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Deficits in sound pattern sequencing in children with specific language impairment: A networks approach

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DEFICITS IN SOUND PATTERN SEQUENCING IN CHILDREN WITH SPECIFIC LANGUAGE IMPAIRMENT: A NETWORKS APPROACH

A Thesis
Submitted to the Faculty
of
Purdue University
by
Sara J. Benham

In Partial Fulfillment of the
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of
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To my Granddad, Gerald V. Mendenhall

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ABSTRACT

Benham, Sara J. M.S., Purdue University, May 2016. Deficits in Sound Pattern Sequencing in children with Specific Language Impairment: A Networks Approach. Major Professor: Lisa Goffman.

Children with specific language impairment (SLI) demonstrate primary deficits in morphosyntax, which has served as the central theme in theoretical and clinical approaches. However, a striking number of children with SLI also exhibit speech sound deficits, characterized both by increased error patterns and by high levels of variability. These speech sound deficits have been under-studied and are not explicitly tied to accounts of SLI. In the present study, theoretical approaches drawn from dynamical systems and sequence learning are used to address speech production learning in children with SLI. Standard approaches to sound accuracy and variability and articulatory variability are integrated with novel applications of network science to assess sound learning trajectories over time.

The purpose of the present study was to examine how measures of accuracy and variability are related when assessing nonword production over three sessions. A networks approach is proposed that highlights quantitative and qualitative relationships of sound sequences. Results demonstrate that children with SLI are less accurate and more variable, yet there is a dissociation between these two indices. Examination of movement trajectories reveals that group differences in performance cannot be accounted for solely by articulatory ability. There is a strong correlation between segmental variability and the networks measures, and the information provided by this novel methodology demonstrates gaps in classic approaches to error analysis. Results suggest that children with SLI have difficulty with sound sequencing, and that network science may capture error patterns that classic approaches do not.

INTRODUCTION

Variability is a critical component of learning. Children learn by exploration and, as Thelen and Smith (1994) suggest, exploration also helps the child become aware of what needs to be learned. In the process of goal-oriented exploration, children discover solutions with a wide range of individual variability, yet as time progresses stable and effective patterns emerge as a result of learning. For instance, infants and toddlers are highly variable in exploratory behaviors such as reaching and grasping (Thelen et al., 1993), and take variable individual paths in acquiring motor milestones such as postural control, crawling, and walking (Adolph, 1997).

The same principle of exploration and variability can be applied to the development of speech production. Over the course of infancy, pre-linguistic vocalizations and first word forms organize and reorganize in conjunction with changes in anatomical structure and motor control (Studdert-Kennedy, 1983; Vihman, 1993). In a classic study of consonant development in toddlers, Ferguson and Farwell (1975) observed a high degree of within-child variability of word forms produced, for example *ba:ɪ*, *baɪu*, and *baju* all for the target *bottle;* over time these word forms stabilized. The authors also documented a high degree of variability in children’s individual trajectories of phonetic development.

Children integrate new information and adapt as they acquire speech production skills, while increasing efficiency and stability over the course of development.

In speech and language production, variability is observed in typical phonological, morphological, and articulatory development. For example, Ferguson and Farwell (1975) reported that some words appeared to be more phonologically accurate at the onset of production, then regressed to less accurate forms. Following a period of learning, the words then began to approximate adult forms. This pattern of regression has also extended to typical development of inflectional morphology through the use of over-regularizations of regular past tense for irregular past tense verbs (e.g., Marcus et al., 1992).

In the production of grammatical morphemes, children are highly inconsistent when marking tense in obligatory contexts, and therefore commonly revert to an infinitive verb form despite knowledge of finite properties (Wexler, 1994). Regression and variability have also been characterized in movement patterns of articulators (Grigos, 2009; Smith & Zelaznik, 2004). For example, Iuzzini-Seigel and colleagues found that the contribution of lip verticality to lip aperture over development was not a linear progression, but rather it regressed when children made substantive gains in expressive communication (Iuzzini-Seigel, Hogan, Rong, & Green, 2015). This is a typical non-linear, or “U-shaped” pattern of development that is characteristic throughout child speech and language development and is an index of variable learning trajectories.

The purpose of the present paper is to assess a particular component of variability in typical, but more centrally, atypical learners using standard approaches and also incorporating a relatively novel approach, network science. As described above, variability is a hallmark of early typical development (e.g., Ferguson & Farwell, 1975) and has also played an important role in the identification of children with speech and language disorders. Perhaps the most well discussed application of variability in children is in the diagnosis of Childhood Apraxia of Speech (CAS). In 2007, a technical report released by the American Speech-Language-Hearing Association defined CAS as a neurological impairment affecting the planning and programming of motoric components required to produce sound sequences. It is noteworthy that variability and inconsistency in speech production is a prominent feature of this disorder and thus intervention programs treating linguistic aspects of the disorder target word and sound consistency in order to stabilize productions, leading to an increase in sound accuracy (Crosbie, Holm, & Dodd, 2005; Iuzzini & Forrest, 2010).

There has been less attention to the construct of variability in other groups of children, such as those with speech sound disorders of unknown origin and with specific language impairment (SLI). SLI is identified on the basis of impairments in language ability, which cannot be explained by low nonverbal skill, neurological deficits, or hearing loss (Leonard, 2014). Morphosyntactic deficits have been a focus of investigation (e.g., Leonard, 2014; Rice, Wexler, Cleave, 1995), with little attention directed to speech errors in these children. Speech impairments, while often co-occurring, are regarded as a distinct deficit. Despite this, speech errors are well documented (Conti-Ramsden, Crutchley, & Botting, 1997; Deevy, Wisman Weil, Leonard, & Goffman 2010; Shriberg & Kwiatkowski, 1994; Shriberg, Tomblin, & McSweeny, 1999; Sices, Taylor, Freebairn, Hansen, & Lewis, 2007) and some investigators have incorporated standardized speech measures into their assessment batteries of children with SLI (Alt, Plante, & Creusere, 2004; Goffman, 2004; Brumbach & Goffman, 2014; Gray, 2006). While speech errors are not the primary focus of research in SLI, these measures show that a large proportion of 4- to 6-year-old children with SLI also show impaired performance on measures of articulation, such as the Goldman-Fristoe Test of Articulation-2nd Edition (GFTA-2; Goldman & Fristoe, 2000) and the Bankson-Bernthal Test of Phonology (BBTOP; Bankson & Bernthal, 1990).

For children with speech sound disorders, speech sound accuracy has served a focus of assessment and intervention (e.g., Gierut, 1989). In the clinical setting, phonetic accuracy measures, usually percent sounds correct, are the basis for determining outcomes on standardized articulation assessments and on treatment probes. While accuracy is certainly a critical outcome measure for treating errors in speech production, relying solely on this level of measurement fails to provide crucial insight into processes supporting sound acquisition. Furthermore, children with a disorder such as CAS, for example, who are highly variable in their speech, are often inconsistent in the errors they produce, and thus an accuracy measure does not capture changes in error patterns (Iuzzini & Forrest, 2010). Inconsistently produced phonemes are characteristic of very young typical learners, as well as children with CAS and, as discussed in the present study, children with SLI.

The following sections will examine potential contributing factors to speech errors in children with SLI, including influences of working memory, word learning, and motor skill and will conclude by proposing an alternative to traditional assessment tools that captures central features of the error patterns observed in children with SLI. The present work will focus on production of nonwords that include low frequency medial clusters (Munson, 2001) and will not incorporate other lexical and semantic components of word learning.

Influence of Working Memory on Speech Production in SLI

One of the most well studied domains hypothesized to account for speech production deficits in SLI is phonological working memory. This is a memory system proposed to process and store sound sequences for the purpose of learning novel word forms (Gathercole & Baddeley, 1990). Deficits in phonological working memory have been documented in children with SLI (see Leonard, 2014 for a review). Due to difficulties in acquiring novel sound sequences, working memory deficits may also be linked to weaknesses in word learning (e.g., Baddeley, Gathercole, & Papagno, 1998).

