduate student training in speech-language pathology, independently verified these transcriptions. The observers documented the amount of cueing required for a correct target utterance, orthographically transcribed the productions following syntactic primes, and also documented participants' errors. The utterances that the children with SLI and their ND peers produced directly after the syntactic prime were scored as correct or as inconsistent with the target. "Correct" utterances included the critical grammatical elements (i.e., [verb] [preposition or particle] [determiner] [noun]). The proportion of correctly primed utterances for each child was calculated to assess the influence of group and syntactic condition on the production of correct primes. In addition to omission errors, disfluencies were documented (e.g., "lift up thththththe the box") and were compared across particle and preposition conditions.

Kinematic analysis. The utterances perceived as fluent and consistent were pooled together for kinematic analysis. Only utterances that contained errors that were stable across productions were subjected to kinematic analysis (e.g., target: "Tip over the block"; child's repeated utterance: "Tip over a block" throughout the session). For this analysis, each child's first 10 fluent and phonetically consistent spontaneous target productions were analyzed. If there were not 10 fluent spontaneous productions of the target utterance, a second pass through the data included self-corrections (e.g., "push over the boxes, no I mean, tip over the boxes"). Iterative passes through the data were completed, beginning with primes and ending with direct imitation, until 10 fluent productions were selected. In many cases, 10 productions were obtained; however, a minimum of five phonetically comparable utterances were included (30% of cells for children with SLI and 13% of cells for ND children had between five and nine productions). The number of utterances assessed kinematically was matched across particle and preposition conditions for individual participants. Data from two children with SLI in one syntactic frame (lift and climb) could not be analyzed kinematically.

Kinematic records for the two phonetically similar (e.g., "Jump over the block" and "Tip over the block") syntactic targets were extracted from long data files (see Figure 1). The actual portions selected for analysis ("p over the b") were identical. In this example, the onset of the selected movement record corresponded to the closure of the lips for the /p/ (the final consonant in the verbs "jump" and "tip"). This segment of the movement record was initially identified visually in MATLAB at the point of peak displacement of the lower lip. Then an algorithm selected the maximum displacement (within a 25-point, or 100-ms, analysis window) which corresponded to the velocity zero crossing. As shown in Figure 1, the offset of the target lower lip movement was selected in a similar fashion and corresponded to the peak displacement of the word initial /b/ in the word

Figure 1. Extracted portion of long data file. The top panel depicts the movement of the lower lip and jaw while a participant produces the particle phrase "Tip over the block." The bottom panel depicts the lower lip and jaw movement during the production of the prepositional phrase "Jump over the block." Downward movement corresponds to lower lip opening, and upward movement corresponds to lip closing. The area between the two vertical lines indicates the portion of the data that was extracted and analyzed.



"block." The kinematic selections were then confirmed by playing the time-locked acoustic signal.

Stability. To determine the stability of the underlying movement patterning of the articulators, the 10 movement trajectories extracted from the long data files were amplitude and time normalized (Smith, Goffman, Zelaznik, Ying, & McGillem, 1995; Smith, Johnson, McGillem, & Goffman, 2000). Amplitude normalization was accomplished by setting the mean of each movement trajectory to zero and the standard deviation to one (top panel of Figure 2). Each movement record was forced to the same time scale of 1,000 points, using a spline function to interpolate between points. The purpose of the normalization procedure was to remove the effects of changes in rate and loudness and to reveal the variability of the spatiotemporal organization of the repeated movement sequences. An example of this normalization is shown in the middle panel of Figure 2.

The lip aperture variability (LAVAR) index is a measure that quantifies the stability of the underlying movement patterning from the normalized records. It is calculated as the difference between the upper and lower lips and directly measures lip aperture. All time and amplitude normalized movement trajectories are shown in the middle panel of Figure 2. Standard deviations of the 10 normalized trials were computed at 2% intervals (bottom panel of Figure 2). The LAVAR index was then computed, which is a numerical value of the sum of the 50 standard deviations. The LAVAR index was used to compare the articulatory stability of the productions of the preposition versus the particle sentences in ND children compared with those with SLI. A high LAVAR indicates increased articulatory variability.

