Characterizing the Motor Deficits in Children with Specific Language Impairment

by

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Abstract

The objective of this dissertation was to characterize the motor deficits in children with specific language impairment (SLI). This research was motivated by the hypothesis that the motor deficits provide a window into the underlying cause of SLI, which is currently unknown.

The motor abilities of children with and without SLI were explored through a broad range of tasks across three experimental studies. The first study examined children’s gross, fine, oral motor and speech motor skills. The second study investigated children’s motor sequence planning and execution, adaptation and retention abilities. And the last study explored temporal aspects of the manual communicative gesture productions of children with SLI.

The results of these studies revealed that children with SLI had significant difficulties with novel balance, fine limb and speech motor skills. At the processing level, children with SLI exhibited impaired fine motor sequence planning and execution, while adaptation and retention appeared to be unaffected. These procedural measures were also significantly correlated with performance on grammar and vocabulary measures. Finally, the temporal relationship between speech and communicative gesture was comparable between children with and without SLI.
This profile of motor impairment in SLI and its association with language ability may be best explained by deficits in procedural learning. Future studies should examine whether procedural motor measures can supplement current diagnostic protocols of SLI and whether treatment approaches that target procedural learning capacity are more effective at treating the language, motor and cognitive deficits in SLI.
The doctoral journey is a tough one. What gets you through it is the interest and curiosity you have for your line of work and of course, a great support system.

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Chapter 1

Literature Review

1.1. What is specific language impairment?

Specific language impairment (SLI) is a developmental language disorder that is characterized by deficits in language abilities that cannot be explained by acquired neurological damage, social and emotional disturbances, hearing loss or frank oral motor dysfunction (Leonard, 1998, 2014). It is estimated that the prevalence of SLI is 7.4% in the kindergarten population (Tomblin et al., 1997). Currently, the etiology of this disorder is unknown. Due to our limited understanding of SLI, the services delivered to these children may not address the underlying deficits of this disorder. Consequently, this shortcoming may result in language difficulties that continue in adolescence, which in turn can significantly impact their learning in school and has been linked to reduced social relationships, employment opportunities and overall quality of life in adulthood (Clegg, Hollis, Mawhood & Rutter, 2005).

In recent years, studies have reported motor deficits in SLI (Hill, 2001; Sanjeevan et al., 2015). Given this new-found comorbidity in SLI, establishing the parallels between the motor and language deficits are crucial for identify the underlying mechanisms of SLI. Our current understanding of the motor impairment in SLI, however, is limited relative and has hindered our ability to specify this relationship between language and motor ability. Thus, to address this gap in the literature, this dissertation aimed to characterize the motor impairments in children with SLI.

1.2. Linguistic deficits in SLI

Previous studies have established that children with SLI primarily exhibit deficits in the areas of language, including morphology, syntax and phonology that affect their learning of grammar and comprehension and production of grammatical speech. Specifically, studies examining inflectional morphology in children’s speech revealed that children with SLI have difficulty
using morphemes specifying past tense (Norbury et al., 2001; Rice et al., 1995; Rice & Wexler, 1996; Ullman & Gopnik, 1999), pluralization (Gopnik & Crago, 1991; Oetting & Rice, 1993) and number agreement (Gopnik & Crago, 1991; Rice & Oetting, 1993). There is also some evidence that children with SLI exhibit issues with derivational morphology (Gopnik & Crago, 1991). In the area of syntax, studies have reported that children with SLI are capable of processing simple and short sentence structures, but exhibit difficulties understanding and producing complex sentence structures. This deficit includes issues with recognizing errors in word order or syntactic agreement (Rice et al., 1999) and identifying syntactic relationships within sentences such as those consisting of relative clauses and long-distance dependencies (Montgomery, 1995; Riches, Loucas, Baird, Charman & Simonoff, 2010). Though passive sentences such as *the dog was chased by the cat*, are difficult to process, children with SLI do not exhibit issues with all passive sentence types (e.g. Norbury et al., 2002; van der Lely, 1996). Non-reversible passive sentences such as *the cookie was eaten by the girl*, where the subject and object assignments are clear and short passives such as, *the girl had slept*, that require few syntactic movements, are less difficult for children with SLI. Complex sentences such as, *the boy was kissed by the girl*, where the subject and object can only be inferred by the syntactic structure (Montgomery & Evans, 2009) are challenging for children with SLI. Phonological processing is also impaired; children with SLI demonstrate poor phonological awareness (Claessen, Leitao, Kane & Williams, 2013; Vandewalle, Boets, Ghesquiere & Zink, 2012) and exhibit weak phonological representations (Classen & Leitao, 2012; Claessen et al., 2013).

Apart from these primary language deficits, studies have reported subtle difficulties with lexical and semantic areas of language. Some children with SLI exhibit reduced associations between words and their respective meanings as evidenced by semantic-related errors (Lahey & Edwards, 1999; McGregor, 1997), repeated word associations (Sheng & McGregor, 2010) and poor word definitions (Mainela-Arnold, Evans & Coady, 2010; Marinellie & Johnson, 2002).

In sum, the language deficits in SLI are predominately related to grammar. Their impairment lies in their difficulty to learn and apply rule-based aspects of grammar affecting their language.
comprehension and production (Leonard, 2014). While there is evidence to suggest some difficulties with vocabulary development in more severe cases of SLI (e.g. Lahey & Edwards, 1999; Mainela-Arnold et al., 2010; Sheng & McGregor, 2010), lexical and semantic areas of language are a relative strength in this population overall (e.g. Hick, et al., 2002).

1.3. Diagnosis of SLI

SLI can be difficult to diagnose given the overlap in symptomatology with other developmental disorders (e.g. Georgopoulous, Malandraki & Stylios, 2003). While there is considerable variability in the diagnostic criteria in research, the following series of inclusionary and exclusionary criteria are used to identify SLI in children (Leonard, 1998, 2014).

1. Children with SLI must show poor language ability. Children who score 1-2 standard deviations or lower below the mean on a standardized measure of language ability are typically identified as exhibiting language difficulties. The cut-off scores and the number of language assessments used to make this decision vary significantly between regions, research studies, clinics and schools. The best practice includes using a standardized language test that recommends cut-off scores based on diagnostic accuracy estimates.

2. Children with SLI must exhibit nonverbal intelligence that is within normal range. This cut-off score also varies considerably between regions, research studies, clinics and schools.

3. Children with SLI must exhibit normal hearing. Children are subjected to hearing screens that involve the detection of pure tones presented at 20 or 25 decibels in the right and left ear at frequencies of 500, 1000, 2000 and 4000 Hertz. If children are able to detect all of the presented tones, they are identified as having normal hearing.
4. Children with SLI must not exhibit frank neurological damage. Children must not have a history of brain lesions, traumatic brain injury, cerebral palsy or seizure disorders. This information is commonly gathered from parental reports.

5. Children with SLI must not show frank oral motor dysfunction. Children cannot exhibit evidence of physiological abnormalities of the oral-motor speech apparatus. This information is typically gathered from parental reports and confirmed by observation.

6. Children with SLI must not have a history of social or emotional difficulties. Children cannot show evidence of impaired social behaviour or significant emotional disturbances. This information is generally gathered from parental reports.

7. Children with SLI must not be diagnosed with another developmental disorder. Children cannot have a previous or existing diagnosis of the following disorders: Autism Spectrum Disorder, Asperger syndrome, Down syndrome, Fragile X syndrome, cerebral palsy, cognitive disability or intellectual disability. Labels including speech language disorder or delay, learning disability and attention deficit hyperactivity disorder are typically permitted.

There are significant limitations of these research criteria. The first involves the significant variability in cut-off scores between regions, research studies, clinics and schools. Given that there are no universal cut-off scores for the language criteria, the same child might receive services in one school, but not at another. This suggests that a number of children with language difficulties may not receive language treatment.

The second major limitation is with regards to the diagnosis of SLI in bilingual children. The language abilities of bilingual children can sometimes resemble the language abilities of children with language impairments. Given that most standardized measures of language ability are normed on monolingual populations, bilingual children with SLI tend to be either under- or
over-identified as being at risk of SLI (Paradis, 2010). As a result, the language difficulties of bilingual children with SLI can be left untreated or typically developing bilingual children may be treated unnecessarily. If parallels between the language and motor deficits in SLI are established, then a nonverbal diagnostic measure could perhaps be used to identify children at risk of SLI in both monolingual and bilingual populations.

1.4. Treatment approaches for SLI

The most common treatment approaches for SLI include: elicited imitation, modeling, focused stimulation and recasting (Leonard, 2014). These methods provide children with repeated exposure to a word or grammatical structure that they find difficult, hereby referred to as the target form.

In elicited imitation, the experimenter produces the target form and explicitly asks the child to repeat it. Earlier in this treatment program, the child imitates the target form in isolation or short phrases. Once the child is comfortable using the target form in simpler contexts, the child imitates the target form in more complex contexts like long sentences or question and answer dialogues. The expectation is that over time, the child will be able to produce the target form without having to hear it first (Leonard, 2014).

In the modeling approach, the experimenter (or model) provides the child with several exemplars containing the target form and the child is asked to focus on how the model uses the target form. Unlike elicited imitation, modeling does not require the child to repeat the target form. Instead, the child may be asked to provide the target form in new linguistic contexts or correct incorrect uses of the target form, thereby providing the child with a variety of examples illustrating where, when and how to use the target form (Leonard, 2014).

In focused stimulation, the experimenter provides the child with significant exposure to the target form in structured dialogue. Unlike modeling, the child is unaware that the target form has been systematically integrated into their conversations and activities. The rationale behind focused stimulation is
that the implicit exposure to the target form will increase the child’s use of that form in his or her own speech production (e.g. Girolametto, Pearce & Weitzman, 1996; Leonard, 2014).

In recasting, the child produces an utterance containing the target form and the experimenter modifies the child’s utterance by correcting or adding syntactic or semantic information. Unlike focused stimulation, recasting is primarily conversational and naturalistic. The experimenter does, however, attempt to integrate the target form or modifications into their conversations with the child, which is expected to provide children with ample exposure and correct use of the target form (e.g. Camarata, Nelson & Camarata, 1994; Leonard, 2014; Nelson, Camarata, Welsh, Butkovsky & Camarata, 1996).

While these interventions, and others not discussed here, can effectively treat some language areas through increased exposure to and practice with target forms (e.g. phonology and vocabulary), there are mixed findings for other language areas (e.g. morphosyntax) (Law, Garrett & Nye, 2004; Leonard, 2014). The reasons for these differences, however, are unclear. It is expected that with a better understanding of the mechanisms involved in SLI, we will be able to identify which mechanisms are involved in treatment gains and modify ineffective treatment approaches accordingly.

1.5. Motor deficits in SLI

Contrary to the name of this disorder and its diagnostic criteria, research studies have shown that children with SLI exhibit deficits in several nonverbal areas (Leonard, 1998, 2014). One area of impairment that was discovered fairly recently is motor ability (see Hill, 2001; Sanjeevan et al., 2015 for reviews).

Hill’s (2001) review of early studies on motor deficits associated with SLI aimed to establish the prevalence of motor impairment in SLI. This review revealed significant concomitant motor deficits in children with SLI and in particular with gross praxis and fine motor abilities. Based on this finding, Hill concluded that SLI may be associated with a broader cognitive impairment that manifests in the language and motor areas rather than a domain specific to language. More
recent studies regarding the comorbid motor impairments in SLI have been consistent with the conclusions of Hill (2001) and also indicated potential impairments in execution of communicative movements (reviewed in Sanjeevan et al. 2015). These motor issues in SLI will be reviewed in the following sections.

1.5.1. Gross and fine motor abilities

There are several studies that have explored the gross and fine motor abilities of children with SLI. Gross motor ability refers to the large muscle movements that enable us to perform motor actions with our arms, legs and whole body. Fine motor ability, on the other hand, refers to the small muscle movements that enable us to perform actions with our fingers, hands and wrists (Encyclopaedia of Children’s Health, 2015).

Several studies have explored the gross and fine motor abilities of children with SLI (e.g. Finlay & McPhillips, 2013; Flapper & Schoemaker, 2013; Vukovic, Vukovic & Stojanovik, 2010; Zelaznik & Goffman, 2010). One study conducted by Flapper and Schoemaker (2013) aimed to qualify the motor deficits in SLI by examining motor performance in children with SLI against criteria for Developmental Coordination Disorder (DCD), a developmental motor impairment that restricts the ability to perform day-to-day activities (Flapper & Schoemaker, 2013). One criterion of DCD is poor motor performance as defined by a total score on a standardized measure of nonverbal motor ability that is below the 15th percentile. This study found that about a third of children with SLI met this criterion as indicated by their performance on the Movement Assessment Battery for Children (Henderson & Sugden, 1992). On this test, children with SLI exhibited deficits in the areas of manual dexterity, balance aiming and catching.

Children with SLI experience difficulties in other aspects of motor ability as well. Vukovic, Vukovic and Stojanovik (2010) examined coordination and imitation in children with and without SLI. Using the McCarthy’s Scales of Children’s Abilities (McCarthy, 1973) and the Test of Imitation of Movements (Berges & Lezine, 1972), they found that children with SLI exhibited difficulties with leg and arm coordination and were unable to imitate both larger
movements, involving the arms and hands, as well as smaller movements involving the wrists and fingers (Vukovic et al., 2010).

Another study, conducted by Zelaznik and Goffman (2010), examined the motoric timing in children with SLI based on the hypothesis that timing inherently underlies performance across a range of motor abilities. Using a series of circle drawing and finger and hand tapping tasks, the study showed that children with SLI were able to keep time just as well as the TD children.

Together, these studies indicate that children with SLI exhibit difficulties with gross and fine motor abilities including coordination and imitation of movements (Finlay & McPhillips, 2013; Flapper & Schoemaker, 2013; Vukovic et al., 2010; Zelaznik & Goffman, 2010). Motoric timing, on the other hand, may be unaffected in SLI (Zelaznik & Goffman, 2010).

1.5.2. Speech motor ability

Our understanding of the speech motor abilities in SLI is limited to a handful of studies. Speech production involves the execution of a sequence of articulatory movements (Duffy, 2013). While frank oral motor dysfunction is an exclusionary criterion of SLI, studies have reported subtle speech motor deficits in SLI (Sanjeevan et al., 2015).

One study conducted by Goffman (1999) examined the productions of iambic (weak-strong) and trochaic (strong-weak) stress patterns in invented words in children with SLI and speech deficits. The results revealed that the size of articulatory movements for iambic and trochaic forms were comparable between the children with SLI and TD children. The duration of movements for both forms, however, were longer for children with SLI than TD children. Furthermore, an examination of children’s open-close-open-close movement sequences revealed significant spatiotemporal variability for the children with SLI in comparison to the TD children, while isolated open-close sequences were unaffected in both groups. Comparing these findings with younger children and older adults reported in Goffman and Malin (1999), Goffman (1999) interpreted the findings of this study to suggest that children with SLI have less mature motor systems relative to their age-matched TD peers.
These observations have been replicated in recent SLI studies as well (Archibald, Joanisee & Munson, 2013; Brumbach & Goffman, 2014, Goffman, 2004). Children with SLI have exhibited unstable articulatory movements in their production of real words (Goffman, 2004), nonwords (Archibald et al., 2013) and short phrases (Brumbach & Goffman, 2014). Apart from studies examining articulatory movements, studies have analyzed other speech characteristics to examine speech motor control in SLI. For example, Andrade et al. (2014) examined rate of speech and frequency of disruptions (e.g., repetitions, revisions, hesitations) in the spontaneous productions of children with SLI aged 3 to 7. Their findings revealed that while the younger children with SLI (aged 3 and 4) had significantly slower speech rates, the older children with SLI (aged 5, 6 and 7) had comparable speech rates to TD children. Also, the frequency of disruptions between groups was not significantly different. While these findings may suggest that speech motor control is relatively intact, there is some debate on whether speech rate is a measure of motor control or language processing or perhaps both. While speech rate can be affected by poor articulatory control, difficulties formulating sentences can impact speech rate in a similar manner. For these reasons, this result must be interpreted with caution. Collectively, these findings suggest that children with SLI exhibit issues with articulatory control and speech rate (Goffman, 1999, 2004; Andrade et al., 2014). Also, these difficulties appear to be more pronounced when producing complex sequences of sounds and words (Goffman, 1999, 2004; Archibald et al., 2013; Brumbach & Goffman, 2014).

1.5.3. Manual Gestures

Communicative gestures, unlike goal-directed motor actions, are motoric representations of meaning that occur naturally alongside speech production (Cartmill, Beilock & Goldin-Meadow, 2012). The extent of our understanding about the gesture productions in SLI in relation to motor ability is limited to two studies (Sanjeevan et al., 2015).

The first study examined the quality of gesture productions in children with and without SLI (Botting, Riches, Gaynor & Morgan, 2010). Children were shown images of objects and events (e.g. rain) and asked to produce gestures representative of the provided images. The quality of
the gesture production was then quantified by assigning scores based on the rater’s ability to recognize the object or event represented by the child’s gesture. The results showed that the quality of the gesture productions of children with SLI were comparable to those produced by TD children. A secondary analysis examining associations between gesture production scores and, motor and language abilities revealed that, while gesture production scores were significantly related to fine motor performance in TD children, this relationship was not observed in children with SLI. Instead, gesture production scores were significantly related to language ability in children with SLI. The authors interpreted these results to suggest that while gesturing is not significantly impacted in SLI, its association with motor and language abilities do not appear to be the same in children with SLI and TD children.

Using a different methodological approach, the second study also examined gesture production in relation to motor and language ability in children with SLI (Iverson & Braddock, 2011). Gesturing frequency and rate in narrative productions, and in fine and gross motor performance on the Battelle Developmental Screening Inventory (BDI; Newborg, Stock, Wneck, Guidubaldi & Suinick, 1994) and the Child Development Inventory (CDI; Ireton, 1992) were examined. The study found that, while not significantly different from TD children, children with SLI trended towards a greater frequency and rate of gesturing. Also as expected, performance on the four measures of motor ability, however, were significant different between children with SLI and TD children. Furthermore, regression analyses showed that the frequency of gesturing was negatively associated with expressive language ability in children with SLI. These findings were interpreted to suggest that gesture plays a compensatory role in SLI.

Based on these two studies, it appears that manual gestures may be unimpaired in SLI or at least may not be impacted by the motor deficits in this disorder (Botting et al., 2010; Iverson & Braddock, 2011). Alternatively, the aspects of gesturing that were examined in these studies may not have adequately captured the difficulties that children with SLI experience with gesturing, if difficulties truly exist.
1.6. Domain-general hypotheses of SLI

In the past, researchers have explored language-specific explanations of SLI, which suggest that mechanisms dedicated to language learning are affected in SLI (e.g. Rice & Wexler, 1996; van der Lely, 1996). Given that the impairments in SLI are not specific to language, many researchers have steered away from these language-specific hypotheses. Instead, domain-general hypotheses, which suggest that cognitive mechanisms involved in multiple areas of development are impaired, have received more consideration. Some of the suggested hypotheses include weak temporal perception (e.g. Tallal, Stark, & Mellits, 1985), reduced processing speed (e.g. Kail, 1994, Miller et al., 2001), limited working memory capacity (e.g. Gathercole & Baddeley, 1990; Montgomery et al., 2010), poor attention (e.g. Finneran, Francis & Leonard, 2009; Spaulding, Plante & Vance, 2008) and procedural memory impairment (Ullman & Pierpont, 2005). These hypotheses suggest that an underlying cognitive impairment may contribute to the language, motor and cognitive deficits observed in SLI.

1.6.1. Temporal processing

In the early 1980s, Tallal and colleagues suggested that weak temporal perception explained the language deficits in SLI. Temporal perception or processing refers to the ability to perceive time-based properties such as duration, time and rhythm of events (Studdert-Kennedy & Mody, 1995). A series of experiments examining the perception of auditory stimuli revealed that children with SLI had significant difficulties discriminating rapidly changing tones (Tallal & Piercy, 1973, 1974). This impairment was hypothesized to underlie the problems children with SLI exhibited with speech perception (Tallal & Piercy, 1974, 1975; Tallal & Stark, 1981). Tallal, Stark and Mellits (1985) further argued that assessment of the perception and production of nonverbal and speech cues could correctly identify children as typically developing or specific language impaired and that language difficulties in SLI could be treated by targeting their auditory temporal processing abilities. In recent years, however, studies have found that auditory processing deficits in SLI are (1) not limited to rapidly changing stimuli, (2) not observed in all individuals with SLI and (3) not linked to language impairment, but rather
associated with nonverbal ability (for review see Rosen, 2003). Given these findings, it does not appear that auditory deficits account for the language impairment observed in SLI. Furthermore, it is unclear how speech perception deficits could explain the limb motor impairments in SLI.

1.6.2. Processing speed

Limitations in processing speed have also been offered as an explanation for the deficits observed in SLI (Kail, 1994; Miller et al., 2001; Leonard et al., 2007). In the mid-1990s, Kail offered the generalized slowing hypothesis to explain the increased performance times in children with SLI relative to TD children on various tasks. He argued that the processes involved in completing a cognitive task, defined as: \( \text{Response Time (RT)} = a + b + c \), are slowed down by a common factor referred to as the slowing coefficient \( m \), in SLI: \( \text{RT} = ma + mb + mc = m(a + b + c) \). Given that speech rapidly changes in time, processing incoming linguistic information is degraded in children with SLI. Several studies found that children with SLI exhibit slower speeds of processing on linguistic tasks including picture matching, naming, truth-value judgment, grammaticality judgment and judging rhymes (Archibald & Gathercole, 2007; Lahey, Edwards & Munson, 2001; Miller et al., 2001; Montgomery, 2002; Leonard et al., 2007; Windsor & Hwang, 1999) as well as non-linguistic tasks including motor tapping and responding to the presence of a tone (Miller et al., 2001; Leonard et al., 2007; Windsor & Hwang, 1999). It is unclear the extent to which limitations in speed of processing account for the difficulties in motor ability that children with SLI experience.

1.6.3. Working memory

Theories of working memory suggest that both phonological short-term memory and general working memory are affected in SLI (Gathercole & Baddeley, 1990; Jonides, Lacey & Nee, 2005; Lum, Conti-Ramsden, Page & Ullman, 2012; Montgomery et al., 2010). General working memory is associated with the simultaneous processing and storage of information, including language (Montgomery, 2003). Baddeley (2003) argued that working memory is essential for acquiring vocabulary and grammatical structures. On measures of general working memory
such as the Competing Language Processing Task (CLPT; Gaulin & Campbell, 1994), a measure involving two tasks that are performed concurrently (e.g. a word recall task paired with a sentence comprehension task), children with SLI are unable to perform at levels comparable to TD children (Archibald & Gathercole, 2007; Ellis Weismer et al., 1999, Leonard et al., 2007; Montgomery, 2000a, 2000b). Phonological short-term memory is a capacity-limited memory system involved in the temporary maintenance of incoming phonological information (Baddeley, 2004). On tasks of nonword repetition, commonly used to measure phonological short-term memory, children with SLI perform significantly worse relative to their TD peers (Coady & Evans, 2008; Gathercole & Baddeley, 1990; Edwards & Lahey, 1998; Ellis Weismer et al., 2000; Estes et al., 2007; Montgomery, 1995). Moreover, phonological working memory has been found to account for variation in language performance of children with SLI (Leonard et al., 2007). It is important to note, however, that there is some debate on which processes the nonword repetition task measures (Estes et al., 2007). While some researchers use it as a measure of phonological working memory, others have used it as a measure of speech motor ability (Archibald et al., 2013) and speech motor planning (Stark & Blackwell, 1997). Given this variability in the measures used to assess working memory, it is unclear what impact working memory deficits have on the language and motor abilities of children with SLI.