Based on these difficulties in form acquisition, investigators have developed measures to evaluate imitation of novel sound sequences, such as the Children's Test of Nonword Repetition (Gathercole, Willis, Baddeley, & Emslie, 1994) and the Nonword Repetition Task (NRT; Dollaghan & Campbell 1998). In these tasks, children repeat nonwords increasing in syllable length such as *rubɪd* or *dɔɪtaʊvæb* and the overall accuracy of their productions is analyzed. Striking differences in accuracy are repeatedly observed, with children with SLI consistently performing more poorly than typical peers, especially as the sound sequences increase in length (Dollaghan & Campbell 1998; Gathercole, Willis, Baddeley, & Emslie, 1994; Montgomery, 1995). However, children with SLI are not the only population with weaker nonword repetition performance, as will be discussed below.

In their comprehensive meta-analysis of nonword repetition in children with SLI, Graf Estes and colleagues (2007) found group differences for single syllable nonwords, suggesting that variables beyond working memory may be influencing task performance. These factors may include weaker perception, encoding, and representational skills. They further suggest that lexical familiarity, frequency factors such as neighborhood density and phonotactic probability, articulatory complexity, and length may influence children's productions of nonwords.

It is important that, while initially framed as a measure of working memory, many other factors may account for poor performance on nonword repetition tasks such as weaker lexical representations and motor skill, as well as deficits in perceptual target representations (Munson, Baylis, Krause, & Yim, 2010; also see Shriberg et al., 2009). Furthermore, while children with SLI consistently demonstrate weaker performance on nonword repetition tasks, similar results are found in children with autism spectrum disorder (Whitehouse, Barry, & Bishop, 2008); dyslexia (Catts et al, 2005); children who stutter (Hakim & Ratner, 2004), as well as children with speech sound disorders (Shriberg et al., 2005). Therefore, the specificity of the nonword repetition task as it relates to children with language impairments is not established.

Influence of the Lexical-Phonological Interface on Speech Production in SLI

The processes of phonological and lexical development are highly interactive. Children demonstrate a robust connection between the size of their lexicons and phonological development even at the age of 2 years, revealing that factors beyond physiological maturation and chronological age influence phonological performance (Smith, McGregor, & Demille, 2004).

Children are sensitive to phonological characteristics when acquiring new words. These include phonotactic probability (Vitevitch & Luce, 2005), referring to the likelihood that two sounds co-occur in a given language, and neighborhood density (Luce & Pisoni, 1998), which is the number of words that differ by the substitution, addition, or deletion of a single phoneme (e.g., the word cat has the neighbors mat, bat, fat, at, etc.). The influences of phonological factors on word production in children often show conflicting results depending on the age of the child, the nature of the speech and language disorder, whether the words are real or nonsense words, as well as the task demands. For example, when comparing novel word learning with manipulations in high and low phonotactic probability, children more readily learn novel words with high phonotactic probability (Storkel, 2001). This effect is even more pronounced in children with SLI when compared to typical peers and is highly associated with lexical size (Munson, Kurtz, & Windsor, 2005). Novel words with high neighborhood density are also repeated more easily (Storkel, 2004) but word recognition from high-density neighborhoods can also prove to be a disadvantage, perhaps due to lexical competition and interference (see Storkel, Armbrüster, & Hogan, 2006 for a summary).

Along with their grammatical deficits, children with SLI also demonstrate weaknesses in lexical knowledge, which leads to difficulties with word learning (McGregor, Newman, Reilly, & Capone, 2002; Oetting, Rice, & Swank, 1995). They also have weaker phonological representations compared with their typically developing peers (Claessen & Leitão 2012; Edwards & Lahey, 1996), leading to deficits in mapping phonological forms to meaning (Alt & Plante, 2006). Word learning studies that examine semantic richness and its effects on phonetic accuracy in children with SLI demonstrate that children with SLI are comparable to typical language learners in terms of sensitivity to semantic richness of novel words, yet accuracy of form production remains impaired when deprived of rich semantic content (Gladfelter, Goffman & Steeb, in prep; Heisler et al., 2010).

The results above have demonstrated how phonological properties of words influence lexical development, yet this interface is also bidirectional. One prominent account of lexical acquisition influencing phonology is the Lexical Restructuring Model (Metsala & Walley, 1998). In essence, this model proposes that lexical growth promotes more fine-grained phonological representations. Young children store words as holistic representations, then gradually fine-tune the individual segments in order to distinguish new lexical items from previous representations. Taken together, these results suggest that there are bidirectional interactions between the lexicon and phonology. For children who demonstrate weaknesses in both lexical acquisition and phonology, this interface may be particularly important to consider. In the present work, we strip away the lexical components and focus exclusively on sound learning in nonwords.

Other accounts of speech errors in children with SLI frame errors within the context of motor skill. The next section will examine motor deficits as a potential source of speech sound errors in children with SLI.

Influence of Motor Skill on Speech Production in SLI

It is well documented that children with SLI demonstrate gross and fine motor deficits (Bishop, 2002; Bishop & Edmundson, 1987; Brumbach & Goffman, 2014; Hill 2001; Iverson & Braddock, 2011; Zelaznik & Goffman, 2010). Speech production is a motor skill that requires exquisite control and coordination, and children with SLI often show differences in lip movement patterns as compared to typically developing peers, such as increased articulatory variability (Brumbach & Goffman, 2014; Goffman, Gerken, & Lucchesi, 2007; Goffman 1999; 2004). In their production of prosodic structure, children with SLI are also poorer at producing the small and short movements required to produce weak, as differentiated from strong, syllables (Goffman 1999; 2004). However, children with SLI do not show speech motor deficits in all aspects of their language production. When producing highly familiar words and phrases, they are similar to their typical peers (Benham, Saletta, Brown, & Goffman, in prep; Brumbach & Goffman, 2014), suggesting that speech motor deficits are constrained to specific contexts.

Articulatory variability is a documented feature of speech production in children with SLI. However, there is evidence to support a dissociation between articulatory variability as measured by movement analyses and segmental transcription (Benham & Goffman, 2014; Goffman, Gerken, & Lucchesi, 2007), suggesting that the speech errors in children with SLI are not explained by impairments in articulatory capability alone. What we propose in this study is that sequencing deficits are at the core of the speech impairment in children with SLI and cannot be accounted for solely by an articulatory deficit. The procedural deficit hypothesis will be reviewed in the next section, which proposes a system-wide deficit in sequencing ability in children with SLI, which may also impair the production of novel sound sequences.

Procedural Deficit Hypothesis and Sequencing in SLI

One potential explanation for deficits in sequencing can be found in the procedural deficit hypothesis (Ullman & Pierpont, 2005). This hypothesis states that children with SLI have impairments in the procedural memory system, which subserves rule learning in areas such as syntax, phonology, and morphology, as well as sequence learning in linguistic and non-linguistic tasks. Furthermore, children with SLI are shown to have deficits in coordination and sequencing in the manual domain (Vuolo, Goffman, & Zelaznik, in revision). A finding that is inconsistent with the procedural deficit hypothesis is that simple metronomic timing is not affected in SLI. However, tasks that require the timed coordination of two hands reveal impairments in coordinated bimanual activity. Children with SLI also show deficits in rhythmic manual tasks such as drumming to a music sequence (Goffman, Vuolo, Zelaznik, Saletta, & Berlin in prep). Hsu and Bishop (2014) have also found that not all aspects of procedural learning are impaired. Children with SLI demonstrate typical performance on a rotor task, but are impaired in a serial reaction time task. These results provide a framework to support the notion of sequencing deficits in children with SLI that also extend to the speech sound domain.

