Characterizing the Motor Skills in Children with Specific Language Impairment

Running title: Motor Skills in SLI

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Abstract

Background/Aims. Specific language impairment (SLI) is characterized by deficits in language ability. However, studies have also reported motor impairments in SLI. It has been proposed that the language and motor impairments in SLI share common origins. This exploratory study compared the gross, fine, oral, and speech motor skills of children with SLI and children with typical development (TD) to determine whether children with SLI would exhibit difficulties on particular motor tasks and to inform us about the underlying cognitive deficits in SLI.

Methods. 13 children with SLI (ages 8-12) and 14 age-matched children with TD were administered the Movement Assessment Battery for Children (2nd Edition) and the Verbal Motor Production Assessment for Children to examine gross and fine motor skills and oral and speech motor skills, respectively.

Results. Children with SLI scored significantly lower on gross, fine and speech motor tasks relative to children with TD. In particular, children with SLI found movements organized into sequences and movement modifications challenging. On oral motor tasks, however, children with SLI were comparable to children with TD.

Conclusion. Impairment of the motor sequencing and adaptation processes may explain their performance on these tasks, which may be suggestive of a procedural memory deficit in SLI.

Key words: specific language impairment, gross and fine movement, oral and speech movement, motor sequencing, motor adaptation, procedural memory

Introduction

Specific language impairment or SLI is a developmental disorder primarily characterized by deficits in language development. Currently, the cause of this disorder is unknown and cannot be explained by acquired neurological damage, hearing loss, or social/emotional disorder [1]. Children with SLI have difficulty comprehending and constructing grammatical structures, while vocabulary is less affected [2-4]. Paradoxically and contrary to the name of this disorder, studies have reported subtle deficits in non-verbal areas in SLI, including motor deficits [1].

The presence of these co-morbid non-verbal deficits has changed the focus of SLI studies from examining purely language-specific explanations to exploring domain-general hypotheses. A basic premise in these hypotheses is that impairment in general cognitive mechanisms shared across multiple areas of development result in language learning difficulties in SLI.

Findings from several studies suggest a functional relationship between language and motor skills [11-13] in typical development. For instance, two studies found that when an object of fixed size was labeled “large” or “small” participant grasps were larger or smaller, respectively, suggesting that movement is affected by lexical semantic abilities [11, 12]. The reverse association has been observed in Myung, Blumstein and Sedivy’s [13] study, which showed that motor actions, such as playing the violin, primed the retrieval of action words involving similar movements, such as sawing. Similar effects have also been observed in transcranial magnetic stimulation (TMS) studies, which have shown that the stimulation of motor regions in the brain influence lexical processing [14, 15]. Pulvemüller et al. [14] found that TMS to the arm motor area of the left-hemisphere of the brain of typical adults led to faster “arm” word responses on a lexical decision task in comparison to “leg” word responses. Similarly, TMS to the leg motor area of the brain led to faster “leg” word responses than to “arm” word responses. Willems and colleagues [15] showed that theta-burst TMS to the hand area of the left but not right premotor cortex of typical adults resulted in faster responses to action verbs such as “to jump” than to non-action words such as “to think” on a lexical decision task. Furthermore, Saletta, Goffman, Ward and Oleson [16] have reported evidence of a language-motor relationship in children with SLI. Specifically, they found that when children with SLI produced rehearsed sentences, their speech movements were less variable. However, their productions of novel and spontaneous sentences resulted in more articulatory variability. These findings indicate that linguistic load impacts speech production in SLI. Given these results, it is reasonable to hypothesize that the language and motor deficits in SLI share functionally related origins in the form of a domain-general impairment that would impair both language and motor skills.

Although the specific nature of the domain general impairment in SLI remains uncertain, theories have been presented. Language impairment has been explained by slow processing speed [5], limited attention [6, 7] impairment of the procedural memory system, [8] and limited working memory capacity [9], to name a few. Deficits in these hypothesized domain-general mechanisms could impact performance on motor measures in different ways. For instance, slow processing speed might result in group differences between children with SLI and with typical development (TD) on timed motor tasks. On the other hand, deficits in procedural memory may be evident on tasks that require execution of sequences of actions and adaptation of movements. Impairment of the phonological working memory system may surface on tasks requiring repetition of longer sequences of sounds and words while limitations in attention may be evident on motor tasks that are more time consuming resulting in difficulty maintaining attention.

In our recent review, we synthesized research reporting motor deficits in SLI and argued that a comprehensive investigation of the motor deficits could provide a unique window into the potential underlying domain-general cognitive impairment in SLI [10]. Describing these deficits becomes important to establish the underlying cause of SLI and improve identification of SLI and service development. SLI can be difficult to diagnose given the overlap in symptomatology with other developmental disorders [17]. Establishing the mechanisms involved in SLI will allow us to modify the diagnostic criteria to reflect the impairment profile more accurately and thus improve the identification of children at risk of SLI. We can also ensure that intervention programs are structured to include activities that target the underlying cognitive impairment and thereby build and strengthen the motor skills affected in children with SLI.

Motor deficits in SLI

Hill's [18] review of early studies on motor deficits associated with SLI aimed to establish the prevalence of motor impairment in the disorder. Her review revealed significant concomitant motor deficits, specifically with gross and fine motor skills, in children with SLI. More recent studies regarding the comorbid motor impairments in SLI have been consistent with the conclusions of Hill [18] and indicated potential impairments in other motor domains as well [10]. To date, SLI studies have reported deficits in (1) gross motor skill [18-23], (2) fine motor skill [18, 19, 21-26], (3) oral motor skill [27-29], and (4) speech motor skill [16, 30-33].

Gross motor skills involve the movement and coordination of large muscle groups including the arms, legs, and whole body [34]. Measures of gross motor skill typically assess balance and coordination through tasks such as standing on one leg, walking in a straight lin,e and catching a bounced ball [10, 18]. Children with SLI typically stand on one leg for shorter periods of time, have their feet stray more often while walking in a straight line, and catch a bounced ball less frequently than children with TD [19, 20, 22, 23].

Fine motor skills involve the coordination of the fingers, hands, and wrists to perform small and exact movements [34]. Relative to children with TD, children with SLI generally require more time to complete fine motor tasks such as drawing trails (drawing a line within the space of two lines), moving pegs, and threading lace [19, 20, 22-25] and reduced timing precision with bimanual clapping [26].

Oral motor skills involve the coordination of the lips, tongue, and jaw [35]. Speech is an extension of oral motor production, involving neurocognitive and neuromotor innervation to the muscles of the respiratory, phonatory, resonatory, and articulatory systems [35, 36]. Oral motor skills are generally examined by evaluating simple isolated movements, such as opening the mouth, to complex movements such as whistling, repetitions of a single movement, or sequences of different movements. The few studies that have explored oral motor skill in SLI have reported group differences between children with SLI and children with TD in their repetitions of oral movement sequences, but not with simple isolated movements [27-29]. Speech motor skill in SLI, on the other hand, is more evidently impaired. Speech motor skills are typically assessed by examining the consistency of word and nonword productions as well as spontaneous and structured phrases [37]. Several studies examining speech motor skill have shown that relative to children with TD, children with SLI are significantly less consistent in their repetitions of nonsense [30] and real words and phrases [31-33] on tasks of word and nonword repetition and show increased variability in their articulatory movements of spontaneous sentences [16] on syntactic priming tasks.