Duration. The duration of the kinematic records was also measured to assess influences of linguistic difficulty on the production of particles compared with prepositions. It is important to note that, as in the variability analysis, the extracted duration segments were phonetically identical across particle and preposition pairs (e.g., from the /p/ to the /b/ in "Tip over the block" and "Jump over the block").

Results

Perceptual Analyses

Comprehension. Children with SLI understood both syntactic structures more poorly than their ND peers, $F(1, 17) = 15.5$, $p < .005$. In addition, there was a trend toward a particle versus preposition effect, $F(1, 17) = 3.51$, $p = .078$, with particles marginally weaker than prepositions. There were no interactions, $F(1, 17) = 0.919$, $p = .351$ (see Table 1).

Accuracy of particles versus prepositions. Utterances were scored as correct if they included the critical grammatical elements. There was a group effect, $F(1, 20) = 8.63$, $p = .008$, with children with ND more frequently producing the correct structure after a syntactic prime (see Figure 3). There was no condition effect of syntactic frame, $F(1, 20) = 0.37$, $p = .551$, suggesting that the two different sentences used to test prepositions and the two different sentences used to test particles did not differ from one another. There was

Figure 2. Extracted portion of target utterances. The top panel displays 10 amplitude-normalized sequences of movement extracted from the long data file from one child. The center panel illustrates these movement trajectories after both time and amplitude normalization. The bottom panel shows standard deviation values obtained at 2% intervals across the movement trajectory. The lip aperture variability (LAVAR), which is shown above the bottom panel, is the sum of these 50 standard deviations.