As discussed above, there are multiple levels and processes influencing speech production errors, yet we are lacking tools that specifically assess the types of errors found in children with SLI. We propose that sequencing skill is a core deficit in children with SLI and thus a novel approach to speech error analysis is needed. The next section explores one such approach within the framework of network science. This methodology was specifically selected given its capacity to analyze how sequences are patterned and connected in the speech of children with SLI. Additionally, we hypothesize that a network science approach will offer insights into phonological error patterns beyond the scope of traditional analyses and will explicitly address the sequencing deficits that have been documented in other domains.

Network Science as a Methodology for Assessing Sequencing in Children with SLI

The application of network science has been growing exponentially in the fields of information technology, genetics, sociology, biology, neurology, and epidemiology, and has proven to be extremely relevant to the field of linguistics. For instance, language features such as semantic word mapping (e.g., Sigman & Cecchi, 2002), syntactic dependencies (e.g., Ferrer i Cancho, Solé, Köhler, 2004), phonological networks (e.g., Vitevitch, 2008), and lexical modeling in typical and atypical learners (Beckage, Smith, & Hills, 2011), are highly amenable to a network analysis. These features of language production and processing change over time and are affected by factors such as the input provided by caregivers, properties of words such as length or complexity, or how frequently sound sequences occur in a given language. Perhaps one of the most overt benefits of network science for the field of linguistics, along with many other disciplines, is the ability to examine a dataset in a visually salient manner. In doing so, one can explore the structure or the topology of the network, and determine how the network is arranged spatially. One can also identify the emergence of local hubs or clustering of nodes. This in turn supports subsequent fine-grained and quantitative analysis of specific network properties or sub-components (Vitevitch, 2015).

Network analysis is especially promising for understanding developmental phenomena, considering the dynamic nature of the graphics, and the precision in delineating crucial linguistic transitions. For instance, in an attempt to identify universal properties of lexical growth, Barceló-Coblijn and colleagues (2012) analyzed syntactic structures by coding 3-year-old children's utterances in Dutch, German, and Spanish. Syntactic structures were analyzed based on the relationships between lexical items, which provided a network of direct or indirect dependencies. The authors tracked these syntactic structures as they developed and found that the network topology shifted from tree-like networks to small-world networks. This transition indicates a shift in interconnectivity of the syntactic network, from a sparsely interconnected system to one characterized by a high degree of interconnectivity in which all the nodes are easily accessed by a short path length from one node to another. This shift occurs between approximately 700-800 days of age, regardless of the language analyzed. Furthermore, independent of the language the child was acquiring, hubs emerged in the small-world network that were populated by syntactically functional words such as “the,” “a,” and “that,” which allows for a greater degree of syntactic specificity and lexical expansion. Utilizing network analysis in this way provides a qualitative interpretation of how crucial lexical elements interact across development, as well as the time course for linguistic transitions to occur.

Understanding how language development unfolds in terms of transitions and variable processes in early childhood provides a critical foundation for characterizing typical language acquisition. With a more sophisticated understanding of these processes comes the ability to detect irregularities and atypical trajectories among populations with disorders, which in turn directs the course of appropriate clinical intervention practices. Vitevitch

(2015) further highlights the utility of network science in the field of speech and language, as it affords multiple levels of analysis of language skill, starting with smaller components of speech in individual nodes broadening out to system-wide structure. Vitevitch identifies an emerging analysis in network science called *multiplex networks*, in which it is possible to assess the influence of multiple factors simultaneously. In a highly variable developmental process such as language development, this approach could prove quite useful when examining how multiple aspects of language such as phonology and semantics interact with each other over the course of typical or disordered development.

Returning to the lexical-phonological interface, network analysis has become a robust tool used to demonstrate phonological effects on lexical access and growth, especially neighborhood density, as described above. When applied to network science, Chan and Vitevitch (2009) demonstrated how manipulating network properties such as *degree* and *clustering coefficient* can affect spoken word recognition. Degree is defined as the number of connections to a particular node, or a measure of word similarity between two nodes. Clustering coefficient is the extent to which phonological neighbors are neighbors of each other. These two properties are related to the notion of neighborhood density. Chan and Vitevitch found that when adults were presented with words with a lower clustering coefficient, or low neighborhood density, they were able to produce faster responses in a lexical retrieval task than words with a higher clustering coefficient.

Carson and colleagues (2014) applied network modeling to examine the effects of neighborhood density on lexical development in toddlers between the ages of 14 and 50 months. Speech samples of child-caregiver dyads were transcribed and modeled in a phonological network configuration. In this type of network, the lexical entries (words) were the nodes, and the connections between the nodes were determined based on phonological similarity, that is neighborhood density. The authors used a statistical measure known as survival analysis, which analyzes data collected during the time prior to an event of interest, in this case, the emergence of a word. They were then able to determine how the phonological structure of the network influenced the appearance of a lexical entry in the speech sample. In other words, through network science the authors were able to visualize and quantify the critical role of neighborhood density in lexical acquisition and production.

Surprisingly the authors also found that certain network properties such as *degree, clustering coefficient,* and *coreness,* which measures how embedded a node is in the network, affect children differently over development. In this particular study, all three properties were found to be influential in lexical access prior to 30 months of age, but afterwards showed little effect on acquiring the lexicon. These findings suggest that, over time, children become less sensitive to these network properties. The authors propose that this may be due to the fact that there is more time between the moment a child learns to produce a word and when it is actually used in spontaneous speech. These findings add to the body of literature surrounding phonological contributions to the emerging lexicon from a developmental perspective, suggesting that this connection is not linear, and other factors besides phonology may influence lexical acquisition. Another interpretation may be that this is a natural pattern of stabilization and destabilization so prevalent throughout speech and language development, often characterized by the “U-shape” pattern, or regression, described above. As Carson and colleagues demonstrate, network science is a valuable tool for modeling this type of effect.

The results outlined above extend the body of literature surrounding the lexical-phonological interface into the field of network science and provide quantifiable measurements of the structure and strength of these network connections, which is what this study will also address.

Goals of the Present Study

The aims of the present study are threefold. First, we document speech production errors in children with SLI and typically developing children using standard analytic approaches of measuring phonetic accuracy and variability. The second aim is to determine how these patterns of speech production accuracy and variability align with variability at the kinematic level in order to determine if these errors relate to motor deficits. Finally, our third aim is to present a novel framework of error analysis, network analysis, and determine how results from this analysis correlate with measures of segmental accuracy and variability.

We predict that children with SLI will demonstrate reduced segmental accuracy and increased segmental and kinematic variability in comparison with their typically developing peers. Network analyses will reveal that children with SLI show a higher average degree, with more nodes and edges than typical peers. They will also demonstrate reduced weighted degree as compared to typical peers, indicative of more disorganized speech patterning. Further, variability measures will not correlate with accuracy of speech sound production, but will correlate with network analyses such as weighted degree. We will examine processes of variability and stabilization as children acquire novel phonological sequences over multiple sessions. We propose that a network analysis has the potential to reveal core components of the speech production deficit in SLI that are not evident in standard phonological and articulatory approaches. In sum, we hypothesize that the speech production deficits in children with SLI arise as a result of weaker higher-order sequencing skills. How these core deficits fit into current theoretical accounts will also be discussed, along with clinical implications for intervention.

METHODS

Participants

Twenty-four preschoolers participated, ranging in age from 4;0-6;0 (years; months). Twelve children met exclusionary criteria for SLI (*M* = 5;3, *SD* = 0.51, range=4;1 to 6;0). Twelve additional children with typical language development (TLD) were included in the control group (*M* =5;0, *SD* = 0.52, range=4;0 to 5;6). The SLI group included 7 males and 5 females, and the TLD group 6 males and 6 females. All children were monolingual English speakers. These participants were drawn from a larger experiment examining semantic effects on word learning (Gladfelter, Goffman, & Steeb, in prep) in children with SLI and children with typical language.