1.6.4. Attention

Attention, a resource-limited system involved in general information processing, has been linked to language learning (e.g. Conner, Alber, Helm-Estabrooks & Obler, 2000). There is a significant amount of evidence in the SLI literature indicating that the attentional abilities of children with SLI are impaired (Ellis Weismer, Plante, Maura & Bruce, 2005; Finneran, Francis & Leonard, 2009; Marton, 2008; Noterdaeme, Amorosa, Mildenberger, Sitter & Minow, 2001; Spaulding, Plante & Vance, 2008; Willinger et al., 2003). These attention-based deficits include impulsive behaviour, such as responding to a question without listening to the question in its entirety, errorful performance, inability to inhibit habituated responses and increased reaction times (Finneran et al., 2009; Marton, 2008; Noterdaeme et al., 2001; Spaulding et al., 2008). A
functional magnetic resonance imaging study conducted by Ellis Weismer et al. (2005) revealed that while performing a linguistic listening span measure, children with SLI not only performed significantly worse than the TD controls, activation in brain regions associated with attention and language processing were also significantly reduced in children with SLI. Despite support for a relationship between the attention and language deficits in SLI, it is not clear whether attention deficits contribute to the language and motor impairment in SLI or whether the attention, language and motor impairments in SLI are the result of an underlying deficit (Redmond, 2005).

1.6.5. Procedural memory

The last of the hypotheses offered to explain the deficits in SLI is impairment of the procedural memory system or the Procedural Deficit Hypothesis (PDH; Ullman & Pierpont, 2005). The procedural memory system supports the learning of habitual cognitive and sensorimotor skills. With regards to motor ability, procedural memory supports the learning and automatization of motor skills ranging from day-to-day activities such as tying shoelaces to more complex skills such as playing an instrument. Furthermore, procedural memory has been linked to several processes associated with motor skill acquisition including motor sequence learning, sequence planning, visuo-motor adaptation and motor memory consolidation (Doyon et al., 2009).

Pertaining to language ability, procedural memory is argued to support the rule-based learning that is used to develop an individual’s grammar (Ullman, 2001, 2004). Ullman and Pierpont (2005), in their review of the SLI literature, argued that deficits in procedural memory could explain the described language and motor deficits in SLI.

Since the inception of the PDH, a handful of studies have examined motor sequence learning in children with SLI. These studies have found that children with SLI take significantly longer to learn a sequence of button-presses on a button-press task relative to TD children (Lum et al., 2014), thus supporting the PDH. Studies exploring other procedural motor processes such as visuo-motor adaptation, sequence planning and motor memory consolidation are scarce (these processes will be explained in greater detail in Chapter 3). A review of the studies that have
examined these processes has revealed conflicting findings for the visuo-motor adaptive abilities of children with SLI (Adi-Japha et al., 2013; Hsu & Bishop, 2014), inconclusive findings for motor memory consolidation in SLI (Hedenius et al., 2011; Hsu & Bishop, 2014) and no studies that directly investigate motor sequence planning in SLI. Though the PDH is the only hypothesis that directly predicts the language and motor deficits in SLI, it is controversial and not well understood.

To date, there is no consensus on a theory that explains the impairments in SLI. Though the aforementioned domain-general hypotheses can account for the language impairments in SLI, most of these hypotheses do not adequately explain the motor impairments observed in this clinical population. And while the procedural deficit hypothesis predicts motor deficits in SLI, we do not know enough about the motor impairments in SLI to determine whether the procedural deficit hypothesis holds merit as an explanation for this disorder. Therefore, a thorough investigation of the motor deficits in SLI is crucial.

1.7. Gaps in the literature

While we have a general understanding of the motor impairments in SLI (described in section 1.4.), there are a few issues that need to be addressed.

First, the literature lacks a comprehensive assessment of the motor abilities of children with SLI. To my knowledge, only one study has examined performance across different motor areas in the same sample of children with SLI (Brumbach & Goffman, 2014). This study, however, only examined children’s single word and phrase, and nonword productions, while productions of isolated speech sounds and sequences of non-speech oral movements were not assessed. To determine which general cognitive mechanism may be contributing to the motor impairments in SLI, it is important to establish whether children with SLI exhibit difficulties with isolated speech sounds, which in turn affect their sequence productions (i.e. word and phrase productions) or whether their issues surface only at the sequencing level. Also, it is crucial to establish whether deficits are observed across domains (speech and non-speech oral...
movements) or are exclusive to speech motor ability. Furthermore, SLI research has not identified, descriptively or qualitatively, the types of errors that children with SLI produce that differentiate them from typically developing children on motor tasks. For example, the outcome measures typically collected on standardized assessments of motor ability include time, speed or accuracy. While it is clear that children with SLI are slower or less accurate than TD children on a variety of motor tasks, it is not clear whether the child’s spatial orientation reduced their ability to maintain balance on a walking backwards task or whether a perseverative action caused them to be slower on a peg moving task. Examining the types of errors children make can inform us about the affected motor processes in SLI and bring us closer to identifying which cognitive mechanism(s) may be involved in SLI.

Second, the procedural deficit hypothesis (PDH; Ullman & Pierpont, 2005) requires further investigation. The procedural impairment in SLI has only been captured using button-press tasks, which brings into question the generalizability of these results onto skill-oriented motor skills such as tying shoelaces or riding a bicycle. Additionally, SLI studies exploring other procedural motor processes are either inconclusive (visuo-motor adaptation and motor memory consolidation) or do not exist (motor sequence planning). To specify the procedural deficits in SLI, these motor processes must be examined in children with this disorder.

Third, research suggests that the movements involved in picking up a cup are different from the movements used to communicate. Motor actions such as those needed to tie shoelaces involve a series of movements that come together to achieve a specific goal. Nonverbal forms of communication such as manual gestures, on the other hand, convey meaning and are a motoric representation of our thoughts (Cartmill, Beilock & Goldin-Meadow, 2012). Thus far, only two studies have examined the effects of the motor impairments in SLI on their gesture productions (Botting et al., 2010; Iverson & Braddock, 2011) and found evidence to suggest that fine motor abilities are related to the quality of children’s gesture productions. This finding, however, is not based on a direct examination of the motoric quality of children’s communicative gestures and
thus warrants the investigation of the communicative gesture productions of children with SLI to inform our understanding of the mechanisms underlying SLI.

1.8. Thesis studies and goals

The primary objective of my dissertation was to characterize the motor deficits in SLI. The first study aimed to establish parallels between the verbal and nonverbal deficits in children with SLI to determine which general cognitive mechanism(s) may be contributing to the motor impairments in SLI. To meet this objective, this study systematically examined the gross, fine, oral motor and speech motor abilities of children with and without SLI using two standardized assessments of verbal and nonverbal motor ability. The quality of children’s movements were examined using (1) an error coding protocol to determine what aspects of their limb movements contributed to their performance on the nonverbal motor measure and (2) a custom scoring procedure for the verbal motor measure to determine what features of oral and speech motor ability were challenging for children with SLI.

The second study aimed to explore the procedural motor abilities of children with SLI to determine whether the procedural deficits in SLI are specific to motor sequencing. To achieve this goal, this study examined sequence planning and execution, adaptation and retention in children with and without SLI using two sequence-based and one non-sequenced based tasks of procedural motor ability.

The third study aimed to analyze the quality of the manual communicative gesture production in children with SLI to establish whether the motor impairment in SLI impacts spontaneous movements. To address this gap in the literature, this study examined the temporal characteristics of gesture-speech productions in children with and without SLI.
Chapter 2

A Comprehensive Assessment of the Motor Abilities of Children with Specific Language Impairment

This manuscript has been submitted for publication in the Journal of Speech, Language, and Hearing Research (under review, second round)

Abstract

**Purpose:** This study compared the motor abilities of children with specific language impairment (SLI) and typically developing (TD) children to bring us closer to understanding the underlying impairment of SLI.

**Method:** Standardized measures of gross, fine, oral motor and speech motor ability were administered to 17 children with SLI (ages 8-12) and 18 age-matched TD children. Errors produced while performing gross and fine motor tasks were coded for each child.

**Results:** Children with SLI experienced difficulties with aspects of gross, fine and speech movements, but not oral movements. In particular, children with SLI exhibited significant difficulties with manual dexterity, balance and sequence productions of speech sounds.

**Conclusions:** Impairment of the motor sequence planning and execution, and adaptation processes may explain their performance on these measures, which is suggestive of a procedural memory deficit in SLI.

**Key Words:** specific language impairment, developmental disorders, speech motor control, children
2.1. Introduction

Specific language impairment or SLI is a developmental disorder characterized by deficits in language development in the absence of other disabilities. Currently, the cause of this disorder is unknown and cannot be explained by acquired neurological damage, hearing loss, frank oral motor dysfunction or social disorders (Leonard, 1998, 2014). Children with SLI exhibit particular difficulty with the processing and production of grammatical structures, while other areas of language are less affected (e.g. Rice & Wexler, 1996; Ullman & Gopnik, 1999; Riches, Loucas, Baird, Charman & Simonoff, 2010). Contrary to the name of this disorder, studies have reported subtle deficits in nonverbal areas as well (reviewed in Leonard, 2014).

The presence of these co-morbid nonverbal deficits has changed the focus of SLI studies from examining purely language-specific explanations to exploring domain-general hypotheses. These hypotheses suggest that general mechanisms shared across multiple areas of cognition including language, are impaired in SLI. In our recent review, we synthesized research reporting motor deficits in SLI and argued that these deficits provide a unique window into the potential domain-general cognitive impairment in these children (Sanjeevan et al., 2015). Therefore, in the current experimental study, we examined the motor deficits in SLI to establish the parallels between language and motor ability.

2.1.1. Motor deficits in SLI

SLI studies have reported deficits in a wide range of motor areas. This includes (1) gross motor function (Finlay & McPhillips, 2013; Flapper & Schoemaker, 2013; Hill, 1998; Marton, 2009; Powell & Bishop, 1992; Vukovic, Vukovic & Stojanovik, 2010; Zelaznik & Goffman, 2010), (2) fine motor ability (Finlay & McPhillips, 2013; Flapper & Schoemaker, 2013; Iverson & Braddock, 2011; Owen & McKinlay, 1997; Powell & Bishop, 1992; Zelaznik & Goffman, 2010), and (3) speech motor control (Archibald, Joanisse & Munson, 2013; Brumbach & Goffman, 2014; Andrade, Befi-Lopes, Juste, Cáceres-Assenço & Fortunato-Tavares, 2014; Goffman, 1999, 2004).
Gross motor skills involve the movement and coordination of large muscle groups including the arms, legs and whole body (Encyclopaedia of Children’s Health, 2015). These skills support abilities such as balance, walking, and running and more complex actions such as catching a ball or riding a bicycle. Standardized measures that examine gross motor ability such as the Bruininks-Oseretsky Test of Motor Proficiency – Second Edition (BOT-2; Bruininks & Bruininks, 2005) include tasks like standing on one leg, walking on a balance beam, and catching a bounced ball (Zelaznik & Goffman, 2010). Studies have reported significantly lower numbers of successful attempts on these types of tasks for children with SLI in comparison to typically developing (TD) children (Finlay & McPhillips, 2013; Flapper & Schoemaker, 2013; Powell & Bishop, 1992; Vukovic et al., 2010; Zelaznik & Goffman, 2010).

Fine motor skills involve the coordination of muscle movements in the fingers, hands and wrists to perform small and exact movements (Encyclopaedia of Children’s Health, 2015). These skills support day-to-day actions like buttoning clothing, tying shoelaces and writing. Standardized assessments that examine fine motor ability such as the Movement Assessment Battery for Children (MABC-2; Henderson, Sugden & Barnett, 2007) include timed tasks like tracing, moving pegs and threading lace. Several studies have reported that children with SLI are less accurate and take significantly longer to complete these and other related tasks in comparison to TD children (Finlay & McPhillips, 2013; Flapper & Schoemaker, 2013; Iverson & Braddock, 2011; Powell & Bishop, 1992; Zelaznik & Goffman, 2010).

Speech is a complex motor activity that involves neurocognitive and neuromotor innervation to the muscles of the respiratory, phonatory, resonatory and articulatory systems (Duffy, 2013; Smith & Zelaznik, 2004). Standardized assessments of speech motor ability such as the Kaufman Speech Praxis Test (KSPT; Kaufman, 1995) include the imitation of oral movements and the production of single and complex sounds and words. Measures such as rate, consistency and speech intelligibility are used to assess whether a child’s speech motor function is within normal range.
While frank speech motor deficits are an exclusion criterion for SLI (Leonard, 1998, 2014), subtle deficits in speech motor ability have been observed in children with this disorder (Archibald et al., 2013; Brumbach & Goffman, 2014; Goffman, 1999, 2004). These studies have reported that children with SLI have significantly less control of their articulatory movements relative to TD children in their repetitions of both nonsense (Archibald et al., 2013) and real words (Brumbach & Goffman, 2014; Goffman, 1999, 2004).

2.1.2. Cognitive theories of SLI

As discussed in the previous chapter, there are four hypotheses of SLI that have received serious consideration. These hypotheses are based on the notion that a central underlying cognitive deficit may contribute to the language impairments and impairment in certain nonverbal tasks observed in SLI. Some of the suggested hypotheses concerning the nature of the domain general deficit include processing capacity limitations in the form of limited processing speed (e.g. Kail, 1994, Leonard et al., 2007; Miller et al., 2001), working memory capacity (e.g. Gathercole & Baddeley, 1990; Leonard et al., 2007; Montgomery et al., 2010), or attention (e.g. Finneran, Francis & Leonard, 2009; Spaulding, Plante & Vance, 2008); or deficits in the procedural memory system (Ullman & Pierpont, 2005). A few of these hypotheses could explain motor deficits as well as language impairments SLI.

A basic premise in the processing capacity limitation theories is that children with SLI exhibit limitations in resources available for temporarily maintaining information in memory or the speed with which information is processed (e.g. Leonard et al., 2007). Several studies suggest that children with SLI exhibit generalized slowing across linguistic (e.g. Archibald & Gathercole, 2007; Lahey, Edwards & Munson, 2001; Miller et al., 2001; Montgomery, 2002), nonverbal cognitive and motor areas (e.g. Miller et al., 2001; Leonard et al., 2007; Windsor & Hwang, 1999). Based on these findings, it was expected that primary deficits in processing speed would manifest as longer task completion times irrespective of motor area. Moreover, complex tasks such as building a structure from individual parts, which involve greater processing demands, should take longer than simpler tasks such as placing pegs on a pegboard.
Apart from typical speed-accuracy trade-offs, children with SLI were expected to exhibit slow but accurate movements across different tasks.

Other theories have argued that the primary capacity challenge in SLI involves limitations in processing and temporarily maintaining incoming information in working memory, either in the form of more general memory or restricted to phonological short-term memory (e.g. Gathercole & Baddeley, 1990; Lum, Conti-Ramsden, Page & Ullman, 2012; Montgomery et al., 2010). Children with SLI have exhibited difficulties in recall and accuracy on measures of general working memory such as the Competing Language Processing Task, a measure involving two tasks that are performed concurrently (e.g. Archibald & Gathercole, 2007; Leonard et al., 2007; Montgomery, 2000a, 2000b) and tasks of nonword repetition, commonly used to measure phonological short-term memory. If motor deficits in SLI were primarily explained by phonological memory, it was expected that difficulties would be restricted to the production speech sounds and not extend to non-linguistic movements. If the primary deficits involved more general working memory capacity limitations, we expected to see difficulties that were specific to more complex tasks such as those involving multi-step maneuvers or problem-solving.

Yet another form of capacity limitation, restrictions in attention, has been linked to language learning (e.g. Conner, Alber, Helm-Estabrooks & Obler, 2000). There is considerable evidence that children with SLI exhibit attentional difficulties including reduced accuracy, increased reaction times, perseveration of habituated responses and impulsive behaviour (Finneran et al., 2009; Marton, 2008; Noterdaeme et al., 2001; Spaulding et al., 2008). Given that children with SLI can be easily distracted and have difficulty inhibiting habituated responses, it was expected that motor accuracy may be hindered by perseverative errors including the repetitive use of one’s dominant hand on a trial attempt that requires the use of one’s non-dominant hand, or unsustained errors such as dropping task materials. These errors would be observed across different motor tasks.
The last and relatively new hypothesis put forward to explain the impairments in SLI is procedural memory impairment (Ullman & Pierpont, 2005). Procedural memory supports the acquisition of habitual cognitive and sensorimotor skills including simple movements such as balance and complex actions such as riding a bicycle. Though procedural memory is often associated with acquired skills, it is also involved with skill learning. During the acquisition stage of motor learning, we know that the procedural memory system underlies (1) sequence planning, specifying the sequence of actions needed to perform a novel skill; (2) sequence execution, implementing the sequence of actions; (3) adaptation, adjusting the movements to ensure the intended result is achieved and; (4) memory consolidation, developing the motor memory that allows for automatic execution of the learned skill (Doyon et al., 2009; Ullman, 2004; Ullman & Pierpont, 2005). In language ability, procedural memory arguably underlies rule-based learning that is hypothesized to support grammar learning (Ullman, 2001, 2004).

After an extensive review of the SLI literature, Ullman and Pierpont (2005) argued that the unique profile of language and motor deficit in SLI could be explained by a procedural sequencing impairment.

Efforts to substantiate this hypothesis have been limited to studies exploring the sequence learning and execution in children with SLI. Consistent with the procedural hypothesis, these studies have consistently reported that children with SLI take longer to learn a sequence of button-presses on a button-press task in comparison to their TD peers (Lum et al., 2014). Studies exploring other procedural motor processes are severely limited. To my knowledge, studies examining motor adaptation are few in number, but suggest that the visual-motor adaptation abilities of children with SLI are unaffected (e.g. Hsu & Bishop, 2014). Studies exploring motor memory consolidation are inconclusive. While one study has suggested that the consolidative abilities are affected in SLI (Hedenius et. al. 2011), another study has suggested that consolidation is unimpaired (Hsu & Bishop, 2014). The sequence planning abilities of children with SLI are unclear given that no studies have directly investigated this motor process in SLI. If primary deficits in procedural memory explained the motor difficulties in SLI, it was expected that tasks involving sequence-specific information would be difficult for children with
SLI, while other tasks that are not dependent on sequencing were left relatively unimpaired. If visual-motor adaptive difficulties exist, we predicted to observe issues related to spatial orientation such as being unable to orient their hands in the correct position to catch a ball. We also expected to observe difficulties with balance as evidenced by a greater need for external aids (e.g. body part) for support.

2.1.3. Study aims

To summarize, studies have established that children with SLI exhibit difficulties with gross and fine movements. There is also preliminary evidence of subtle speech motor deficits in SLI. Given that the domain-general hypotheses of SLI predict different profiles of motor impairments, it is critical to examine performance on a broad range of motor tasks across different motor areas in the same sample of children with SLI. To our knowledge, only one study, conducted by Brumbach and Goffman (2014), has explored the gross, fine and speech motor abilities of children with SLI. Their exploration of children’s speech motor abilities, however, only included an assessment of single word, phrase, and nonword productions, while productions of isolated speech sounds and sequences of non-speech oral movements were not examined. Analyzing isolated speech sounds can help determine whether children with SLI have difficulties executing isolated movements, which in turn affect their sequenced movements (e.g. word and nonword productions) or whether problems only arise at the level of sequencing. It is additionally important to establish whether these difficulties are observed in the productions of non-speech oral movements, both in isolation and in sequences, to determine whether difficulties are specific to the speech domain or extend to oral movements. Furthermore, SLI research has not qualitatively examined the types of errors that children with SLI produce that differentiate them from typically developing children on motor tasks. While it is understood that children with SLI are less accurate or slower than TD children on a range of motor tasks, it is unknown whether a child’s inability to sustain attention contributed to their longer completion times on a thread lacing task or whether a child’s atypical arm orientation reduced their accuracy on a ball catching task. Supplementing quantitative analyses with analyses exploring
the types of errors produced on motor tasks and the task features that elicit these errors will allow us to specify the parallels between their verbal and nonverbal motor impairments, and gain insight on which cognitive processes may be contributing to the motor deficits in SLI.

To characterize the motor deficits in SLI, we examined the fine, gross, oral motor and speech motor skills of children with SLI and TD children by (1) administering standardized assessments of nonverbal and verbal motor ability, (2) comparing the types of errors produced on tasks of gross and fine motor ability and, (3) identifying which aspects of oral motor and speech motor ability were challenging for children with SLI.

If the motor deficits in SLI were a result of reduced processing speed, we expected to find that children with SLI would be significantly slower at completing complex tasks across different areas of motor ability relative to their TD peers. If phonological working memory impairments explained the deficits in SLI, we expected to find that children with SLI would experience difficulties exclusive to speech motor tasks. A more general working memory deficit, however, may result in errors on tasks involving longer multi-step procedures. If the underlying impairment in SLI was reduced attention capacity, we expected to observe perseverative behaviours and deviation from the task at hand as a consequence of being distracted and unable to sustain attention. Finally, if deficits in procedural memory contributed to the impairments in SLI, we expected that children would have difficulties with sequence-based tasks across different motor areas, spatial orientation and use of body parts and objects to aid balance.

2.2. Methods

2.2.1. Participants

Typically developing children were recruited from the Toronto District School Board (TDSB) elementary schools located in downtown Toronto. Recruitment letters outlining the details of the experiment were distributed to children between the third and sixth grades. Children with SLI were also recruited through the TDSB. The TDSB identified children who were currently receiving services for language difficulties and mailed recruitment letters to the home addresses
of those children. For both children with SLI and TD children, interested families were asked to contact the laboratory and children who passed a short screening questionnaire were scheduled to participate in the study.

Thirty-five children (ages 8;3 – 12;4), including 17 with SLI and 18 age-matched TD controls, participated in this study. Children completed several sessions associated with a larger project and were later invited back (M = 12.38, SD = 5.51) for additional oral and speech motor testing. Participants who returned a year or more later had their language abilities reassessed. Eight participants, however, did not return for the additional session, reducing our sample size to 27 children (ages 8;3 – 12;4), including 13 SLI and 14 age-matched TD controls, for the speech motor measure.

