Published in final edited form as:
J Commun Disord. 2015 ; 55: 31–43. doi:10.1016/j.jcomdis.2015.02.001.

Learning Trajectories for Speech Motor Performance in Children with Specific Language Impairment

Peter T. Richtsmeier[a] and **Lisa Goffman**[b]
Purdue University

Keywords

specific language impairment; speech motor learning; motor skill; nonword repetition; speech kinematics

While specific language impairment (SLI) was initially defined as the quintessential impairment of language, many cognitive and motor deficits co-occur with the observed language deficit (cf. Leonard, 2014, for a history of the term ‘specific language impairment’). Concomitant impairments have been observed in the domains of auditory processing (Tallal et al., 1996), short-term phonological memory (Dollaghan & Campbell, 1998; Gathercole, 2006), statistical and procedural learning (Hedenius et al., 2011; Lum, Conti-Ramsden, Morgan, & Ullman, 2014; Plante, Gómez, & Gerken, 2002; Tomblin, Mainela-Arnold, & Zhang, 2007), and motor skill (Bishop & Edmundson, 1987; Hill, 2001; Zelaznik & Goffman, 2010). One notable exception is general intelligence, which by definition, is not implicated in SLI (Leonard, 2014; Lee & Tomblin, 2014; but cf. Gallinat & Spaulding, 2014).

Focusing on motor skill, children with SLI often perform poorly on motor tasks. This performance lag is to such an extent that about one third to one half meet diagnostic criteria for developmental motor coordination disorder (Brumbach & Goffman, 2014; Flapper & Schoemaker, 2013). Not surprisingly, children with SLI score more poorly than their peers with typical development (TD) across many—though not all—movement tasks. Powell and Bishop (1992) found motor impairments in children with SLI in tasks including peg moving, bead threading, rolling a ball with a stick, and balancing on one foot. Zelaznik and Goffman (2010) compared children with SLI and TD on the Bruininks-Oseretsky motor tasks (Bruininks, 1978), including balance, bilateral coordination, and visuo-motor control.

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[a] Corresponding author. prichtsmeier@yahoo.com. Address: Department of Speech, Language, and Hearing Sciences, Purdue University, 715 Clinic Drive, Lyles-Porter Hall, West Lafayette, IN 47907-2122, USA. Telephone: 1+(405) 744-8030..
[b]goffman@purdue.edu. Address: Department of Speech, Language, and Hearing Sciences, Purdue University, 715 Clinic Drive, Lyles-Porter Hall, West Lafayette, IN 47907-2122, USA. Telephone: 1+ (765) 496-1826..
Present Address: Department of Communication Sciences and Disorders, South Murray Hall 018, Oklahoma State University, Stillwater, OK 74078, USA. Telephone: 1+(405) 744-8030.

Children with SLI performed more poorly than their peers with TD, indicating relative difficulties in fine and gross motor performance. However, in a tapping task assessing timing, Zelaznik and Goffman reported similar performance for the the SLI and TD groups. Tapping tasks are closely related to cerebellar function, and the cerebellum is generally thought to manage movement precision and timing. Based on their findings, Zelaznik and Goffman did not find evidence of cerebellar disfunction in children with SLI. Their conclusions are further supported by recent studies of typical eyeblink conditioning in children with SLI, a task that also relies heavily on the cerebellum (Hardiman, Hsu, & Bishop, 2013; Steinmetz & Rice, 2010).

Bishop and Edmundson (1987) analyzed longitudinal performance on language and motor tasks in children with SLI and their peers with TD, beginning at age four. They found that children with SLI were slower in a peg-moving task and were more likely to move pegs to the wrong locations. Over the course of three sessions spanning 18 months, however, children with SLI improved at a rate comparable to the improvement rate of their peers with TD.

Motor impairments accompanying SLI can also be seen in tasks focusing on speech movements (hereafter *speech motor* tasks). Goffman (1999) asked children with TD and SLI to produce multiple tokens of CVCVC nonwords with either trochaic stress (e.g., /pΛpəp/, compare to ‘BA-by‘) or iambic stress (e.g., /pəpΛp/, compare to =bal-LOON‘). Lip and jaw movements during these productions were then overlaid and compared to one another to derive a measure of articulatory stability. Children with SLI showed less stable lip and jaw movements compared to their peers with TD across words and across stress patterns. Similarly, Goffman (2004) found that children with SLI were less stable when producing iambic sequences composed of a function word followed by a novel content word (e.g., ‘a babb’, compare to ‘a cow’). Overall, children with SLI are poorer at implementing the articulatory movements associated with prosodic sequences than their typically developing peers.

In addition to motor deficits, learning deficits are commonly observed alongside SLI, particularly in procedural and statistical learning tasks. Plante et al. (2002) compared language/learning disabled young adults to typical peers in a statistical word-order-learning paradigm. Both groups listened to strings of syllables that were arranged according to word-order rules. For example, the rule might allow the syllable *jed* to be followed by *fim* and then *tup*, or *jed fim tup*. However, *jed* could not be followed by *tup* and then *fim*. Participants then had to distinguish between new strings that were either consistent with the word-order rules or violated them. The language/learning disabled group performed more poorly on the task than their peers with TD, primarily because they rated rule-breaking strings like *jed tup fim* as acceptable.

Evans, Saffran, and Robe-Torres (2009) used a speech segmentation task (cf. Saffran, Aslin, & Newport, 1996) to examine statistical learning in children with TD and SLI. Both groups listened to a stream of syllables like *dutabatutibupidabupatubibupadababupudutaba*, in which groups of three syllables tended to occur together. For example, the syllable *pi* was always followed by *dabu*, although what followed *bu* varied. Thus, *pidabu* acted like a word in the syllable stream but *dabupa* did not. Across two experiments, children with SLI struggled to learn the consistent syllable combinations compared to their peers with TD.