Children with SLI met exclusionary and inclusionary criteria as outlined by Leonard (2014). All children showed normal hearing (20 dB HL of pure tones at 250, 500, 1000, 2000, 4000, and 6000 Hz bilaterally), typical nonverbal IQ scores as measured by the Columbia Mental Maturity Scale (CMMS; Burgemeister, Blum, & Lorge, 1972), and had no history of neurological impairments. The Structured Photographic Expressive Language Test – Preschool 2nd edition (SPELT-P2; Greenslade, Plante, & Vance, 2009) was used to assess language performance, and a standard score of 87 or less was required for inclusion in the SLI group (Greenslade, Plante, & Vance, 2009). Additionally, all participants performed within normal limits on the structural component of the Robbins and Klee (1987) oral mechanism exam to rule out structural deficits that could account for speech errors.

All participants underwent additional standardized testing to measure speech performance using the Consonant Inventory score on the BBTOP. Because gross and fine motor deficits have frequently been identified in children with SLI (Hill, 2001; Zelaznik & Goffman, 2010), fine and gross motor skills were assessed using the Movement Assessment Battery for Children, 2nd Edition (MABC-2; Henderson, Sugden, & Barnett, 2007), which identifies motor deficits in the domains of manual dexterity, aiming and catching, and balancing. A summary of group performance on all tasks is provided in Table 1 below.

Table 1. Group Performance on Behavioral Assessments

	SLI			**TD**		
Assessment	**Mean**	**SD**	**Range**	**Mean**	**SD**	**Range**
CMMS	103	9	94-125	118	8	108-136
SPELT-P2	79	9	67-87	112	11	90-125
BBTOP CI	73	9	65-90	100	9	86-113
BBTOP Percentile	6	9	1-25	51	22	18-81
MABC-2 Manual Dexterity	7	3	2-14	10	3	6-15
MABC-2 Aiming & Catching	11	3	6-16	11	2	8-16
MABC-2 Balancing	9	4	5-16	12	3	8-16
MABC-2 Total	8	4	4-17	11	2	8-15

Stimuli

The stimuli consisted of six trochaic CVCCVC nonwords that were part of a larger study on how semantic attributes affect word learning in children with language impairments as well as children with typical language (Gladfelter & Goffman, in revision; Gladfelter et al., in prep). However, for the purpose of the present study, only the nonwords that were not assigned a semantic meaning were included for analysis. Therefore, the focus of this study was on the production of nonwords over time. All stimuli were controlled for neighborhood density and for phonotactic probability, since both of these factors also influence word learning (Storkel et al., 2006). Both neighborhood density and phonotactic probability were low, because previous work has indicated that short term learning is more likely to be observed in low frequency forms (Gladfelter & Goffman, 2013; Heisler & Goffman 2016; Storkel, 2001). Additionally, stimuli were constrained such that labial consonants were present in the initial, medial, and final positions in order to demarcate word onset and offset points for kinematic analyses. The six nonwords are /p^vgəb/, /f^ʃpəm/, /p^btəm/, /f^spəb/, /b^pkəv/, and /m^fpəm/. Stimuli were recorded as discrete CVC rather than ambisyllabic sequences. Neighborhood density ranged from 0-15 neighbors, with a mean of *M*=5.8 and *SD*=4.2, which meets the criteria for low neighborhood density as outlined by Munson, Swenson, and Manthei (2005). Biphone sequences were calculated using the online phonotactic probability and neighborhood density calculator (Storkel & Hoover, 2010). All biphone sequence frequencies were lower than 0.0066, meeting criteria for low phonotactic probability as outlined in Storkel (2001).

Procedures

Each child was randomly assigned one word pair that remained constant over the course of the three sessions, with assignment equally distributed across children so that four children in each group produced each word pair. The specific pairings were /f^ʃpəm/ and /p^vgəb/, /m^fpəm/ and /b^pkəv/, and /p^btəm/ and /f^spəb/. Participants were seated approximately 8 feet in front of a 76.2 cm Dell monitor, which presented PowerPoint slides containing audio playback of the stimulus words recorded in a child friendly female voice. Audio stimuli were digitized and equalized at 70 dB using Praat (Boersma & Weenink, 2012). The slides also contained randomly varying, novel, colorful images in order to obtain attention, visually engage the participants, and facilitate optimal data capture, as the motion capture system was positioned directly above the monitor. Participants produced the stimuli in direct imitation a total of 24 times per session over the course of 3 sessions. The two words were quasi-randomly ordered, with no more than two productions in a row of the same word. Children repeated each word 12 times in direct imitation. Then the children heard the words 7 times each in a listening phase, and finally produced the words 12 times each once again. To be certain the children slept between exposures and consolidation could occur, the sessions occurred at least 24 hours apart, but no more than 1 week apart (Diekelman & Born, 2010; McGregor, 2014).

Data Capture

The 3D Investigator (Northern Digital Inc., Waterloo, Ontario, Canada) motion capture system was used to record movement of the lips and jaw during speech production. One infrared light emitting diode (IRED) was placed on the child's upper lip, one on the lower lip, and one on the jaw. Four additional diodes were placed on child-sized sports goggles and aligned at the corners of the eyes and mouth, and one additional diode was placed on the forehead. These served as reference points in order to subtract head movement during subsequent analysis. The kinematic signal was captured at a rate of 250 samples per second. An acoustic signal was time locked to the kinematic data and captured at a sampling rate of 16000 samples per second. A high-quality audio signal was recorded using a Marantz CD recorder, and video was captured with a Panasonic DVD camcorder.

Analyses

Transcription

All productions were transcribed using broad phonetic transcription by trained research assistants using audio and video recordings. A sample of 20% of all productions quasi-randomly selected and distributed equally across experimental groups was coded by a second transcriber to calculate inter-rater reliability. The two coders agreed with 93% reliability. Transcription data were used for three analyses pertaining to the present study: segmental accuracy, segmental variability, and the network analysis, each further discussed below.

Segmental Accuracy

To calculate segmental accuracy, the number of consonants produced correctly is divided by the total number of target consonants and multiplied by 100 to yield a percentage. For this analysis, PCC was calculated for the first 10 productions for each child by session. Productions that were disfluent, had long pauses (2 standard deviations or greater than the mean word duration), contained yawning, whispering, laughter or sighing were excluded from analysis.

Because the objective was to assess accuracy of segments that were “in” the child’s phonetic inventory, those that were never produced throughout the entire experimental nonword repetition task were referenced in relation to performance on the Consonant Inventory of the BBTOP. Segments that were never produced in the BBTOP in any position were discarded from the analysis. A total of 60 consonants from the SLI group (out of 1916 total consonants), and 20 consonants from the TD group were excluded from analysis (out of 1900 total consonants). The consonants excluded from analysis were distributed in the following manner: two participants with SLI did not produce “ʃ” and one did not produce “k.” In the TD group, one participant did not produce “ʃ.” Overall, this represents a minimal data loss with a total of 2% of phonemes not amenable to analysis.

Segmental Variability

To capture phonetically transcribed production variability, Iuzzini & Forrest (2010) created an Inconsistency Severity Percentage (ISP), which is calculated as the number of different substitutes across all targets divided by the total number of productions, multiplied by 100 to yield a percentage. This formula was modified in the present study for use at the segmental level to track the variability of each child. This was achieved by calculating the number of different phonemes by position across all targets divided by the total number of target phonemes, multiplied by 100. For instance, for the target /f^ʃpəm/, if a child produced /p^spəm/ five times, and /f^ʃpəm/ five times, this analysis would identify the number of varying phonemes in each consonant position. Table 2 illustrates how the ISP was calculated. There were two variants in the initial position, two variants in the first medial position, one variant in the second medial position, and one variant in the final position, for a total of 6 variants. This number is then divided by the number of target phonemes in a typical production set of 10 words, (equivalent to 40 phonemes). It should be noted that a perfectly stable set of productions would result in a minimum of 10% variability, so in order to avoid penalizing these productions, we set no variance equal to zero. Therefore in this example, the child receives a score of 5% as an index (15%-10%).