The children in the SLI group had been receiving services for language-related difficulties. The children in the TD group, however, must not have had any history of receiving language- or learning-related services. All of the participants met the following inclusionary criteria: (1) monolingual speakers of English based on parental report, (2) no frank neurological damage based on parental report, (3) scored at or above 75 on the nonverbal index of the Wechsler Abbreviated Scale of Intelligence – Second Edition (WASI-II; Wechsler, 2011) as a measure of nonverbal intelligence, (4) passed a hearing screen at 500, 1000, 2000, and 4000 Hz and 20 dB HL (ASHA, 2014), (5) no emotional or social disorders based on parental report, and (6) no frank oral motor or speech dysfunction based on parental report. At the time this study was conducted, the language abilities of each child was assessed using the Clinical Evaluation of Language Fundamentals – Fourth Edition (CELF-4; Semel, Wiig, & Secord, 2003), the Peabody Picture Vocabulary Test – Fourth Edition (PPVT-4; Dunn & Dunn, 2007) and the Expressive Vocabulary Test – Second Edition (EVT-2, Williams, 2007) to confirm each child’s group status. Descriptive statistics and group differences on these diagnostic measures are presented in Table 1.
Table 1. Descriptive statistics for ages and standardized IQ and language test scores

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

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

<sup>a</sup> Wechsler Abbreviated Scale of Intelligence – Second Edition: Perceptual Reasoning Index Composite Score; <sup>b</sup> Clinical Evaluation of Language Fundamentals – Fourth Edition: Core Language Score; <sup>c</sup> Clinical Evaluation of Language Fundamentals – Fourth Edition: Receptive Language Score; <sup>d</sup> Clinical Evaluation of Language Fundamentals – Fourth: Expressive Language Score; <sup>e</sup> Peabody Picture Vocabulary Test – Fourth Edition: Standard Score; <sup>f</sup> Expressive Vocabulary Test – Second Edition: Standard Score; * p < .05, ** p < .01

The language profiles of the children with SLI were as follows: (1) no children exhibited vocabulary-only impairments as indexed by standard scores below 1.25SD on the PPVT-4 and/or EVT-2 and within normal range on the remaining language measures, (2) five children had receptive-only language difficulties as indexed by standard scores below 1.25SD on the Receptive Language Index (RLI) on the CELF-4 and within normal range on the Expressive Language Index (ELI) on the CELF-4, (3) four children had expressive-only language deficits as indexed by standard scores below 1.25SD on the ELI and within normal range on the RLI, (4) five children exhibited receptive and expressive language impairments as indexed by scores
below 1.25SD on both of the RLI and ELI and within normal range on the PPVT-4 and EVT-2 and, (5) three children had vocabulary and language difficulties as indexed by scores below 1.25SD on either the PPVT-4 or EVT-2 and scores below 1.25SD on either the RLI or ELI.

2.2.2. Procedure and stimuli

2.2.2.1. Standardized measures of verbal and nonverbal motor ability

Children’s nonverbal motor abilities were assessed using the Movement Assessment Battery for Children – Second Edition (MABC-2; Henderson et al., 2007), a standardized norm-referenced measure of gross and fine motor skill. The MABC-2 was developed to identify difficulties or delays in gross and fine motor development in children. The inter-rater reliability and test-retest reliability across the items of the MABC-2 were high with an average intra-class correlation coefficient of 0.97 and 0.80, respectively. The MABC-2 manual reports that a panel of experts in the content area judged content validity. These experts deemed the MABC-2 to adequately represent the abilities being measured (Henderson et al., 2007).

The MABC-2 includes eight tasks that are divided into three sections: Manual Dexterity, Aiming and Catching, and Balance. The Manual Dexterity section examines the coordination of a child’s hands and eyes when performing spatially and temporally-confined fine motor 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). For the first two tasks, performance is based on completion times. For the first task only, both hands were tested separately. For the third task, performance is based on the number of times the drawn line falls outside of the trace.

The Aiming and Catching section assesses a child’s coordination and timing of spatially-demanding gross movements. The tasks in this section include: catching a ball with two hands (ages 8-10) or one hand (ages 11-12) and throwing a beanbag onto a mat target (ages 8-10) or a ball at a wall target (ages 11-12). For both tasks, performance is 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-toe forwards (ages 8-10) or backwards (ages 11-12) on a line, and hopping on mats (ages 8-10) or zigzag hopping (ages 11-12). For the first task, performance is based on the length of time a child is able to balance. For children between the ages of 8-10, both feet were tested separately. For the second task, scores are assigned based on the number of successful consecutive steps walked along the line up to a maximum of 15 steps or the entire line, whichever the child reaches first. For the last task, performance is based on the number of successful continuous hops that land in the center of 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.

Children’s speech motor skills were assessed using the Verbal Motor Production Assessment for Children (VMPAC; Hayden & Square, 1999), a standardized measure of oral motor and speech motor ability. It was developed to identify whether difficulties or delays in children with speech motor difficulties are influenced by a motor disruption. The inter-rater reliability and test-retest reliability across the items of the VMPAC were high, with an average reliability coefficient of 0.97 and 0.89, respectively. With regards to content validity, the VMPAC manual discusses the relevance of including each item in the assessment in relation to the speech motor literature. Given the cited evidence, the tasks in the assessment appear to adequately represent the abilities being measured (Hayden & Square, 1999).

The VMPAC includes eight tasks that are divided into three main sections: General Motor Control, Focal Oromotor Control and Sequencing. The General Motor Control section examines the postural, respiratory and phonatory support required for speech production. This section includes 20 items that evaluate posture, and functions such as mouth opening, biting, and chewing. For the items in this section, the child receives a score of 0 (unsuccessful) or 1 (successful) in accordance with their ability to perform the requested movement.
The Focal Oromotor Control section was designed to test the control of the jaw, lips and tongue to produce speech and non-speech oral movements. This section includes 23 items that assess single oromotor non-speech movements, such as smiling and sticking out your tongue, and single oromotor speech movements, such as productions of vowels and consonants such as /i/ and /p/, respectively. For the items in this section, the child receives a score of 0 (severely imprecise), 1 (partially imprecise) or 2 (completely precise) in relation to their precision of execution of the requested movements. Some of the vowel and consonant items also assess consistency across 4 repetitions (e.g. /p/-/p/-/p/-/p/), which is assigned a score of 0 if the repetitions are inconsistent or 1 if they are all consistent.

The third section of the VMPAC is Sequencing, which examines the ability to produce speech and non-speech movements in a particular sequence. This section includes 23 items that evaluate paired oromotor non-speech movement sequences, such as blowing and then kissing, and double and triple speech movement sequences such as producing the sequence /o/-/u/-/i/. For the items in this section, the same score assignment for the Focal Oromotor Control section is implemented in addition to a second set of scores that assess sequence maintenance. The child receives a score of 0 if less than half of the items are in the correct sequence, 1 if more than half of the items are in the correct sequence and 2 if all of the items are in the correct sequence. For each item across all three sections, raw scores were converted into percent scores by dividing the child’s raw score from the maximum raw score that could be achieved for each section.

The VMPAC also consists of two supplemental sections, Connected Speech and Language Control, and Speech Characteristics. The Connected Speech and Language Control section examines changes in motor control while producing a narrative sample. In the Speech Characteristics section, the normality of several aspects of speech including pitch, prosody, rate etc. are judged throughout the testing session (Hayden & Square, 1999). Given that the supplemental sections of the VMPAC assess speech motor control as a function of language complexity, only performance on the General Motor Control, Focal Oromotor Control and Sequencing sections were analyzed.
The first author and two other PhD students, who were not blinded to participant diagnosis, administered these measures. All administrators were trained on the MABC-2 and VMPAC using training videos. A speech-language pathologist was also available to address any questions or concerns with regards to administration of these assessments. Video recordings of children’s performances were also obtained.

2.2.2.2. Coding for error types

A coding system was used to describe the types of errors produced while performing tasks on the MABC-2. This system was based on an error coding protocol developed by Hill et al. (1998) to qualitatively examine imitated movements of children with SLI. In developing this protocol, inter-rater reliability was conducted on fourteen error types. Across six naïve raters, seven categories achieved an acceptable amount of agreement, five error categories achieved a low amount of agreement and two categories could not be analyzed because no instances of either error were observed in any of the children’s responses (Hill et al., 1998). When selecting the error categories to use in this study, we considered the nature of the MABC-2 tasks and the predictions that were made in relation to the domain-general hypotheses of SLI. Given these criteria, we selected five error categories. These error types are described further in Table 2.

To code the errors, video recordings of the participants’ performances on each task of the MABC-2 were obtained and later reviewed for these error types. To count error frequency, the procedure developed by Hill et al. (1998) was used. In this procedure, if a specific action met the criteria for an error type listed in the coding protocol, raters were asked to write down the error type and the frequency with which it was observed in the task.

For example, if a child repeated a previous action, such as stepping forward with the same foot on the walking heel-to-toe task, the action was identified as a perseveration error. Raters were also informed that (1) more than one error type could be coded for a single action, (2) not every error type had to be observed in a video and, (3) correct performances were possible (Hill et al., 1998). A complete coding protocol with examples for each error type can be found in the Appendix.
<table>
<thead>
<tr>
<th>Type of error</th>
<th>Description</th>
<th>Hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Part Aid</td>
<td>Uses a different body part in attempt to complete a task, other than what was required</td>
<td>Balance difficulties associated with procedural memory deficits</td>
</tr>
<tr>
<td>Perseveration</td>
<td>Repeats a previous action</td>
<td>Difficulty with inhibiting habitual movements associated with attention deficits</td>
</tr>
<tr>
<td>Spatial Orientation</td>
<td>Body position deviates from the appropriate spatial position</td>
<td>Visual-motor adaptation difficulties associated with procedural memory deficits</td>
</tr>
<tr>
<td>Target Mislocation</td>
<td>Completes task, but final position is incorrect</td>
<td>Difficulty with processing multi-step tasks associated with working memory deficits</td>
</tr>
<tr>
<td>Unsustained</td>
<td>Movement starts accurately, but quickly deteriorates as indicated by dropping task materials or falling</td>
<td>Difficulty with sustaining attention</td>
</tr>
</tbody>
</table>

Two coders independently coded errors for 20% of the participants. For the frequency of errors produced, a percent agreement of 85%, 94% and 90% was achieved for the Manual Dexterity, Aiming and Catching and Balance sections, respectively. For the classification of error type, a percent agreement of 100% for perseveration errors, 80% for spatial orientation errors, 82% for target mislocation errors and 91% for unsustained errors was achieved. A percent agreement of 76% was achieved for body part aid errors. As a result, coders reached consensus agreement on each of the body part aid errors.

2.2.2.3. VMPAC comparisons

We deconstructed the main sections of the VMPAC and re-categorized items to examine variables that impact children’s speech production and are not currently captured by the VMPAC’s scoring system. In the Focal Oromotor Control and Sequencing sections, for example, performance on non-speech oral and speech items are combined into a single score. For the purposes of this study, examining non-speech oral and speech productions separately
can inform the phonological working memory hypothesis of SLI. Similarly, isolated and sequence productions are on the VMPAC are combined into a single score. Separate analyses of these production types allowed us to establish whether problems arise at the sequencing level and inform the procedural deficit hypothesis. Given that the VMPAC does not test sequences of 3 non-speech oral items like it does for the speech items, only sequences of 2 non-speech and 2 speech items were compared between groups.

2.2.4. Statistical analyses

A series of analyses of covariance (ANCOVAs) were conducted to address the aims of this study. First, performance on sections of the MABC-2 and VMPAC was compared between the SLI and TD groups. This comparison was done by examining the effects of section (sections of the standardized assessments) and group (SLI and TD) on standard scores on the MABC-2 followed by a second analysis examining the same effects on percent scores on the VMPAC. Next, the types of errors produced on the MABC-2 were compared between the SLI and TD groups. This comparison was achieved by examining the effects of error type (see Table 2), section and group on the frequency of errors produced. Finally, the performance on non-speech oral and speech items in single and sequence productions was compared between the SLI and TD groups. This comparison was done by examining the effects of item type (non-speech oral and speech), production type (single and sequence) and group on percent scores on the VMPAC. In each of these comparisons, nonverbal IQ was entered as a covariate to control for significant differences in IQ between groups.

Prior to conducting these 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 and error-type data violated the ANCOVA assumption of equal variances. Therefore, the Greenhouse-Geisser corrections were used for these data. Furthermore, the covariate, nonverbal IQ, was found to be linearly and positively related to performance on the MABC-2 and VMPAC for both SLI and TD groups, fulfilling the remaining assumptions required for an ANCOVA.
Additionally, the MABC-2, VMPAC and error type data was examined for outliers. Data points that were more than 1.5 interquartile ranges below the first quartile and above the third quartile were identified as outliers. No outliers were identified for the MABC-2 or the VMPAC. For the error type data, 1 outlier (in TD group) was identified for the spatial orientation error type in the Balance section. In the Manual Dexterity error type data, 4 outliers were identified: 2 (1 in the SLI group, 1 in the TD group) for the perseveration error type and 2 (1 in the SLI group, 1 in the TD group) for the unsustained error type. These outliers were not used in the analysis.

2.3. Results

2.3.1. Performance on the MABC-2 and VMPAC

Descriptive statistics and group differences on the MABC-2 and VMPAC are presented in Table 3. Our first set of analyses compared performance on sections of the MABC-2 and VMPAC between the SLI and TD groups. On the MABC-2, the analysis showed that there was a significant interaction between section and group, $F(2, 64) = 3.24, p = .046, \eta^2 = .092$, but no effect of group, $F(1, 32) = 2.40, p = .131, \eta^2 = .070$, after controlling for IQ. A closer examination of this interaction revealed that the SLI group scored significantly lower than the TD group on the Manual Dexterity, $F(1, 33) = 13.55, p = .001, \eta^2 = .291$, and Balance, $F(1, 33) = 12.42, p = .001, \eta^2 = .273$, sections on the MABC-2. Scores on the Aiming and Catching section, however, were not significantly different between the SLI and TD groups, $F(1, 33) = .132, p = .719, \eta^2 = .004$.

Next, performance on sections of the VMPAC between SLI and TD groups was compared. We found main effects of section, $F(1.23, 29.53) = 8.58, p = .003, \eta^2 = .263$, and group, $F(1.23, 29.53) = 11.64, p = .002, \eta^2 = .327$ and a significant interaction between section and group, $F(1.231, 29.53) = 11.92, p = .001, \eta^2 = .332$, after controlling for IQ. Further exploration of this interaction showed that the SLI group scored significantly lower than the TD group on the Focal Oromotor Control, $F(1, 24) = 9.94, p = .004, \eta^2 = .284$ and Sequencing, $F(1, 24) = 37.82, p = \ldots$
Scores on the General Motor Control section reached ceiling for both of the SLI and TD groups.

Table 3. Descriptive statistics for performance on the MABC-2 and VMPAC

<table>
<thead>
<tr>
<th></th>
<th>MABC-2</th>
<th>VMPAC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MD(^a)</td>
<td>AC(^b)</td>
</tr>
<tr>
<td><strong>SLI</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>5.47*</td>
<td>8.41</td>
</tr>
<tr>
<td>SD</td>
<td>2.18</td>
<td>2.92</td>
</tr>
<tr>
<td>Range</td>
<td>2-11</td>
<td>4-14</td>
</tr>
<tr>
<td><strong>TD</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>8.17*</td>
<td>8.78</td>
</tr>
<tr>
<td>SD</td>
<td>2.15</td>
<td>3.04</td>
</tr>
<tr>
<td>Range</td>
<td>5-11</td>
<td>2-13</td>
</tr>
</tbody>
</table>


2.3.2. Error type analysis

Our next analysis examined the types of errors produced by the SLI and TD groups while performing MABC-2 tasks. Because the SLI group differed significantly from the TD group on the Manual Dexterity and Balance sections, only these sections were examined further. The analysis showed a main effect of group, \(F(1, 28) = 7.27, p = .012, \eta^2 = .21\) and a significant three-way interaction between error type, section and group, \(F(1.54, 43.20) = 3.59, p = .047, \eta^2 = .114\), after controlling for IQ.
Table 4. Descriptive Statistics for Error Types on the Manual Dexterity and Balance Sections of the MABC-2

<table>
<thead>
<tr>
<th></th>
<th>Body Part Aid</th>
<th>Perseveration</th>
<th>Unsustained</th>
<th>Spatial Orientation</th>
<th>Target Mislocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual Dexterity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SLI</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>1.05</td>
<td>0.82</td>
<td>4.71</td>
<td>5.35</td>
<td>1.12</td>
</tr>
<tr>
<td>SD</td>
<td>1.30</td>
<td>1.42</td>
<td>3.42</td>
<td>3.12</td>
<td>1.22</td>
</tr>
<tr>
<td>Range</td>
<td>0-4</td>
<td>0-5</td>
<td>0-14</td>
<td>0-14</td>
<td>0-3</td>
</tr>
<tr>
<td><strong>TD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.72</td>
<td>0.5</td>
<td>2.83</td>
<td>4.17</td>
<td>0.94</td>
</tr>
<tr>
<td>SD</td>
<td>1.07</td>
<td>1.15</td>
<td>1.95</td>
<td>3.35</td>
<td>1.16</td>
</tr>
<tr>
<td>Range</td>
<td>0-3</td>
<td>0-4</td>
<td>0-7</td>
<td>0-12</td>
<td>0-4</td>
</tr>
<tr>
<td>* p &lt; .05, ** p &lt; .01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Body Part Aid</th>
<th>Perseveration</th>
<th>Unsustained</th>
<th>Spatial Orientation</th>
<th>Target Mislocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SLI</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>2.88*</td>
<td>0.12</td>
<td>4.53**</td>
<td>11.88</td>
<td>0.24</td>
</tr>
<tr>
<td>SD</td>
<td>3.60</td>
<td>0.33</td>
<td>1.91</td>
<td>9.01</td>
<td>0.75</td>
</tr>
<tr>
<td>Range</td>
<td>0-11</td>
<td>0-1</td>
<td>2-9</td>
<td>0-27</td>
<td>0-3</td>
</tr>
<tr>
<td><strong>TD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.44*</td>
<td>0.00</td>
<td>2.78**</td>
<td>4.89</td>
<td>0.33</td>
</tr>
<tr>
<td>SD</td>
<td>0.70</td>
<td>0.00</td>
<td>1.83</td>
<td>5.83</td>
<td>0.59</td>
</tr>
<tr>
<td>Range</td>
<td>0-2</td>
<td>--</td>
<td>0-6</td>
<td>0-19</td>
<td>0-2</td>
</tr>
<tr>
<td>*p &lt; .05, **p &lt; .01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Investigating the three-way interaction further revealed that on the Manual Dexterity section, the SLI group did not significantly produce any error type in greater frequency than the TD group. On the Balance section, however, children with SLI produced a greater number of body
part aid, $F(1, 33) = 7.93, p = .008, \eta^2 = .194$, spatial orientation, $F(1, 32) = 9.99, p = .003, \eta^2 = .238$, and unsustained errors, $F(1, 33) = 7.67, p = .009, \eta^2 = .189$, but were no different in the frequency of perseveration, $F(1, 33) = 2.26, p = .142, \eta^2 = .064$, and target mislocation, $F(1, 33) = 1.84, p = .671, \eta^2 = .066$, errors relative to the TD group (Table 4).

2.3.3. Non-speech versus speech items

In the last analysis, we aimed to explore the differences in performance on non-speech oral and speech items in single and sequence productions between the SLI and TD groups. Given that the SLI and TD groups performed at ceiling for single productions of non-speech oral and speech items, only sequence productions of both item types were explored. The analysis showed a significant two-way interaction between item type and group, $F(1.00, 24.00) = 4.76, p = .039, \eta^2 = .166$, after controlling for IQ. Examining this interaction further revealed that sequence productions of speech items were significantly different between groups, $F(1, 25) = 17.21, p = .000, \eta^2 = .408$, while sequence productions of non-speech items were not significantly different, $F(1, 25) = .324, p = .574, \eta^2 = .013$ (Table 5).

*Table 5. Descriptive Statistics for Sequence Productions of Non-Speech and Speech Items*

<table>
<thead>
<tr>
<th></th>
<th>Non-speech</th>
<th>Speech</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SLI</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>97.69</td>
<td>84.03**</td>
</tr>
<tr>
<td>SD</td>
<td>4.39</td>
<td>7.50</td>
</tr>
<tr>
<td>Range</td>
<td>90-100</td>
<td>75-100</td>
</tr>
<tr>
<td><strong>TD</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>98.57</td>
<td>94.64**</td>
</tr>
<tr>
<td>SD</td>
<td>3.63</td>
<td>6.21</td>
</tr>
<tr>
<td>Range</td>
<td>90-100</td>
<td>83-100</td>
</tr>
</tbody>
</table>

*p < .05, **p < .01
2.4. Discussion

The aim of this study was to characterize the motor deficits in SLI by (1) comparing performance on standardized measures of gross, fine, oral motor and speech motor ability between children with and without SLI, (2) exploring the types of errors produced by children with and without SLI while performing general motor tasks and, (3) identifying which aspects of speech motor ability were difficult for children with SLI. These aspects of motor ability were assessed to better understand the cognitive underpinnings of SLI.

On the Movement Assessment Battery for Children – Second Edition (MABC-2; Henderson et al., 2007), we found that children with SLI were significantly slower at completing the Manual Dexterity tasks and less successful at completing the Balance tasks relative to the TD children. Exploring the types of errors produced by children on these sections revealed that on the Manual Dexterity section, children with SLI were no different from the TD children in the types of errors produced. On the Balance section, however, children with SLI produced significantly more body part aid, spatial orientation and unsustained errors than TD children. Consistent with previous studies, the findings of this study suggest that children with SLI exhibit gross and fine limb motor deficits (e.g. Finlay & McPhillips, 2013; Flapper & Schoemaker, 2013; Iverson & Braddock, 2011; Vukovic et al., 2010; Zelaznik & Goffman, 2010).

On the Verbal Motor Production Assessment for Children (VMPAC; Hayden & Square, 1999), we found that children with SLI scored significantly lower than TD children on the Focal Oromotor Control and Sequencing sections. Further examining the items within these sections revealed that children with SLI were no different from TD children in their single or sequence productions of non-speech oral items. For speech items, however, only the sequence productions were more challenging for children with SLI, while single productions of these items were comparable to those of TD children. Replicating previous findings, this study suggests that children with SLI exhibit subtle deficits with speech production (Andrade et al., 2014; Archibald et al., 2013; Brumbach & Goffman, 2014; Goffman, 1999, 2004).
2.4.1. Affected cognitive processes in SLI

We predicted that if motor difficulties in SLI were a result of slow processing speed, we would observe slow movements across different motor tasks. Accuracy, on the other hand, would be relatively unaffected apart from speed-accuracy trade-offs. In fact, we found that children with SLI were slower, yet successful at completing the Manual Dexterity tasks relative to the TD children. Also, children with SLI and the TD children were comparable in the number of errors produced of each error type on these tasks. Although reduced processing speed can explain performance on the Manual Dexterity section, it is difficult to posit how it would explain the greater production of body part aid, spatial orientation and unsustained errors on the Balance section and the differences in consistency between sequence productions of non-speech oral and speech items on the VMPAC. It is, therefore, unlikely that slow speed of processing fully explains performance on the verbal and nonverbal motor tasks in the children with SLI.

If attention deficits affected the motor abilities in SLI, we expected to observe distracted performance with perseverative and unsustained errors across different motor tasks, which in turn could also compromise task completion times and accuracy. Not only do the longer task completion times on the Manual Dexterity section support this hypothesis, the greater number of unsustained errors on the Balance section of the MABC-2 does as well. We could also argue that reduced attention resulted in the imprecise productions on the Sequencing section of the VMPAC. We did not, however, find evidence of perseverative errors on either of the Manual Dexterity or Balance tasks, which we argued would be indicative of attention deficits. Also, children’s abilities with aiming and catching and steady sequence productions of the non-speech oral movements are not consistent with limitations in attention alone.

If children with SLI’s motor deficits were a result of phonological working memory impairments, we expected to see omissions of speech sounds in longer productions while exhibiting intact sequencing of non-speech oral movements. This prediction was borne out. Children with SLI were significantly less accurate in their sequence productions of speech
sounds, but were comparable in their non-speech oral sequence productions to TD children. Although this finding may be consistent with the nonword repetition literature (e.g. see Estes et al., 2007 for review), our findings further suggest that difficulties arise with much shorter sequences. That is, although, nonword repetition tasks used in previous studies commonly consist of nonwords that comprise 4-15 different sounds or 2-7 syllables (Estes et al., 2007), the sequence productions on the VMPAC that were analyzed in this study were much shorter and only examined 2-sound combinations. Thus, it is unlikely that phonological working memory limitations in the form of space available for temporary storage and processing explain the imprecise speech sequence productions observed in the present study. Additionally, if the underlying impairment was restricted to phonological working memory or processing, it is difficult to explain the observed challenges in manual dexterity and balance – tasks that are much unlikely to rely on these systems.