Regarding procedural learning in serial reaction time tasks, a veritable explosion of studies have been conducted in the last few years. There are a few reports of typical performance in children with SLI (Gabriel, Maillart, Guillaume, Stefaniak, & Meulemans, 2011), but more often children with SLI perform poorly relative to their peers with TD (cf. Lum, Conti-Ramsden, Morgan, & Ullman, 2014 for a meta-analysis). For example, Lee and Tomblin (2014) had young adults (age range 19-25) with and without language difficulties complete several procedural learning tasks, including a serial reaction time task, a pursuit rotor task, a weather prediction task, and a nonword repetition priming task. Participants with language difficulties performed significantly more poorly than their typical peers on all tasks but the first, suggesting that language impairment correlates with procedural learning impairment across a variety of tasks.

A similar study with younger children (age range 7-11) was recently completed by Hsu and Bishop (2014). Those authors observed impaired performance in children with SLI relative to same-age peers on a serial reaction time task and a word learning task. In contrast to Lee and Tomblin (2014), they observed a non-significant difference between the groups in a pursuit rotor task. The two groups even performed similarly after a two-week hiatus. Given the apparent strengths and weaknesses of their participants with SLI, Hsu and Bishop conclude that the procedural deficit may be most striking in tasks with sequential patterns.

Many studies have reported procedural learning impairments in children with SLI during immediate learning, but Hedenius et al. (2011) tested procedural learning over time. In that study, children with SLI and TD completed an Alternating Serial Reaction Time task in which participants pressed a key corresponding to the location of a picture on a screen. A repeating sequence occurred across trials, but was interspersed by trials where the location was random. The results revealed similar performance across the two groups on the first day, but children with language impairments—and children with grammatical impairments, in particular—were unable to retain that learning on a subsequent testing day. Hedenius et al. concluded that children with SLI appear to have impaired short-term and long-term procedural learning.

To summarize, there is evidence for both motor and learning deficits in SLI. However, *motor learning* specifically, or the ability of children with SLI to improve a motor skill over time, is still relatively under-studied in children with SLI. The work that has been done on motor learning is inconclusive, for example, the divergent findings from a pursuit rotor task in Hsu and Bishop (2014) and in Lee and Tomblin (2014). Most of the procedural and statistical learning studies discussed above have a motor component, but it is unclear whether the poor performance of children with SLI in those studies should be attributed to impaired motor skills or to some other impairment, for example, in planning. Thus, the literature evinces a need for more research on motor learning in children with SLI. Before laying out two hypotheses regarding speech motor learning in SLI, we briefly review some findings on speech motor learning in the general population.

Generally, speech motor skill improves into adulthood, as young children gradually become more stable, fluent speakers (A. Smith & Zelaznik, 2004; B. L. Smith & Kenney, 1999). For example, A. Smith and Zelaznik (2004) looked at speech stability across age groups ranging from four-year-olds to twenty-one-year-olds. Participants produced the sentences ‘Buy Bobby a puppy,’ and, ‘Mommy bakes pot pies,’ multiple times. The authors measured the sentence durations and the degree of articulatory variability from one production to the next. Both measures showed gradual improvements across age groups—shorter durations and less articulatory variability—even in teenaged participants. The results suggest that children become faster and more stable speakers until speech motor skill stabilizes in the early twenties, but also that speech motor development has a protracted timecourse.

In a related study, Sadagopan and Smith (2008) compared developmental trends for two different motor speech measures: speech stability and production durations. Durations moved rapidly towards adult levels, reaching a plateau around age 9. In contrast, articulatory stability developed more slowly, with gradual gains in stability occurring even through the teenage years. In addition to providing further evidence that the speech motor system is tuned throughout development, Sadagopan and Smith concluded that different components of the speech motor system, as reflected by duration and stability, follow different developmental courses.

Speech motor learning has also been the focus of recent learning studies taking place over shorter periods of time (Gladfelter & Goffman, 2013; Walsh, Smith, & Weber-Fox, 2006; Sasisekaran, Smith, Sadagopan, & Weber-Fox, 2010). Walsh and colleagues (2006) assessed learning as a result of repetition. Participants produced nonwords of varying length (e.g., *mab*, *mabshaib*, and *mabshaytiedoib*) 12 times each, and articulatory stability was compared across their first 5 and last 5 productions. For the longer words, children showed a ‘practice effect’; that is, they were more stable for their last 5 productions. Sasisekaran et al. (2010) used similar nonwords of varying length and complexity to look at learning across two days. Children became more stable as a result of practice, but they were also more stable on the second day, indicating a ‘consolidation effect’; that is, speech stability improved following sleep. In sum, the speech motor learning literature demonstrates that speech motor learning occurs over both the long term and the short term.

We are now in a position to generate some predictions about speech motor learning in children with TD and SLI. The literature that was reviewed above on motor skill and statistical and procedural learning presents some evidence that children with SLI may have deficits in both areas (e.g., Evans et al., 2009; Lee & Tomblin, 2014; Lum et al, 2014). Thus, we might predict that children with SLI will exhibit a speech motor learning deficit, and we would expect them to have poorer performance over time on a speech motor learning task. In contrast, the developmental trends observed by Bishop and Edmundson (1987) and the typical motor abilities observed in timing by Zelaznik and Goffman (2010) and in the pursuit rotor task by Hsu and Bishop (2014) suggest that a speech motor learning deficit may not always be found. That is, children with SLI are not impaired in all motor tasks, and longitudinal data suggest that their rate of motor development may be typical. Thus, there are also reasons to expect typical speech motor learning in children with SLI. We set out to test these two competing hypotheses by studying changes in motor speech in a nonword imitation task using two relatively independent measures, namely, speech motor stability and production duration (Sadagopan & Smith, 2008; B. L. Smith, 1994).

Method

Participants

Twenty-five children participated in the study. Twelve children met exclusionary criteria for SLI: They scored one standard deviation (*SD*) or more below the mean on the Structured Photographic Expressive Language Test (SPELT-P 2, Dawson, Stout, Eyer, Tattersall, Fonkalsrud, & Croley, 2005), but above a −1 *SD* cutoff on the Columbia Mental Maturity Scale (CMMS, Burgemeister, Blum, & Lorge, 1972). Thirteen age-matched peers with TD also participated. Children with TD scored above the −1 SD cutoff on both the SPELT-3 (Dawson, Stout, & Eyer, 2003) and the CMMS. Children in both groups passed a hearing screening (American Speech-Language-Hearing Association, 1997), and had no history of neurological insult or autism. Additionally, children in both groups completed standardized tests for speech production (Bankson-Bernthal Test of Phonology, BBTOP, Bankson & Bernthal, 1990), expressive vocabulary (Expressive Vocabulary Test, EVT, Williams, 1997), and receptive vocabulary (Peabody Picture Vocabulary Test, PPVT-4, Dunn & Dunn, 2007); both groups also completed a nonword repetition task (Dollaghan & Campbell, 1998). A summary of group performance on these tests is given in Table 1.