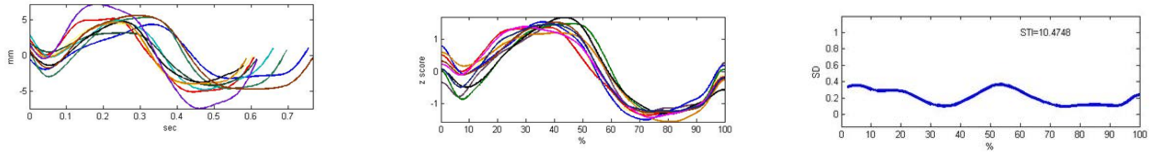
Table 2. Calculation of ISP Score for /f^ʃpəm/

	Initial	Medial 1	Medial 2	Final	Total
# variants	2	2	1	1	6
# consonants produced (10 productions)					40
ISP score-10%					.05

The same exclusionary criteria outlined for the productions in the PCC calculation were considered for this analysis with the exception of discarding segments that did not appear in the child's Consonant Inventory on the BBTOP. This was done so as not to penalize children for sounds on the nonword task that did not appear in their phonetic inventory.

Kinematic Signal

The kinematic signal was processed using locally customized Matlab routines (Mathworks, 2014) to extract each word from the speech signal based on velocity and displacement measurements of the articulators of interest (lips and jaw). Words without an initial or final labial consonant, as well as words that contained an extra syllable, were excluded from analysis. Words that met the exclusionary criteria for transcription purposes were also discarded from kinematic analysis. A minimum of 5 and a maximum of 10 acceptable productions were used for each individual novel word form. The variability of lip aperture (upper lip-lower lip displacement) was calculated by normalizing the time and amplitude for each production then measuring the standard deviation at 2% intervals. The 50 standard deviations were summed, which yielded an index of variability called the spatiotemporal index (STI; Smith, Goffman, Zelaznik, et al., 1995). A higher STI value represents a highly variable production of each target word, and a low STI value represents productions that were produced in a stable manner. Figure 1 below depicts the process of calculating the STI.



Gladfelter and Goffman, in prep

Figure 1. Spatiotemporal Index Generation. The left figure shows 10 productions of a word extracted from the continuous speech signal. In the middle figure, the productions are normalized in the time and amplitude domains, and the sum of the standard deviations is shown on the right to yield the spatiotemporal index.

Network Analysis

The transcriptions were first converted to Klattese (Klatt, 1987), a computer-readable version of the International Phonetic Alphabet transcription system, in order to facilitate computer analysis. Productions were divided into first and second syllables. For most cases, each syllable was treated as one CVC unit. However, some children omitted a medial consonant, as in the case of /f^pəb/. For these productions, the syllable boundary was determined by the maximal onset principle (Kahn, 1976). This principle dictates that boundaries are determined by the maximum number of consonants at the onset of the syllable. Therefore, the syllable boundary would be as follows: /f^/ for the first syllable, and /pəb/ for the second syllable. Productions were then uploaded to Gephi (Bastian, Heymann, & Jacomy, 2009), an open-source network software program, in order to render a network depiction of the productions for each experimental group. Once in network format, syllable connections were determined in a directed manner, such that the link (also known as an *edge*) was established between the two *nodes* (in this case, a node is a syllable) if the first and second syllable were produced together in the child's speech. For example, if the child produced "f^ʃpəm," the nodes "f^ʃ" and "pəm" would be connected by an edge.

Figure 2 depicts a sample of ten productions of the word /f^ʃpəm/ listed below in Table 3. Note that all productions are first converted into Klattese. Represented graphically, each syllable becomes a node. The nodes are linked by an edge if the syllables were produced concurrently. The number of nodes and edges provide insight into the number of different syllables produced by each child, as well as the number of different co-occurrence patterns. More complex analyses include *average degree*, which is the average number of connections per node, as well as the *average weighted degree*, represented graphically as the thickness of each connection. This represents the weight of a particular connection, or the strength of the relationship between two nodes; in the present study, the weight between nodes represents the frequency of production. For instance, if the average weighted degree is equivalent to 5, there are several possible node and edge configurations. There could be one node with 5 edges, each with a weight, or frequency of 1, or there could be a node with 1 edge with a weight of 5, etc. As demonstrated by the table, "p^npxm" was produced more frequently than the other sequences. Therefore, on the network plot, the edge connecting the nodes "p^n" and "pxm" is shown to have a thicker line reflecting the frequency of that connection. For this study, four network metrics are used for analysis: number of nodes, number of edges, average degree, and average weighted degree.

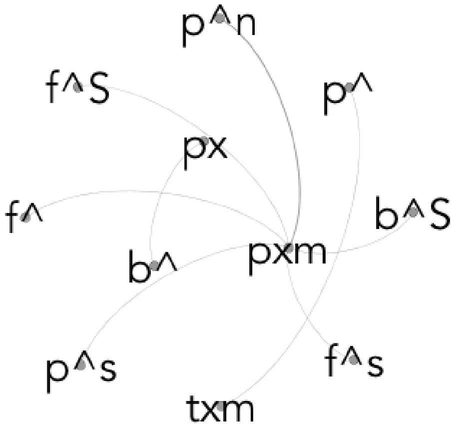


Figure 2. Network graphic of ten sample productions of /f^ʃpəm/. This figure illustrates how productions would be converted to Klattese and displayed in network format.

Table 3. Ten Sample Productions of /f^ʃpəm/

Target Word	Syllable 1	Syllable 2	Whole Word
f^Spxm	p^s	pxm	p^spxm
f^Spxm	b^	px	b^px
f^Spxm	p^n	pxm	p^npxm
f^Spxm	p^n	pxm	p^npxm
f^Spxm	p^	txm	p^txm
f^Spxm	p^n	pxm	p^npxm
f^Spxm	f^S	pxm	f^Spxm
f^Spxm	f^	pxm	f^pxm
f^Spxm	b^S	pxm	b^Spxm
f^Spxm	f^s	pxm	f^spxm

In the present analysis, we emphasized the syllable rather than the segmental level. The objective was to evaluate how children, both typically developing and those with SLI, acquire novel words. We hypothesize that children with SLI would show syllable co-occurrences that reveal a high level of variability and unstable sequencing abilities.

Network science provides novel information about speech production based on the structural characteristics of the network, in this case the stability of syllable co-occurrences. This type of analysis holds great promise for characterizing how phonological variability is represented in children, including young typical learners and those with SLI, and provides useful statistical information to support variability as a critical marker of speech production in children with SLI.

Statistical Analyses

Mixed analysis of variance (ANOVA) was conducted to examine group differences between the two experimental groups (SLI and TD), as well as within group differences across sessions 1-3 and word differences, where relevant. Post-hoc analyses were performed using the Tukey Honestly Significant Difference testing (HSD), with results significant at $p<0.05$.

Correlation analyses were also conducted to assess the interactions among different sources of variability at the segmental (ISP), syllable (network analyses), and kinematic levels (STI). Relationships of these sources of variability to segmental accuracy (PCC) were also examined.

RESULTS

A mixed ANOVA was conducted to examine group effects between children with SLI and typical peers at the three time points for each variable measured: segmental accuracy, segmental variability, and the networks analyses (number of nodes and edges, average degree, and average weighted degree). Tukey Honestly Significant Differences (HSD) were also used to ascertain differences across the three sessions. We were also interested in exploring specific word effects; even though words were controlled for phonotactic probability and neighborhood density, we expected there would be item effects. ANOVAs were also used to investigate these potential word differences for both segmental accuracy (PCC) and variability (ISP).