Current study

Thus far, studies have established that children with SLI exhibit difficulties with gross and fine movements [18-26]. There is also preliminary evidence of oral motor deficits and growing evidence of speech motor impairment in SLI [16, 27-33]. Yet, the mechanisms contributing to these deficits remain unknown. One explanation is that the language and motor deficits in SLI arise from functionally unrelated neural maturational processes. Alternatively, we can assume that a domain-general cognitive impairment explains the motor impairments in SLI. If this is the case, identifying parallels in performance across gross, fine, oral, and speech motor areas within the same sample of children with SLI becomes important to determine what that underlying cognitive mechanism might be. If the types of motor tasks children experience difficulties with are random in nature, it is unlikely that a single underlying mechanism would explain their difficulties. However, if children with SLI significantly differ from children with TD on particular types of tasks, this could shed some light on which domain-general cognitive impairment may be impaired. Surprisingly, after decades of research examining motor skills in SLI, we found only one study that examined these four motor domains using a variety of tasks within the same sample of children [31]. However, oral motor skill was only assessed to determine participant eligibility and was not described systematically. Thus, in this exploratory study, we set out to describe which types of motor tasks children with SLI exhibit particular difficulty with and hypothesize which cognitive processes may be involved in completing those tasks. To address this objective, we asked whether children with SLI differed from children with TD on tasks assessing different motor areas.

Our specific research questions were:

1. How do gross and fine motor skills differ between children with SLI and children with TD?
2. How do oral and speech motor skills differ between children with SLI and children with TD?

Methods

Participants

Thirty-five children (ages 8;3 – 12;4), including 17 with SLI and 18 age-matched children with TD and their parents, gave their informed consent to participate in this study. This study protocol was approved by the University of Toronto and the Toronto District School Board Research Ethics Committees. Children completed several sessions associated with a larger project and were later invited back for additional oral and speech motor testing. Eight children, however, did not return for the additional session, reducing our sample size to 27 children, including 13 with SLI and 14 age-matched children with TD, for the oral and speech motor measure.

All of the participants: (1) were monolingual speakers of English, (2) had no frank neurological damage (e.g., obvious motor dysfunction, epilepsy, cerebral palsy), (3) scored at or above 75 on the nonverbal index of the Wechsler Abbreviated Scale of Intelligence – Second Edition (WASI-II) [38], (4) passed a hearing screening, and (5) had no emotional or social disorders.

At the time this study was conducted, the language abilities of each child were assessed using the Clinical Evaluation of Language Fundamentals – Fourth Edition (CELF-4) [39], the Peabody Picture Vocabulary Test – Fourth Edition (PPVT-4) [40], and the Expressive Vocabulary Test – Second Edition (EVT-2) [41] to confirm each child's group status (Table 1). To be included in the SLI group, children were required to score at least 1.25SDs below the mean on at least one of the language indices of the CELF-4. To be included in the TD group, however, children were required to score within normal limits across all language measures.

Within normal limits was defined as a score that is within or above 1.25SDs of the mean on these language measures.

INSERT TABLE 1 HERE

The language profiles of the SLI group can be described as follows: (1) three children obtained standard scores that were 1.25SDs below the mean on the Expressive Language Index (ELI) of the CELF-4 and within typical range on the PPVT, EVT and Receptive Language Index (RLI) of the CELF-4 and were identified as having expressive-only language difficulties, (2) four children obtained standard scores that were 1.25SDs below the mean on the RLI and within normal limits on the PPVT, EVT and ELI and were identified as having receptive-only language difficulties, (3) three children obtained standard scores that were 1.25SDs below the mean on the RLI and ELI and within normal limits on the PPVT and EVT and were identified as having expressive and receptive language difficulties, (4) three children obtained standard scores that were 1.25SDs below the mean on either the PPVT or EVT and standard scores that were 1.25SDs below the mean on either the RLI or ELI and were identified has having both vocabulary and sentence-level language difficulties, and (5) no children had vocabulary-only language difficulties as defined by standard scores that were 1.25SDs below the mean on the PPVT and/or EVT and within normal limits on the remaining language indices.

Children assigned to the SLI group were recruited from school board language programs and had received services for language- or learning-related difficulties. Children assigned to the TD group did not previously participate in school board language programs and had no history of receiving language- or learning-related services according to parental report. Furthermore, three of the children's parents from the SLI group reported that their child had both limb motor and speech motor difficulties, one parent reported limb motor difficulties only, and three parents reported speech and articulation issues only. The parents of the remaining six children with SLI and all of the parents of the children with TD reported that their child had no limb motor or speech motor difficulties.

Stimuli and Procedure

Children's gross and fine motor skills were assessed using the Movement Assessment Battery for Children – Second Edition (MABC-2) [42] and children's oral and speech motor skills were assessed using the Verbal Motor Production Assessment for Children (VMPAC) [37]. These assessments were chosen because of the variability in the types of tasks they include.

Gross and fine motor skill. The MABC-2 includes eight tasks that are divided into three sections: (1) Manual Dexterity, which evaluates fine motor skill, (2) Aiming and Catching, which assesses the coordination of fine and gross motor skills, and (3) Balance, which evaluates gross motor skill. The Manual Dexterity section examines the coordination of a child's hands and eyes when performing spatially and temporally-confined tasks. These tasks include placing (ages 8-10) or turning (ages 11-12) pegs on a 12-hole pegboard, threading lace through an 8-hole lacing board (ages 8-10), building a triangular structure with nuts and bolts (ages 11-12) and drawing trails (all ages). Although these tasks are used to assess fine motor skill, the fine movements involved in performing these tasks are arguably different. The placing/turning pegs task involves a single repetitive movement while the drawing trails task requires adapting hand and wrist movements. The threading lace and building a triangular structure tasks require the execution of movement sequences. We acknowledge that other movements and processes are required to perform these tasks, but have chosen to focus on these specific movement types to address the objectives of our study. For the placing/turning pegs and threading lace/building a triangular structure tasks, performance is based on time to complete. The drawing trails task requires using a single wrist movement to draw a line between two lines without lifting one's hand. Performance on this task is based on the number of errors produced (the number of times the child's drawn line crosses the bolded path lines).

The Aiming and Catching section assesses a child's coordination and timing of spatially demanding gross movements. The tasks in this section include: throwing a beanbag onto a mat target (ages 8-10) or a ball at a wall target (ages 11-12) and catching a ball with two hands (ages 8-10) or one hand (ages 11-12). Both sets of tasks involve coordinating fine and gross movements with performance based on the number of successful attempts (e.g. number of successful ball catches or ball/beanbag throws at the target).