Materials

Children produced four phonotactically complex nonwords with trochaic stress and a CVCCVC structure: /biptəm/, /fomkəp/, /mæfpəm/, and /pɛzməf/. Nonwords were chosen to eliminate the possibility of differences in practice across participants. Such differences might occur for real words, but nonwords provide a uniform standard for learning for all participants. The nonwords were also chosen to have varying phonotactic probabilities, particularly in terms of their word-medial consonant sequences. Consonant-sequence and whole-word probabilities, as determined by the Online Phonotactic Probability Calculator (Vitevitch & Luce, 2004, http://www.people.ku.edu/~mvitevit/PhonoProbHome.html), are reported in Table 2. Finally, the nonwords were designed to be relatively difficult motorically so that learning effects could be observed (Walsh et al., 2006). In other words, we expected that our participants would have the opportunity to become more proficient at producing these nonwords. All words started and ended with labial consonants—and the word-medial consonant sequence included at least one labial consonant—so that productions could be analyzed based on corresponding lip and jaw movements, discussed further in the Procedure section. Throughout the experiment, nonwords were tied to a visual referent, in this case, colorful make-believe animals (Ohala, 1999). However, the task did not require participants to remember the association of the words to visual referents.

Procedure

Children completed a nonword repetition task in which they heard a recording of the nonwords—produced by an adult speaker—and then repeated them. Each word was produced over three blocks, nine times in each block. Block 1 and Block 2 occurred during the same session; Block 3 occurred one week later. This design was selected to allow for an analysis of long-term learning, but the three sessions were compressed into two days because of the summer schedules of 8 of the participants with SLI.

We recorded an audio signal of children‘s productions with a high-quality microphone. The sampling rate was 44.1 kHz, and recordings were digitized directly to compact disc. A video recording was also made. Video and audio recordings were later used for a transcription-based accuracy analysis, and the audio recording also served for one of two production duration analyses.

Nonword repetition is a useful task, and has been successfully applied to analyses of verbal working memory (Dollaghan & Campbell, 1998), word learning (Gladfelter & Goffman, 2013), and phonological learning (Richtsmeier, Gerken, Goffman, & Ohala, 2009). In general, previoius studies have focused on explicit aspects of what children learn (e.g., the phonological form), but here we focus on implicit aspects of learning, including production duration and stability (cf. also Goffman, 1999, 2004). Although we did not specifically probe our participants to confirm this, instructions were not given regarding how they should produce the words, and we consider it unlikely that they were conciously controlling either the duration or the stability of their productions.

We recorded speech movements using an Optotrak camera system. Children wore small light-emitting diodes (7 mm diameter) on their upper and lower lips, jaw, and on a pair of safety glasses customized for the diodes. The diodes that were attached to the safety glasses were used to track head movements, which could then be subtracted from the signal to isolate the lip and jaw movements. Kinematics were recorded with a sampling rate of 250 Hz and combined with a time-locked acoustic signal by Matlab software (www.matlab.com; acoustic signal sampled at 16 KHz, not used for transcriptions). Individual kinematic records of the nonword productions were identified using customized tools in Matlab. Note that, for the kinematic analysis, speech movements must be observable to the camera and in the kinematic record, so productions had to begin and end with labial consonants. If children did not produce an initial or a final labial, as sometimes occurred in errors, then no kinematic analysis could be completed.

Children were recruited for a larger ongoing study of learning effects in speech production, and the data reported here were drawn from this larger study. Participants and their parents provided written or verbal consent for their participation, and the study methods were approved by Purdue‘s institutional review board.

Analysis

An accuracy analysis was conducted with transcriptions of the four consonants in each nonword (for example, /b p t m/ in /biptəm/). Transcriptions were made from the video and audio recordings by the first author at a level of specificity comparable to English phonemic categories. A first pass was made using the audio recording, then the video recording was used to confirm uncertainties about place of articulation. For each consonant, an accurate production was given a score of 3. A score of 2 was given for an incorrect production that was off by a single feature, that is, off by place of articulation, manner of articulation, or voicing. For example, producing /mæfpəm/as [mæspəm] would result in a score of 2 for the second consonant. A score of 1 was given for any other production that included at least one consonant in that position (e.g., the [d] in [mædpəm] or the [st] in [mæstpəm] would both receive a 1) . A score of 0 was given when no identifiable consonant was produced (e.g., [mæpəm], containing no perceivable /f/). There were 48 cases (1.8% of the data) where the children‘s productions were either inaudible or absent and were not included in the accuracy analysis.

A second transcriber independently transcribed 25% of the productions using the video signal. Agreement between the two transcribers was 83.3% for the first consonant, 74.0% for the second consonant, 90.0% for the third consonant, 86.1% for the fourth consonant, and acceptable overall (83.2%). The full set of transcriptions made by the first author were used for later statistical analyses.

Kinematic data of children‘s productions were first scanned for consistency. Productions for these analyses were required to match in terms of transcriptions, and at least four productions were required for a given block. For example, if during Block 2 a child produced /mæfpəm/as [mæspəm] on seven attempts and as [mæfpəm] on the other two attempts, only the attempts transcribed as [mæspəm] were used in the kinematic analysis. Because vowel transcription is more challenging (Raymond et al., 2002), variation in vowel transcriptions that remained within adjacent regions of the vowel space was allowed. For example, productions of [mæfpəm] and [mɛfpəm] within a single block were combined. The purpose of matching productions within the kinematic data is to examine motor speech functioning apart from the phonemic or phonological target that the child may be attempting. In other words, the kinematic analysis attempts to look at speech motor learning apart from children‘s accuracy for the phonological form of the words they produced. Following the removal of inconsistent productions, the number of productions per block (out of nine) was similar for both groups ($M_{\mathrm{SLI}} = 7.48$, $M_{\mathrm{TD}} = 7.24$, $p > .2$).