We expected that general working memory impairments would have affected performance on complex tasks such as those requiring maintaining and processing multiple steps, but not on simple single step tasks. Our results revealed longer completion times for the nuts and bolts task, which arguably involves planning which pieces to pick up first while simultaneously putting pieces together and therefore poses more demands on general working memory. However, difficulties were also observed on simpler tasks. On the placing/turning pegs task, we found that children with SLI exhibited significantly longer completion times than TD children and on the balance tasks such as standing on one leg, children with SLI performed poorly. Thus, general working memory deficits do not completely explain the observed overall profile of relative motor strengths and weaknesses.

The final explanation for the motor deficits in SLI we considered was procedural memory impairment. Deficits in this memory system were expected to primarily affect performance on tasks involving the execution of sequences across motor areas, but not the execution of similar movements when only one movement is required. Procedural memory deficits would also explain difficulties with visual-motor adaptation and balance. The accurate, but longer
completion times on the Manual Dexterity tasks and the consistent repetitions of isolated speech sounds and inconsistent repetitions of sequences of speech sounds on the VMPAC could be explained by sequencing deficits. For the Manual Dexterity tasks, children with SLI may not have planned or executed the most efficient sequence of movements. To further examine this explanation informally, performance on the placing and turning pegs task was further analyzed. It revealed that 8 of the children with SLI did not place and turn pegs in a logical sequential order on the pegboard (left to right, top to bottom or vice versa), but instead placed and turned pegs in a random order. On the VMPAC, children with SLI were capable of producing speech sounds in isolation indicating that the articulatory movements needed to produce those specific speech sounds were known to the children with SLI. However, when those same speech sounds were organized into sequences, the precision of their speech movements was significantly impacted.

While Ullman does not make specific predictions concerning the visual-motor adaptation abilities in SLI, we predicted that visual-motor adaptation difficulties may be observed given that this motor process is also supported by the procedural memory system. One might speculate that the higher frequency of body part aid, spatial orientation and unsustained errors on the Balance section of the MABC-2 may not only suggest difficulties with balance in general, but also potential deficits with visual-motor adaptation. Visual-motor adaptation involves the ability to, based on the outcomes of the first movements, modify future motor commands to improve the accuracy of subsequent movements in an ongoing sequence of movements (Doyon et al., 2009; Doyon, 2008). While children with SLI appear to initially be able to control their balance, they have difficulty orienting their bodies, or parts of it, to maintain balance. As a result, children with SLI rely on other parts of the body (e.g. the opposite foot on a one foot balance task) or objects (e.g. table or chair) to regain control of their balance and maintain it. This behaviour suggests that children with SLI have difficulties adjusting their ongoing movements and thus can be interpreted as a form of motor adaptation deficit. While difficulties with motor
adaptation are clearly explained by procedural memory impairment, it is difficult to conceive how other domain general hypotheses would account for them.

There are, however, some findings that are not consistent with our predictions that were based on the PDH. First, if children with SLI exhibit difficulties with visual-motor adaptation, why did children with SLI perform comparably to TD children on the Aiming and Catching section of the MABC-2? The Aiming and Catching section consists of tasks including catching a ball with one/two hands and throwing a ball/beanbag at a target. Presumably, to excel in these tasks requires trial-and-error type behaviour, where children regularly adjust their hand, arm and bodily movements to improve the accuracy of their catches and throws. One possible explanation is that the measures and tasks were not sufficiently sensitive or difficult to challenge the children with SLI and expose motor deficits. Another, potentially more relevant and optimistic, explanation is that the familiarity of the tasks contributed to their performance. These tasks simulate activities that school-aged children regularly engage in, perhaps during recess with friends or at home with siblings or parents. Thus, it can be speculated that these activities are motor skills that children with SLI and TD children had extensive practice at before. Because of this extensive practice, the children with SLI perform as well as their peers without SLI. In contrast, the skills that these individuals had shown deficits on, such as walking backwards heel-to-toe or building a triangular structure with nuts and bolts, are likely to be skills that they have not had previous experience with. This interpretation, therefore, suggests that difficulties exist earlier in the time-course of learning, specifically affecting new and unfamiliar motor skills. Although this interpretation is not entirely predicted by the PDH, the specificity of the motor deficits observed in this study is best explained by deficits in procedural learning and thus supports the PDH.

The familiarity hypothesis may have also contributed to the typical sequence productions of non-speech oral movements by the children with SLI on the VMPAC. The non-speech oral items consisted of commonly used actions such as blowing, smiling and kissing. Additionally, the items were paired in familiar sequences such as kissing followed by smiling and biting.
followed by opening your mouth. The speech sounds, on the other hand, were also familiar, but arranged in unusual and uncommon sequences in English such as /i/-/o/-/a/. As a result, children with SLI may have found it easier to produce the paired sequence of non-speech oral items as they may already be well practiced and require less cognitive effort to organize, control and execute.

2.4.2. Limitations

While the findings of this study significantly contribute to our understanding of the motor deficits in SLI, there are a couple of limitations that must be taken into consideration when interpreting the results.

The first limitation concerns the non-speech oral items on the VMPAC. The items used to assess non-speech oral motor ability included movements such as blowing (involving a simple rounding of the lips) and exertion of air and opening one’s mouth (involving creating space between the top and bottom lips). It is, therefore, possible that these movements were not difficult enough to yield differences in precision or consistency between the children with SLI and the TD children. Furthermore, the non-speech oral movements were arranged into pairs to examine sequencing. Thus, the length of the sequence may have been too short to affect children’s performance on this measure. To address this limitation, future research should explore children’s productions of invented non-speech oral movements in longer sequences to determine whether deficits are specific to the speech domain or span across both speech and non-speech motor areas.

The second limitation involves the descriptive nature of this study. This less hypothesis-driven approach was adopted and required because this project is a first step towards clarifying the cognitive deficits that underlie motor difficulties in SLI. Now that there is initial evidence from this study that the profile of strengths and weaknesses is arguably best captured by the procedural deficit hypothesis, future research should examine this hypothesis as the explanation for motor deficits in SLI with more targeted and hypothesis-driven tasks.
2.5. Conclusions

The present study examined the motor deficits in children with SLI to inform general cognitive explanations of SLI. Given the findings of this study, procedural memory deficits appear to best explain children’s performance on verbal and nonverbal motor tasks in SLI. The types of errors produced, or lack thereof, on the Manual Dexterity sections of the MABC-2 coupled with the selective difficulties with sequence productions of speech items on the VMPAC can be interpreted to suggest that children with SLI primarily exhibit problems with motor sequencing. In addition, the errors produced on the Balance section of the MABC-2 have been interpreted to indicate subtle visual-motor adaptation difficulties as well. Given that the assessments used in this study were not direct measures of these processes, future studies examining these motor processes are needed to better specify the nature of the procedural memory deficits in SLI and determine whether procedural motor abilities are related to language ability. This next step is critical so that services delivered to these children can target these processes, improve their learning capacity and over time, their language and motor abilities.
**Appendix A. Error type coding manual (modified from Hill et al., 1998)**

<table>
<thead>
<tr>
<th>Error Category</th>
<th>Definition of Error</th>
<th>Coding Instructions</th>
<th>Examples of Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Part Aid</td>
<td>Uses different body parts to help complete task, other than what is required</td>
<td>Score as error if any of the following criteria are met:</td>
<td>Balance board</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a) Uses opposite hand during a one-sided hand trial</td>
<td>▪ Touches opposite foot to ground for less than a second to steady oneself</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Uses opposite foot during a one-sided foot trial</td>
<td>▪ Rests opposite foot on top of foot that is being used for task</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c) Upper and/or torso makes contact with task materials (e.g. ball)</td>
<td>Ball catch</td>
</tr>
<tr>
<td></td>
<td></td>
<td>d) Opposite hand blocks child in attempt to complete task</td>
<td>▪ Ball hits off chest or legs during catch</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>▪ Uses other hand in 1-handed catch task</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Drawing trails</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>▪ Opposite hand blocks path in drawing trial causing error</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hopping</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>▪ Switches to opposite foot</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>▪ Lands with two feet on final square</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pegs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>▪ Uses opposite hand to help rotate pegs</td>
</tr>
<tr>
<td>Perseveration</td>
<td>Repeats action that is required in previous trial</td>
<td>Score as error if any of the following criteria are met:</td>
<td>Threading lace</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a) Uses same foot as on previous trial, when alternating pattern was required</td>
<td>▪ Threads lace through hole on same side of board as previous trial</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Repeats threading action on the same side of the board</td>
<td>Walk the line</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>▪ Uses same foot to step forward with</td>
</tr>
<tr>
<td>Spatial Orientation</td>
<td>Body position deviates from</td>
<td>Score as error is any of the following criteria are met:</td>
<td>Ball catch</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>▪ Attempts to catch, but arms are incorrectly</td>
</tr>
</tbody>
</table>

45
appropriate spatial position

a) Attempts task, but upper extremities (i.e., arms, hands, fingers) are incorrectly oriented
b) Incorrectly grips task materials (pen, pegs, lace, paper) and/or repositions object in fingers in order to successfully complete task
c) Feet deviate from correct spatial position during task

oriented

Drawing trails
- Abnormal hand grip on pencil, needs to reposition

Hopping
- Foot lands on the crack

Nuts and bolts
- Needs to remove nut or bolt and repositions due to incorrect initial position
- Readjusts or manipulates materials in hands

Pegs
- Adjusts fingers in order to complete task
- Misses slot due to orientation of peg

Threading lace
- Misses hole on first attempt and repositions to put in hole

Walk the line
- Places foot off the line
- Gap between feet
- Repositions foot
- Places foot on top of other foot

Unsustained

Movement starts accurately, but quickly deteriorates as a result of a fall

Score as error if any of the following criteria are met:

a) Task materials make contact with the hands and are then dropped
b) Falls during task

Balance board
- Falls off board

Ball catch
- Ball touches any part of hands and drops

Nuts and bolts/threading lace
- Drops task materials

Pegs
- Picks up peg and then drops it
- Peg leaves contact of fingers

Target Mislocation

Completes task, but final target position is

Score as error if any of the following criteria are met:

Bean bag throw
- Hits target and bounces out
incorrect

a) Misses final target
   (overshoots, undershoots, to the sides)

b) Does not land in correct position on final target square

c) Attempts to put task materials in correct final position, but comes back out

Hopping

- Misses final target square (more than half of foot is outside circle boundary on first landing)

Pegs

- Puts into slot (correct final position), but comes back out
Chapter 3

The Procedural Abilities of Children with Specific Language Impairment

This manuscript will be submitted for publication in Research in Developmental Disabilities

Abstract

Background: Specific language impairment (SLI) is a developmental disorder that affects language and motor development in the absence of a clear cause. An explanation for these impairments is offered by the procedural deficit hypothesis, which predicts an association between motor and grammar learning. Aims: The purpose of this study was to (1) examine the procedural motor abilities of children with and without SLI and (2) determine whether procedural motor and grammatical abilities are related. Methods: 13 children with SLI and 14 age-matched typically developing (TD) children completed the following procedural motor measures: (1) a knot-tying task as measure of motor sequence learning, (2) a mirror-tracing task as a measure of visuo-motor adaptation and (3) a dowel task as a measure of motor sequence planning. Children also completed standardized measures of language ability. Results: Children with SLI exhibited difficulties on the knot-tying and dowel tasks, but performed comparably to TD children on the mirror-tracing task. Correlation analyses revealed that not only grammar, but also vocabulary test scores were related to performance on the procedural motor tasks. Conclusions: The procedural deficits in SLI may be specific to planning and executing sequences. The relationship between motor and language ability, however, may be broader than predicted by the current framework of the procedural deficit hypothesis.
3.1. Introduction

Specific language impairment (SLI) is a neurobiological disorder that delays language development in the absence of other developmental deficits such as acquired brain damage, social or emotional difficulties, frank motor deficits, loss of hearing or abnormalities of the speech apparatus (Leonard, 1998, 2014). The mechanisms that contribute to SLI are currently unknown.

Despite the exclusion criteria, recent studies have reported motor deficits in SLI (see Sanjeevan at el., 2015 for review). These impairments have been documented in the following motor areas: (1) fine motor ability (Iverson & Braddock, 2011; Katz et al., 1992; Owen & McKinlay, 1997), (2) gross motor function (Iverson & Braddock, 2011; Zelaznik & Goffman, 2010) and (3) speech motor ability (Archibald, Joanisse & Munson, 2013; DiDonato Brumbach & Goffman, 2014; Andrade, Befi-Lopes, Juste, Cáceres-Assenço & Fortunato-Tavares, 2014; Goffman, 1999, 2004). The findings of our previous study, assessing different areas of motor ability in children with SLI, suggest that children with SLI have difficulties performing novel motor tasks. This finding may be attributed to difficulties with learning motor sequences, which can be explained by procedural memory impairment. This hypothesis predicts that deficits in procedural memory, a memory system involved in cognitive and sensorimotor skill acquisition, contribute to the comorbid language and motor impairments observed in SLI (Ullman & Pierpont, 2005).

3.1.1. Procedural memory

Procedural memory is an implicit long-term memory system that stores information on how to execute habitual cognitive and sensorimotor skills. These routine actions are recalled and performed with little-to-no conscious awareness (Mochizuki-Kawai, 2008; Ullman, 2004; Ullman & Pierpont, 2005). Though procedural memory is often associated with learned skills, it is also involved in several aspects of motor learning. These processes include motor sequence planning, sequence execution, adaptation and consolidation (Doyon, 2008; Doyon et al., 2009).
These motor processes have been outlined in a motor learning model developed by Doyon and Benali (2005). Since its inception, this model has seen several revisions and the current framework explains these motor processes as follows (Doyon et al., 2009). Motor sequence planning involves specifying the specific sequence of movements needed to achieve the goal of the task prior to execution. This process is most active during the initial stages of skill acquisition and is less involved as the skill becomes more familiar. Sequence execution involves learning and implementing the sequence of movements. Depending on the type of skill, procedural learning can begin with explicit instruction (e.g. learning how to tie shoelaces for the first time) or no instruction at all (e.g. subconscious recognition of a repeating sequence of buttons on a reaction time task). Motor adaptation involves fine-tuning the executed movements to improve skill accuracy and to ensure the goal of the skill is achieved. Lastly, motor memory consolidation involves transforming the acquired procedural knowledge from a vulnerable state, susceptible to interference and loss, to a permanent state that is stored in the long-term procedural memory system. At this stage, the learned skill can become automatized.

Although the association between these processes and procedural memory is rooted in theory, there is neurophysiological evidence to support this construct as well. The frontal cortex, basal ganglia circuit and cerebellum have been implicated in the procedural memory system (e.g. Mochizuki-Kawai, 2008). This brain-behaviour relationship has been primarily supported by clinical studies examining the procedural abilities of individuals with basal ganglia impairment such as those with Parkinson’s disease (e.g. Harrington et al., 1990; Pascual-Leone et al., 1993) or Huntington’s disease (e.g. Heindel, Butters & Salmon, 1988; Knopman & Nissen, 1991). These brain structures have also been implicated in the motor processes discussed above. Specifically, the striatum, a subcortical structure that provides input to the basal ganglia, is linked to sequence planning, learning, execution and consolidation (e.g. Fischer, Nitschke, Melchert, Erdmann & Born, 2005; Geradin et al., 2004; Grafton, Hazeltine & Ivry, 1995; Monchi, Petrides, Strafella, Worsley & Doyon, 2006). Motor adaptation, on the other hand has been linked to the cerebellum (e.g. Graydon, Friston, Thomas, Brooks & Menon, 2005; Laforce
Taking these properties of the procedural memory system into consideration, Ullman (2001, 2004) proposed that language learning is supported by the procedural memory system. Analogous to implicitly learning a series of movements, Ullman suggested that sequence learning also supports the subconscious learning of structural and categorical aspects of language. This information would then be used to develop the morphosyntactic framework of a language or in other words, grammar. On the other hand, aspects of language that are consciously learned and recalled, such as vocabulary, are hypothesized to be supported by the declarative memory system (Ullman, 2001, 2004; Ullman & Pierpont, 2005).

3.1.2. Procedural deficit hypothesis

3.1.2.1. Motor sequencing in SLI

Considering that the language deficits in SLI primarily affect grammar learning and the motor impairment could be explained by difficulties with sequencing movements, Ullman and Pierpont (2005) posited that deficits in procedural sequencing contributed to both the language and motor deficits in SLI.

To date, a handful of studies have explored the procedural sequencing abilities of children with and without SLI. Most of these studies have used some variation of the serial reaction time (SRT) task, a common test of implicit visuo-motor sequence learning (see Lum et al., 2014 for review). In this task, a visual stimulus appears in one of four locations. Subjects are asked to press one of four buttons that corresponds to the location of the visual stimulus as quickly as possible. In the most popular version of the task, 400 trials are organized into 4 blocks. In the first and last blocks, the location of the visual stimulus is randomly assigned. In the second and third blocks, a fixed sequence of ten locations repeats ten times in each block. This is when procedural learning is expected to take place. As exposure to the repeating sequence of locations increases, reaction times decrease indicating that subjects have implicitly learned the predetermined sequence.
SRT studies have consistently shown that children and adolescents with SLI take significantly longer to learn the fixed sequence of locations relative to their age-matched TD peers. This suggests that children with SLI show a slower rate of visuo-motor sequence learning in comparison to TD children (Gabriel et al., 2013; Hsu & Bishop, 2014; Lum et al., 2010; Tomblin et al., 2007). This difference in learning rate has also been observed when children have been divided into groups based on normal and poor grammar ability (Hedenius et al., 2011; Tomblin et al., 2007), suggesting that grammar ability is associated with procedural motor sequencing. When groups were divided based on vocabulary, however, associations with procedural motor sequencing were not found.

3.1.2.2. Visuo-motor adaptation and motor memory consolidation in SLI

To our knowledge, only three experimental studies have directly explored visuo-motor adaptation and motor memory consolidation in SLI (Adi-Japha, Strulovich-Schwartz & Julius, 2011; Hedenius et al., 2011; Hsu & Bishop, 2014).

Hedenius et al. (2011) examined consolidation of sequence learning in children with and without SLI using an alternating serial reaction time (ASRT) task. Unlike the standard SRT task, the repeating sequence in the ASRT task consists of alternating fixed and random locations. In this study, the repeating sequence was set to 1r2r4r3r, where numbers corresponded to fixed locations and r corresponded to random locations, which were different in each repetition of the sequence. The results showed that children with SLI were marginally worse at consolidating the alternating sequence while their rate of initial sequence learning was no different from TD children. When children were re-categorized on the basis of grammar ability, however, initial sequence learning rates remained comparable, but consolidation of the alternating sequence was significantly different between children with impaired grammar and children with normal grammar. Based on these findings, the authors suggested that children with SLI exhibited difficulties consolidating sequence-specific procedural information.
Adi-Japha et al. (2011) suggested that consolidation deficits in SLI also extend to non-sequence-specific information. Adi-Japha et al. (2011) studied the acquisition of a grapho-motor skill in preschool children with and without SLI. Children were taught how to draw an invented two-segment letter, which was posited to assess visuo-motor integration and not sequence learning given that no sequence-related information was taught. Their results showed that while children with SLI were significantly slower than TD children at producing the invented letter across all conditions (practice, learning, retention and consolidation), their speed improved by the consolidation condition. This was at the expense of reducing the accuracy in which they produced the invented letter, which did not improve after the first session. These findings suggest that children with SLI exhibit difficulties with learning and consolidating procedural information that is not sequence-specific.

Hsu and Bishop (2014) tested the procedural abilities of children with and without SLI. They used three measures of procedural learning, one of which included the pursuit rotor task, a classic test of visuo-motor adaptation. The objective of this task is to use a stylus pen to maintain contact with a red dot moving clockwise on a computer screen. Children performed this task in two separate sessions to examine consolidation of the learned skill. The results indicated that children with SLI were no different from TD children in maintaining contact with the red dot in the first or second sessions. Unlike Adi-Japha et al. (2011), this study suggests that children with SLI show a comparable rate of adaptive learning and consolidation as TD children.

3.1.3. Study aims

While these findings may suggest that children with SLI have difficulties acquiring sequence-specific information, there are three issues that must be addressed. The first issue concerns the generalizability of the SRT findings. The procedural information acquired from the SRT task is, more or less, implicit. Apart from being told that the SRT task measures reaction time, subjects are unaware that the same sequence of button presses repeats and generally have no knowledge of learning the repeating sequence. When learning how to tie our shoelaces, however, the goal
of the task is clear and the instructions that are provided are explicit. Only after practicing the skill for some time does that information become implicit procedural knowledge. Current evidence suggests that children with SLI have difficulties with implicit procedural sequence learning, but it is unknown whether the same can be said for the explicit type, the type that, arguably, accompanies the development of central motor skills that comprise our day-to-day activities.

The second issue concerns the inconsistent findings of studies exploring visuo-motor adaptation and motor memory consolidation in SLI. First, it remains unclear whether visuo-motor adaptation is affected in SLI. Adi-Japha (2011) suggests that it is affected while Hsu and Bishop (2014) suggest that it is not. One explanation for this discrepancy is that the motoric demands of the tasks were not age-appropriate. The pursuit rotor task is a motorically simple measure of hand-eye coordination and may not have been complex enough to capture difficulties in visuo-motor adaptation in the older children with SLI tested in Hsu and Bishop’s (2014) study. On the other hand, the invented letter task may have been too complex for the preschool children tested in Adi-Japha et al.’s (2011) study and as a result, their poor performance on this measure may have been falsely attributed to issues with visuo-motor adaptation. Second, it remains unclear whether motor memory consolidation is affected in SLI. Though the findings of Hedenius et al. (2011) indicate that consolidation of sequence-specific information is affected, it is not understood whether difficulties with retention extend to information that is not sequence-specific. If, however, learning and consolidation of sequencing and visuo-motor adaptation were examined concurrently in SLI, the nature of these issues could be specified.

The third issue concerns the lack of studies exploring motor sequence planning in SLI. No studies that we are aware of, have directly explored motor sequence planning in SLI. Given their difficulties with sequence learning, it is speculated that children with SLI would exhibit difficulties with sequence planning. Currently, it is unknown whether motor sequence planning is affected in SLI.
While there is evidence to suggest that children with SLI exhibit procedural deficits, it is unclear whether these deficits are specific to procedural sequencing or extend to all areas of procedural learning. To address this gap in the literature, this study compared children with SLI and TD children on measures of procedural motor sequence execution, visuo-motor adaptation, motor sequence planning. Note that motor consolidation was not examined in the present study because consolidation refers to the establishment of a change in performance (learning) over a long time and a long-term retention test was not included in the present design. A secondary objective of this study was to examine the relationship between children’s language test scores and their performances on these procedural tasks.