The last section of the MABC-2 is the Balance section, which examines a child's ability to control their body in both static and dynamic balance tasks. These tasks include: balancing on one (ages 8-10) or two boards (ages 11-12) for a maximum of thirty seconds, walking heel-to-toe forwards (ages 8-10) or backwards (ages 11-12) on a line, and hopping on mats (all ages). Similar to Manual Dexterity, the Balance section includes tasks that involve different types of gross movements and chose to focus on the following movement types. The balancing on one/two board(s) task involves adapting one's gross movements while the hopping on mats task involves a single repetitive movement. Walking heel-to-toe forwards/backwards requires the execution of movement sequences. For the balancing on one/two board(s) task, performance is based on the length of time a child is able to balance on the board(s). For the walking heel-to-toe task, scores are assigned based on the number of successful consecutive heel-to-toe steps walked along the line up to a maximum of 15 steps or the entire line, whichever the child reaches first. For the hopping task, performance is based on the number of successful continuous hops that land on the mat for a maximum of 5 hops.

For each item across all three sections, raw scores were converted into standard scores that were based on the child's age.

Speech and oral motor skill. The VMPAC includes 10 sections that are grouped into five performance areas: (1) General Motor Control, (2) Focal Oromotor Control, (3) Sequencing, (4) Connected Speech and Language Control and, (5) Speech Characteristics. The General Motor Control assesses the physiological structure and function of the child's oral and speech motor system. It is made up of two sections: General Motor Control and Oromotor Integrity. The General Motor Control section is comprised of statements relating to the child's muscle tone (e.g., head and neck are stable), respiration/phonation (e.g., respiration is adequate for phonation when child says "Ah" for two to three seconds long), reflexes, and vegetative functions (e.g., chewing is coordinated while eating the cookie). The Oromotor Integrity section consists of statements relating to the muscles of the child's face, lips and tongue (e.g., soft palate contracts fully during phonation of /a/). For both sections, a score of 1 or 0 is given if the examiner agrees or disagrees, respectively, with each statement.

The Focal Oromotor Control section evaluates the movements of the jaw, lips and tongue while producing single and multiple oral actions and speech sounds. It is comprised of five sections: Single Oromotor (Non-Speech) Movements, Double Oromotor (Non-Speech) Movements, Single Oromotor-Phoneme (Speech) Movements, Multiple Oromotor-Phoneme (Speech) Movements, and Oromotor Production in Word Sequences and Sentences. These sections consist of items asking the child to produce individual oral actions (e.g., show me how to bite), sequences of two oral actions (e.g., show me how you bite and blow), individual consonant and vowel sounds, sequences of two and three consonant and vowel sounds, sequences of words (e.g., say pea, tea, key), and short sentences, respectively. The Focal

Oromotor Control area is based on the assessment of motor control for each of the five sections and consistency for the Single Oromotor-Phoneme (Speech) Movements section. Motor control is evaluated on a scale of 0 to 2. A score of 2 is given if the movement is precise in all listed parameters, 1 if the movement is partially imprecise in one or more listed parameters, or 0 if the movement is severely imprecise in one or more listed parameters. Consistency is scored as either a 0 or 1. A score of 1 is given if the phoneme is produced in the same way 3 or 4 out of 4 times while a score of 0 is given if the phoneme is produced inconsistently across 2 or more repetitions.

It is important to note that the administration of the Single Oromotor (Non-Speech) Movements, the Double Oromotor (Non-Speech) Movements, and the Multiple Oromotor-Phoneme (Speech) Movements involves a cueing hierarchy. Items are first administered in the auditory modality, which requires the examiner to simply state the task instructions. If the child does not understand what is asked of them, the examiner probes the subsequent modalities, visual followed by tactile, to assist the child in producing the correct action or sound. In the visual modality, the examiner models the movement. In the tactile modality, the examiner physically guides the child's movements as shown in the training video. Even though this cuing hierarchy was implemented, children's performance only in response to the task instructions (auditory modality) was considered because we were not interested in how modifiable children's motor skills were.

The third area, Sequencing, tells us about the child's ability to maintain a given sequence of oral actions and speech sounds. It comprises three of the five sections that make up the Focal Oromotor Control area: Double Oromotor (Non-Speech) Movements, Multiple Oromotor-Phoneme (Speech) Movements, and Oromotor Production in Word Sequences and Sentences.

Performance in this area is based only on sequence maintenance, which is based on a scale of 0 to 2. A score of 2 is given if all of the items are produced in the correct sequence, 1 if more than half of the items are in the correct sequence, or 0 if less than half of the items are not in the correct sequence.

The last two areas of performance are Connected Speech and Language Control and Speech Characteristics, supplemental areas of the VMPAC. The Connected Speech and Language Control section evaluates the changes in the child's oromotor production in linguistic contexts using narrative samples and automatic verbal sequences (e.g., saying your ABC's), while the Speech Characteristics section assesses several paralinguistic aspects of the child's speech production across the testing session including pitch, resonance, prosody, rate etc. We did not include these sections in our analysis given that these sections examined speech production as a function of language complexity, which was not the aim of this study.

The VMPAC was not designed to directly compare single oral movements with single speech movements and sequenced oral movements with sequenced speech movements. Items within these two areas were, therefore, re-categorized so that we could directly compare the motor control of single oral movements with their single speech movements and maintenance of sequenced oral movements with sequenced speech movements between groups. This was done by comparing the raw motor control scores of the single oral items with the raw motor control scores of the single speech items and the raw sequence maintenance scores of the sequenced oral items with the raw sequence maintenance scores of the sequenced speech items. Since the VMPAC does not include sequences of three oral items like it does for the speech items, only sequences of two oral items and two speech items were compared between groups.

For each of the five performance areas, raw scores across designated sections were added and then divided by the total possible raw score to generate a percent score for each area (see Appendix for scoring breakdown). The same approach was used to generate percent scores for our analysis of single oral movements with single speech movements and sequenced oral movements with sequenced speech movements.

Statistical Approach

We examined performance on measures of gross, fine, oral, and speech motor skill using a series of mixed effects analyses of variance (ANOVA) with section, task, and item as the within subjects factors and group as the between subjects factor. Due to significant group differences in nonverbal IQ, we also considered mixed effects analyses of covariance (ANCOVA) with IQ as a covariate. Both ANOVA and ANCOVA analyses yielded similar results. In the following however, we report the results only from the mixed effects ANOVA analyses because studies have reported that entering IQ as a covariate can lead to misinterpretations of the data and does not accurately represent the profile of the population being examined [43, 44]. Also, to reduce the occurrence of Type 1 errors, we corrected for multiple comparisons using the Bonferroni correction method.

Prior to conducting the analyses, normality and homogeneity of variances for all dependent variables were tested. The MABC-2 data was homogenous and normally distributed. However, the Mauchly’s test of sphericity indicated that the VMPAC data violated the ANOVA assumption of equal variances. Therefore, the Greenhouse-Geisser corrections were used for these data. Furthermore, no outliers were identified for the MABC-2 or the VMPAC data.

Results

The first set of analyses aimed to determine on which MABC-2 tasks of gross and fine motor skill the SLI group differed from the TD group. We conducted a mixed effects ANOVA with section (Manual Dexterity, Aiming and Catching and Balance) as the within subjects factor, group (SLI and TD) as the between subjects factor, and MABC-2 subsection standard scores as the dependent variable. The analysis revealed main effects of section, $F(1, 33) = 10.66$, $p < .001$, $\eta^2 = .24$ and group, $F(1, 33) = 10.63$, $p < .001$, $\eta^2 = .24$, and a significant interaction between section and group, $F(1, 33) = 4.98$, $p = .01$, $\eta^2 = .13$. A post hoc comparison of means using one-way ANOVA revealed that the SLI group scored significantly lower than the TD group on the Manual Dexterity, $F(1, 33) = 13.55$, $p < .001$, $\eta^2 = .29$, and Balance, $F(1, 33) = 12.42$, $p < .001$, $\eta^2 = .27$, sections of the MABC-2. Scores on the Aiming and Catching section, however, were not significantly different between the SLI and TD groups, $F(1, 33) = .13$, $p = .72$, $\eta^2 = .00$, (Figure 1). Given that the SLI group differed significantly from the TD group on the Manual Dexterity and Balance subsections, only performance on these subsections were examined further.