Kinematic data were used to derive measures of speech motor stability and duration Individual productions were extracted for each word in each of the three blocks. Onsets and offsets were initially selected by visually inspecting the lower lip displacement. The onset signal corresponded with the lip closure for the first consonant associated with each two-syllable word. Zero-crossings in velocity (i.e., the point where movement changes direction and velocity is zero) were then used to extract each word via a procedure developed in Matlab (The Mathworks, 2012). Durations were calculated for these extracted productions. Subsequently, the productions were time and amplitude normalized (see Figure 1; for greater detail about the normalization procedure, see A. Smith, Goffman, Zelaznik, Ying, & McGillem, 1995). To normalize amplitude, the mean for lower lip displacement values was set to 0 and the standard deviation to 1. To normalize time, a spline interpolation function provided by Matlab software (The MathWorks, 2012) translated each movement record onto a time base of 1000 points. This allowed the relative movement properties common to all productions to be compared on a common scale. Using the normalized records, standard deviations were calculated at 2% increments across all productions, resulting in a total of 50 standard deviations per word. The 50 standard deviations were then summed to create a single value, referred to as the spatiotemporal index (STI). This measure captures motor stability across repeated productions of the same word. Large STI values reflect less stability; smaller STI values reflect greater stability. The STI measure has been shown to distinguish between children with SLI and TD (Goffman 1999, 2004), children with TD and developmental speech disorders (Terband, Maasen, van Lieshout, & Nijland, 2011), and it captures speech motor learning (Walsh et al., 2006; Sasisekaran et al., 2010). Here, learning was examined by looking at changes in the STI values across the three production blocks. The top row of Figure 1 provides examples of multiple trimmed productions from two children. Normalized productions and the calculation of STIs are shown in the second and third rows of Figure 1, respectively.

Some of the productions that children made were not amenable to the kinematic analysis. For example, productions of /pɛzməf/as [pɛzməs] did not contain a word-final labial consonant, so records of these productions could not be extracted reliably. For children with SLI, 28 of the possible 144 values for both durations and STIs were missing for this reason (19% missing, note that the missing duration and STI values were always from identical productions); 16 of those 28 missing values were for productions of /pɛzməf/. For children with TD, 5/156 (3%) of the possible values for durations and STIs were missing. Percentages of missing data were calculated for each participant and entered into a two-tailed *t*-test. The percentage of missing data was significantly higher for children with SLI compared to children with TD ($t = 3.14$, $p = .005$). We return to the issue of missing data in the discussion.

A second duration analysis was conducted with a subset of the acoustic records of participants‘ productions. Durations were measured by two research assistants who were blind to the purpose of the analysis. Onsets and offsets for four of the nine productions per block (productions 2, 4, 6, and 8) were identified by for each participant using Praat software (www.praat.org). Onsets were marked at the onset or release of the initial consonant. Offsets were marked at the cessation of noise for the final consonant. When a production was missing, the next production was selected (e.g., production 3 was used when production 2 was missing). Productions from one participant with SLI were not available for the third block due to experimenter error.

In contrast to the kinematic analysis, there was no requirement in the acoustic analysis that productions matched in terms of transcriptions. Approximately 25% of the measurements were reviewed by the first author for measurement fidelity, which was considered to be adequate, but no changes to the original measurements were made.

Based on the wider SLI literature, we expected that, overall, children with SLI would have less accurate speech, slower production durations, and less production stability. This should be reflected by relatively low accuracy scores, longer durations, and high STIs relative to the children with TD. Regarding speech motor learning, however, two competing predictions were considered. Note that separate predictions were not made for our two motor speech measures (production durations and STIs), although previous research suggests that the two measures are not redundant (Sadagopan & Smith, 2008; B. L. Smith, 1994).

Given deficits in both speech motor skill and in procedural learning, we might predict that children with SLI will have a speech motor learning deficit. This should result in flat or unchanging production durations and/or STIs across the three blocks compared to relatively steeper learning slopes for children with TD. However, the developmental trends observed by Bishop and Edmundson suggest that children with SLI may not have a motor learning deficit—even when a motor deficit is observable—and therefore children with TD and SLI might both have the downward trending slopes for both production durations and STIs that indicate learning.

Results

Production accuracy data are presented in Figure 2. Mean accuracy values for each participant for each block and each word were entered into a repeated measures ANOVA with language group (TD, SLI) as a between-subjects factor; block (Block 1, Block 2, Block 3) and word (/biptəm/, /fomkəp/, /mæfpəm/, /pɛzməf/) as within-subjects factors. There was a main effect of language group, $F = 7.56$, $p = .011$, but no main effects for word or block (*p*s > .15). Interactions between the variables were not significant (*p*s > .25) except for a significant Block × Word interaction, $F = 2.64$, $p = .019$. The interaction stemmed from significant changes in accuracy across blocks for /pɛzməf/, $F = 3.91$, $p = .027$ but not for the other three words (*p*s > .10). As can be seen in Figure 2, however, accuracy rose and then fell for /pɛzməf/, and generally does not reflect consistent learning over time. Relevant to the kinematic analyses, accuracy for both the TD and the SLI groups changed similarly, and there was no interaction involving the language group factor.