Because a major question was how standard measures of error analysis (e.g., accuracy and variability) relate to the networks analysis in children with SLI as compared to typical children, Pearson correlation coefficients were calculated to explore these relationships. Results from ANOVAs are presented for the experimental variables first, followed by correlation coefficients.

Segmental Accuracy (PCC)

There were significant group differences between experimental groups, *F*(1,22)=14.68, *p*<.01 and session effects, *F*(2,44)=3.59, *p*=.04 where children with SLI were weaker in segmental accuracy than typical peers, consistent with our predictions. No session * group interaction was observed, *F*(2,44)=0.47, *p*=.63. Both groups of children showed a limited range in protracted PCC performance. Children with SLI ranged from 65% at session 1 to 67% by session 3, and typical children ranged from 85% at session 1 to 89% by session 3 (Figure 3 below). Both groups demonstrated a trend in improvement between sessions 1 and 2 (*p*=.07), but there were no differences between sessions 2 and 3 (*p*=.99), with an overall trend between sessions 1 and 3 (*p*=.06).

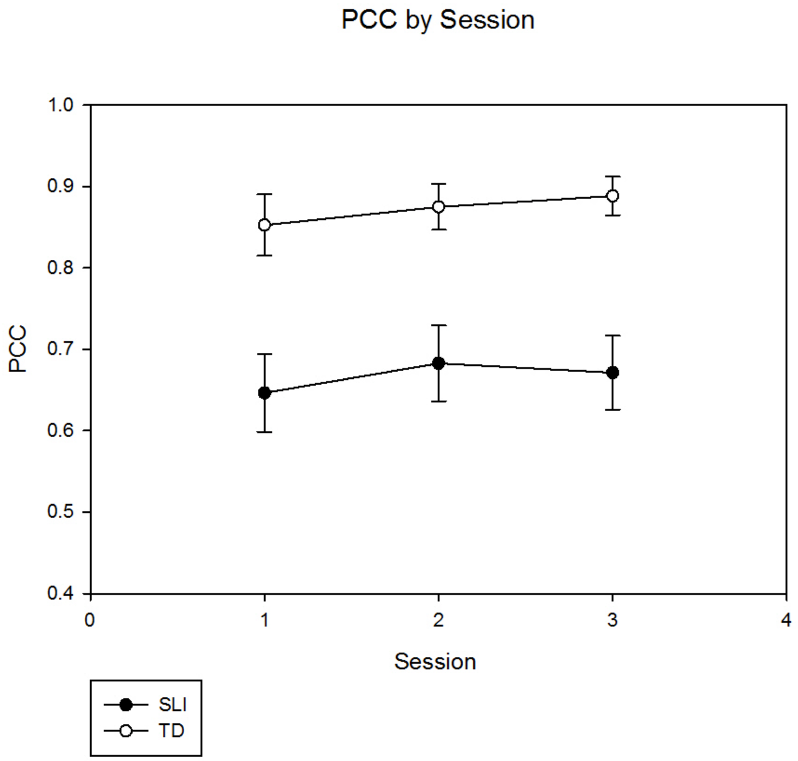


Figure 3. PCC Performance by Session

Segmental Variability (ISP)

As predicted, children with SLI were also significantly more variable at the segmental level than typical peers, *F*(1,22)=21.22, *p*<.01 (Figure 4). A session effect was also observed, *F*(2,44)=20.31, *p*<.01, where learning occurred the most from sessions 1 to 2, *p*<.01 and 1 to 3, *p*<.01, but there was no difference between sessions 2 and 3, *p*=.77. Similarly, there was no session * group interaction, *F*(2,44)=1.87, *p*=.17. See Table 4 below for individual data for both the PCC and the ISP.

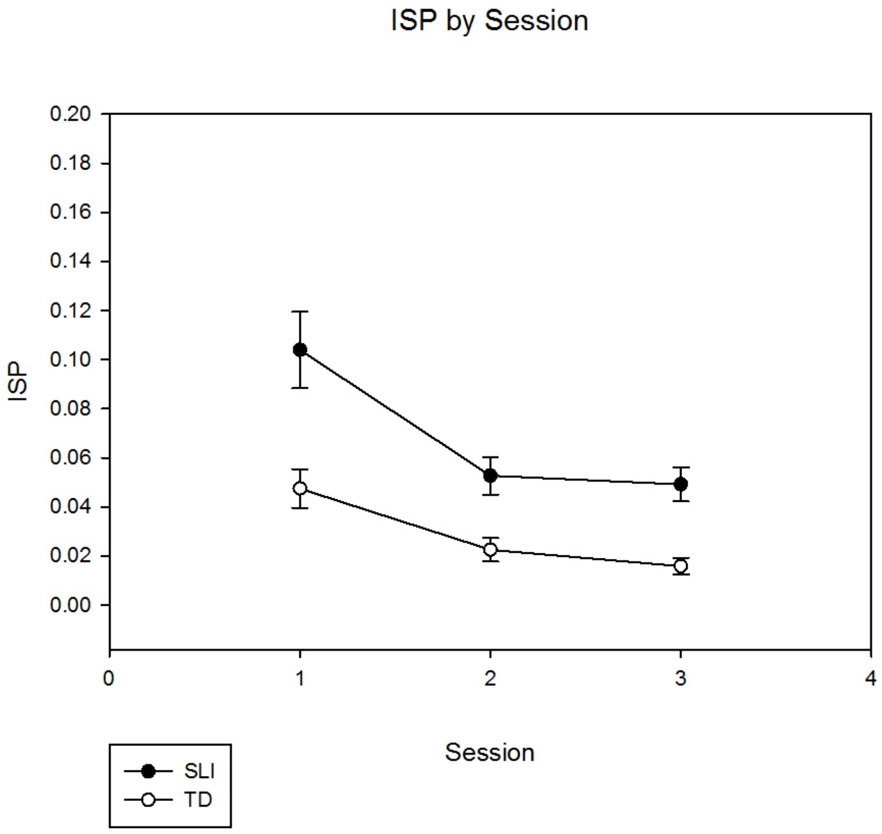


Figure 4. ISP Performance by Session

Table 4. Individual Performance on PCC and ISP

	Session 1		**Session 2**		**Session 3**	
SLI	**PCC**	**ISP**	**PCC**	**ISP**	**PCC**	**ISP**
1	.65	.14	.58	.10	.58	.10
2	.69	.03	.76	.07	.64	.06
3	.51	.05	.52	.02	.56	.03
4	.79	.15	.86	.07	.80	.03
5	.35	.08	.35	.06	.35	.06
6	.76	.08	.76	.04	.75	.06
7	.96	.03	.96	.03	.97	.03
8	.42	.16	.62	.03	.61	.04
9	.67	.18	.73	.03	.72	.03
10	.71	.17	.61	.09	.60	.08
11	.61	.09	.69	.06	.67	.05
12	.64	.09	.78	.03	.82	.02
Mean	.65	.10	.68	.05	.67	.05
SD	.17	.05	.16	.03	.16	.02
TD	**PCC**	**ISP**	**PCC**	**ISP**	**PCC**	**ISP**
1	.99	.13	1.00	.11	.98	.12
2	.96	.13	.94	.13	.95	.12
3	.90	.12	.88	.10	.88	.10
4	.91	.16	.88	.14	.88	.12
5	.76	.15	.78	.13	.87	.11
6	.96	.14	.97	.13	.96	.12
7	.99	.13	.96	.13	.96	.12
8	.85	.13	.88	.10	.88	.10
9	.91	.16	.95	.14	.96	.13
10	.74	.17	.86	.14	.86	.12
11	.66	.18	.72	.16	.72	.14
12	.61	.14	.71	.14	.76	.13
Mean	.85	.15	.87	.13	.89	.12
SD	.13	.02	.10	.02	.08	.01

Kinematic Variability (STI)

An ANOVA was used to assess group differences in kinematic stability of the nonwords prior to the listening phase of the experiment (Figure 5). This analysis did not reveal any group effect, *F*(1,17)=0.73, *p*=.40, word effect, *F*(1,17)=2.08, *p*=.17 or session effect, *F*(2,34)=2.90, *p*=.07, or session * group interaction, *F*(2,34)=0.42, *p*=.66. This suggests that children with SLI are no different from typical peers in the production of the novel nonwords. However, there is a trend of a session effect, and visual inspection suggests a pattern of convergence by session 3. In a larger data set, this trend is carried by children with SLI converging with their peers and becomes statistically significant (Gladfelter et al., in prep). This result demonstrates that the group differences in accuracy, variability, and networks analysis, as described below, cannot be explained by articulatory performance.