INSERT FIGURE 1 HERE

First, to better understand fine motor performance on the Manual Dexterity section, we examined differences across the fine motor tasks by conducting a mixed effects ANOVA with task (peg moving, lace threading/nuts and bolts and drawing trails) as the within subject factor, group as the between subjects factor, and MABC-2 task standard scores as the dependent variable. The results yielded significant effects of task, $F(1, 33) = 5.61$, $p = .01$, $\eta^2 = .03$, and group, $F(1, 33) = 14.72$, $p < .001$, $\eta^2 = .31$ only. No significant interaction between task and group was found, $F(1, 33) = 1.11$, $p = .34$, $\eta^2 = .03$.These effects suggest that children across the two groups scored lower on the drawing trails tasks and that the SLI group scored significantly lower than the TD group across all of the manual dexterity tasks (Figure 2).

Second, to better understand gross motor performance on the Balance section, we examined differences across the gross motor tasks by conducting a mixed effects ANOVA with task (one/two foot balance, walking forwards/backwards and hopping) as the within subjects factor, group as the between subjects factor, and MABC-2 task standard scores as the dependent variable. The results yielded a main effect of group only, $F(1, 33) = 8.95$, $p = .01$, $\eta^2 = .21$. No effect of task, $F(1, 33) = 1.30$, $p = .28$, $\eta^2 = .04$, or task by group interaction, $F(1, 33) = 2.42$, $p = .10$, $\eta^2 = .07$, were found. This effect indicated that the SLI group scored significantly lower than the TD group across all of the balance tasks (Figure 2).

INSERT FIGURE 2 HERE

The next set of analyses aimed to determine on which VMPAC tasks of oral and speech motor skill the SLI group differed from the TD group. We conducted a mixed effects ANOVA with section (General Motor Control, Focal Oromotor Control and Sequencing) as the within subjects factor, group as the between subjects factor, and VMPAC subsection percent scores as the dependent variable. The analysis revealed effects of section, $F(1.21, 30.29) = 109.84$, $p < .001$, $\eta^2 = .82$, and group, $F(1.21, 30.29) = 32.33$, $p < .001$, $\eta^2 = .56$, and a significant interaction between section and group, $F(1.21, 30.29) = 35.25$, $p < .001$, $\eta^2 = .59$. A post hoc comparison of means using one-way ANOVA showed that the SLI group scored significantly lower than the TD group on the Focal Oromotor Control, $F(1, 25) = 9.94$, $p < .001$, $\eta^2 = .28$, and Sequencing, $F(1, 25) = 37.82$, $p < .001$, $\eta^2 = .60$, areas of the VMPAC. Scores on the General Motor Control reached ceiling for both the SLI and TD groups (Figure 3).

INSERT FIGURE 3 HERE

To further characterize group differences in the Focal Oromotor Control and Sequencing areas, we compared performance on oral and speech items between SLI and TD groups. As such, we conducted a mixed effects ANOVA with item type (oral and speech) as the within subjects factor, group as the between subjects factor, and VMPAC item percent scores as the dependent variable. This analysis revealed main effects of item type, $F(1.00, 25.00) = 43.54$, $p < .001$, $\eta^2 = .64$, and group, $F(1, 25) = 12.53$, $p < .001$, $\eta^2 = .33$, and a significant interaction between item type and group, $F(1.00, 25.00) = 14.90$, $p < .001$, $\eta^2 = .37$. A post hoc examination of this interaction using one-way ANOVA revealed that the SLI group differed from the TD group on sequences of speech items, $F(1, 25) = 17.21$, $p < .001$, $\eta^2 = .41$, but not with sequences of oral items, $F(1, 25) = .32$, $p = .57$, $\eta^2 = .01$ (Figure 4).

INSERT FIGURE 4 HERE

Qualitative analysis and discussion

The objective of this exploratory study was to characterize the motor deficits in SLI. We assumed that deficits in general cognitive processes in SLI would appear as difficulties in some motor tasks but not in others. Accordingly, we compared children with SLI and children with TD on different kinds of standardized tasks of gross, fine, oral, and speech motor skill. Although each of the tasks in isolation require a number of cognitive and motor processes to execute, we reasoned that considering children's performance across several different kinds of tasks would inform us about the types processes children with SLI do and do not have particular difficulty with.

Consistent with previous literature, children with SLI performed significantly different from children with TD on the following tasks: (1) all three fine motor tasks of the Manual Dexterity section of the MABC-2 (peg moving, threading lace/nuts and bolts and drawing trails) [19, 20, 23-25], (2) all three gross motor tasks of the Balance section of the MABC-2 (walking forwards/backwards, balancing on one foot/two feet and hopping) [19, 20, 23-25], and (3) the sequence maintenance of a speech items on the VMPAC [16, 30-33]. In contrast, children with SLI did not significantly differ from children with TD on the following tasks: (1) both tasks of the Aiming and Catching section of the MABC-2 (catching a ball with one/two hands and throwing a beanbag/ball at a target), (2) the motor control of single and sequenced oral items of the VMPAC, and (3) the motor control of single and sequenced speech items on the VMPAC. In the following, we qualitatively analyze and discuss parallels among the tasks children with SLI had difficulty with (Table 2) and the ways in which these tasks differ from the tasks children with SLI did not have difficulty with to further understand these findings.

Parallels across tasks that were difficult for children with SLI

One commonality among the threading lace/nuts and bolts fine motor tasks, the gross motor task involving walking heel-to-toe forwards and backwards, and the speech sequencing tasks (a subset of tasks that children with SLI had difficulty with) is the demand for producing motor sequences, one of several motor processes involved in early motor learning [45, 46]. These tasks require that movements are executed in a specific sequence for the task to be completed correctly. For example, when constructing the triangular figure with nuts and bolts, the nuts must be assembled first before the bolts can be used. Assembling the bolts first would prevent the figure from being correctly put together. For the walking heel-to-toe task, one foot must be placed in front of the other to ensure that the toes of the foot that is behind are always touching the heel of the foot that is in front. Moving the same foot forward would generate a gap between the feet and thus render the trial incomplete. Finally, the speech sequencing items require that the speech sounds be produced in a particular order. Any deviation from this specified sequence would be considered incorrect.