Given that the procedural deficit hypothesis suggests that sequencing is significantly affected in SLI, it was expected that children with SLI would perform worse on measures of motor sequence execution and planning relative to TD children. The current framework of the procedural deficit hypothesis, however, does not specify whether deficits in visuo-motor adaptation or retention would be observed in children with SLI. Based on the findings of the first study (see Chapter 2), it was expected that children with SLI would exhibit difficulties with visuo-motor adaptation in comparison to TD children. Furthermore, it was predicted that language test scores related to grammar would be significantly correlated to performance on the motor sequence execution and planning tasks.

3.2. Methods

3.2.1. Participants

Twenty-seven children (ages 8;10 – 12;11), including 13 with SLI and 14 age-matched TD controls, participated in this study (Table 1). Children in the SLI group met the following inclusionary criteria: (1) received services for language-related difficulties, (2) scored at or above 80 on the nonverbal index of the Wechsler Abbreviated Scale of Intelligence – Second Edition (WASI-II; Wechsler, 2011), (3) passed a hearing screen at 500, 1000, 2000, and 4000 Hz at 20 dB HL (ASHA, 2014), (4) were monolingual speakers of English, (5) had no history of
acquired brain damage based on parental report, (6) no emotional or social difficulties based on parental report and, (7) no frank abnormalities with their oral motor and speech motor function based on parental report. Children in the TD group were required to meet the same inclusionary criteria as the children in the SLI group with the exception of not having a history of receiving services for language- and/or learning-related difficulties.

*Table 1. Descriptive statistics for ages and standardized IQ and language test scores*

<table>
<thead>
<tr>
<th></th>
<th>Age</th>
<th>IQ&lt;sup&gt;a&lt;/sup&gt;</th>
<th>CLS&lt;sup&gt;b&lt;/sup&gt;</th>
<th>RLS&lt;sup&gt;c&lt;/sup&gt;</th>
<th>ELS&lt;sup&gt;d&lt;/sup&gt;</th>
<th>PPVT&lt;sup&gt;e&lt;/sup&gt;</th>
<th>EVT&lt;sup&gt;f&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SLI</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>10.43</td>
<td>89.62**</td>
<td>77.00**</td>
<td>76.85**</td>
<td>80.77**</td>
<td>91.85**</td>
<td>91.38**</td>
</tr>
<tr>
<td>SD</td>
<td>1.23</td>
<td>9.24</td>
<td>11.72</td>
<td>9.11</td>
<td>14.42</td>
<td>6.62</td>
<td>10.68</td>
</tr>
<tr>
<td>Range</td>
<td>9.5-12.83</td>
<td>80-104</td>
<td>52-90</td>
<td>61-94</td>
<td>53-98</td>
<td>79-104</td>
<td>73-115</td>
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<tr>
<td><strong>TD</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
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<td>107.14**</td>
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*Note. Standard scores have a mean of 100 and a standard deviation of 15.*

<sup>a</sup> Wechsler Abbreviated Scale of Intelligence – Second Edition: Perceptual Reasoning Index Composite Score; <sup>b</sup>Clinical Evaluation of Language Fundamentals – Fourth Edition: Core Language Score; <sup>c</sup>Clinical Evaluation of Language Fundamentals – Fourth Edition: Receptive Language Score; <sup>d</sup>Clinical Evaluation of Language Fundamentals – Fourth Edition: Expressive Language Score; <sup>e</sup>Peabody Picture Vocabulary Test – Fourth Edition: Standard Score; <sup>f</sup>Expressive Vocabulary Test – Second Edition: Standard Score; *<sup>p</sup> < .05, **<sup>p</sup> < .01

To confirm each child’s group status, the language abilities of each child were assessed using the Clinical Evaluation of Language Fundamentals – Fourth Edition (CELF-4; Semel, Wiig, & Secord, 2003), the Peabody Picture Vocabulary Test – Fourth Edition (PPVT-4; Dunn & Dunn,

Descriptive statistics and group differences on these measures are presented in Table 1.

The language profiles of the children with SLI were as follows: (1) no children exhibited vocabulary-only impairments as indexed by standard scores below 1.25SD on the PPVT and/or EVT and within typical range on the remaining language measures, (2) four children had receptive-only language difficulties as indexed by standard scores below 1.25SD on the Receptive Language Index (RLI) on the CELF-4 and within normal range on the PPVT, EVT and Expressive Language Index (ELI) on the CELF-4, (3) three children had expressive-only language deficits as indexed by standard scores below 1.25SD on the ELI and within typical range on the PPVT, EVT and RLI, (4) three children exhibited receptive and expressive language impairments as indexed by scores below 1.25SD on both of the RLI and ELI and within normal range on the PPVT and EVT and (5) three children had vocabulary and language difficulties as indexed by scores below 1.25SD on either the PPVT or EVT and scores below 1.25SD on either the RLI or ELI.

3.2.2. Procedure and stimuli

Children’s procedural abilities were tested using (1) a knot-tying task (modified from Garland & Sanchez, 2013) as a measure of motor sequence learning and execution, (2) a mirror-tracing task (modified from Vicari et al., 2005) as a measure of visuo-motor adaptation, and (3) a dowel task (modified from Weigelt & Schack, 2010) as a measure of motor sequence planning and, (4) a second administration of the knot-tying and mirror-tracing tasks two hours after completing the tasks for the first time as a measure of initial motor adaptation (possibly early motor memory retention) of sequence-specific and non-sequence-specific procedural information, respectively.

3.2.2.1. Knot-tying task

While there is evidence to suggest that children with SLI have difficulties with implicit procedural sequence learning, it is unknown whether children with SLI respond differently to the explicit form that is often associated with the development of motor skills such as tying.
shoelaces. Tying knots, like tying shoelaces, requires that a series of steps be performed in a specific order. While the instructions provided to children are explicit, it also has the potential of becoming implicit procedural knowledge with practice making a knot-tying task a suitable measure of procedural sequence learning and execution.

In this study, a modified version of the knot-tying task developed by Garland and Sanchez (2013) was used. In this adapted version, children studied two instructional videos that outlined the 4-step knot-tying procedures of two different and unfamiliar knots: the figure 8 and cow hitch knots (Figure 1). The figure 8 knot, as the name suggests, resembles the shape of the number 8 and is tied using one rope. The cow hitch knot, on the other hand, resembles the shape of a bow tie and is tied using two ropes. The cow hitch and figure 8 knots were classified as simple and complex, respectively. This classification was rationalized based on the intricate looping involved in the tying of the figure 8 knot. Despite the need for a second rope to tie the cow hitch knot, only one rope is maneuvered while the other remains stationary. This classification was also confirmed by pilot testing.

Figure 1. Knot-tying procedures for cow hitch and figure 8 knots

Cow Hitch

Figure 8
After watching the instructional video of one of the knots, children were given an unlimited amount of time to learn how to tie the knot (learning condition). In this condition, children were allowed to practice tying the knot with the rope(s), re-watch the instructional video any number of times and request feedback. When children were confident that they had learned how to tie the knot, the video was turned off, the rope was laid flat on the table and the child was instructed to tie the knot as quickly as possible (test condition). Children were given up to five attempts, if needed, to tie the knot correctly. If a child remained unsuccessful after the fifth attempt, feedback was provided to ensure that they understood how to tie the knot. This procedure was immediately repeated with the second knot. Two hours after the test condition, children were retested on the figure 8 and cow hitch knot-tying procedures (retest condition).

The performance measures that were recorded while children completed the task included: (1) time spent learning how to tie the knot (learning condition), (2) time it took to tie the knot (test and retest conditions) and (3) the number of errors made (test and retest conditions).

3.2.2.2. Mirror-tracing task

Conflicting results on the studies examining visuo-motor adaptation could be attributed to the motoric demands of the tasks used. Administering a test of visuo-motor adaptation where the degree of difficulty can be adjusted ensures that the motoric demands are age-appropriate. The mirror-tracing task is a test of procedural learning that allows this flexibility.

In this study, a modified version of the mirror-tracing task used by Vicari et al. (2005) was implemented. In this adapted version, children traced two four-pointed stars seen only as a reflection in a mirror. The two stars varied in the width of space available to trace the line, one at a width of 1.0cm and the other at 0.5cm (Figure 2). The 1.0cm and 0.5cm width stars were classified as simple and complex, respectively.

After tracing the stars for the first time (baseline condition), children were given traces of vertical and horizontal lines and angles at varying widths to complete (training condition). The widths for each type of practice trace were 2.0cm, 1.5cm, 1.0cm and 0.5cm. Children were also
given an unlimited amount of time to complete the practice traces. Once completed, children were instructed to trace the 1.0cm and 0.5cm four-pointed stars as quickly as possible (test condition). Two hours after the test condition, children were retested on the 1.0cm and 0.5cm four-pointed stars (retest condition).

Figure 2. 1.0cm and 0.5cm four-pointed star traces

The performance measures that were recorded in this task included: (1) the time it took to trace the stars (all conditions) and (3) the number of errors made (all conditions). An error was identified as a line drawn outside the lines of the tracing space.

3.2.2.3. Dowel task

To our knowledge, this is the first study to directly examine motor sequence planning in SLI. A review of the motor cognition literature revealed one measure of motor sequence planning used in clinical pediatric populations; the dowel task. The dowel task is a measure of the end-state comfort (ESC) effect. This phenomenon is defined by the use of an awkward initial grasp to produce a comfortable end grasp in goal-directed movements. This observation suggests that acquiring comfort in the final grasp position is a priority in object manipulation and thus indicates that the sequence of hand movements needed to achieve ESC must be planned prior to execution (Rosenbaum et al., 2012). Given that motor sequence planning was defined as the pre-organization of a sequence of movements prior to execution, the, ESC tasks were viewed as representative measures of motor sequence planning.
In this study, a modified version of the dowel task used by Weigelt and Schack (2010) was administered. In this adapted version of the dowel task, a paper dowel, coloured green on one end and black on the other, was moved from a central vertical position (home position) to either the left (position 1) or right (position 2) sides of the home position. Children were instructed to place either the green or black end in positions 1 or 2.

*Figure 3. End-state comfort grasp on the dowel task*

Sixteen trials were administered in random order. Eight of these trials were control trials where the transfer from home position to positions 1 or 2 did not necessitate an awkward initial grasp, but instead could be completed using comfortable thumb-up start and end grasps. The remaining eight trials were classified as end-state comfort (ESC) trials. If children planned to end in a comfortable grasp, the transfer from home position to positions 1 or 2 required a thumb-down start grasp (awkward grasp) and a thumb-up end grasp (Figure 3).

The performance measures that were recorded in this task included: (1) percent of control grasps used on control trials and, (2) percent of ESC grasps used on ESC trials.

3.2.3. Reliability of coding

Two coders independently coded the performance measures of each task for 20% of the participants. For the knot-tying task, an absolute agreement of 88% and 100% was achieved for the time and error measures, respectively. For the mirror-tracing task, an absolute agreement of 94% and 91% was achieved for the time and error measures, respectively. For the dowel task, an absolute agreement of 100% was achieved for both the number of successful control grasps and the number of successful ESC grasps.
3.2.4. Statistical analyses

To determine whether deficits in procedural learning are specific to sequencing, a series of mixed-design analyses of covariance (ANCOVAs) were conducted. For the knot-tying task, performance on the figure 8 and cow hitch knots was compared between the SLI and TD groups. This comparison was done by examining the effects of knot (figure 8 and cow hitch), condition (test and retest) and group (SLI and TD) on (1) the time spent during the learning condition, (2) the number of errors produced and, (3) the time it took to tie the knots. For the mirror-tracing task, performance on the 0.5cm and 1.0cm traces was compared between SLI and TD groups. This comparison was achieved by examining the effects of trace (0.5cm and 1.0cm), condition (baseline, test and retest) and group on (1) the time it took to trace the figures and (2) the number of errors produced. For the dowel task, the proportion of successful control and ESC grasps was compared between SLI and TD groups. This comparison was done by examining the effects of grasp type (control and ESC) and group on the percent of correct grasps. Finally, performance across conditions in the knot-tying and mirror-tracing tasks was compared between SLI and TD groups. This comparison was achieved by identifying whether significant changes in performance occurred across test and retest conditions in the knot-tying and mirror-tracing tasks. In each of these comparisons, nonverbal IQ was entered as a covariate to control for significant group differences in IQ.

To understand the relationship between procedural motor and language abilities, a series of Pearson’s correlations were conducted. Each of the outcome measures for all three procedural motor tasks were correlated against the CELF-4 subtest scores, PPVT standard scores and EVT standard scores.

Prior to conducting the ANCOVAs, normality and homogeneity of variances for all dependent variables were tested. The data was homogenous and normally distributed for the following measures: (1) cow hitch test time, (2) figure 8 learning time, (3) figure 8 retest time and, (4) 0.5cm trace baseline time. However, the Mauchly’s test of sphericity indicated that the remaining variables violated the ANCOVA assumption of equal variances. Therefore, the
Greenhouse-Geisser corrections were used for these data. Furthermore, the covariate, nonverbal IQ, was found to be linearly and positively related to performance on the procedural tasks for both SLI and TD groups, fulfilling the remaining assumptions required for an ANCOVA.

Assumptions were also checked for the correlation analyses. The data for the dowel task violates the first assumption which requires that variable be continuous. For this reason, the outcome measures from the dowel task were not examined. The data for the knot-tying and mirror-tracing tasks, however, are continuous and are linearly related to the language measures of interest. They also do not consist of significant outliers. Not all of the outcome measures for the knot-tying and mirror-tracing tasks are normally distributed as mentioned above. Therefore, for the variables that were not normally distributed, a series of Kendall’s correlation analyses were conducted.

### 3.3. Results

#### 3.3.1. Performance on knot-tying task

In the first set of analyses, performance on the figure 8 and cow hitch knots by the SLI and TD groups was examined. The learning stage condition was analyzed separate from the test and retest conditions because the time recorded for this condition reflects several attempts and is, therefore, not comparable to the test and retest conditions which reflect a single attempt.

Examining the time spent in the learning condition revealed no main effects of group, $F(1, 24) = .71, p = .41, \eta^2 = .029$ or knot, $F(1.00, 24.00) = .002, p = .96, \eta^2 = .000$. Also, the knot by group interaction was not significant, $F(1.00, 24.00) = .25, p = .62, \eta^2 = .010$. This finding suggests that the SLI group did not significantly differ from the TD group in the time that they spent practicing the figure 8 and cow hitch knots.

Next, the number of errors produced on the figure 8 and cow hitch knots between SLI and TD groups was examined. The analysis revealed no significant effects of group, $F(1, 24) = .000, p = 1.00, \eta^2 = .000$, knot, $F(1.00, 24.00) = 4.0, p = .056, \eta^2 = .14$, or condition, $F(1.00, 24.00) = .60, p = .45, \eta^2 = .024$. Also, the following interactions were not significant: (1) knot by group,
Collectively, these findings suggest that the SLI group was not significantly different from the TD group in the number of errors produced on the cow hitch and figure 8 knots.

When examining the time it took to tie the knots in the test and retest conditions, however, the analysis showed a main effect of knot, $F(1.00, 24.00) = 6.70, p = .016, \eta^2 = .218$, and a significant two-way interaction between knot and group, $F(1.00, 24.00) = 4.83, p = .038, \eta^2 = .167$ after controlling for IQ. No effect of condition, $F(1.00, 24.00) = 1.37, p = .714, \eta^2 = .006$, or interaction between condition and group, $F(1.00, 24.00) = .267, p = .61, \eta^2 = .011$, or knot, condition and group, $F(1.00, 24.00) = 3.46, p = .075, \eta^2 = .126$, were found. Further analysis of this interaction revealed that the SLI group was comparable to the TD group in the time it took to tie the cow hitch knot in both test, $F(1, 25) = .577, p = .45, \eta^2 = .023$, and retest, $F(1, 25) = .015, p = .90, \eta^2 = .001$, conditions, but took significantly longer to tie the figure 8 knot than the TD group in both test, $F(1, 25) = 4.28, p = .048, \eta^2 = .146$, and retest, $F(1, 25) = 5.1, p = .033, \eta^2 = .178$, conditions (Figure 4).

*Figure 4. Time spent tying the cow hitch and figure 8 knots (means and standard errors)*

### Cow Hitch

![Cow Hitch Graph](Image)
### 3.3.2. Performance on mirror-tracing task

In the second set of analyses, performance on the 0.5cm and 1.0cm traces by the SLI and TD groups was examined (Tables 2 & 3). The results showed that for the number of errors produced, there were no effects of trace width, \(F(1.00, 24.00) = .72, \ p = .41, \ \eta^2 = .030\), condition, \(F(2.00, 24.00) = .66, \ p = .52, \ \eta^2 = .028\), or group, \(F(1, 24) = 2.27, \ p = .15, \ \eta^2 = .090\), or significant interactions between trace width and group, \(F(1.00, 24.00) = .11, \ p = .75, \ \eta^2 = .005\), condition and group, \(F(1.00, 24.00) = .051, \ p = .88, \ \eta^2 = .002\), or trace width, condition and group, \(F(1.00, 24.00) = .62, \ p = .51, \ \eta^2 = .026\). Also, for the time it took to trace the figures, there were no effects of trace width, \(F(1.00, 24.00) = .13, \ p = .73, \ \eta^2 = .005\), condition, \(F(2.00, 24.00) = .027, \ p = .91, \ \eta^2 = .001\), or group, \(F(1, 24) = .15, \ p = .70, \ \eta^2 = .006\), or significant interactions between trace width and group, \(F(1.00, 24.00) = .19, \ p = .67, \ \eta^2 = .008\), condition and group, \(F(2.00, 24.00) = .024, \ p = .91, \ \eta^2 = .001\), or trace width, condition and group, \(F(2.00, 24.00) = .19, \ p = .69, \ \eta^2 = .008\). These results suggest that the SLI group was not significantly different from the TD group in the time they took to trace the two figures or in the number of errors they produced across conditions.
Table 2. Descriptive statistics for performance on 1.0cm trace

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<th>Baseline errors</th>
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* p < .05, ** p < .01

Table 3. Descriptive statistics for performance on 0.5cm trace

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* p < .05, ** p < .01
3.3.3. Performance on dowel task

The last analysis examined performance on the dowel task, specifically comparing the proportion of correct control and ESC grasps used on control and ESC trials, respectively, between the SLI and TD groups. The results revealed a main effect of group, $F(1,24) = 8.087$, $p = .009$, $\eta^2 = .252$, but no effect of grasp, $F(1.00, 24.00) = .48$, $p = .50$, $\eta^2 = .019$. The interaction between grasp and group, however, appears to be trending towards significance, $F(1.00, 24.00) = 1.58$, $p = .221$, $\eta^2 = .062$, after controlling for IQ. Further analysis of the group effect revealed that the SLI group produced a significantly lower proportion of correct control grasps, $F(1, 25) = 8.88$, $p = .006$, $\eta^2 = .262$, but a comparable proportion of correct ESC grasps, $F(1, 25) = .636$, $p = .433$, $\eta^2 = .025$, relative to the TD group (Figure 5).

Figure 5. Performance on control and ESC trials (means and standard errors)

While administering this task, however, it was noted that many children in the SLI group used ESC grasps for control trials. Therefore, an additional analysis comparing the number of times an ESC trial preceded a control trial (where an ESC grasp was used) between SLI and TD groups was conducted. Using the same statistical approach as the previous analyses, the effects of preceding trial (ESC and control) and group (SLI and TD) on the number of ESC grasps used
during a control trial was examined. The results showed that there were no effects of preceding trial, $F(1.00, 24.00) = .34$, $p = .57$, $\eta^2 = .014$, or group, $F(1, 24) = 3.46$, $p = .075$, $\eta^2 = .126$, but there was a significant interaction between preceding trial and group, $F(1.00, 24.00) = 6.22$, $p = .020$, $\eta^2 = .020$. As expected, a closer look at this interaction revealed that the SLI group was significantly more likely to use an ESC grasp on a control trial when the control trial was preceded by an ESC trial, $F(1, 25) = 11.40$, $p = .002$, $\eta^2 = .313$, but not if a control trial preceded the incorrect control trial, $F(1, 25) = 1.08$, $p = .309$, $\eta^2 = .041$ (Figure 6).

Figure 6. Proportion of ESC grasps on control trials by preceding trial (means and standard errors)

3.3.4. Changes in performance across conditions in SLI – Adaptation and retention

On the knot-tying task, no main effect of condition, $F(1.00, 24.00) = .60$, $p = .45$, $\eta^2 = .024$, or interaction between condition and group, $F(1.00, 24.00) = .56$, $p = .46$, $\eta^2 = .023$, or condition, knot and group, $F(1.00, 24.00) = .63$, $p = .44$, $\eta^2 = .025$, were found for the number of errors produced on the figure 8 and cow hitch knots between SLI and TD groups. Also, when examining the time it took to tie the knots, no effect of condition, $F(1.00, 24.00) = 1.37$, $p = .714$, $\eta^2 = .006$, or interaction between condition and group, $F(1.00, 24.00) = .267$, $p = .61$, $\eta^2 = .005$. 
.011, or knot, condition and group, $F(1.00, 24.00) = 3.46, p = .075, \eta^2 = .126$, were found. This finding suggests that the SLI group was not significantly different from the TD group in their performance across conditions for the knot-tying task.

On the mirror-tracing task, no main effect of condition, $F(2.00, 24.00) = .66, p = .52, \eta^2 = .028$, or significant interactions between condition and group, $F(1.00, 24.00) = .051, p = .88, \eta^2 = .002$, or trace width, condition and group, $F(1.00, 24.00) = .62, p = .51, \eta^2 = .026$, were found for the number of errors produced on the 1.0cm or 0.5cm traces between SLI and TD groups. Also, when examining the time it took to trace the figures, no effect of condition, $F(2.00, 24.00) = .027, p = .91, \eta^2 = .001$, or significant interactions between condition and group, $F(2.00, 24.00) = .024, p = .91, \eta^2 = .001$, or trace width, condition and group, $F(2.00, 24.00) = .19, p = .69, \eta^2 = .008$, were found. This finding suggests that the SLI group was not significantly different from the TD group in their performance across conditions for the mirror-tracing task.

3.3.5. Correlations between procedural and language measures

The performance measures from each procedural task were correlated against children’s language test scores, despite only finding group effects for a few of the procedural measures. This outcome could be attributed to increased variability in the language and motor abilities of the children within both of the SLI and TD groups. However, we expected individual differences in procedural memory to be associated with individual differences in language abilities above and beyond language disorder. Thus, we expected that strong procedural motor performance would be associated with high language test scores. Groups were combined for all measures to provide a larger sample size to examine the relationship between motor and language ability. On the knot-tying task, the number of errors produced during the test condition for the cow hitch knot was significantly correlated with children’s expressive vocabulary scores, $\tau = -.40, p = .011$, while the time spent tying the cow hitch knot in the retest condition was significantly correlated with children’s expressive language scores, $\tau = -.30, p = .037$ (Figure 7).

A closer look at the plotted graph of the cow hitch test condition errors revealed a ceiling effect
for the TD group and was therefore not analyzed further. For the figure 8 knot, the collected performance measures were not significantly correlated with any language test scores.

**Figure 7. Significant correlation between knot-tying and receptive language measures**

\[ \tau = -0.30, p = 0.037 \]

**Figure 8. Significant correlations between mirror-tracing and language measures**

\[ \tau = -0.29, p = 0.044 \]
\[ \tau = -0.29, \ p = 0.038 \]

\[ \tau = -0.37, \ p = 0.008 \]
On the mirror-tracing task, the number of errors produced while tracing the 1.0cm figure during the test condition was significantly correlated with children’s expressive vocabulary scores, $\tau = -0.97$, $p = .000$. Also, the time spent tracing the 0.5cm figure during the retest condition was significantly correlated with children’s expressive, $\tau = -0.37$, $p = .008$, and receptive, $\tau = -0.29$, $p = .038$, vocabulary scores and core language scores, $\tau = -0.29$, $p = .044$ (Figure 8).