Kinematic duration data are presented in Figure 3. Statistical tests like ANOVA require that there be no missing cells in the data. Due to missing data, this requirement was not met here, and a traditional ANOVA analysis was not appropriate. Instead, missing values were estimated using the multiple imputation procedure offered by SAS (PROC MI, http://support.sas.com/rnd/app/papers/miv802.pdf). The advantage of multiple imputation is that missing values are not replaced with a single value, but instead a range of values, one for each imputation. This procedure better captures the uncertainty inherent in missing data (Rubin, 1987). Five imputations were computed, and the five imputed data sets were then entered into SAS‘s MIANALYZE procedure, which generated a mixed effects model of the data, with language group, block, and word as fixed factors. This model combines statistical tests for each of the five imputations and derives a single *t*-test for each factor or combination of factors. There was no main effect for language group, $t = -0.50$, $p = .622$, or for word, $t = -0.9$, $p = .372$. However, there was a main effect of block, $t = -3.84$, $p = .0001$, corresponding to an average slope of -.02. The effect of block is attributable to decreasing production durations with each successive block ($M_{\text{BLOCK 1}} = .74$, $M_{\text{BLOCK 2}} = .71$, $M_{\text{BLOCK 3}} = .70$). No interaction was significant *p*s > .20).

Mean acoustic durations are plotted in Figure 4. Missing data were minimal, so the data were entered into a repeated measures ANOVA with language group (TD, SLI) as a between- subjects factor; block (Block 1, Block 2, Block 3) and word (/biptəm/, /fomkəp/, /mæfpəm/, /pɛzməf/) as within-subjects factors. The results for the block factor and the block × word interaction violated the sphericity assumption (For the block factor, $\chi^2 = .5.19$, $p = .075$, for the block × word interaction, $\chi^2 = 34.71$, $p = .023$), so a Greenhouse-Geisser correction to the degrees of freedom was applied to reduce the risk of Type I error. There was a signficant effect of word, $F = 3.57$, $p = .026$. This is expected because the words are composed of different phonemes which have different lengths in and of themselves. There was also a significant effect of block, $F = 11.12$, $p < .001$. There was not a significant difference between the language groups, $F = .78$, $p = .387$; nor were there any significant interactions (block × language group $F = 2.39$, $p = .116$, all other ps > .3). Parallel to the kinematic duration analysis, the effect of block is attributable to decreasing production durations with each successive block ($M_{\text{BLOCK 1}} = .81$, $M_{\text{BLOCK 2}} = .76$, $M_{\text{BLOCK 3}} = .74$). Also as expected, the durations in the acoustic analysis were slightly longer due to the inclusion of the word-final consonants.

Mean STIs are presented in Figure 5. Multiple imputation was again used to estimate missing values, and five imputations were computed and entered into the MIANALYZE procedure. There was a nonsignificant trend for more stable productions across blocks, $t = -1.49$, $p = .137$, corresponding to an average slope of -.48. There was also a nonsignificant trend for more stable productions in the TD language group, $t = 1.58$, $p = .114$. The four words were not significantly different in terms of STIs, $t = -0.42$, $p = .673$. Significantly less stable articulatory movements have been observed in children with SLI in previous studies (e.g., Goffman, 1999, 2004), so contrasts were used to compare children with TD and SLI separately for each of the three blocks. No contrast was significant (all ps > 0.1), although the SLI group had numerically higher STI means for all three blocks (Block 1: $M_{\text{SLI}} = 23.0$, $M_{\text{TD}} =21.4$; Block 2: $M_{\text{SLI}} = 21.8$, $M_{\text{TD}} = 20.3$; Block 3: $M_{\text{SLI}} = 21.3$, $M_{\text{TD}} = 21.1$).

Discussion

When producing nonwords, children with SLI were less accurate compared to their peers with TD as assessed by transcription. Over the course of the experiment, however, both groups of children established more efficient speech motor patterns, with significantly shorter durations and a trend towards more stable productions. These learning effects contrast with the absense of of an effect of language group. We therefore conclude that the trajectories of speech motor learning in children with SLI appeared comparable to trajectories in typical development, at least in this study.

There is a notable correspondence between our data and the findings reported by Bishop and Edmundson (1987). Looking at longitudinal trends from four- and five-year-old children with SLI, Bishop and Edmundson found compelling evidence for a typical rate of motor development. Parallel to that finding, we observed comparable speech motor learning in children with TD and SLI on a more narrowly-focused time scale. Thus, our data offer a perspective of the day-to-day learning that may subtend the broader patterns observed by Bishop and Edmundson. The data suggest that children with SLI can learn some speech motor skills at a normal rate. More speculatively, we might predict that speech motor learning—apart from general speech motor performance—is not impaired in children with SLI. Additional data are needed to substantiate this claim, but it is worth noting that normal rates of learning have been observed for children with SLI in other domains, for example, in relatively simple procedural learning tasks (Gabriel et al., 2011), when learning word associations (McGregor et al., 2011), in eyeblink conditioning (Hardiman et al., 2013;

Steinmetz & Rice, 2010), and in one study that included a pursuit rotor task (Hsu & Bishop, 2014).

One might argue that the missing data are responsible for the lack of language group effects. Although we cannot rule this possibility out entirely, we note that children with SLI clearly streamlined production durations across blocks, and we therefore had sufficient power to capture learning effects. Furthermore, the acoustic duration analysis had very little missing data, yet the results corroborated the kinematic analysis, and the group difference was not significant. Even if children with SLI had been slower or less stable throughout the experiment, the relevant effect with respect to learning is change over time, and children with SLI did change in the same direction and to the same degree as the children with TD.

If we take seriously the possibility that there may be no speech motor learning deficit in SLI, what are we to make of the fact that children with SLI typically exhibit both motor skill and procedural learning deficits? It appears that children with SLI trail their peers with TD as the result of a pervasive, specific, but poorly delineated deficit. The SLI profile clearly includes weaknesses in language and motor skills, but strengths are also present, such as in general intelligence (Leonard, 1998), declarative memory (Ullman & Pierpont, 2005), timing (Zelaznik & Goffman, 2010), and possibly in speech motor learning. As such, proposals that posit a global maturational delay (Locke, 1997; Hill, 2001) do not capture many specifics of the SLI profile. Our data may be used to refine future descriptions of SLI, however.