A review of the recorded sessions showed that some children with SLI threaded lace through the same side of the board on the threading lace task instead of following the front-back-front-back sequence and others prematurely assembled the bolts before the nuts on the nuts and bolts task, which resulted in children having to take the pieces apart and start from the beginning. On the walking forwards or backwards tasks, some children with SLI moved the same foot forward or backward instead of using the alternate foot to move forward or backward resulting in gaps of space between their feet. On the speech sequencing tasks, many children with SLI were unable to produce the speech sounds in the correct sequence. Based on these findings, it appears that children with SLI have difficulties with movement sequencing. Other tasks, such as catching a ball with one or both hands, require a simple two-step process of throwing and catching and therefore, do not place heavy demands on sequencing. Likewise, the single oral and speech items, which involve isolated oral movements and speech sounds, place little to no demands on sequencing. Given that we found no significant group differences on these tasks is also suggestive of a potential sequencing deficit in SLI.

A second similarity among the subset of tasks children with SLI scored significantly lower than the TD group on emerged among the fine motor task involving drawing trails and the gross motor task of balancing on one foot or two feet. Instead of placing heavy demands on producing sequences of movement, these tasks require adapting continuous movements, another motor process involved in the early stages of motor learning [45, 46]. On the drawing trails task, the wrist movements must be adjusted to ensure that the line that is being drawn stays within the provided path space. If wrist and hand movements are not adapted, the drawn line can easily touch or cross the lines of the path. To balance on one or two feet on the balance boards, the arms, legs, and core must coordinate with one another. If one body part shifts, the others need to reorient or adapt to ensure that no falls occur and balance is maintained.

A closer look at the video recordings showed that for the balance board tasks, children with SLI were initially able to control their balance, but were unable to reorient themselves when body parts shifted. As a result, children with SLI relied on objects (a nearby table or chair) to regain control of their balance and maintain it. Similarly for the drawing trails tasks, it appeared that the children with SLI had trouble adapting their wrist movements to ensure that the line they were drawing stayed within the confines of the two bolded lines, repeatedly touching and, in many cases, crossing the lines completely. This behaviour may be indicative of difficulties with motor adaptation in children with SLI.

Third, the remaining tasks that children with SLI had trouble with shared the commonality of involving repetitive movements. These tasks included the fine motor task involving moving pegs and the gross motor task involving hopping. Peg moving requires a recurring lifting and turning motion when moving each peg. Similarly, hopping involves a recurring jumping motion when moving from one mat to another. Examining the recorded sessions revealed that on the peg moving task, the movements produced by children with SLI appeared qualitatively similar to their peers with TD. Given that the performance measure on this task is completion time suggests that children with SLI may simply be slower in their execution of repetitive movements than children with TD. On the hopping task, however, we found that the children with SLI performed similarly to how they did on the balance board tasks, unable to adapt the body movements needed to maintain balance while hopping from mat to mat. This particular finding suggests that the hopping task also taxed movement adaptation skills and may have contributed to the poor performance on this task by children with SLI. Thus, we speculate that children with SLI may have difficulties with repetitive movements, perhaps due to the slower speed with which the repetitive movements are executed or due to the adaptive demands present in these tasks.

INSERT TABLE 2 HERE

Parallels across tasks that were not difficult for children with SLI

If the parallels among the tasks that produced group differences were demands on producing movement sequences and adapting movements, then why did children with SLI not significantly differ from their peers with TD on the Aiming and Catching tasks and the sequence maintenance of oral items? While typical performance on single and isolated oral and speech sounds has been previously reported [27-29], typical performance on tasks such as catching and throwing a ball [29, 20, 23-25] and sequences of oral actions is not consistent with past study findings [27-29]. The Aiming and Catching tasks, catching a ball and throwing a ball or beanbag at a target, assess the coordination of gross and fine movements. Accuracy on these tasks is driven by trial and error, fine-tuning ones hand and foot orientation to successfully catch or throw a ball requiring movement adaptation. The sequenced oral items on the VMPAC, which consist of actions such as smiling and kissing, place demands on sequencing given that these movements must be produced in a specific sequence and would have, therefore, been challenging for the children with SLI.

One explanation for their typical performance on the Aiming and Catching tasks and the oral items on the VMPAC may have to do with children’s familiarity with the tasks or rather, the movements themselves. Catching a ball with one or two hands and throwing a ball or a beanbag at a target are activities that school-aged children regularly engage in, conceivably during recess with friends or at home with siblings or parents. Regular engagement with a motor skill facilitates the acquisition of that skill [47]. It is, therefore, possible that the familiarity of these tasks, which come from exposure and practice at school or at home, enabled the children with SLI to perform comparably to their peers with TD.

Likewise, many of the oral items were organized into pairs that naturally go hand-in-hand, such as opening one's mouth followed by biting or kissing followed by smiling, which may explain the typical performance we observed by children with SLI on these items. Our interpretation suggests that the sequencing and adaptation difficulties may perhaps be specific to novel movements rather than movements that children have had previous exposure to or practice with. If this finding is replicated across different tasks and contexts, it becomes clinically relevant. Specifically, increased exposure or repetition of stimuli in therapy may be essential for children with SLI to achieve robust language and/or motor skills.

Cognitive mechanisms underlying the motor deficit in SLI

We now turn to hypothesizing what domain-general mechanism could explain the observed difficulties children with SLI exhibited with speech and limb movement sequencing and adaptation specifically when the tasks are novel.

One could argue that the imprecise sequenced speech productions observed in this study are explained by limitations in phonological working memory. According to working memory theories, language difficulties in SLI are a result of limitations in space available for temporarily storing phonological information in working memory [9]. Indeed, previous studies reporting group differences between children with SLI and children with TD in repeating nonwords are interpreted as evidence of limited phonological working memory [48]. However, it is difficult to phantom how the observed difficulties in executing a sequence of limb movements would tax the phonological working memory system. Therefore, we argue that limitations in phonological working memory are not a viable explanation for the combined challenges of sequenced limb and sequenced speech movements observed in this study.

The co-occurring difficulties with speech and limb movement sequencing and adaptation could, however, be accounted by the Procedural Deficit Hypothesis (PDH). The PDH argues that the language deficits in children with SLI are explained by limitations in procedural memory [8]. Procedural memory is part of long-term memory that supports the acquisition of habitual sensorimotor and cognitive skills including simple movements such as balance and complex actions involving sequences such as riding a bicycle. Procedural memory underlies processes that facilitate motor learning. These processes include: (1) sequence planning and execution, specifying and then implementing a sequence of actions needed to perform a novel movement and (2) adaptation, adjusting or modifying ongoing movements to ensure the intended result is achieved [8, 46, 49].

Procedural memory also underlies rule-based learning that is hypothesized by Ullman [49, 50] to support grammar learning. Specifically, it is argued that aspects of sentence construction that can be formed using rules such as adding –ed to form past tense for regular verbs or –s to indicate third person singular are supported by the procedural network. Based on the role procedural memory is hypothesized to play in language and motor development and the unique profile of language and motor deficits observed in SLI, Ullman and Pierpont [8] argued that the underlying mechanism contributing to these deficits is impairment of the procedural memory system. Thus, the procedural deficit hypothesis predicts that children with SLI have difficulties sequencing and adapting movements, and using motor memory for learned skills. In the following, we will discuss the extent to which the findings of the current study are consistent with these predictions.