3.4. Discussion

The aim of this study was two-fold. The first aim was to determine whether the procedural deficits in SLI were specific to sequencing or extend to all processes related to procedural memory. This first aim was achieved by comparing children with SLI to TD children on three procedural tasks: (1) a knot-tying task as a measure of motor sequence learning and execution, (2) a mirror-tracing task as a measure of visuo-motor adaptation, (3) a dowel task as a measure of motor sequence planning and (4) a second administration of the knot-tying and mirror-tracing tasks two hours later to measure short-term motor adaptation. The second aim of this study was
to understand the relationship between language and motor abilities by examining correlations between children’s language test scores and their performances on the described procedural tasks.

On the knot-tying task, children with SLI were not significantly different from TD children in the time spent and number of errors produced while tying the cow hitch knot. For the figure 8 knot, the number of errors produced by children with SLI and TD children was similar. The children with SLI did, however, take significantly longer to tie the figure 8 knot than the TD controls. These results suggest that while children with SLI are proficient enough to perform sequence-specific motor skills, these processes are still not comparable to TD children.

On the mirror-tracing task (modified from Vicari et al., 2005), the time it took to trace the 1.0cm and 0.5cm four-pointed star figures was similar between children with SLI and TD children. Furthermore, the frequency of errors produced by children with SLI and TD children while tracing the two figures was also statistically similar. This suggests that the visuo-motor adaptive skills of children with SLI do not differ significantly from TD children. On the dowel task, (modified from Weigelt and Schack, 2010), while the proportion of ESC grasps used on ESC trials was not significantly different between children with SLI and TD children, the proportion of control grasps used on control trials was significantly different. Further examination of the control grasps revealed that relative to TD children, children with SLI used a significantly greater proportion of ESC grasps on control trials if the control trial was preceded by an ESC trial. This finding indicates that the motor sequence plan that was created to maneuver the dowel on the preceding ESC trial perseverated onto the proceeding control trial in children with SLI.

To examine short-term motor adaptation, children repeated the test conditions (retest condition) of the knot-tying and mirror-tracing tasks two hours after completing the test condition for the first time. For both tasks, no significant effects of condition or interactions with condition were found. This observation means that the time and frequency of error productions in the knot-tying task did not change significantly from test to retest conditions for children with SLI or TD children. Consolidation refers to the later stages of motor learning, where the learned skill is
maintained in long-term memory and the changes in performance are stable and persistent (Doyon, 2008; Doyon et al., 2009). This process is often associated with sleep and gains in performance, whether with speed or accuracy (e.g. Maquet, 2001; Stickgold et al., 2001; Walker et al., 2002). Given that the children in this study were not tested after 24 hours (or longer) and no improvements were found across conditions in the TD group, the observed effects can be interpreted to reflect retention or short-term adaptation. Thus, the findings of this study could be interpreted to suggest that children with SLI do not exhibit difficulties retaining procedural information, both sequence-specific and non-sequence specific.

Finally, the correlation analyses revealed that performance measures collected from the knot-tying, mirror-tracing and dowel tasks were significantly correlated with children’s vocabulary (PPVT-4 and EVT-2) and grammar test scores (core, expressive and receptive language indexes on the CELF-4). These significant associations suggest that language and motor ability are, in some form, related.

3.4.1. Informing the procedural deficit hypothesis

3.4.1.1. Sequencing in SLI

The procedural deficit hypothesis makes two important predictions about the motor impairments in SLI. The first prediction is that the deficits in SLI are related to sequencing (Ullman, 2004; Ullman & Pierpont, 2005). The findings of this present study only partially support this prediction. First, children with SLI exhibited differences in the time it took to tie the figure 8 knot in comparison to the TD children. This finding is consistent with previous SRT studies examining procedural motor sequence learning in SLI (see Lum et al., 2014 for review), which have consistently shown that children with SLI are capable of implicitly learning the predetermined sequence of locations on an SRT task, but require more exposure to the recurring sequence than TD children before the expected decrease in reaction times are observed. Likewise, the comparable frequency of errors produced on the figure 8 knot in children with SLI and TD children suggests that children with SLI were able to learn the sequence of steps needed
to tie the knot. Their reduced speed, however, indicates that they needed more time to think through the sequence of steps to ensure that the knot was tied correctly. Moreover, children with SLI were no different from TD children in the amount of time they spent practicing how to tie the figure 8 knot (the learning condition). If, however, children with SLI spent more time practicing the knot, it is possible that the time it took to tie the figure 8 knot would have been similar to those of the TD children. Furthermore, this finding suggests that implicit and explicit sequence learning is not different from one another and that the sequence learning deficit extends to skill-oriented habitual motor skills.

Second, children with SLI were no different from TD children in their error productions or their tracing times on the mirror-tracing task. Given that this task is a procedural learning measure that does not involve learning or executing sequences, it can be argued that procedural abilities that are not sequence-specific, such as visuo-motor adaptation in this case, are relatively unaffected in SLI. These results are consistent with the findings of Hsu and Bishop (2014). Hsu and Bishop (2014) used the pursuit rotor task, a task of visuo-motor adaptation, to measure procedural learning in SLI. In this task, the objective is to maintain contact with a moving target. Hsu and Bishop (2014) found that the percentage of time that contact was made with the moving target was comparable between children with SLI and TD children. Similarly on the mirror-tracing task, children with SLI were able to trace the 0.5cm and 1.0cm figures just as well as TD children despite its greater motoric demands than the pursuit rotor task. The most obvious explanation for their typical performance on this measure relative to the sequencing measure is the lack of a sequence-specific element in the mirror-tracing task. Children were free to begin at any point on the trace and move in any direction so long as they did not move the trace itself. Thus, the task did not necessitate that children follow a specific procedure in order to complete the task successfully, but rather, required that children adapted their movements to stay within the lines. Thus, this finding further suggests that children with SLI experience difficulties specific to sequencing.
While these findings are in support of a sequence-specific deficit in SLI, some of the other findings of this study are not. First, children with SLI performed comparably to TD children on the cow hitch knot. Given that the PDH broadly predicts sequencing deficits in SLI suggests that difficulties should be observed across all sequencing measures. However, the children tested in our pilot studies indicated that the figure 8 knot was more difficult to tie than the cow hitch knot. This observation could be interpreted to suggest that the figure 8 knot involved a more complex sequence of movements, thus explaining the selective difficulties children with SLI had with the figure 8 knot. This interpretation is also supported by SRT studies conducted by Gabriel and colleagues (Gabriel, Maillart, Guillaume, Stefaniak & Meulemans, 2011; Gabriel et al., 2013). In their first study, they examined motor sequence learning in children with SLI using a fixed sequence of 8 button-presses. The analyses revealed that children with SLI were able to learn the fixed sequence of button-presses at a rate comparable to TD children (Gabriel et al., 2011). Given that this finding was inconsistent with previous SRT studies (e.g. Lum et al., 2012; Lum et al., 2010; Tomblin et al., 2007), Gabriel et al. (2013) aimed to determine whether sequence complexity, as defined by sequence length, could account for the differences observed in other SRT studies. Using a fixed sequence of 12 button-presses, they found that children with SLI had difficulties learning the sequence relative to TD children. Based on this finding, Gabriel et al. (2013) concluded that children with SLI are affected by complex sequence structures. While length does not account for the complexity in the figure 8 knot, the set of the movements involved in tying the figure 8 knot may perhaps be more complex, involving more intricate looping in comparison to the cow hitch knot. Taken together, the performance on the knot-tying task suggests that children with SLI experience difficulties learning and executing complex sequences.

Second, children with SLI produced the end-state comfort (ESC) grasp at a comparable proportion to TD children on ESC trials. This finding suggests that the sequence planning abilities in SLI are unaffected given that the sequence of hand movements needed to achieve ESC has to be planned prior to execution. Although the PDH does not specify the nature of the
sequencing deficits in SLI, it is unlikely that the learning and execution of sequences would be impacted, but not the planning of sequential information, a process that is plays an important role in motor learning (Doyon et al., 2009). Furthermore, children’s performance on the control trials revealed that children with SLI perseverated their ESC grasps onto control trials. Diedrich, Thelen, Smith and Corbetta’s (2000) study examining perseverative reaching tendencies using the “A not B” Piagetian task can bring us closer to understanding why children with SLI may perseverate ESC grasps onto control trials. They argued that complex motor sequence plans are more susceptible to perseveration than simpler motor sequence plans. Since ESC grasps are more complex than the control grasps in the dowel task, it is speculated that the cognitive resources used to develop the motor sequence plans for ESC grasps are greater than those needed to create motor sequence plans for control grasps. Therefore, the resources available to process a control trial that is preceded by an ESC trial may be slightly diminished in TD children, but greatly limited in children with SLI. To compensate, children with SLI might use the remaining resources to process the novel pieces of information such as which cup to move the dowel to and which end of the dowel (green or black) to place in the cup, which change every trial, and reuse the motor sequence plan that was implemented in the previous trial. This behaviour could perhaps be explained by limited resources in the procedural memory system. Considering that children with SLI experience difficulties with sequencing, much of the available resources may be allocated to planning and/or executing the sequence of movements, leaving little to no resources available to modify the grasp accordingly.

Third, children with SLI performed comparably to the TD children on the retest conditions on the knot-tying task. Given that procedural memory is associated with learned and consolidated motor skills, it would be expected that motor adaptation and consolidation of sequence-specific information would be impacted. This result is not consistent with Hedenius et al. (2011), where it was reported that children with SLI showed difficulties consolidating an alternating sequence of button-presses on an ASRT task. However, it is important to note that the time that elapsed between the first and second assessments of the sequencing measures differed considerably.
between this study and Hedenius et. al’s (2011) study. While performance on the knot-tying task was examined two hours post-test condition, performance on the ASRT task was examined five to seven days later leaving room for interference or loss to comprise the development of the motor memory. At the most, based on the present data, it can be concluded that the earliest moments of motor memory retention are not affected in children with SLI.

Taken together, the findings of this study suggest that children with SLI do experience difficulties with sequencing. However, it appears that these deficits may be specific to learning, planning and executing sequences rather retaining sequence-specific information. However, future research must explore the planning, retention and consolidation abilities of children with SLI to verify the specificity of the sequencing deficits in SLI.

3.4.1.2. Language and procedural motor learning

The second prediction made by the PDH relates to the association between motor and language ability. Specifically, the PDH predicts that parallels between procedural motor ability and language ability exist, but not between motor ability and vocabulary (Ullman, 2004; Ullman & Pierpont, 2005). The findings of the present study also only partially support this prediction. While some of the procedural motor measures were significantly correlated with the collected language measures, significant correlations were also observed with vocabulary as well. Vocabulary and more generally speaking, our mental lexicon, is argued to be supported by declarative memory (Ullman, 2004; Ullman & Pierpont, 2005). The declarative memory system is hypothesized to underlie the learning and storage of words and word-related information including its meaning and use. Although declarative memory plays a different role in language learning than procedural memory, Ullman (2004) argues that declarative memory can adapt its role in language acquisition to parallel that of the procedural memory system, specifically with motor sequencing, if the circumstances arise. Given that this study’s findings suggest that the motor sequencing abilities in children with SLI are atypical, these findings could be interpreted to suggest greater involvement of the declarative memory system to support motor sequencing.
This hypothesis, however, is highly controversial and is perhaps not the best explanation for these significant correlations.

A second, and more likely explanation for these results is differences in statistical learning. Statistical learning, much like sequence learning, is the ability to learn and abstract regularities in speech input, but arguably supports both grammar and vocabulary learning. Studies using invented languages have shown that adults, children and infants are able to identify word boundaries in fluent speech by detecting differences in the transitional probabilities of sounds within and across words in the absence of prosodic and acoustic cues (Saffran, Aslin & Newport, 1996; Saffran, Newport & Aslin, 1996). When exposed to variants of two distinct sounds, infants are able to extract the relevant statistical properties of each variant to facilitate the distinction between the two sounds in natural speech and develop phonetic categories (e.g. Maye, Werker & Gerken, 2002). Syntax studies have also shown that that children’s likelihood to use a primed passive construction was directly related to their performance on an implicit statistical learning task suggesting that the ability to detect and extract statistical relations between words contributes to the acquisition of syntax (e.g. Kidd, 2012). Furthermore, at least one research paper discusses the idea of procedural memory underlying both statistical and sequence learning processes (Hsu & Bishop, 2011). This paper suggests that while the roles of these processes overlap considerably, the distinguishing factor may be the domains that they support. Specifically, they posit that statistical learning may be linked more closely to language learning, while sequence learning may predominately support motor learning. Thus, the correlations that were observed may be capturing the attributes that are common between the statistical learning and sequence learning processes, perhaps procedural memory.

In addition to finding associations between procedural motor ability and vocabulary, the correlations appear to suggest the presence of two distinct clusters of participants with SLI. Further examination of the children comprising these two groups revealed a heterogeneous cluster of children with SLI with regards to their profiles of strengths and weaknesses in language ability. For instance, the children with SLI with longer tracing times on the 0.5cm
trace on the mirror-tracing task (e.g. 100 seconds or longer) consisted of six children with SLI, three with expressive-only deficits, one with receptive-only deficits and two with vocabulary and language deficits. Thus, subgroups within SLI cannot account for this clustering. One potential explanation for these clusters, however, may be related to severity of impairment, which suggests that children with weaker language abilities will exhibit weaker motor abilities and children with stronger language abilities will show exhibit motor abilities. This explanation would be consistent with the predictions of the PDH. A group comparison between the means of the core language scores of the two clusters of participants, however, did not reveal any significant differences ($p = 0.93$). The relatively small sample size may be impacting the sensitivity of our analysis of severity in this study. Thus, future research should explore these associations with larger sample sizes.

Collectively, these findings suggest that procedural motor ability is related to both language and vocabulary learning, which is not supported by the current framework of the PDH. However, at the processing level, it appears that these broader associations between motor and language ability are better explained by individual differences in statistical learning rather than sequence learning. Future research should consider exploring the parallels between statistical and sequence learning to understand the roles of these processes in motor and language development and how they relate to procedural memory.

3.4.2. Alternative explanations

While the results of this study can be explained by a procedural impairment, other cognitive processes can also account for the results presented in this study. Given that the significant differences on the knot-tying task were related to time, performance on this measure could be attributed to deficits in processing speed. While complexity may account for the differences in tying time on the figure 8 and cow hitch knots, it does not explain why differences in completion time were only observed on the knot-tying task and not the mirror-tracing task, despite having both a simple and complex trace. For the dowel task, the perseverated ESC grasp could be attributed to insufficient time to process which cup to transfer the dowel and which end
of the dowel to place in the cup. This explanation, however, assumes that the time to transfer the
dowel from one position to another was comparable to that of the TD children. This
interpretation, therefore, assumes that the perseverated grasps are the outcome of speed-
accuracy tradeoffs. Finally, the associations between performance on the procedural motor tasks
and language test scores could potentially be explained by processing speed deficits given that
many of the significant correlations involve time-based outcome measures. Other factors, such
as working memory, however, could also account for this relationship.

Limited working memory capacity can better account for the results in this study. Similar to the
explanation for processing speed, the significantly longer completion times on the figure 8 knot,
relative to the cow hitch knot in children with SLI can also be explained by complexity. This
added complexity may have increased the working memory loads of the children with SLI by
increasing the number of processes involved in tying the knot, and caused secondary effects on
the time it took them to tie the figure 8 knot. Furthermore, the cognitive demands of the mirror-
tracing task may not have differed significantly between the simple and difficult traces given
that no new or additional information needs to be processed for the more difficult trace. Thus
the level of complexity may be minimal placing less demand on the working memory system
and explain their typical performance by the children with SLI on the mirror-tracing task. The
perseverative behaviour observed in children with SLI on the dowel task can also be explained
by reduced working memory capacity. Children with SLI may have used their available
cognitive resources to process which cup to transfer the dowel to or which end of the dowel to
place, which may have significantly reduced the resources available to adjust the grasp type.
Future research will need to explore this interface in-depth to determine which cognitive
mechanism may be contributing to their perseverative behaviour.

Although research suggests that working memory and procedural memory are distinguishable
memory systems (Baddeley, 2003), there is evidence to suggest that these systems interact with
one another (e.g. Byrne & Bovair, 1997). Thus, working memory limitations could contribute to
the performance on these procedural tasks.
3.4.3. Limitations

While the findings of this study significantly contribute to our understanding of the nature of the procedural deficits in SLI, a couple of limitations should be considered when interpreting the results. The first limitation pertains to the motor tasks that were used to assess the procedural motor abilities of children. While it was our expectation that the procedural tasks administered in the present study were direct measures of motor sequence learning and execution, sequence planning and visuo-motor adaptation, it is possible that other cognitive processes may be involved in performing these tasks. As a result, these unknown cognitive processes, such as working memory or processing speed, may have contributed to the group differences that were observed in this study. However, care was taken to choose age-appropriate tasks with limited confounding factors. Future studies should examine the impact of these factors on children’s procedural learning abilities.

The second limitation concerns the examination of learning and consolidation. Consolidation plays an important role in long-term automatizing a learned motor skill and generally involves assessing performance gains days or even weeks after learning. To minimize participant attrition, however, our second assessment of the knot-tying and mirror-tracing tasks were conducted only two hours post-test condition, a timeframe that is better suited to explore short-term adaptation and retention, rather than learning and long-term consolidation. While we cannot comment on the consolidation abilities of children with SLI based on the present data, this study does suggest that at least the earliest moments of retention are comparable between children with SLI and TD children. This finding is a novel contribution to our understanding of the motor learning abilities of children with SLI given that no studies, to our knowledge, have examined retention in SLI.

3.5. Conclusions

The findings of this study suggest that children with SLI may exhibit a procedural learning deficit, which predominately manifests itself in motor sequence planning, learning and
execution. Furthermore, these motor processes, specifically sequence execution and visuo-motor adaptation, appear to be related to measures of language and vocabulary. While the shared mechanism may presumably be sequencing, differences in statistical learning can better explain the associations with vocabulary. Overall, the findings of this study suggest that the PDH should be revised (1) to specify the aspects of sequencing that are affected and (2) to broaden the role of procedural memory in language development to include vocabulary learning. Prior to modifying the theoretical framework of the PDH, future studies should replicate these findings and further explore the nature of the sequence planning abilities of children with SLI and the correspondence between motor and language ability in relation to statistical and sequence learning.

While it is clear that the motor deficits in SLI affect learned motor skills, it remains unknown whether spontaneous movements, such as communicative gestures, are impacted. Learned motor skills are goal-directed and involve executing a series of movements to achieve a specific outcome (Doyon et al., 2009). Communicative gestures, on the other hand, are nonverbal representations of meaning, making learned motor skills and communicative gestures conceptually different from one another (Cartmill, Beilock & Goldin-Meadow, 2012). Studies have speculated that they may be affected (e.g. Iverson & Braddock, 2011) and thus warrants the investigation of the communicative gesture productions of children with SLI.
Chapter 4

The Temporal Relationship between Speech and Manual Communicative Gesture in Children with Specific Language Impairment

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Abstract

This study examined the relationship between word frequency and timing of communicative gestures in children with specific language impairment (SLI) and typically-developing (TD) children. Nine children with SLI and twelve age-matched TD children produced a narrative after watching an animated cartoon. Redundant gesture-speech pairs were identified and coded for temporal alignment between gesture and speech onset and gesture duration. Word frequency for the co-occurring words was determined using the SUBTLEXus database. No significant group differences were found for temporal alignment or gesture duration. However, word frequency was associated with temporal alignment and gesture duration in TD children, but not in children with SLI. This finding suggests that the role communicative gestures play in lexical access is different in children with SLI relative to TD children.

Key words: specific language impairment, temporal alignment, gesture duration, word frequency, children ages 6 to 10 years
4.1. Introduction

This study investigated the temporal alignment of gestures and speech in children with specific language impairment (SLI) and typically-developing age-matched children (TD). SLI is a developmental language disorder, in which children exhibit deficits in language development in the absence of intellectual disabilities, frank neurological damage, social or emotional disorders, hearing loss and frank oral motor dysfunction (Leonard, 2014). The language impairment commonly observed in SLI is primarily in grammatical abilities. Specifically, individuals with SLI show poor application and comprehension of derivational and inflectional verb morphology, and poor production and comprehension of complex sentences consisting of relative clauses and long-distance dependencies (Rice & Wexler, 1996; Ullman & Gopnik, 1999). Although the majority of past research has focused on grammatical impairments in children with SLI, impairments in lexical and semantic areas of language have been observed in children with SLI, as well (Mainela-Arnold, Evans & Coady, 2010; Sheng & McGregor, 2010).

A handful of studies have explored manual gestures accompanying speech in children with SLI. Researchers have hypothesized that, because of their verbal deficits and relative strengths in nonverbal areas, children with SLI may rely more on gesture than TD children when communicating (Evans, Alibali, & McNeil, 2001; Iverson & Braddock, 2011; Blake, Mysczyszyn, Jokel, & Bebiroglu, 2008).

4.1.1. Relationship between speech and co-occurring manual gestures

Gestures typically convey meaning related to the content expressed in spoken language. As such, they may strengthen a recipient’s comprehension by providing information that is redundant with the speaker’s verbal message. They may also function as an organizational tool for the speaker, assisting with the conceptual planning of speech or facilitating lexical access (Alibali, Kita & Young, 2000; McNeill, 1992; Rauscher et al., 1996). An example of such a gesture is a circular motion produced with a hand, which might co-occur with the word “spin” when a speaker talks about someone spinning on an exercise bar (Alibali, Evans, Hostetter,
Ryan & Mainela-Arnold, 2009). The information expressed in gesture is redundant with the information expressed in speech.

Sometimes, however, in addition to supplementing speech with a semantically redundant gesture, gestures relay new content that is not present in speech. A speaker who talks about someone “going faster” and produces a spinning hand motion with the word “faster” is conveying content about the type of movement in the gesture that adds to the content conveyed in speech. This gesture is non-redundant with the information expressed in speech. In order to examine speech-gesture redundancy, investigators have developed gesture lexicons for coding the meanings of particular gestures in particular tasks, enabling them to identify redundant and non-redundant gesture-speech combinations (Alibali et al., 2009).

Some researchers have hypothesized that, because of their verbal deficits, children with SLI would gesture more and would produce more non-redundant gestures, or gestures that convey information that is not present in speech. However, research findings have been inconsistent. Some studies have reported that, in comparison to their peers, children with SLI produce representational gestures at a higher rate (Iverson & Braddock, 2011; Mainela-Arnold, Alibali, Hostetter & Evans, 2014). However, one study reported that children with SLI did not differ from peers in the frequency of iconic gestures, beat (rhythmic) gestures or points (Blake, Myszczyszyn, Jokel & Bebiroglu, 2008).

Children with SLI have also been reported to express information in non-redundant gestures more often than typically-developing children (Evans et al., 2001; Iverson & Braddock, 2011). However, Mainela-Arnold, Alibali, Hostetter and Evans (2014) found that, although participants with SLI produced more non-redundant gestures than TD participants in a narrative task, they also produced more redundant gestures. Thus, the overall likelihood that a gesture was non-redundant did not differ in the two groups.
These mixed results suggest that the hypothesis that children with SLI rely more on gesture when communicating needs to be refined. One factor that may affect gesture use in children with SLI is deficits in manual praxis and coordination.