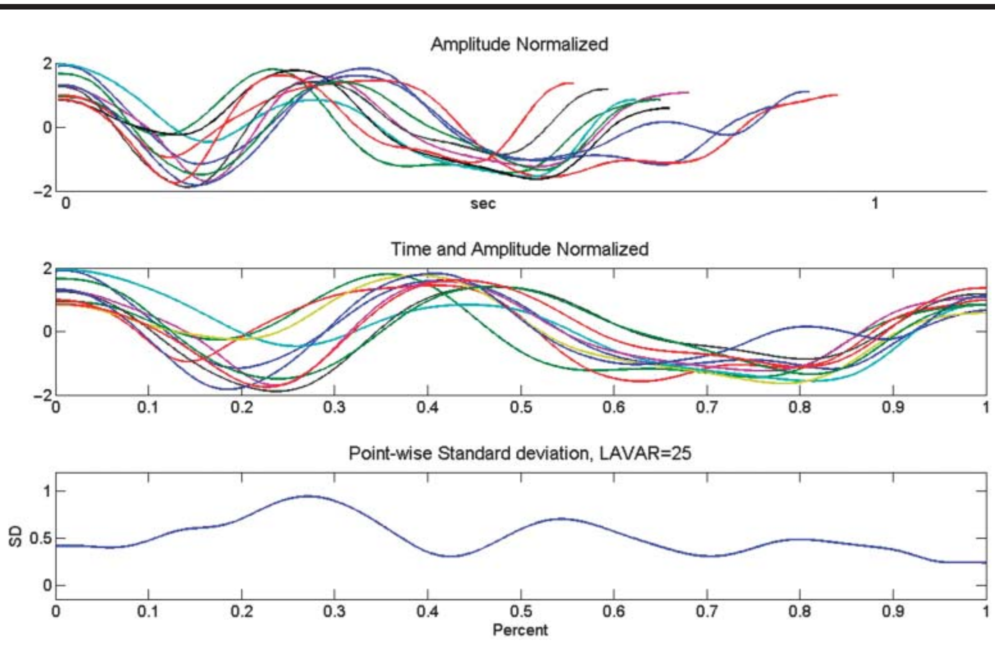
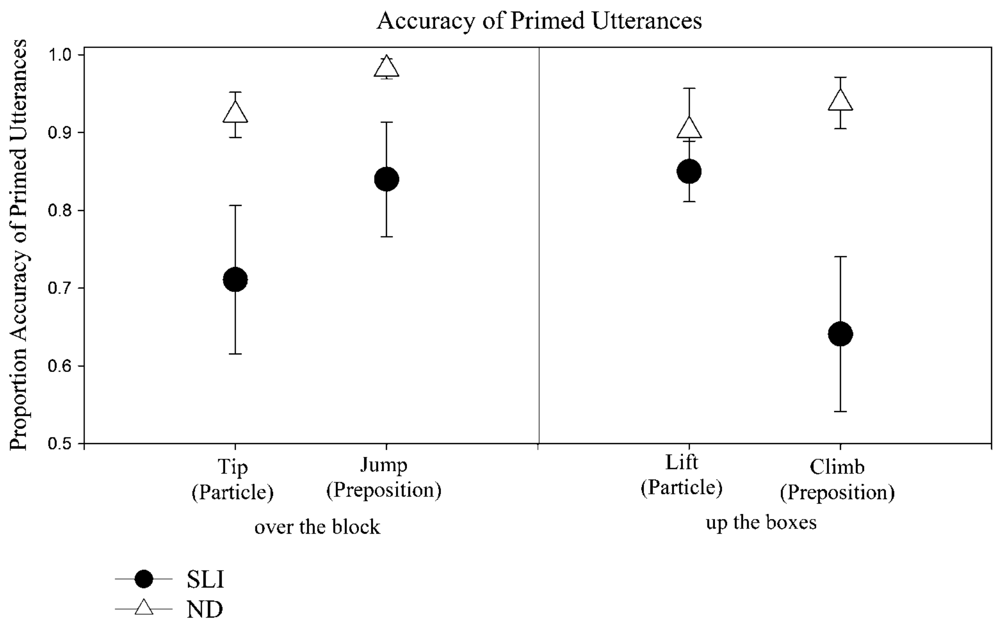


Figure 3. Frequency of accurately primed utterances as a function of group and preposition versus particle. Symbols represent means. Error bars indicate standard error. There was a main effect of group. There also was an interaction: Children who were ND were more likely to be primed for prepositions than for particles.



also no effect of particle versus preposition, $F(1, 20) = 0.02$, $p = .899$, revealing that overall the particle and preposition were comparable in accuracy. There was an interaction of syntactic frame and particle versus preposition, $F(1, 20) = 10.96$, $p = .003$; and there was also a three-way interaction between group, syntactic frame, and preposition versus particle $F(1, 20) = 8.28$ $p = .009$. As depicted in Figure 3, this interaction was due to more accurately produced prepositions than particles by ND children. Children with SLI did not show this effect; they showed opposite patterns of performance for the particle and the preposition in the two sentence frames. Overall, children with SLI were not sensitive to the syntactic differences in particles and prepositions on the basis of this accuracy measure.