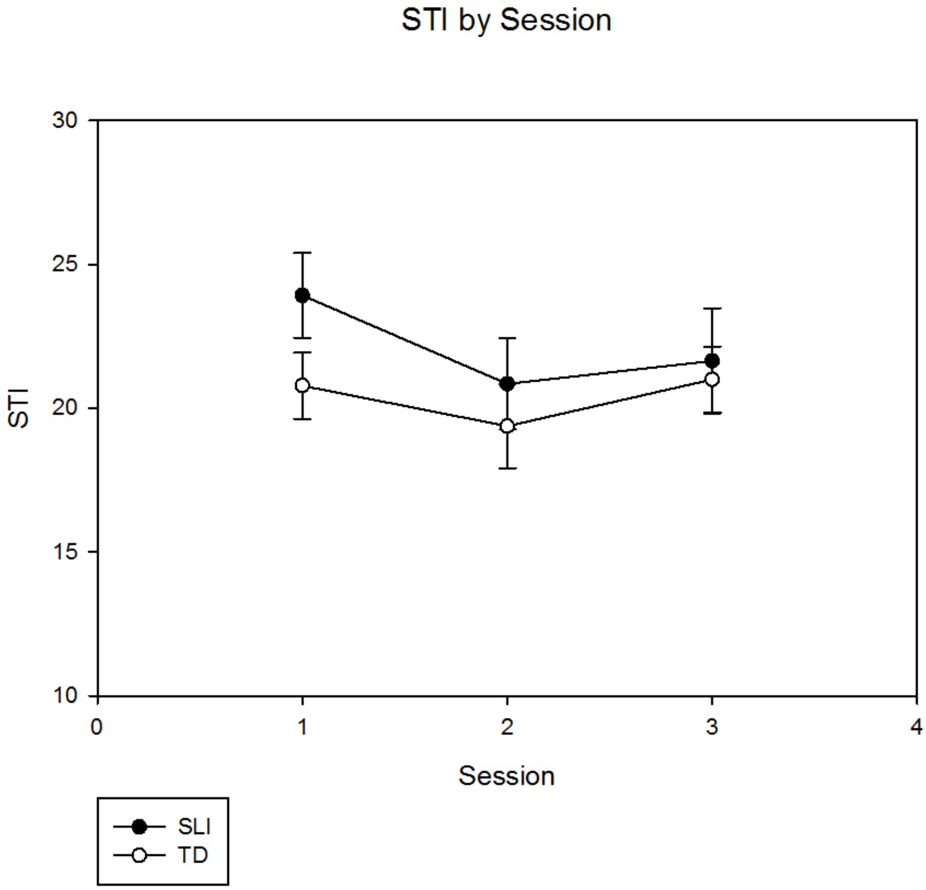


Figure 5. STI Performance by Session

Network Analysis

Each network measure is sensitive to different aspects of children's speech production. For instance, the number of nodes reflects the number of different forms (syllables) produced, whereas the edges inform how syllable co-occurrences are distributed across the nodes. When examining patterns of interactions, degree and weighted degree are particularly informative. A node's degree reveals the number of connections (edges) it contains, and the weighted degree is indicative of the strength or frequency of a particular connection. Hence, for this analysis, more weight represents a more frequent production co-occurrence pattern.

A robust group difference and session effect was observed for all the network variables analyzed (see Figure 6 for a visual representation of the networks and the Appendix for enlarged graphics and individual data). As predicted, children with SLI produced more nodes, $F(1,22)=11.40$, $p<.01$, (Figure 7) and edges, $F(1,22)=14.51$, $p<.01$, (Figure 8) than typical peers, as well as had a higher degree, $F(1,22)=15.87$, $p<.01$, (Figure 9) and higher weighted degree, $F(1,22)=11.51$, $p<.01$, (Figure 10). No session * group interaction was observed for any of the network measures, $F(2,44)<1.58$, $p>.22$. Both groups demonstrated similar patterns of learning, where the greatest degree of learning occurred between sessions 1 and 2 ($p<.01$), and 1 and 3 ($p<.01$), but sessions 2 and 3 were no different from each other ($p>.92$). Average degree, however, demonstrated a different pattern over the three sessions for children with SLI. In this group, the degree remained relatively constant, suggesting that the number of connections per node varied little between sessions, yet the patterns of syllable configurations shifted within the network.

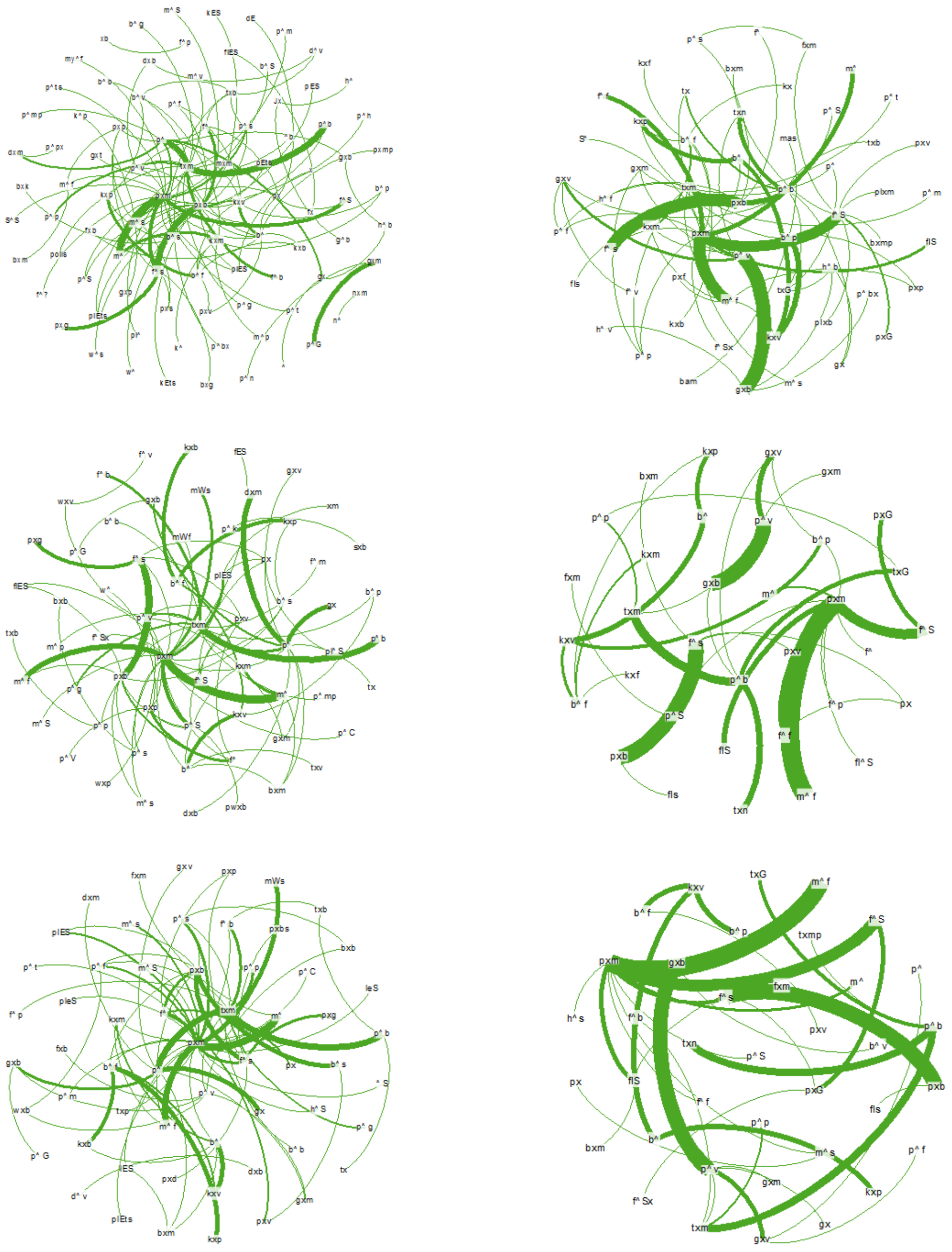


Figure 6. Networks Visualizations. SLI plots are on the left and TD on the right. Sessions 1-3 appear vertically; enlarged versions of the networks are included in Appendix A.