The sequencing difficulties evident on the threading lace, nuts and bolts and sequenced speech motor tasks in this study are consistent with the predictions of the PDH. Other studies have reported challenges with sequencing in SLI, specifically that children with SLI take longer to implicitly learn a fixed sequence of buttons presses relative to their age-matched peers with TD on the serial reaction time tasks involving button-presses [51]. Thus, the results of this study extend the observed sequencing difficulties on the serial reaction time tasks to new types of tasks, adding external validity to the finding of sequencing difficulties in these children.

The adaptation difficulties predicted by the PDH were evident in children's performance on the balance board and drawing trails tasks in this study. However, the few previous studies that have directly explored motor adaptation in SLI have reported no significant differences from children with TD and are, therefore, inconsistent with the results of the current study [52, 53]. One explanation for the inconsistent findings may be that the adaptation tasks used in previous studies did not place heavy enough demands on adaptation processes. Hsu and Bishop [52] used the pursuit rotor task as their measure of motor adaptation, which requires one to maintain contact with a moving dot for as long as possible. This task was used with school-aged children (ages 7 -11) and may have been too simple of a task for potential adaptation deficits to surface. Similarly, [53] used a mirror-tracing task, which requires one to trace a figure seen as reflection from a mirror. The space within which the line was to be drawn was fairly large (1.0cm in width) and may have also been too simple for their school-aged participants (ages 7 -13). In comparison, the drawing trails task from the MABC-2 used in this study provides a space of approximately 0.5cm and decreases to roughly 0.25cm by the end of the path. Thus, the demands placed on adaptation processes may have been greater for the drawing trails tasks relative to the pursuit rotor and mirror-tracing tasks. Furthermore, to our knowledge, no studies have examined adaptation of gross movements in SLI. Therefore, the findings of the current study suggest that children with SLI exhibit adaptation difficulties related to fine movements and gross movements as it pertains to balance.

Even though the movement sequencing and adaptation difficulties in children with SLI are accounted by the PDH, the finding that familiar movements or actions were relatively unaffected is not. Procedural memory is part of long-term memory and is important in memory consolidation, developing the motor memory that allows for automatic execution of a learned skill [8, 46, 49]. Given the role procedural memory has in supporting habitual skills, we would expect familiar skills to be difficult for children with SLI in comparison to children with TD. The findings of the current study were not consistent with this prediction. Instead, it appeared that the familiar movements on the Aiming and Catching tasks and the oral items of the VMPAC were an area of strength in these children. This finding is consistent with other studies that have shown that with more trials or additional practice, children with SLI show the same degree of procedural motor learning as their peers with TD [51]. However, the difficulties observed on these tasks are related to sequencing and adaptation deficits with new, but not habitual skills. This suggests that the PDH does not fully account for the observed findings.

Limitations

One important limitation must be taken into consideration when interpreting our results. It has to do with the exploratory nature of this study. Instead of choosing specified motor tasks to test theories concerning a specific cognitive deficit in SLI, we chose measures that include a selection of various different kinds of motor tasks. For instance, had we a priori decided to test the hypothesis that children with SLI exhibit deficits in oral and speech motor sequencing, it would have been beneficial to supplement the VMPAC with additional speech motor measures as well as longer and more difficult oral motor sequences. While acknowledging the limitations, however, we argue that the exploratory approach we took supplements hypothesis driven research by providing new previously overlooked insights that may be tested in future hypothesis driven research. For instance, research focused on revealing phonological working memory limitations would likely miss difficulties in limb movement sequencing and adaptation, and research focused on revealing an adaptation deficit would likely miss that these deficits appear on tasks that are novel to children.

Conclusions

This study examined the motor deficits in children with SLI across a broad range of motor tasks to inform general cognitive explanations for this disorder. Our findings suggest that children with SLI have difficulties with tasks involving sequencing and adapting novel movements. This finding partially fits within the procedural deficit hypothesis. It suggests that procedural memory, a network linked to motor learning and its associated sequence and adaptation processes, may be contributing to at least some of the deficits observed in SLI. Given that this study was descriptive and qualitative in nature, that the sample size was relatively small and that the tasks used in this study were not direct measures of these processes, future studies should examine these motor processes using controlled experimental designs. These studies can then specify the nature of the procedural memory deficits in SLI, if they do exist, and inform diagnostic protocols, to improve the identification of SLI in children, and service development, to ensure that these motor processes are targeted in intervention programs for SLI.

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Table 1. Descriptive Statistics for Ages and Standardized IQ and Language Test Scores

	Age in Years	**IQ**[a]	**CLS**[b]	**RLS**[c]	**ELS**[d]	**PPVT**[e]	**EVT**[f]
SLI							
Mean	10.01	89.77**	74.12**	76.65**	76.88**	91.85**	91.38**
SD	1.10	11.94	13.36	10.26	15.39	6.62	10.68
Range	8.75-12.17	75-120	42-90	55-94	51-98	79-104	73-115
TD							
Mean	10.50	109.22**	109.22**	109.33**	110.89**	108.43**	110.07**
SD	1.31	12.83	12.50	14.57	12.97	15.81	11.21
Range	8.25-12.33	85-130	82-123	85-128	83-130	82-134	90-124

Note. Standard scores have a mean of 100 and a standard deviation of 15.

[a] Wechsler Abbreviated Scale of Intelligence – Second Edition: Perceptual Reasoning Index Composite Score; [b]Clinical Evaluation of Language Fundamentals – Fourth Edition: Core Language Score; [c]Clinical Evaluation of Language Fundamentals – Fourth Edition: Receptive Language Score; [d]Clinical Evaluation of Language Fundamentals – Fourth: Expressive Language Score; [e]Peaboady Picture Vocabulary Test – Fourth Edition: Standard Score; [f]Expressive Vocabulary Test – Second Edition: Standard Score; ** $p < .01$

Figure 1. Performance on the Sections of the MABC-2 (means and standard errors)