Although the STIs of children with SLI were numerically greater than the STIs of their peers with TD, we did not replicate previous findings of significantly greater speech motor variability in this group (e.g., Goffman, 1999, 2004). This may be attributable to several aspects of this study. For example, it may be that the phonological complexity of the words was more challenging for the children with TD than we initially estimated. In other words, the data may reflect a floor effect, with the result that typical performance was similar to the performance of children with a language impairment. We note that the developmental data presented by Sadagopan and Smith (2008) suggest that, in some contexts, articulatory variability, as captured by the STI, may be less amenable to short-term learning (but cf. Gladfelter & Goffman, 2013; Walsh et al., 2006 for evidence that it can change in other learning contexts). Furthermore, other researchers have observed that production variability may remain flat over even longer periods of time (e.g., McGowan, McGowan, Denny, & Nittrouer, 2014). Ultimately, within-individual articulatory variability may be specific to speech and language contexts that are not yet understood.

It is also possible that statistical power was not sufficient for capturing a language group effect, possibly because of missing items, but more likely because similar group effects are associated with medium effect sizes (c.f., Goffman 1999, 2004). Thus, there is always a chance that the null hypothesis cannot be rejected when looking for group effects of this type. Regardless, the lack of a group difference here does not mean that our participants with SLI had no speech motor deficits, or that speech motor deficits are not typical of the larger population of children with SLI.

The analyses of durations and STIs were not equivalent, at least from a statistical perspective. In previous research, these two dimensions of speech have dissociated. For example, when children produce phrases in isolation compared with embedded in a longer sentence, variability often increases, while duration either decreases or stays flat (Sadagopan & Smith, 2008). Duration and variability for single words also show differential developmental timecourses (Goffman & Smith, 1999).

This finding is also reminiscent of the differences in segmental durations and temporal variability across age groups that were observed by B. L. Smith (1994). B. L. Smith observed that a number of speech sounds were produced with shorter durations and less variability by older age groups, but durations became adult-like at a faster rate. He concluded that the two measures likely reflect independent aspects of progress towards mature speech production capabilities. Similarly, Sadagopan and Smith (2008) found that phrase durations reach adult-like levels between the ages of 7 and 9 years, whereas STIs continue to develop through adolescence. Sadagopan and Smith (2008) argue that the protracted development of speech stability reflects a relatively slow process of cortical maturation for motor speech and other cognitive functions. These conclusions are generally in line with the present findings, and it may be that durations become adult-like faster because they are more sensitive to the kind of learning measured here.

There are some weaknesses in the current study that could be addressed in future research. For example, speech motor learning was measured with just four words, and the task (nonword repetition) likely involves numerous cognitive mechanisms, including but not limited to: verbal working memory, phonological encoding, activation of related lexical items, as well as motor skill. To better understand speech motor learning in both typically developing children and children with SLI, additional tasks should be used in future research.

Another shortcoming of the design was that it did not allow us to examine short- and long-term learning separately. Although participants completed three blocks of repetition, a separate design is necessary to untangle the respective contributions of practice in the short-term and consolidation in the long-term. This could be accomplished, for example, by running a separate condition in which a group of participants only complete the first and third blocks of productions.

Finally, the relationship between production accuracy and motor learning is intriguing but was not directly addressed here. Given that children with SLI were less accurate in their productions overall, but learned to produce the words more efficiently, the results suggest that children with SLI may have improved only when producing incorrect word forms. Previous research suggests that it is very difficult for children with SLI to produce nonwords (e.g., Dollaghan & Campbell, 1998; Gladfelter & Goffman, 2013; Goffman, 1999), and production accuracy simply cannot be controlled when comparing children with and without language impairments. Nevertheless, it may be that motor learning in children with SLI would look different in a simpler production task in which production accuracy was held constant.

To summarize, we asked whether children with SLI have a speech motor learning deficit. We analyzed motor learning in a speech motor task—nonword repetition—but we found that children with SLI learned to produce those nonwords faster and possibly with greater stability. Furthermore, the learning observed in children with SLI was similar to that observed in their typically developing peers. Thus, our findings argue against a speech motor learning deficit in children with SLI, at least as they learn to produce novel words. The findings parallel previous longitudinal findings (Bishop & Edmundson, 1987), and they suggest that children with SLI start with a motor impairment but then learn and develop at a normal rate.

Acknowledgments

This work was supported by NIH R03DC011898 to Peter Richtsmeier, NIH R01DC04826 to Lisa Goffman, and training grant NIH T32DC000030 to Laurence Leonard (supporting the first author as a postdoctoral researcher). The authors extend their gratitude to the children and parents who participated in the “Summer Fun” language therapy program at Purdue University in 2010. Additional thanks to Meredith Saletta, Antigone Fleck, and Janna and Erica Berlin for their assistance with various aspects of this study. Finally, we thank Laurence Leonard for his generosity with time and resources.

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Learning Outcomes

The reader will learn about deficits commonly associated with specific language impairment (SLI) that are in addition to the hallmark language deficit. The authors present an experiment showing that children with SLI improved speech motor performance at a similar rate compared to typically developing children. The implication is that speech motor learning is not impaired in children with SLI.

Highlights

- Specific language impairment likely includes deficits in motor skill and learning
- We asked whether children with SLI also have difficulty with *motor learning* in speech
- We measured children’s lip and jaw movements over time in a nonword repetition task
- Both children with SLI and TD produced shorter word durations over time
- Results suggest the motor deficit in SLI does not reflect impaired speech motor learning, at least in a nonword repetition task