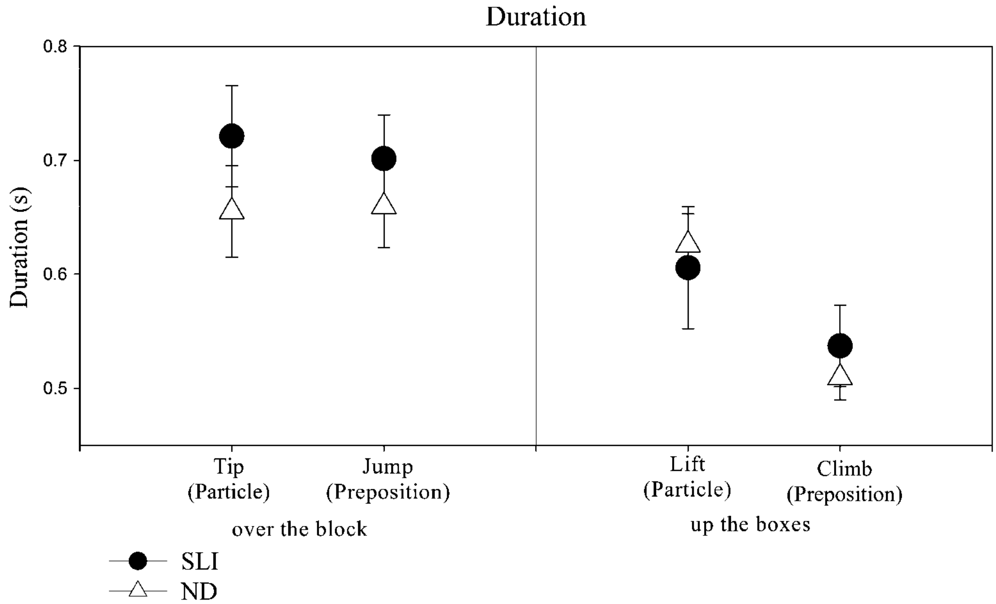
Disfluencies. There were no significant main effects for group, $F(1, 20) = 2.47$, $p = .13$; or sentence frame, $F(1, 20) = 0.99$, $p = .333$. There was a trend toward a syntactic condition effect, $F(1, 20) = 3.69$, $p = .069$, with more disfluencies tending to be produced in the particle condition than the preposition. There were no interactions, $F(1, 20) = 1.87$, $p = .181$. Both groups of children trended toward producing more disfluencies in sentences containing particles than prepositions.

Speech Motor Effects

Primed versus imitated productions. For the kinematic analysis, it was required that productions be fluent and phonetically consistent. To achieve this goal, in addition to primed utterances, those that required verbal cuing were included. For this reason, only a subset of the data reported in the behavioral results above were included in the kinematic analysis. For this subset of accurate and/or stable productions, it is important to note that children with SLI had a lower percentage of primed productions than their ND peers, $F(1, 21) = 7.79$, $p = .01$, revealing that the children with SLI required more cues. There was also a particle versus preposition condition effect, $F(1, 21) = 5.47$, $p = .03$, with fewer primed particles than prepositions. There was no significant Group × Condition interaction, $F(1, 21) = 0.41$, $p = .53$. Overall, children with SLI were primed for 49% ($SE = 7.72$) of particle constructions and 56% ($SE = 7.32$) of preposition constructions. Their ND peers were primed for 73% ($SE = 7.39$) of particles and 85% ($SE = 7.01$) of prepositions. The remainder of the productions for both groups required increased cuing, ranging from “use tip” or “say the whole thing” to direct imitations.