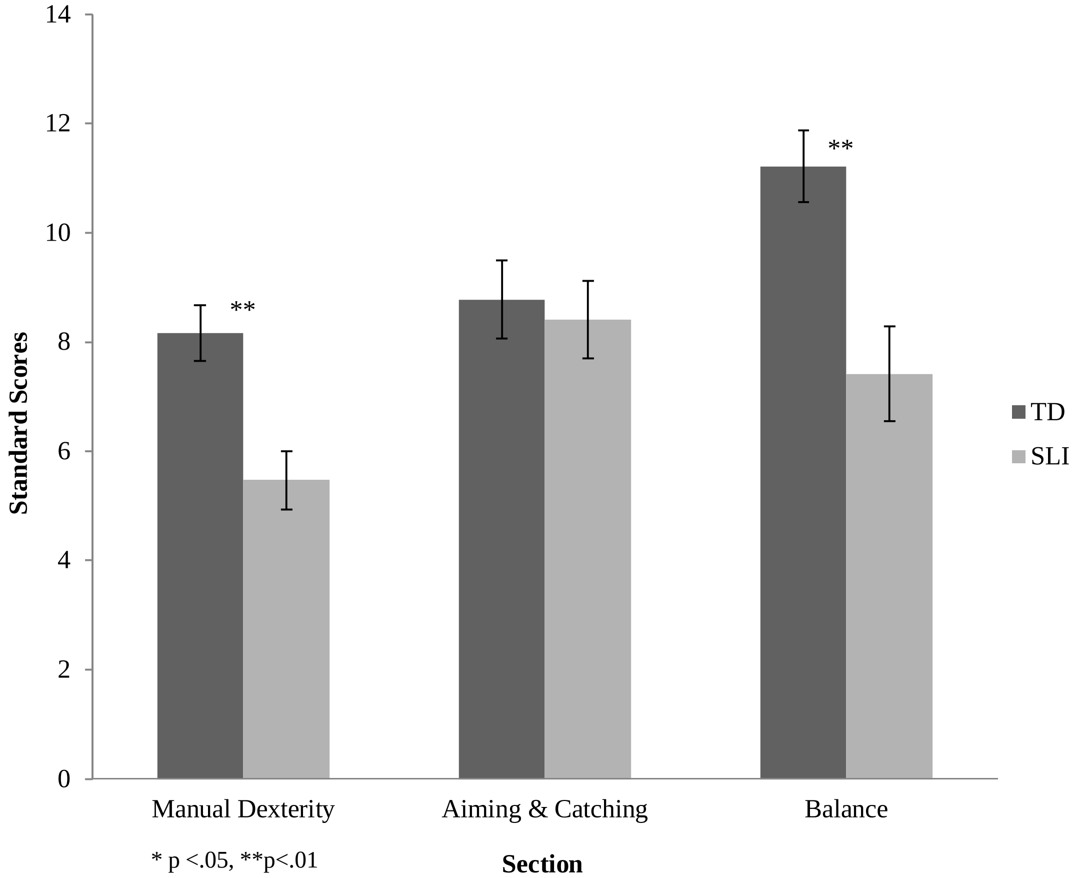
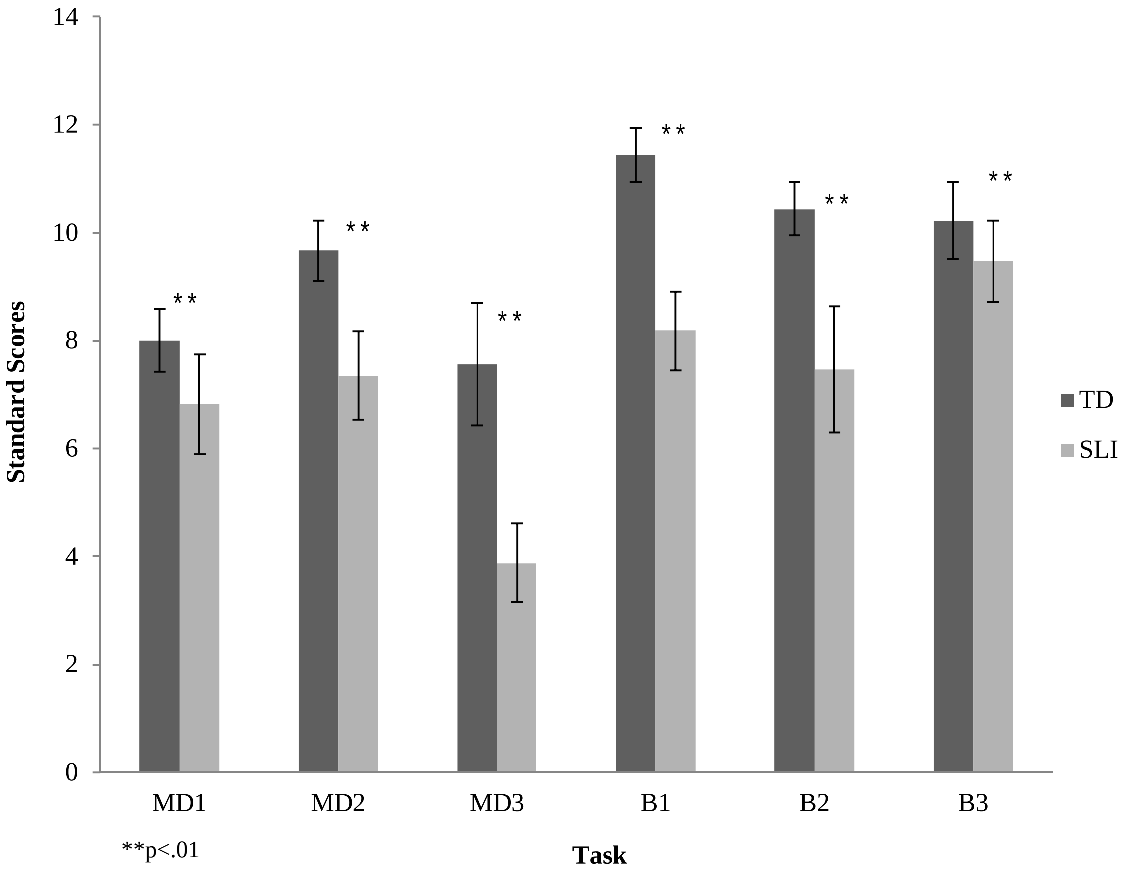


Figure 2. Performance on Manual Dexterity and Balance tasks (means and standard errors)



MD1: placing/turning pegs; MD2: threading lace/nuts and bolts; MD3: drawing trails; B1: balancing on one foot/two feet; B2: walking heel-to-toe forwards/backwards; B3: hopping

Figure 3. Performance on the Sections of the VMPAC (means and standard errors)