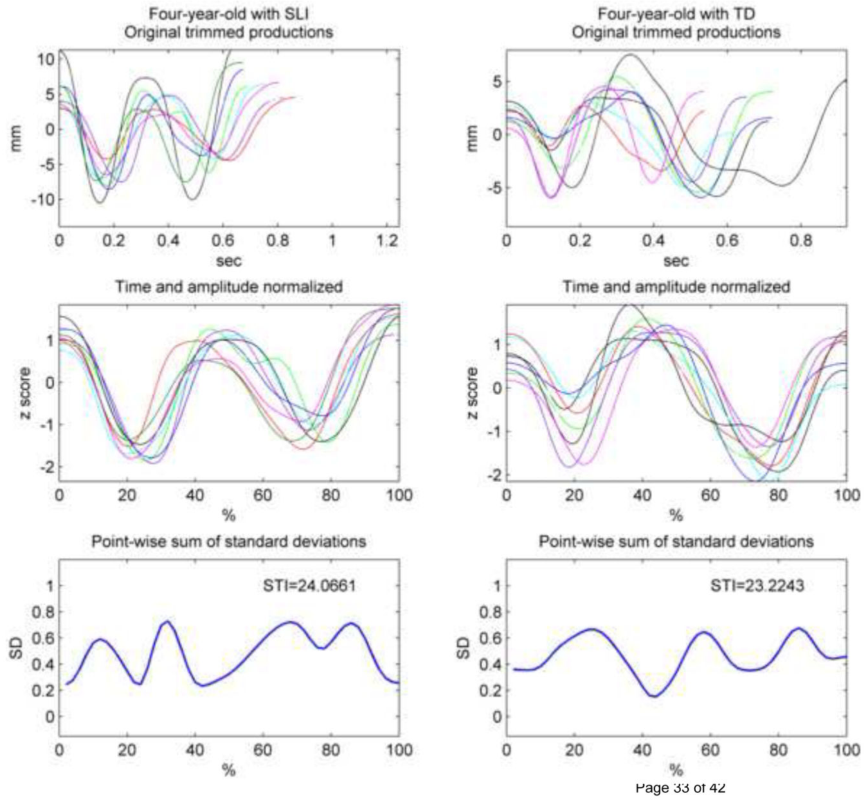

Figure 1.

Examples of the normalization process for the word /mæfpəm/for two children. The x-axis scale for the top row is in seconds and for the middle row in normalized time from 0 to 100. Standard deviations are calculated for 2% sections of the normalized word length. The sum of these standard deviations results in the lip aperture variability measure, or STI.

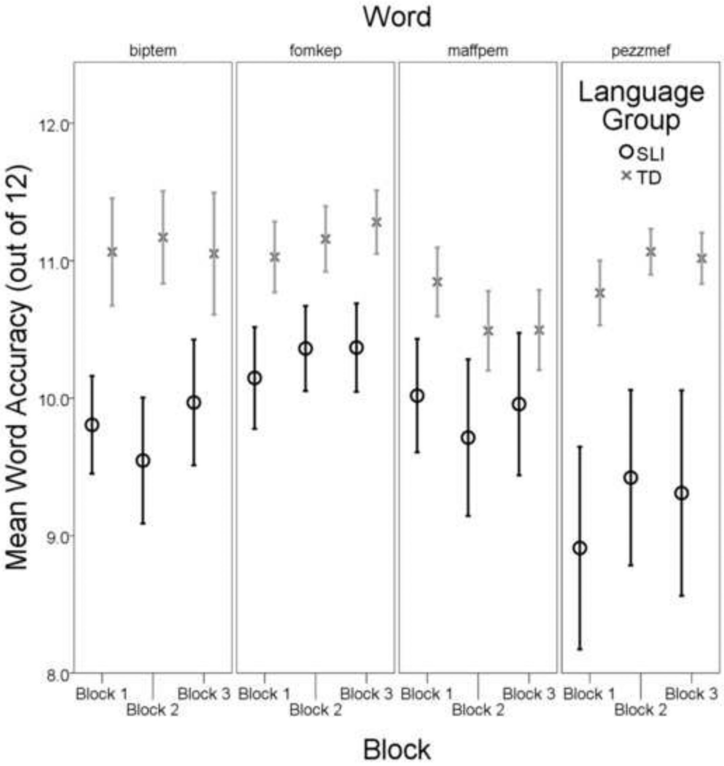

Figure 2.

Mean accuracy values out of a possible score of 12. Error bars represent standard errors.

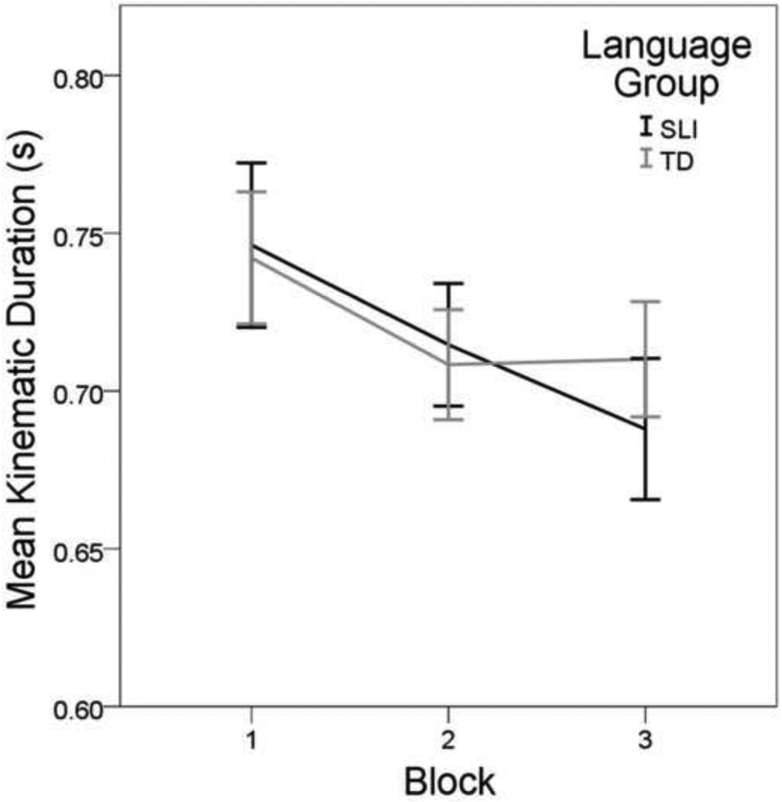

Figure 3.

Mean production duration values obtained from the kinematic records for children with SLI and TD across Blocks 1, 2, and 3.