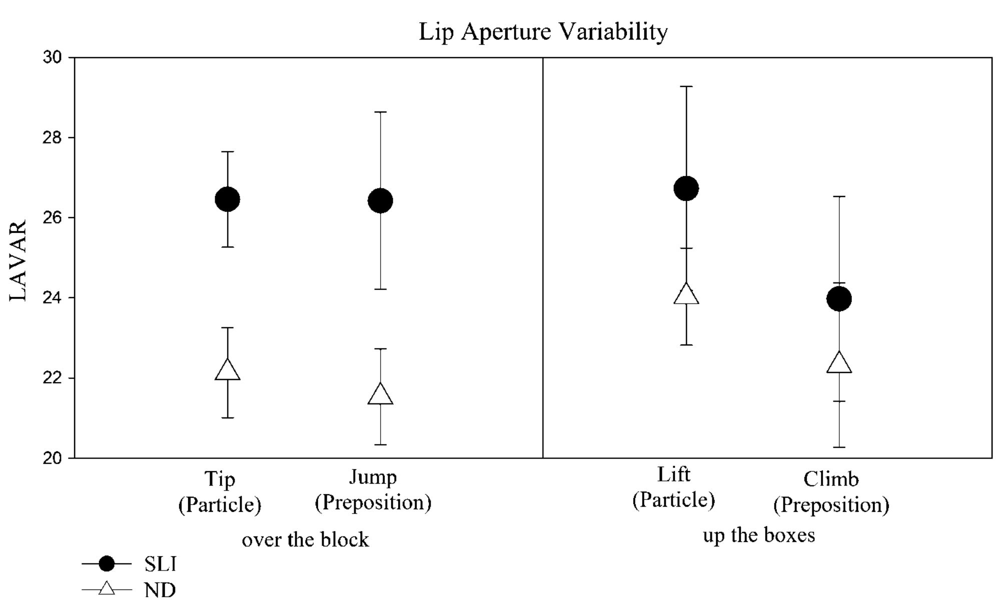
Duration of movement. There was no group effect for duration, $F(1, 18) = 0.30$, $p = .589$, as illustrated in Figure 4. There was a significant effect of sentence frame, $F(1, 18) = 27.49$, $p < .005$, which was expected as the result of the inherent differences in duration in the production of “over” and “up” because of syllable length. It is important to note that there was a particle versus preposition effect, $F(1, 18) = 17.46$, $p = .001$. Pairwise comparisons using the Tukey honestly significant difference procedure revealed that particles were produced with longer durations than prepositions for both groups ($p = .007$). There was also a Sentence × Particle Versus Preposition interaction, $F(1, 18) = 19.45$, $p < .001$, once again illustrating the inherent differences between the two sentence frames.

Figure 4. Duration of trimmed utterances that were segmentally and lexically identical across the particle and preposition conditions (e.g., "tip over the block" and "jump over the block"). Symbols represent means. Error bars indicate standard error. There was a main effect for particle versus preposition. There was also an effect for sentence frame, because of the inherent duration differences in "over the block" compared with "up the boxes."



Stability of movement. There was a group effect of LAVAR, $F(1, 18) = 5.17, p = .035$, demonstrating that children with SLI produced more variable articulatory movement patterns than their ND peers (see Figure 5). There was noeffect of sentence frame, $F(1, 18) = 0.03, p = .861$, or of particle versus preposition, $F(1, 18) = 0.96, p = .340$. The lack of a three-way interaction of sentence, particle versus preposition, and group, $F(1, 18) = 0.25$ $p = .626$, suggests that the particle and preposition were comparable in both sentence frames.

Figure 5. LAVAR as a function of group (SLI, ND), particle versus preposition, and sentence frame. Symbols represent means. Error bars indicate standard error. There was a main effect of group.



Gross and Fine Motor Effects

A repeated measures analysis of variance included the children under the age of 6 who completed the PDMS with group (SLI and ND) as the between-subjects factor and motor scores (gross motor quotient and fine motor quotient) as the within-subjects factors. As shown in Figure 6, our results replicated previous findings showing that children with SLI had significantly lower scores on motor scales than did their ND peers, $F(1, 18) = 11.98$, $p = .003$. There was no condition effect, $F(1, 18) = 0.31$, $p = .586$, with gross motor and fine motor abilities similar overall.