Studies examining praxis in SLI have shown that children with SLI have difficulty executing familiar actions on demand (e.g., imitating combing your hair with a brush) in comparison to imitating sequences of unfamiliar actions (e.g. Hill, 1998). A qualitative analysis of the familiar actions produced by children with SLI revealed that their difficulties executing actions were similar to those of TD children, but greater in frequency (Hill et al., 1998). However, despite the increased number of errors, the actions produced by children with SLI still resembled the intended action. Based on these findings, Hill et al., (1998) suggested that difficulties with manual praxis might not lie in conceptualizing the action, but rather in executing the sequence of movements of the action.

In addition to difficulties with manual praxis, children with SLI exhibit poor motor coordination (Vukovic, Vukovic & Stojanovik, 2010; Zelaznik & Goffman, 2010). Studies have shown that children with SLI show poor upper limb coordination and bilateral coordination (Zelaznik & Goffman, 2010) and a delayed onset of the development of arm and leg coordination in comparison to TD children (Vukovic, Vukovic & Stojanovik, 2010). The observed motor coordination difficulties in SLI, similar to the difficulties with manual praxis, may be the result of poor sequential organization of the separate elements of a coordinated action. This suggests that gesture duration and temporal alignment of speech and co-occurring gestures in children with SLI might differ from TD children.

Iverson and Braddock (2011) found that children who had lower expressive language abilities tended to gesture more, but also performed more poorly on standardized measures of fine motor functioning, than children with higher expressive language abilities. In their regression analysis, the variance in language abilities that was accounted for by gesture use was reduced when measurements of fine motor abilities were entered into the regression model, suggesting that
children’s ability to use gestures to supplement their spoken language is constrained by their fine motor abilities.

In the current study, we investigated temporal alignment between speech and gesture in children with SLI and TD children. Because of the reported motor deficits in SLI, we expected to find group differences in the temporal alignment of speech and gesture, and in gesture duration.

4.1.2. Temporal relationship between gesture and speech

A few studies have directly examined the temporal alignment of speech and the accompanying gesture. Generally, the temporal measures investigated include temporal alignment, the absolute difference between onset times of the word and the associated gesture, and gesture duration, the difference between the start and end of the accompanying gesture.

One recent study (de Marchena & Eigsti, 2010) examined the temporal alignment of speech and gestures in adolescents with autism spectrum disorder (ASD) in a story-telling task. Several aspects of temporal alignment were compared between participants with ASD and age-matched controls. There was a significant difference in the temporal alignment of gesture and speech between groups. The time lag between gesture onset and speech onset for the ASD group was approximately 490ms, while for the control group it was only 240ms. In the control group, the stroke phases of the gestures – the portion of the gesture that contains semantic information – occurred as early as 460ms prior to the onset of the related speech and as late as 280ms after speech onset. The stroke phases of the gestures produced by the ASD group, however, occurred as early as 2770ms before and as late as 930ms after the onset of related speech. This group difference in temporal alignment of speech and gesture was statistically significant. The authors concluded that atypical cerebellar development might affect temporal alignment of speech and gesture in ASD. In addition to collecting temporal information about the speech and co-occurring gesture, the quality of children’s narratives was rated. Not only was the quality of narratives in the ASD group rated lower than that in the control group, but the asynchrony between speech and gesture was associated with the quality of the narratives, as well.
Temporal alignment of gesture and speech may be affected, not only by motor abilities, but also by linguistic factors. Morrel-Samuel and Krauss (1992) hypothesized that if gesture facilitates lexical access, then the difference between the onsets of gesture and corresponding words would be predicted by the accessibility of the lexical items, defined by word familiarity ratings. Participants were asked to produce a narrative description of a series of photographs. The results showed that, in their sample of undergraduate students, gestures always preceded the lexical affiliate, but the range of gesture-speech asynchrony varied considerably (0 – 3800ms). Gesture duration was highly positively correlated with gesture-speech asynchrony, and both gesture-speech asynchrony and gesture duration were predicted by lexical accessibility. These findings indicate that the temporal alignment of gestures with speech is affected by lexical factors. Based on these findings, Morrel-Samuel and Krauss (1992) argued that gestures acted as a conceptual or lexical prime for verbal expression.

Lexical learning and processing in children with SLI differs from age expectations. Children with SLI exhibit compromised picture naming (e.g. Lahey & Edwards, 1999) and spoken word recognition (e.g. Mainela-Arnold, Evans, & Coady, 2008). According to a meta-analysis of word learning studies, children with SLI also exhibit difficulties in learning labels for novel referents (Kan & Windsor, 2010). Studies focusing on word definitions, drawings of word meanings, word associations and novel word learning are indicative of reduced understanding of meanings of words, reduced encoding of semantic features of words, and deficits in semantic organization (Alt & Plante, 2006; Mainela-Arnold, Evans, & Coady, 2010; McGregor, Newman, Reilly & Capone, 2002; Sheng & McGregor, 2010). Because of the reported lexical deficits in SLI, it is of interest to examine the relation between word frequency and gesture timing in this population. If gesture facilitates lexical access, we would expect that when children with SLI produce low frequency words, their gestures should be especially long in duration and should occur far in time from the corresponding word.
4.1.3. Study aims

The primary objective of this study was to compare the temporal alignment of speech and the associated manual communicative gestures between children with SLI and TD children. Temporal alignment was defined as the absolute difference in time between the start of speech and the start of the co-occurring gesture. We also measured gesture duration, defined as the difference in time between the end and the start of a gesture. Based on reports of difficulties with manual praxis and coordination in SLI (Hill, 2001), we predicted that the SLI group would produce gesture-speech pairs that were less temporally aligned and would produce gestures of greater duration, in comparison to a TD group.

The second primary objective of this study was to evaluate the relation between word frequency and temporal alignment and duration in both the SLI and TD groups. Previous research suggests that the temporal alignment of gestures and speech is related to the accessibility of the words occurring with the gesture, as measured by word familiarity ratings (Morrel-Samuels & Krauss, 1992). Based on reports of lexical deficits in SLI, we predicted that the relation between word frequency and temporal alignment and duration would be stronger in the SLI group than in the TD group.

4.2. Methods

4.2.1. Participants

Twenty-nine children (ages 6;0 – 10;0), including 12 SLI and 17 age-matched TD controls, participated in this study. All of the participants met the following criteria: (1) monolingual English home environment, (2) no frank neurological damage, (3) passed a hearing screen at 500, 1000, 2000, and 4000 Hz and 20 dB HL, (4) scored at or above 85 on either the Columbia Mental Maturity Scale (Burgemeister, Hollander Blum, & Lorge, 1972), the Leiter International

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1 The original dataset consisted of 15 children with SLI and 18 children with typical development (e.g. Mainela-Arnold et al., 2014). However, video files of four participants, 3 children with SLI and 1 child with typical development, were corrupted, reducing our sample to 12 children with SLI and 17 children with typical development.
Performance Scale (Roid & Miller, 1997) or the test of Nonverbal Intelligence (Brown, Sherbenou & Johnsen, 1990) as a measure of nonverbal intelligence, (4) no oral motor or speech dysfunction, and (5) no emotional or social disorders.

Children’s language abilities were assessed using the Clinical Evaluation of Language Fundamentals – Revised (CELF-R; Semel, Wiig, & Secord, 1987). To be placed in the SLI group, children were required to score at least one standard deviation below the mean on either the CELF-R Expressive or Receptive Language Index or both, and they must have been receiving services for language-related difficulties. To be placed in the TD group, participants were required to score within the normal range on the Expressive Language Index and the Oral Directions receptive subtest of the CELF-R (see Table 1), and they must not have received or have been receiving services for language-related difficulties.

To reliably measure the effects of word frequency on temporal alignment of gesture and speech, and gesture duration, only redundant gesture-speech pairs were analyzed (as in Morrel-Samuels & Krauss, 1992). We eliminated non-redundant gesture-speech pairs from our analysis, because the information children express in gesture in such pairs might not be part of their vocabulary, and this could affect the duration of the gesture and/or the alignment of gesture and speech in unknown ways. This ensured that the information each child expressed in gesture was also part of the child’s vocabulary.

After excluding participants who produced only non-redundant gesture-speech pairs (n = 1 SLI; n = 2 TD) and participants who did not produce any gestures (n = 2 SLI; n = 3 TD), the sample was reduced to 21 children, including 9 children with SLI and 12 age-matched TD controls (ages 6;2 – 10;0).

The children in this study also participated in a series of other experimental tasks investigating gesture (reported in Mainela-Arnold et al., 2006; Mainela-Arnold et al., 2011). The current analysis is a secondary analysis of a subset of data presented in previous manuscripts (Alibali et al., 2009; Mainela-Arnold et al., 2014).
Table 1. Descriptive statistics for ages and standardized test scores

<table>
<thead>
<tr>
<th></th>
<th>Age in Months</th>
<th>IQ(^a)</th>
<th>ELS(^b)</th>
<th>RLS(^c)</th>
<th>OD(^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SLI</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>97.40</td>
<td>103.60*</td>
<td>72.40*</td>
<td>79.80</td>
<td>6.33*</td>
</tr>
<tr>
<td>SD</td>
<td>13.87</td>
<td>8.03</td>
<td>9.50</td>
<td>19.50</td>
<td>2.78</td>
</tr>
<tr>
<td>Range</td>
<td>74-116</td>
<td>89-118</td>
<td>62-84</td>
<td>50-107</td>
<td>3-12</td>
</tr>
<tr>
<td><strong>TD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>99.33</td>
<td>120.75*</td>
<td>104.67*</td>
<td>N/A</td>
<td>11.50*</td>
</tr>
<tr>
<td>SD</td>
<td>13.89</td>
<td>6.68</td>
<td>10.60</td>
<td>N/A</td>
<td>2.32</td>
</tr>
<tr>
<td>Range</td>
<td>76-120</td>
<td>112-136</td>
<td>93-130</td>
<td>N/A</td>
<td>8-15</td>
</tr>
</tbody>
</table>

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

\(^a\) Columbia Mental Maturity Scale: Standard Score, Leiter International Performance Scale: Standard Score or Test of Nonverbal Intelligence: Standard Score; \(^b\) Clinical Evaluation of Language Fundamentals – Revised: Expressive Language Score; \(^c\) Clinical Evaluation of Language Fundamentals – Revised: Receptive Language Score; \(^d\) Clinical Evaluation of Language Fundamentals – Revised: Oral Directions Standard Score; * \(p < .05\)

4.2.2. Materials

A narrative task was used to elicit speech and gestures. The stimulus was a wordless cartoon video from *Die Sendung mit der Maus*. The sequence of events that took place in the cartoon video is described in Figure 1.

*Figure 1. Wordless cartoon video from *Die Sendung mit der Maus**

1. A mouse swings back and forth on a high bar.
2. An elephant enters the scene and watches the mouse spin on the bar.
3. Once the mouse jumps down, the elephant grabs hold of the bar with its trunk and bends it.
6. The mouse attempts to repair the bent bar, but is unable to fix it.

5. A leprechaun enters the scene and walks underneath the bar. His top hat touches the bar and repairs it.

6. The leprechaun leaves and the mouse pouts in embarrassment.

(c) I. Schmitt-Menzel/Friedrich Streich
WDR mediagroup GmbH
Sendung mit der Maus (R)

4.2.3. Procedure

Each child was accompanied by two experimenters. The first experimenter remained with the child throughout the experiment, presented the cartoon video that the child had to later narrate, and asked questions that encouraged the child to explain certain scenes and characters in more detail. The second experimenter acted as a confederate, and was not present in the room while the child watched the video. It was expected that by leading the child to believe that the second experimenter had never seen the cartoon, the child would provide a more thorough description of the cartoon and would produce more speech-gesture pairs.

After watching the video, the child narrated the story to the confederate. Once the child had finished telling the story, the first experimenter asked a series of questions that prompted the child to elaborate on the narrative. These were: (1) Tell a little bit more about what happened when the mouse was first hanging on the bar, (2) Tell a little bit more about when the mouse’s friend tried to hang on the bar, (3) Tell a little bit more about what the mouse did to try to fix the bar, and (4) Tell a little bit more about the man with the hat.
4.2.4. Coding

For the purposes of this study, we identified representational gestures, defined as movements that express semantic information. These gestures were assigned one of thirteen specific meanings from the lexicon developed by Alibali et al. (2009). For example, a gesture that included a back and forth motion using hands or legs was assigned the meaning SWING or a gesture that included an alternate stomping motion using feet or hands was assigned the meaning WALK. Only gestures that were assigned a meaning from the lexicon were used in the analyses to follow.

For each gesture, we also identified the co-occurring words in the child’s accompanying speech. We classified each gesture-speech combination as either redundant (see example 1) or non-redundant (see example 2). For the purposes of this study, only redundant gesture-speech combinations were included in statistical analyses.

[SPIN]
The mouse was spinning on the bar

[HAT]
The magic man fixed the bar

Once the gestures and the words expressing redundant content were identified, the start and end times of the gestures and co-occurring words were recorded. The onset of the first phoneme of the co-occurring word was coded as the speech start time, while the offset of the last phoneme of the co-occurring word was coded as the speech end time. For gestures, the onset and offset of the stroke phase were coded as the start and end times respectively. If a child produced a sequence of gestures without returning to a rest position (retraction phase), each stroke phase was recorded as a separate gesture.
Children’s narratives were video recorded using a digital high 8 camera and converted into .wav and .mp4 files to code gesture and speech using the multimedia annotator ELAN. This software enables the video recording to be examined frame by frame and the time linked audio recording to be visualized. This ensured maximal accuracy in identifying the start and end times of both gestures and the redundant co-occurring words, and the absolute time difference between the start of the gesture and the redundant co-occurring word.

Word frequency was determined for the co-occurring words in the gesture-speech pairs using the SUBTLEXus database (Brysbaert & New, 2009). Of several measures provided by the database, the log10 frequency measure was used and examined as a continuous variable. The logarithm transformation was preferred because it normalized the data.

4.2.5. Reliability of coding

Two coders independently coded the start and end times for gestures and associated words. Absolute agreement between start and end times was measured using a two-way mixed model intra-class correlation (ICC), a commonly-used measure of inter-rater reliability for ratio variables (Hallgren, 2012). For start and end times of associated words, a single measures ICC = 1.00 (p < 0.01, 95% confidence interval of .999 to 1.00) was achieved for 20% of gesture-speech pairs. For start and end times of gestures, a single measures ICC = .999 (p < 0.01, 95% confidence interval of .998 to .999) was achieved for 20% of gesture-speech pairs.

4.3. Results

4.3.1. Nonverbal IQ comparisons

We sought to compare the following two temporal measures between the SLI and TD groups: (1) the absolute time difference between the beginning of the gesture and the redundant co-occurring word (temporal alignment) and (2) gesture duration (duration) (see Table 2). However, before addressing our primary hypotheses regarding temporal alignment and gesture duration, we noted that there were significant group differences in nonverbal IQ (see Table 1).
Thus, we first examined whether nonverbal IQ was associated with these outcome measures. To do so, we evaluated two mixed-effects models: (1) a model that included participant and gesture type (i.e., the meaning category to which each gesture was assigned; see the Coding section) as random factors to account for the variability associated with each participant and with different gesture meanings, and (2) a model that included participant and gesture type as random factors, and nonverbal IQ as a fixed factor. These models were then compared using an ANOVA test of log likelihood values. The chi-square value from the ANOVA test was used to establish whether the model that included nonverbal IQ as a factor fit the data better than the model without nonverbal IQ. For both temporal alignment and gesture duration, this was not the case, $X^2 (1, N = 21) = 0.32, p = 0.57$ and $X^2 (1, N = 21) = 0.20, p = 0.66$, respectively. Thus, nonverbal IQ did not significantly affect the temporal alignment or gesture duration of gesture-speech pairs.

Table 2. Descriptive statistics for number of representational gesture-speech pairs, number of redundant gesture-speech pairs, temporal alignment of redundant gesture-speech pairs and duration of redundant gestures

<table>
<thead>
<tr>
<th></th>
<th>Total Number of Gesture-speech pairs</th>
<th>Number of Redundant Gesture-speech pairs</th>
<th>Temporal Alignment (ms)</th>
<th>Gesture Duration (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SLI</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>10.56</td>
<td>6.56</td>
<td>423.66</td>
<td>1147.75</td>
</tr>
<tr>
<td>SD</td>
<td>6.84</td>
<td>3.61</td>
<td>297.62</td>
<td>397.42</td>
</tr>
<tr>
<td>Range</td>
<td>5-26</td>
<td>2-12</td>
<td>91-696</td>
<td>397-1797</td>
</tr>
<tr>
<td><strong>TD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>8.92</td>
<td>6.67</td>
<td>396.35</td>
<td>1011.25</td>
</tr>
<tr>
<td>SD</td>
<td>6.76</td>
<td>3.61</td>
<td>236.05</td>
<td>649.45</td>
</tr>
<tr>
<td>Range</td>
<td>2-19</td>
<td>1-15</td>
<td>101-945</td>
<td>201-2191</td>
</tr>
</tbody>
</table>

*Note: *p<.05
4.3.2. Temporal alignment and gesture duration comparisons

We next examined whether language status affected temporal alignment of gesture-speech pairs. Given that at least some children with SLI are reported to present with motor deficits, we predicted that the temporal alignment of gesture-speech pairs would differ between children with SLI and TD children. To test our hypothesis, we compared the second model (i.e., the one that included participant and gesture type as random factors, and nonverbal IQ as a fixed factor) with a model that included participant and gesture type as random factors, and nonverbal IQ and participant group (SLI or TD) as fixed factors. We found that the model that included participant group as a factor did not fit the data better than the model without participant group, $X^2 (1, N = 21) = 0.66, p = 0.42$. Thus, participant group did not account for variation in the temporal alignment of gesture-speech pairs.

We next asked whether gesture duration differed for children with SLI and TD children. Using the same approach as the previous analysis, we again found that the model with participant group did not fit the data better than the model without participant group, $X^2 (1, N = 21) = 0.0031, p = 0.96$. In short, contrary to our predictions, the temporal alignment and duration of gesture-speech pairs did not differ significantly in the SLI and TD groups (Figure 2).

*Figure 2. Gesture duration and temporal alignment of gesture-speech pairs (means and standard errors)*
4.3.3. Effects of word frequency on temporal measures

Our second set of analyses examined the effects of word frequency on temporal alignment and gesture duration in the SLI and TD groups. We predicted that temporal alignment of gesture-speech pairs and gesture duration would be affected by word frequency in both groups. However, given their reported difficulties with lexical access, we expected to see a stronger effect of word frequency on temporal alignment and gesture duration in the SLI group. Thus, we predicted a significant interaction of participant group and word frequency for each outcome measure.

To evaluate word frequency effects on temporal alignment and gesture duration, we compared: (4) a model that included participant and gesture type as random factors and nonverbal IQ and participant group as fixed factors to (5) a model that included participant and gesture type as random factors and nonverbal IQ, participant group and word frequency as fixed factors. Then, to address the effect of word frequency across participant groups on these temporal measures, we compared the fifth model to (6) a model that included participant and gesture type as random factors and nonverbal IQ and the participant group by word frequency interaction as fixed factors.

We first examined predictors of temporal alignment. Based on past work, we expected that the asynchrony between gesture onset and speech onset would be greater for less frequent words; thus we expected a negative relationship in both groups. The comparison between the fourth and fifth models showed that, as expected, word frequency was a significant predictor of temporal alignment, $X^2(1, N = 21) = 6.29, p = 0.012$ and the comparison between the fifth and sixth models showed that the participant group by word frequency interaction was a significant predictor of temporal alignment, $X^2(1, N = 21) = 5.17, p = 0.023$. A closer examination of this effect revealed that as word frequency increased, temporal alignment of gesture and speech decreased in the TD group. In the SLI group however, this effect was not observed (Figure 3).
We next considered gesture duration. The first comparison showed that, as expected, word frequency was a significant predictor of gesture duration, $\chi^2(1, N = 21) = 4.20, p = 0.040$, and the comparison between the fifth and sixth models showed that the participant group by word frequency interaction was also significant, $\chi^2(1, N = 21) = 6.82, p = 0.0090$. Examining this interaction further revealed that as word frequency increased, gesture duration decreased in the TD group, while word frequency was not related to duration in the SLI group (see Figure 4).
Therefore, the effect of word frequency on temporal alignment and gesture duration was not stronger in the SLI group than the TD group. In fact, the opposite was found: the effects of word frequency present in the TD group were not found for the SLI group.

**Figure 4. Gesture duration by word frequency for gesture-speech pairs (means and standard errors)**

4.4. Discussion

The purpose of this study was to examine whether the temporal alignment of gesture and speech and gesture duration differed between children with SLI and TD children, and to examine
whether associations with word frequency were similar between groups. To address these questions, we examined (1) the temporal alignment of speech and gesture and gesture duration and, (2) the effects of word frequency on these temporal measures in children in children with SLI and TD children. We hypothesized that (1) the gesture-speech pairs produced by children with SLI would be less temporally aligned and greater in duration than the gesture-speech pairs produced by TD children, and (2) word frequency effects on temporal alignment and duration would be observed in both children with SLI and TD children, but they would be more pronounced in children with SLI. Contrary to our predictions, we found that that temporal alignment and duration of gesture-speech pairs produced by children with SLI and TD children did not differ significantly. However, the effects of word frequency on temporal alignment and duration differed between the SLI and TD groups. Specifically, as word frequency increased, temporal alignment and duration decreased in the TD group. However, word frequency was not related to temporal alignment or duration in the SLI group. These findings were evident, even after controlling for group differences in nonverbal IQ.

The finding of no significant differences in temporal alignment and duration may suggest that, despite reports of subtle deficits in the production of representational gestures in children with SLI (Hill, 1998; Hill et al., 1998), the temporal alignment and duration of communicative representational gestures is not significantly affected by the reported motor deficits in SLI.

An important factor to consider is that children with SLI may not show deficits in all aspects of motor skill, such as timing and coordination. This suggestion is supported not only by evidence from the current study, but also by evidence from two additional studies that have in some form, tested motor timing and coordination in children with SLI (Hsu & Bishop, 2014; Zelaznik & Goffman, 2010). Zelaznik and Goffman (2010) compared motor skill and timing in children with and without SLI using a standardized measure of motor ability, and several manual timing tasks including finger and hand tapping and circle drawing. Their results confirmed that children with SLI exhibit fine and gross motor difficulties, but revealed that their rhythmic timing was comparable to that of TD children (Zelaznik & Goffman, 2010). Hsu and Bishop (2014)
examined the pursuit rotor task, a hand-eye coordination task, in children with SLI and TD children. Their analyses showed that performance on the pursuit rotor task was comparable in children with SLI and TD children. Based on the findings of these two studies and the current study, it appears that the reported motor deficits may not affect temporal alignment and duration of communicative gestures.

The finding that temporal alignment of speech and gesture and gesture duration were affected by word frequency in TD children, but not in children with SLI, suggests that TD children may use gesture to facilitate lexical access, but children with SLI do not. To our knowledge, the present findings are the first to replicate Morrel-Samuels and Krauss’s (1992) findings on adults and extend them to TD children, and the first to show that these patterns do not generalize to children with SLI. The increased gesture duration and longer delays between gestures and spoken words for less frequent words in TD children may be a reflection of their using gestures to help activate the less accessible lower frequency words. Children with SLI, in contrast, may not be using gesture to facilitate lexical access. In previous work, we postulated that increased gesture rates in children with SLI may reflect either an attempt to facilitate lexical access or a preference for representing information in a more embodied manner (Mainela-Arnold, Alibali, Hostetter & Evans, 2014). Since the current analysis found no relationship between accessibility of words and gesture duration and temporal alignment in children with SLI, it lends support to the idea that increased gesture rates in children with SLI are due to a preference for representing information in an embodied manner, rather than due to children using gesture to facilitate lexical access.