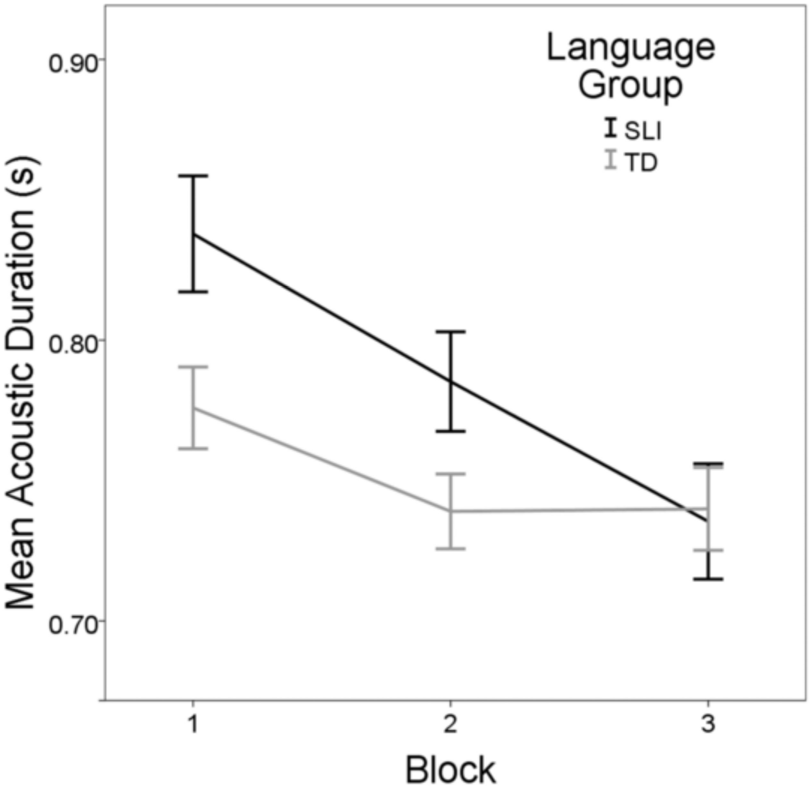

Figure 4.

Mean production durations obtained from the acoustic records for children with SLI and TD across Blocks 1, 2, and 3.

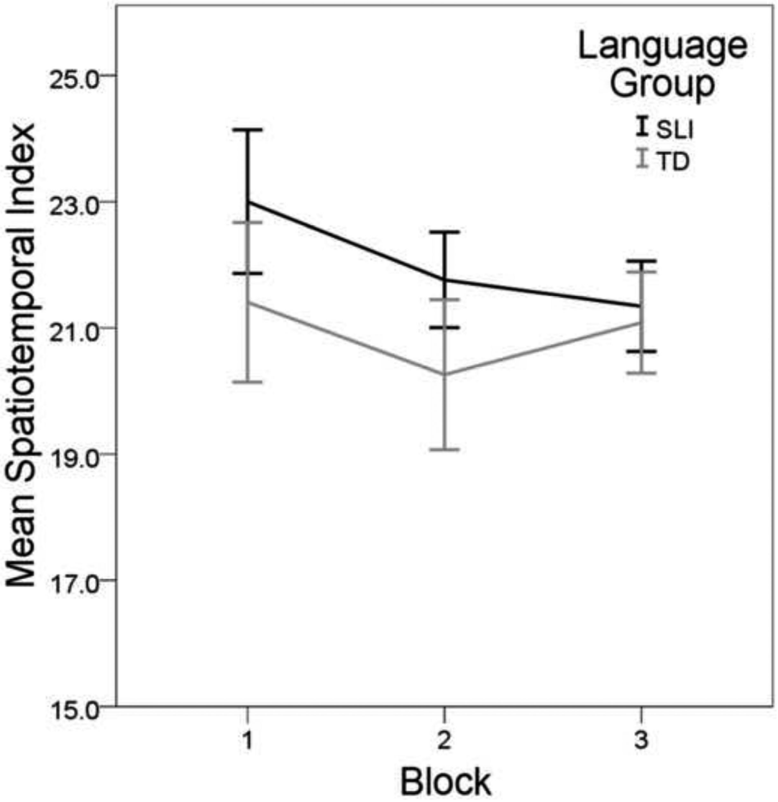

Figure 5.

Mean STI values for children with SLI and TD across Blocks 1, 2, and 3.

Table 1

Means and standard deviations for the children with specific language impairment and children with typical language development. Results of a one-tailed t-test comparison of the two groups are also reported, assuming higher scores in the typical development group. Note that constraints on the schedules of both families and the experimenters limited data collection for standardized tests, and some participants did not complete all tests.

	Specific Language Impairment			**Typical Development**					
Test	**N**	***M***	***SD***	**N**	***M***	***SD***	***df***	***t***	***p***
Mean Age (Mos.)	12	61	6.37	13	55	6.29	24	2.32	.032
SPELT		77.17	11.45		114.70	11.26	22	−7.72	<.001
CMMS		106.17	5.89		116.30	8.43	22	−3.29	.002
BBTOP		77.38	14.17		92.33	16.56	14	−1.82	.080
EVT		100.73	9.97		111.00	9.92	22	−2.41	.013
PPVT		106.75	10.73		109.45	11.89	19	−0.51	.309
Nonword Rep		61.45	6.01		80.63	10.15	16	−4.18	<.001

Note. SPELT = Structured Photographic Expressive Language Test; CMMS = Columbia Mental Maturity Scale; BBTOP = Bankson-Bernthal Test of Phonology; EVT = Expressive Vocabulary Test; PPVT = Peabody Picture Vocabulary Test.

Table 2

Bigram probabilities for the word-medial consonant sequences and whole-word phonotactic probabilities, computed by the Online Phonotactic Probability Calculator (PPC, http://www.people.ku.edu/~mvitevit/PhonoProbHome.html). The PPC calculates bigram probabilities by taking the $\log_{10}$ value of the ratio of the token count for that sequence at that particular position in the word over the total count for any sequence in that position in the word. In this case, the sequence is the bigram containing the third and fourth phonemes in the word. It does not take syllable structure into account. Whole-word phonotactic probabilities are sums of all the component bigram probabilities of a word, for example, the bigram for the first and second phonemes, the bigram for the second and third phonemes, etc. Five bigram probabilities are added together in the whole-word phonotactic probabilities given below.

	Word-medial Consonant Sequence Probability	Whole-Word Phonotactic Probability
biptəm	.0017	.0228
fomkəp	.0002	.0128
mæfpəm	.0000	.0272
pɛzmaəf	.0008	.0169