Exploratory Analyses of Cross-Domain Relationships

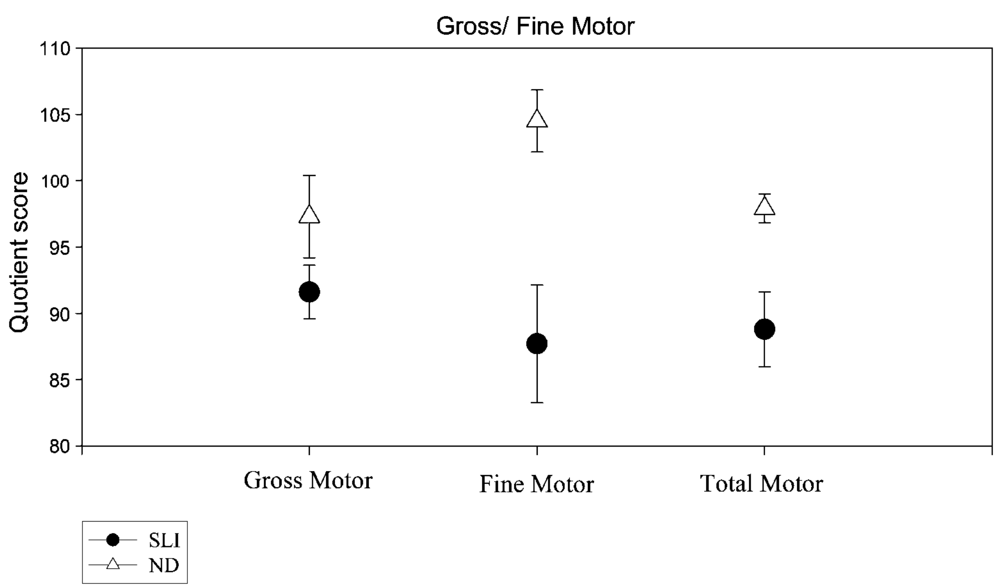
As reported above, children with SLI showed poorer motor performance than their ND peers. However, only approximately half (5 of 11) of the children with SLI showed an overt motor impairment, defined by performance at or greater than one standard deviation below the mean on the otal motor quotient of the PDMS or the Bruininks-Oseretsky Test of Motor Proficiency. Although there were too few participants to conduct analyses of subgroups, correlational analysis of the entire group (ND and SLI) revealed that children's generalized motor and speech motor skills were related. Children with poorer fine motor skill were more likely to demonstrate increased articulatory variability ($r = -.71$, $p < .05$; $r = -.61$, $p < .05$; $r = -.36$, $p > .05$; and $r = -.16$, $p > .05$, respectively) across all four target sentences. Gross motor skills did not relate to articulatory variability (*r*s = –.15, –.15, –.14, and .09 across the four target sentences, respectively, all *p*s nonsignificant).

Another potential relationship to explore is whether performance on behavioral language and speech motor measures relate. In one sentence frame, "jump [tip] over the block," LAVAR correlated with accuracy ("tip," $r = -.62$, $p < .05$; "jump," $r = -.71$, $p < .05$). For this frame, increased errors corresponded with increases in speech motor variability. However, for the frame "climb [lift] up the boxes," no significant correlations were observed ("lift," $r = .02$, *ns*; "climb," $r = .17$, *ns*). It is unclear what is contributing to these effects, and more detailed exploration of language and speech motor interactions is warranted.

We also considered whether two related issues, that is, cognitive status or severity of language deficit, corresponded to speech motor skill. Cognitive measures were obtained from the entire group of participants. These were uncorrelated with speech motor skill across all four sentences (*r*s = –.28, –.25, –.04, and –.11, all *p*s nonsignificant). In addition, performance on an articulation test, the Bankson Bernthal Test of Phonology, was unrelated to articulatory variability (*r*s = –43, –.38, –.22, –.09, all *p*s nonsignificant). From the SLI group only, we evaluated two measures of language performance that show good sensitivity and specificity, the NWR task (*r*s = –.11, .16, .27, and .42, all *p*s nonsignificant) and the FVMC (*r*s = .06, .25, .14, and .56, all *p*s nonsignificant). These hallmark capacities were not related to speech motor skill.

In a final set of exploratory analyses, we wondered whether cognitive, language, and speech variables correlated with gross and fine motor skill. No significant relationships were observed with the exception of the score on the Bankson Bernthal Test of Phonology, which correlated significantly with fine motor ($r = .52$, $p < .05$) but not gross motor ($r = .38$, *ns*) performance.

Figure 6. Gross and fine scores on the Peabody Developmental Motor Scales. Symbols represent means. Error bars indicate standard error. There was a main effect of group.