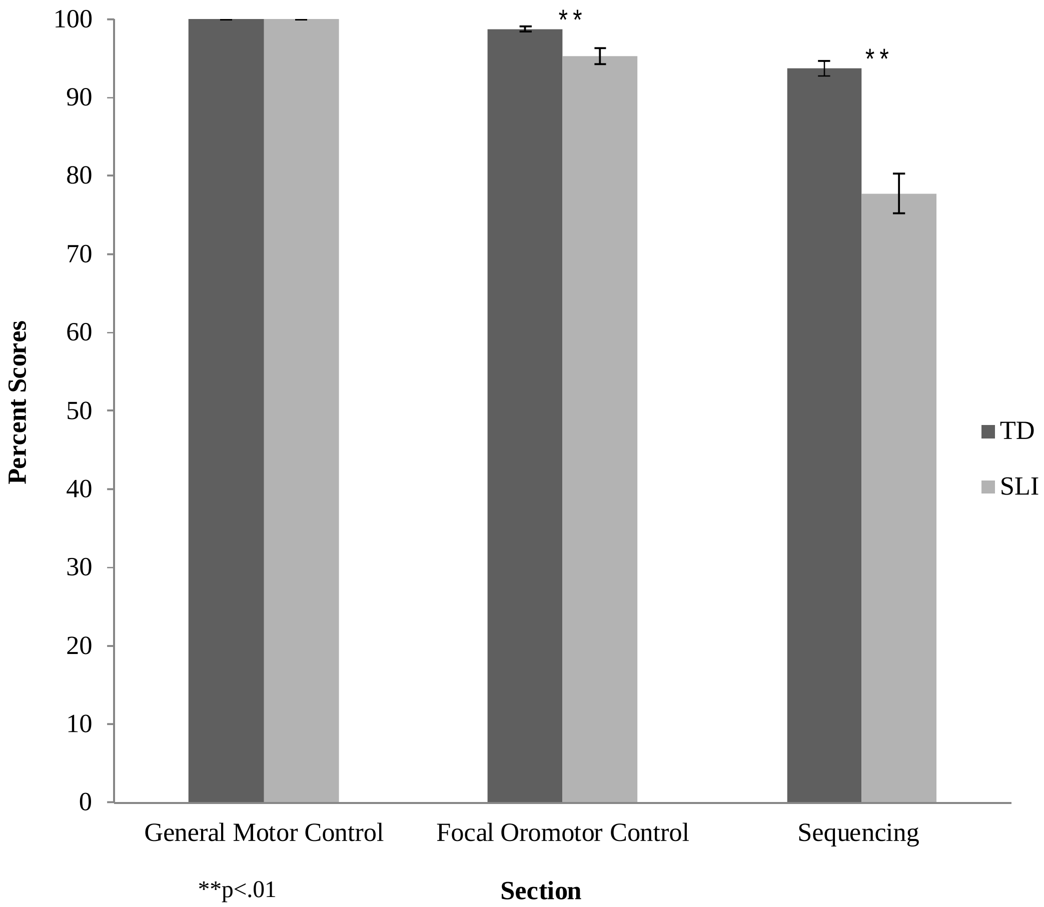
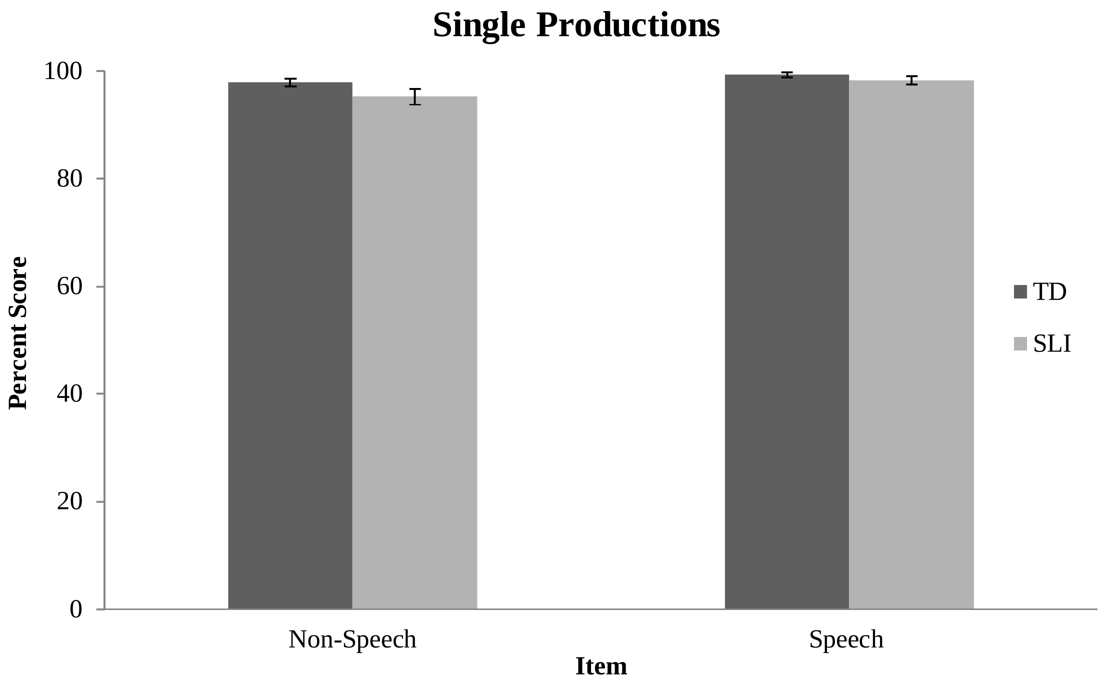
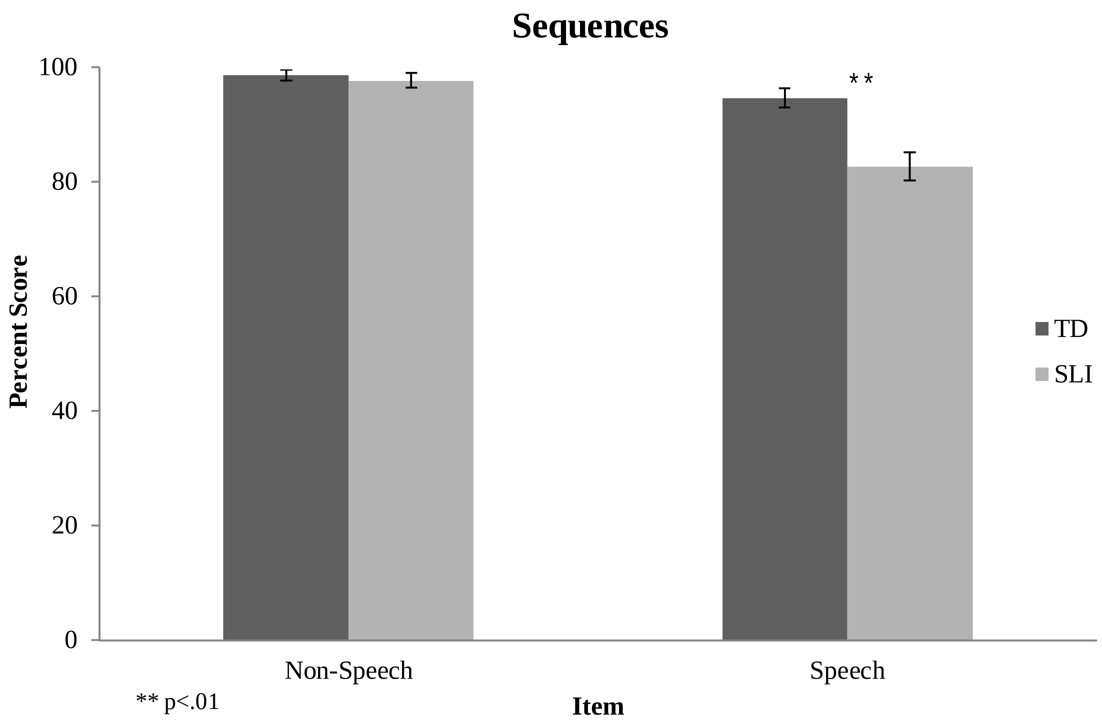


Figure 4. Performance on Oral and Speech Items in Single Productions and Sequences (means and standard errors)





** p<.01

Table 2. Parallels across tasks that were significantly different between children with SLI and TD children

Measure for which quantitative differences between children with SLI and TD children were found	**Qualitative differences between children with SLI and TD children**	**Similarity**
MABC-2 Manual Dexterity - Threading lace/nuts and bolts task	- Threaded lace on same side - Placed bolts before nuts	Sequencing
MABC-2 Balance - Walking forwards/backwards task	- Moved same foot forward - Moved same foot backward	
VMPAC Sequencing - Speech sequence items	- Did not produce speech sounds in correct sequence	
MABC-2 Manual Dexterity - Drawing trails	- Drawn line crossed border - Lifted hand	Adapting movements
MABC-2 Balance - Balance board task	- Used body or object to maintain balance	
MABC-2 Balance - Hopping	- Used body or object to maintain balance - Stopped in between jumps	
MABC-2 Manual Dexterity - Peg moving/turning	- No qualitative differences between groups	N/a