One limitation of this study was that the sample size of 9 children with SLI and 12 TD children was small. Therefore, the power of the analysis could be low, and small but true effects may have not been detected. However, given the significant findings for word frequency, the analyses are unlikely to be severely underpowered. Moreover, as seen in the figures, there was no hint of a relationship between temporal alignment and word frequency in children with SLI,
and the relationship between gesture duration and word frequency was non-significant but in the opposite of the predicted direction.

4.5. Conclusions

Our findings indicate that the temporal alignment of gesture-speech pairs and the duration of gestures produced by children with SLI and TD children are similar. These findings suggest that communicative gestures may be unaffected by the motor deficits in SLI, at least in terms of timing. On the other hand, the effects of word frequency on temporal alignment and gesture duration differed between the SLI and TD groups. Specifically, as word frequency increased, temporal alignment and gesture duration decreased in the TD group, while remaining nearly unaffected in the SLI group. Thus, the role communicative gestures play in lexical access may differ for children with SLI and TD children. We suggest that communicative gesturing in children with SLI may reflect a preference to represent information in an embodied rather than an abstract linguistic manner.
Chapter 5
Discussion

5.1. Dissertation aim and studies

Specific language impairment has been traditionally described as a language learning disorder that cannot be explained by any other frank disability. While the deficits in SLI primarily affect one’s language abilities, studies have reported unexplained impairments in several nonverbal abilities as well, including motor ability (Leonard, 1998, 2014). To date, there is no consensus on a unifying theory of SLI. The lack of consensus concerning the underlying deficit(s) means that the intervention that children with SLI receive may not appropriately target the source of their impairments. Our recent review paper summarizing our current understanding of the motor deficits in SLI argued that further specification of the motor impairment in SLI would inform our understanding of the parallels between language and motor ability and bring us closer to identifying the underlying cause of SLI (Sanjeevan et al., 2015). Thus, the aim of my dissertation was to characterize the motor deficits in SLI. This was accomplished by systematically examining verbal and nonverbal motor ability (study 1), procedural motor learning (study 2) and communicative manual gesturing (study 3) in children with and without SLI. This chapter compiles the findings across these studies to not only specify the motor impairment in SLI, but to set the foundation for studies exploring the interface between language and motor ability.

5.2. Characterizing the motor deficits in SLI: Study findings

While previous studies have provided a general description of the motor impairment in SLI, the studies comprising my dissertation contribute the following to the existing literature.

Consistent with previous findings (see Hill, 2001; Sanjeevan et al., 2015 for reviews), the results of the first study showed that children with SLI exhibited problems with gross, fine and speech movements. These issues, however, were not observed across all motor tasks. Instead, their
difficulties appeared to be exclusive to motor tasks that were novel and unfamiliar such as walking backwards heel-to-toe and creating a structure with nuts and bolts. Exploration of the types of errors produced on these novel motor tasks suggested that performance differences on fine and speech motor tasks between the children with SLI and TD children could be attributed to difficulties organizing and/or executing sequences. There was also evidence to suggest that children with SLI had trouble controlling their balance, which was interpreted as evidence for an adaptation deficit. Taken together, the findings of this study suggest that the motor impairment in SLI could be attributed to a procedural learning deficit given that processes such as sequencing and adaptation, which are supported by the procedural memory system, appear to be impacted in children with SLI.

Given that the procedural deficit hypothesis is a fairly new explanation of the processing challenges that lead to SLI, the nature of the procedural deficits is not well understood. Thus, in the second study, the procedural abilities of children with SLI were examined. The results revealed that children with SLI exhibited difficulties with planning, learning and executing sequences, but not with adaptation or retention. Furthermore, significant correlations between procedural motor ability, grammar and vocabulary were found.

Considering that the motor deficits in SLI are generally associated with learned motor skills, it was important to determine whether spontaneous movements, such as communicative gestures, would be impacted as well. Accordingly, the third study examined the temporal alignment and gesture duration of children’s gesture-speech productions. The results revealed that children with SLI were no different from TD children on these measures, indicating that the temporal synchrony between gesture and speech in children with SLI was not significantly impacted by the motor deficits in SLI.

5.3. Procedural Deficit Hypothesis

In my discussion of these studies’ findings, I proposed that the motor impairments in SLI could be explained by the procedural deficit hypothesis. To briefly recap, procedural memory is
involved in the acquisition and consolidation of sensorimotor and cognitive skills (Ullman, 2001, 2004; Ullman & Pierpont, 2005). This memory system supports several processes that underlie motor skill acquisition. These processes include: (1) motor sequence planning, which involves organizing a sequence of movements, (2) motor sequencing learning and execution, which involves executing the sequence of movements, (3) motor adaptation, which involves modifying aspects of the ongoing movement to improve accuracy and (4) motor consolidation, which involves transferring the motor memory to the procedural memory store and automatizing the learned motor skill (Doyon, 2008; Doyon et al., 2009). Of these processes, sequencing and its cognitive counterpart have been predicted to underlie the language and motor impairments in SLI. Based on this premise, the PDH predicts that (1) the deficits in SLI extend to at least sequencing and that (2) motor and language development are related. The findings across these three studies inform the PDH as follows.

5.3.1. Sequence learning and execution

Between the first two studies, there is ample evidence to suggest that children with SLI have difficulties with executing sequences of movements. These sequencing deficits, however, appear to be specific to complex sequential movements. In the first study, children with SLI were different from TD children on the figure 8 knot (difficult knot), but were comparable to TD children on the cow hitch knot (simpler knot). This is also consistent with children’s performances on the VMPAC. Children with SLI were capable of producing speech sounds in isolation, but showed significant difficulties when producing speech sounds in sequences.

Furthermore, several SRT studies have shown that with additional exposure to the repeating sequence, the learning rates of children with SLI eventually become comparable to those of TD children (Lum et al., 2014). Given the similarities in performance on the knot-tying task and VMPAC with the SRT task, it is likely that children with SLI may be faster tying the figure 8 knot, or more precise when repeating sequences of speech sounds, if they spent more time practicing these skills. This hypothesis also explains why children with SLI were able to perform complex movements such as catching a ball or throwing an object at a target. It is
speculated that with added practice and exposure, children with SLI would be able to perform at a level similar to their age-match TD peers, which may also explain performance on the sequenced non-speech oral items on the VMPAC, which comprised familiar oral movements such as smiling and blowing a kiss.

Given these findings, the motor deficits in SLI may be partially attributed to difficulties with complex sequence learning and execution. Also, there is some evidence to suggest that this impairment may have the potential to resolve with additional exposure and practice. These findings can be interpreted to suggest that difficulties with sequencing only arise when learning new and unfamiliar motor skills, leaving consolidated motor skills relatively unaffected.

5.3.2. Sequence planning

There is evidence to suggest that sequence planning may also be affected in children with SLI. On the dowel task, a reduced proportion of end-state comfort (ESC) grasps on ESC trials relative to TD children is generally considered to be an indication of poor motor sequence planning (Rosenbaum et al., 2012). Children with SLI, however, showed a reduced proportion of control grasps on control trials in comparison to TD children. Further investigation of their performance revealed that children with SLI opted to use an ESC grasp on control trials when the control trial was preceded by an ESC trial. In other words, children with SLI perseverated their planned grasps. Perseveration, in the literature, has been attributed to limited cognitive resources (e.g. Diedrich, Thelen, Smith & Corbetta, 2000). If this is the case, it is speculated that the available cognitive resources would be used to process novel pieces of information leaving the previous motor sequence plan to be recycled so long as it achieves the goal of the task. Though children with SLI did not produce perseveration errors in greater frequency on the Manual Dexterity tasks, limited cognitive resources could explain why children with SLI took longer to complete these tasks. Using their available resources to complete the task correctly could have left little to no resources available for developing an efficient motor sequence plan causing children with SLI to compensate and reduce their speed while performing these fine motor tasks. Given the range of cognitive deficits observed in children with SLI, however, the
nature of this resource limitation is unclear. Thus, further investigation of this behaviour is needed.

Based on the findings of this dissertation, it can be argued that sequence planning is affected in SLI. Considering that sequence planning is largely involved in early stages of motor skill acquisition and less so as a motor skill becomes automatized or habitual (Doyon, 2008; Doyon et al., 2009), these findings can also be interpreted to suggest that novel rather than consolidated motor skills are impacted by the motor deficits in SLI.

5.3.3. Adaptation

The findings of the first and second studies can be interpreted to suggest that children with SLI exhibit difficulties adapting their gross movements, specifically those that are balance-related. On the mirror-tracing task, children with SLI were no different from TD children in their tracing times and error productions on both the simple and difficult traces. This would suggest that children with SLI were able to adapt their fine movements just as well as TD children. The specific types of errors that children with SLI produced suggested that they may have had difficulties adapting their whole body movements to better maintain their balance, which could be explained by motor adaptation deficits. Thus, this suggests that the motor adaptation deficits observed in SLI are limited to gross movements that heavily rely on balance, while their ability to adapt fine movements is relatively unaffected.

This interpretation can also explain the comparable performance between children with SLI and TD children on the Aiming and Catching section relative to their poor performance on the Balance section on the MABC-2. Although this section involves tasks that examine the coordination of gross movements, the tasks were not heavily balance-based and thus, the children with SLI may have had very little difficulty adapting their movements to better aim their beanbag throws or catch a thrown ball. An alternate explanation, however, would be that familiarity or previous exposure with these motor activities might have improved the visuo-motor adaptive abilities of the children with SLI. If this is the case, it could be argued that these
visuo-motor adaptation difficulties in SLI may also have the potential to be resolve once the motor skill is consolidated. It remains unclear, however why these adaptation difficulties affect children’s gross movements, but not their fine limb movements.

5.3.4. Retention

The findings of the procedural study suggest that early motor memory retention is relatively unaffected in children with SLI. This was indicated by comparable tying times, tracing times and frequency of error productions across test and retest conditions on both the knot-tying and mirror-tracing tasks. While this is consistent with Hsu and Bishop’s (2014) study exploring children’s performance on the pursuit rotor task, a measure of procedural learning that is not sequence-specific, it goes against the results of Hedenius et al. (2011) that showed that children with SLI exhibited consolidation difficulties with sequence-specific information. However, it is important to note that the differences observed between children with SLI and TD children were based on a consolidation period of about three days post-test condition. During this time, children’s processing and storage of procedural information can vary considerably. Given that the period of time that elapsed before children were tested again in the second study was about two to three hours post-test condition, suggests that in the earliest moments of retention, the procedural information acquired by children with SLI may be unimpaired.

5.3.5. Communicative gesturing

It was our initial expectation that the impairments in SLI affected a broad range of motor areas, including communicative gesturing. Given that children with SLI experience difficulties with praxis and coordination (e.g. Hill, 2001), it was predicted that the quality of the gesture productions would be impacted. However, a couple of recent studies, revealed that the quality of children with SLI’s gesture productions is not significantly impacted given that the children’s gestures were found to be clearly representative of the items or concepts being conveyed (e.g. Botting et al., 2010; Iverson & Braddock, 2011). We then hypothesized that if the motor deficits were to affect gesturing, then more subtle aspects involved in gesturing such as the temporal
synchrony between the gesture production and the co-occurring speech and the duration of the gesture, may be affected. Thus, these temporal features of children’s gesture-speech productions were specifically explored. We additionally explored the effects of word frequency on the temporal alignment and gesture duration of children’s gesture productions to understand the role of gesture on speech production. Our analysis revealed that the temporal aspects of the gesture-speech pairs were not impacted by the motor deficits in SLI. However, the expected negative relationship between word frequency and temporal alignment and gesture duration that was observed in TD children was not observed in children with SLI. The former result supports the PDH based on the idea that motor actions that are not learned, such as spontaneous gestures produced during conversation, would not be associated with procedural memory, a memory system involved in motor learning. The latter result could also be interpreted to suggest that the association between motor and language, as observed through gesture and co-occurring speech, do not interact in the facilitative manner that can be presumed in the relationships found with the TD children.

It is important to note that the findings of this study could also be explained by the possibility that temporal alignment between speech and gesture and gesture duration may not have adequately captured the effects of the motor deficits in SLI. Instead, we might expect to find that the motoric quality of the movements used in the gesture may be different from TD children. For instance, transitioning from one element of a gesture to another, especially for gestures involving both hands, may be more rigid or effortful to produce for children with SLI than TD children. If these observations were made, it would suggest that the motor deficits in SLI are not exclusive to learned motor skills and that a procedural sequence learning deficit may not be the best explanation for the motor deficits in SLI. Thus, examining these aspects of gesture production in children with and without SLI would be informative.
5.4. Alternative explanations

5.4.1. Considering other domain-general hypotheses

Some of the results can be explained by other domain-general hypotheses of SLI, specifically capacity limitations in the form of reduced processing speed, poor attention or limited working memory capacity.

As demands on processing capacity increase, children with SLI have been reported to have an increasingly difficult time performing tasks efficiently (e.g., Montgomery, 2003; Montgomery et al., 2010). On the knot-tying task, the figure 8 knot may have posed greater demands on processing capacity because of its challenging maneuvers relative to the cow hitch knot. The complexity of the figure 8 knot may have drawn on significantly more processes to complete the knot, which may have contributed to the increased completion times observed in the children with SLI. On the Manual Dexterity tasks, not only did children need to complete the task correctly, they also had to complete the task as quickly as possible. Again, these additional demands on the limited capacity may have contributed to their longer completion times on these tasks. Finally, on the dowel task, the perseverative behaviour that was observed in children with SLI could be attributed to their need to attend to multiple aspects to perform the task correctly, including which cup to place the dowel, which end to place in the cup. These demands may not have left enough working memory capacity to determine which grasp type to use, resulting in the recycling of their planned grasps. Given that working memory capacity can explain several findings, future research should examine the interface of working memory capacity and procedural memory in children with SLI.

5.4.2. Statistical learning and procedural memory

A basic premise in the statistical learning literature is that both grammatical and lexical aspects of language learning are supported by the same mechanism of extracting regularities in language input. The following prediction is that associations exist not only between grammar and
procedural motor skills, but also between vocabulary and motor skills. The findings of the second study revealed that the procedural motor performance measures were significantly correlated with children’s grammar and vocabulary test scores. This suggests involvement of statistical learning rather than sequence learning in language learning as well as common underlying features between the two processes. This interpretation warrants the investigation of the interface between statistical learning and sequence learning, which could lead to the restructuring of the theoretical framework of the PDH.

5.4.3. Direction of causality

Another important topic to consider is the relationship between language, communication, motor, and cognitive abilities. The mechanisms that support these processes are likely to be heavily interconnected and interactive, which makes establishing the underlying cause of SLI challenging. In my dissertation, the assumed direction of causality was that cognitive deficits contributed to the language, communication, and motor difficulties in SLI. An alternative possible direction may involve cognitive deficits manifesting in language deficits, which in turn affects one’s motor and communication abilities. In the third study of this dissertation, examining the effects of word frequency on the temporal alignment and gesture duration of gesture-speech productions revealed that as word frequency increased, the alignment between speech and gesture and gesture duration decreased. While this finding suggests that the processes of language shape motor performance, this direction of causality is not well understood (Brumbach & Goffman, 2014). This relationship must be explored further in TD and SLI populations.

5.5. Informing diagnosis and treatment of SLI

5.5.1. Modifications to diagnostic protocols

Current diagnostic measures of SLI primarily include assessments of language ability and performance IQ. However, the findings of previous studies (reviewed in Hill, 2001; Ullman &
Pierpont, 2005) and this dissertation make it clear that the deficits that children with SLI exhibit are not specific to language, but include difficulties in the motor domain as well. This unique profile should be captured by expanding the diagnostic protocols for SLI to include assessment of children’s motor abilities, verbal and nonverbal. Furthermore, the diagnostic criteria for SLI should be modified to reflect the impairment profile more accurately. For example, the evidence of speech-motor difficulties in this dissertation and in other studies (e.g. Archibald, Joanisse & Munson, 2013; Brumbach & Goffman, 2014; Goffman, 1999, 2004) suggests that the ‘frank speech motor deficits’ exclusionary criterion of SLI should be revised or removed from SLI criteria. Given that treatment gains are optimal when intervention is received at a young age (Leonard 1998, 2014) suggests that diagnostic assessments should be administered at a young age as well. The aforementioned profile of impairment, however, has only been observed in school-aged children with SLI and not younger children or toddlers at risk of SLI. Thus, future research should determine whether younger children with SLI exhibit a comparable profile of strengths and weaknesses before integrating these measures into diagnostic batteries for SLI.

In addition to identifying children at risk of SLI in monolingual populations, including measures of procedural motor ability may also address issues related to assessing children who come from bilingual or even multilingual backgrounds. Many language measures used to assess children from bilingual populations are normed on monolingual populations. This method can result in false identification of language impairment in children who do not have language difficulties and the misuse of services and resources that are available (Paradis, 2010). Since the motor measures are not dependent on which languages or the number of languages a child is exposed to, this could perhaps be used to supplement current diagnostic measures and subsequently reduce the under- and over-identification of language impairment in multilingual populations.

5.5.2. Modifications to treatment approaches

As discussed in the first chapter, a fair few of the intervention programs that treat children’s language deficits involve increased exposure to and practice with words and/or grammatical forms that children with SLI find difficult. In many cases, these treatment approaches have been
successful (Leonard, 2014). Given that the findings of this dissertation suggest that children with SLI have difficulties in the initial stages of motor skill learning and perform at expected levels of competency with highly practiced motor skills is consistent with the hypothesis that increased exposure to and practice with these forms and skills can offset the sequence learning deficit affecting their language and motor abilities. Therefore, current service delivery models should incorporate a recommendation for increased intensity of practice.

In this dissertation, I make an argument for a functional relationship between motor and language abilities. This hypothesis brings forth the exciting and new possibility that treating children’s motor difficulties could directly result in improvements in their language abilities. Future studies should consider developing motor activities or games that mirror the simplicity of the SRT task, to target their motor procedural sequencing abilities and examine if these activities result in language gains. Incorporating motor activities in treatment approaches may also keep children more engaged and willing to practice outside of the clinic setting.

5.6. Limitations

When interpreting the results of these studies, there are limitations that need to be addressed. The first limitation pertains to sample size. The sample sizes for each study could be considered small and, as a consequence, may have not detected small, but real effects due to reduced power of analysis. However, the significant findings across all three studies suggest that the analyses were not underpowered. Thus, it is unlikely that the smaller sample sizes are an issue in this case.

The second limitation involves the nonverbal intelligence scores of the SLI and TD children. While significant efforts were made to ensure that the control and experimental groups were closely matched, the nonverbal intelligence scores were significantly different between the SLI and TD groups. To ensure that performance differences were not confounded by this disparity in nonverbal intelligence, nonverbal IQ scores were entered as a covariate in the statistical analyses for all three studies. By controlling for this extraneous variable, group differences that
were revealed by our analyses could be confidently attributed to the variables that were being explored. Thus, the group differences in nonverbal intelligence are unlikely to have affected the interpretations of the results of this dissertation.

A third limitation pertains to the comparison between performance on the mirror-tracing task and the balance tasks on the MABC-2 as evidence of adaptation difficulties specific to whole-body movements. The balance tasks and the mirror-tracing task are considerably different from one another, which may have led to some misinterpretation of which processes and movement types are affected in SLI. It is important to note, however, that the mirror-tracing task has been used as a measure of motor adaptation in other studies (e.g. Rouleau, Salmon, Vrbancic, 2002; Vicari, Finzi, Menghini, Marotta, Baldi & Petrosini, 2005) and the objective of the Balance section is to examine children’s abilities to adapt and adjust to the demands of the dynamic tasks. Future studies, however, should further examine the visuo-motor adaptive abilities of children with SLI and confirm whether difficulties with adaptation are truly specific to whole-body movements.

A fourth limitation involves heterogeneity of the SLI group. The children in the SLI group exhibited a range of language profiles. While efforts to classify children with SLI into subgroups have been largely unsuccessful, there does appear to be some evidence of clustering in the current data. Although the clusters in this data were not associated with on any specific set of language profile, there may be other factors contributing to the clustering that are currently unknown. The low sample size, however, made it difficult to identify these factors.

5.7. Conclusion

The findings of this dissertation suggest that children with SLI exhibit difficulties with learning novel motor skills, while movements that are consolidated appear to be unaffected due to exposure and practice. Moreover, spontaneous movements that are not learned are left unimpaired. This learning deficit may be attributed to a procedural learning impairment. Of the processes involved in procedural motor learning, motor sequencing learning and planning are
most affected. It appears, however, that performance on these procedural motor measures is significantly related to children’s vocabulary and grammar test scores, which can be interpreted to suggest that procedural memory plays a larger role in language learning than previously hypothesized. These findings also inform a fundamental question in language development, which asks whether or not language learning is supported by general learning mechanisms. Not only do the results of this dissertation suggest that domain-general mechanisms contribute to language learning, it additionally provides evidence to suggest that this mechanism may be the procedural memory system.

5.7.1. Future Directions

The findings of these studies, and their respective interpretations, open up several avenues for future research that can add to our understanding of SLI and the role of procedural memory in language and motor learning. Future studies should examine the nature of the sequence planning deficits in children with SLI. Given that this is the first study to directly examine motor sequence planning in SLI, it is important to replicate these findings. While it is clear that children with SLI in this study perseverated their motor plans, whether or not limited procedural resources contribute to this perseverative behaviour remains uncertain. Future research could, for example, examine how exposure to a small cognitive load while performing an end-state comfort task changes the performances of TD children and children with SLI, to gain a better understanding of this relationship.

Second, the effects of language ability on motor ability should be explored. In the third study exploring the gesture-productions of children with and without SLI, we found that word frequency was negatively associated with temporal alignment and gesture duration of the gesture productions of the TD children. This association, however, was not observed in the children with SLI. This finding suggests that the relationship between the language and motor abilities in SLI are complex and do not mirror those of TD children. If future research were to find additional evidence to suggest minimal interaction between language and motor abilities in
SLI, then examining the cognitive mechanisms involved in this interaction could bring us closer to identifying the underlying cause of SLI.

Third, the brain-behaviour relationship between language and motor performance must be explored in children with SLI and TD children. While the behaviours of children with SLI are suggestive of a procedural learning deficit in this disorder, structural and functional neuroimaging is needed to support this hypothesis. This would include investigating whether the expected neuroanatomical structures in the brain are active while children with SLI perform language and procedural motor tasks and establishing how they differ from the brain activity in TD children.

The studies comprising this dissertation aimed to characterize the motor deficits in SLI and bring us closer to determining the underlying cause of this disorder. Given the findings of this study and the conclusions of previous studies (e.g. Hill, 2001; Sanjeevan et al., 2015; Ullman & Pierpont, 2005), it is clear that the term ‘specific language impairment’ is not an adequate term to describe children with language, motor and cognitive deficits. Given that the primary deficits in this disorder are related to language, it may be more fitting to use the term primary or developmental language impairment, as some do (e.g. Boyle, McCartney, Forbes & O’Hare, 2007), or perhaps procedural learning impairment, if further evidence supporting a causal relationship is found.
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