Although these data are preliminary, because of the small sample size and their correlational nature, they suggest as a whole that (a) not all children with SLI show an overt motor deficit; and (b) the frequently observed motor deficit is correlated with speech motor skill. However, speech motor skill is not correlated with cognitive or language performance. It is intriguing that fine motor skill relates to performance on a test of speech sound accuracy, the Bankson Bernthal Test of Phonology. Both speech accuracy and fine motor performance likely relate to higher order components of cognitive processing, whereas articulatory variability more closely indexes motor implementation.

Discussion

One objective of this research was to develop a speech motor control paradigm that requires talkers to generate sentences without relying on imitation. We used a heavily structured priming task to ask whether children with SLI and their ND peers showed predicted deficits in the production of relatively difficult compared with simple syntactic structures and how these capacities related to motor skill. Using this paradigm, as is consistent with prior research relying on imitation of target structures, we found that children with SLI had deficits in producing complex sequences of articulatory movement (e.g., Goffman, 2004). This was the case even though an increased number of imitations were incorporated into the analysis from the children with SLI compared with their ND peers (52% primed for SLI and 79% for ND) because of their difficulties with the sentence generation task. In future work, it will be important to compare the influence of increased processing load in priming directly to imitation. It is evident that children with SLI show weaknesses in the production of stable sequential articulatory movements, as differences emerge even when a higher proportion of imitated sentences are incorporated into their variability measures. Also corresponding with previous work, our results showed that children with SLI as a group demonstrated motor weaknesses (Hill, 2001). In the present study, on the basis of performance on the PDMS, fine motor skills were especially weak.

In the error analysis portion of the study, we did not replicate the findings of Watkins and Rice (1991). We used a similar hierarchy of prompts to those incorporated in the earlier study. However, because our study required similar productions to make them amenable to kinematic analysis, prompts were used, sometimes even including imitation. In addition, although the prepositions and particles were intermixed, we embedded repetitions of the same utterances. These factors may have reduced the processing demands of the task and resulted in fewer overt errors. However, there was some confirmation that particles are more difficult to produce than prepositions. There was a trend toward increased disfluencies in the particle compared with the preposition condition. Even more critically, particles were produced with relatively longer duration than prepositions. Finally, prepositions were more likely to be primed than particles. We interpreted these findings as indicative of an increase in syntactic complexity for the particle form. Unlike previous work (Kleinow & Smith, 2006; Watkins & Rice, 1991), this increased syntactic complexity did not influence either transcription accuracy or kinematic variability. Further research is needed to determine the specific locus of interactions between processing difficulty and articulatory variability in children with and without language impairment.

There are some additional factors that may have influenced our findings that also need to be considered, the first being the small number of participants. Further, because we required phonetic similarity across the particles and prepositions, we may not have included a sufficiently taxing complex syntactic condition. Finally, the frequency and phonological content of the target words could have influenced our results. For instance, the two verbs in the particle phrases, "tip" and "lift," are less frequent than the two verbs in the prepositional phrases, "jump" and "climb" (Carroll, Davies, & Richman, 1971). However, if the frequency of the verbs in the study contributed to the results, we would have expected increased errors and higher articulatory variability during the production of the less frequent particles; this was not the case. The incorporation of a priming task was both a strength and weakness. Processing load was clearly affected; however, as a consequence, children with SLI had more difficulty than their age-matched peers and required more cues. It is possible that this could have allowed children with SLI more learning opportunities and motor practice (Walsh, Smith, & Weber-Fox, 2006), which may have increased the similarities between the groups.

Children with SLI showed increased articulatory variability and relative weaknesses in gross and fine motor skill in comparison with their ND peers. We report some preliminary findings that merit further investigation. It is interesting to note that although gross and fine motor and speech motor skill were correlated, other core aspects of SLI, particularly nonword repetition and finite verb morphology, were not related to speech motor skill. Grammatical deficits are thought to be the hallmark of SLI (Leonard, 1998) and are hypothesized to comprise a common factor underlying movement sequencing and language deficits (Ullman & Pierpont, 2005). The present data provide some preliminary support that other mechanisms may need to be considered when relating language and motor domains in the developmental profile observed in children with SLI.

Theoretical Implications

Consistent with previous findings, this study revealed that children with SLI, as a group, demonstrate both language and motor deficits. However, it not surprising that children with SLI are heterogeneous, and only some showed an overt motor deficit. It seems from these preliminary results that the motor impairments in children with SLI may not be due to a single deficit or a global maturational impairment as has been posited in some accounts of language impairment (Bishop & Edmundson, 1987; Kail, 1994; Locke, 1997). The interaction of language and motor domains appears more complex.

Ullman and Pierpont (2005) proposed a framework for considering these more complex interactions. They hypothesized that SLI may be explained by a deficit in procedural memory, an organized network of neural structures that control learning and execution of motor and cognitive skills. This system is theorized to be important in learning concrete and abstract rules and sequences (e.g., riding a bike, producing a sentence). It is often described as implicit, because rule learning is not a conscious process. In this system, there are tendencies for particular neural structures to be involved and for a set of deficits, including, for example, co-occurring difficulties in sequential ordering in speech production and movement (Tomblin et al., 2007). Indeed, this profile may describe children with SLI who participated in the present study in reference to their language and motor deficits.

However, these relationships are complex, as acknowledged by Ullman and Pierpont (2005), who did discuss heterogeneity and variability. Ullman and Pierpont pointed out that, depending on the location and extent of the affected brain region, the domains involved (i.e., language, motor, memory) may differ, as may the severity of the disorder. The procedural memory system contains, but is not restricted to, Broca's area. In this theory, grammatical and motor deficits are linked to Broca's area (Arbib, 2006; Greenfield, 1991; Kent, 2004). The co-occurrence of language and motor deficits in some children could be due to lesions in motor tracts that lead to Broca's area, whereas other children with SLI may have deficits in tracts that affect only language ability. The procedural deficit hypothesis provides a framework to begin to describe and understand the motor and language deficits in children with SLI.

As suggested by Ullman and Pierpont (2005), it may be that the procedural deficit is not a necessary condition underlying SLI. Although children with SLI are more likely than their ND peers to show a speech motor or generalized motor deficit, 5 of the 11 children studied here demonstrated no overt motor impairment. It is intriguing that, contrary to our expectation, grammatical factors did not appear to be the connector linking motor and language variables. Performance on language measures did not relate in any consistent manner to speech motor or generalized motor skill. Grammatical sequencing has been proposed as particularly likely to be implicated.

These findings, though preliminary, suggest that more work needs to be done to evaluate whether the motor and language deficits in SLI may share common mechanisms or are relatively independent comorbidities. Uncovering this relationship, or of factors underlying individual differences, is significant for understanding the nature of SLI and for developing appropriate intervention approaches for these children.

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Appendix

Example of One Block of Stimuli

Category	Prime sentence	Produced sentence
Particle	Knock over the box	Tip over the block
Preposition	Lean over the table	Walk over the book
Preposition	Walk over the book	Jump over the block
Target preposition	Jump over the block	Climb over the wall
Particle	Push over the glass	Knock over the box
Particle	Turn over the book	Tip over the block
Preposition	Walk over the book	Jump over the block
Preposition	Lean over the table	Jump over the block
Target particle	Tip over the block	Kick over the chair
Particle	Kick over the chair	Tip over the block
Preposition	Step over the book	Jump over the block
Preposition	Climb over the wall	Lean over the table
Particle	Turn over the book	Tip over the block
Particle	Kick over the chair	Turn over the book
Particle	Push over the glass	Tip over the block
Preposition	Climb over the wall	Step over the book
Particle	Knock over the box	Push over the glass
Preposition	Step over the book	Jump over the block