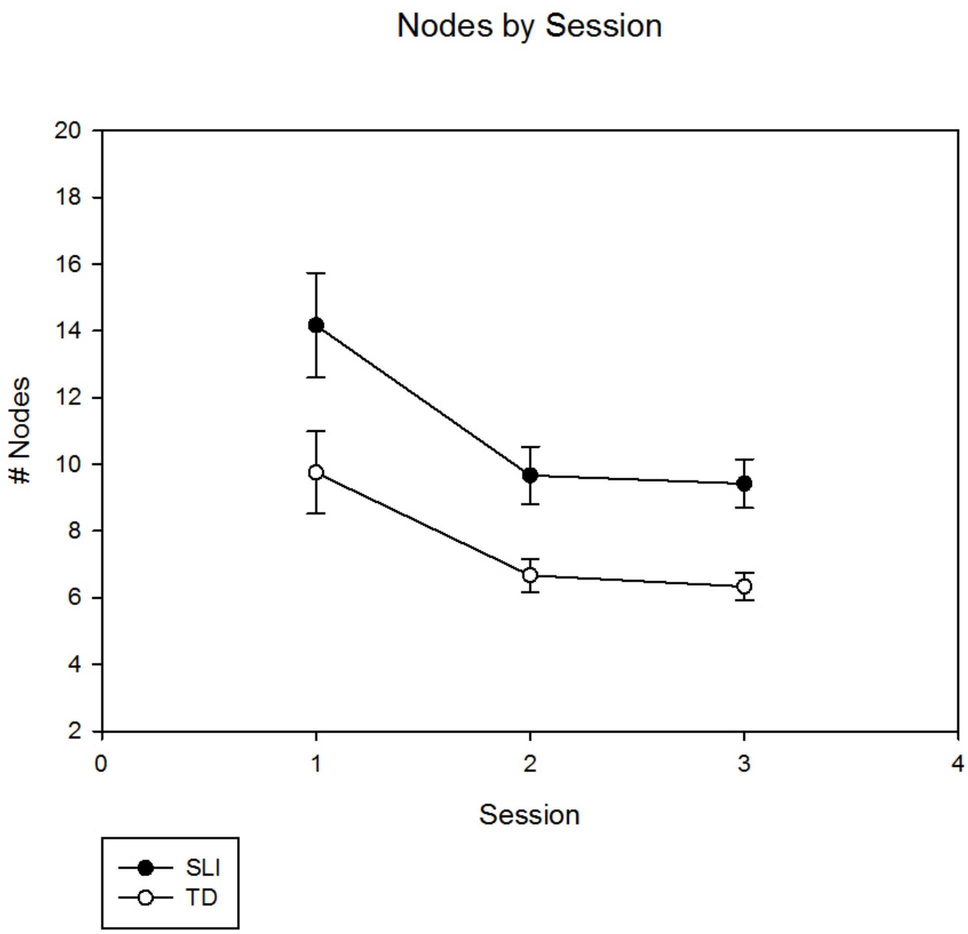


Figure 7. Number of Nodes by Session

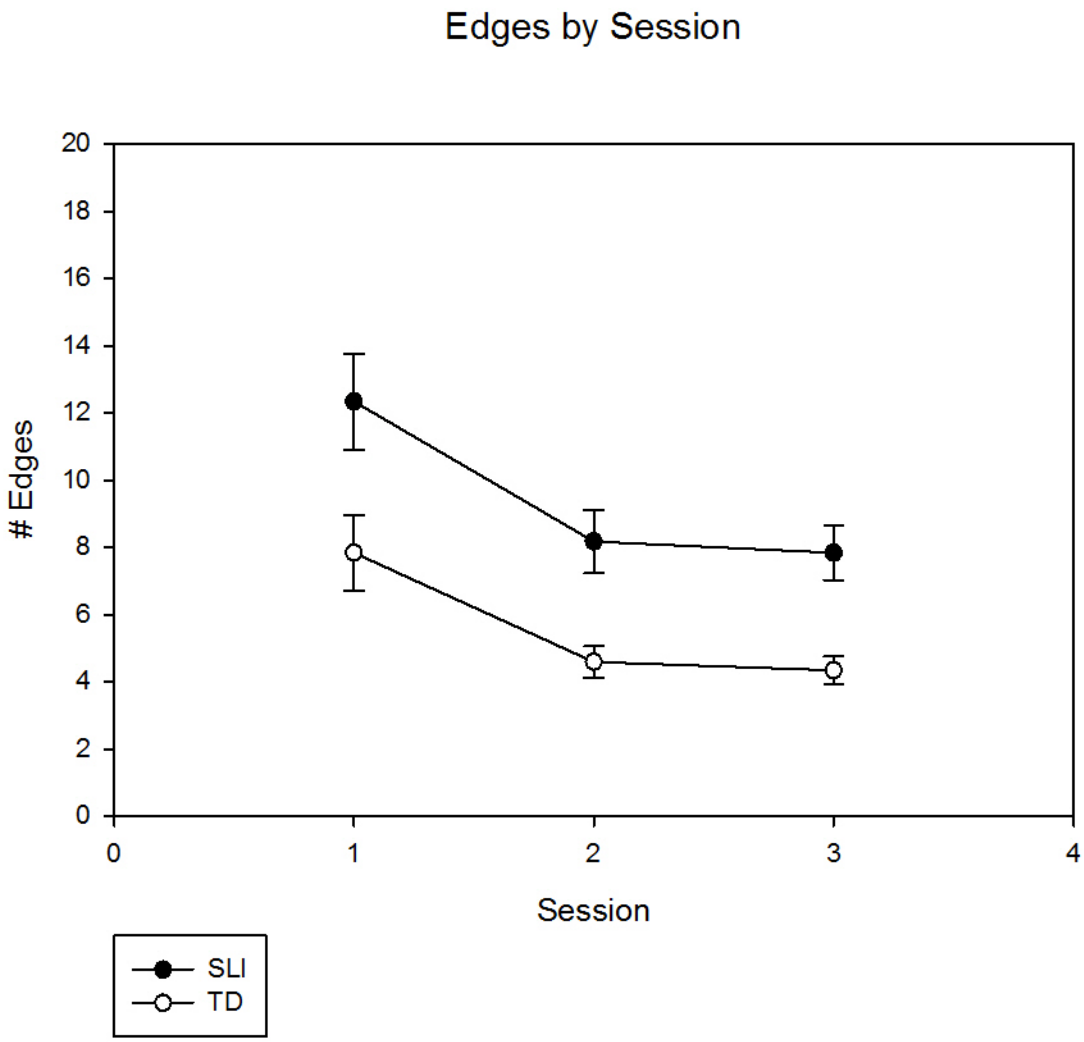


Figure 8. Number of Edges by Session

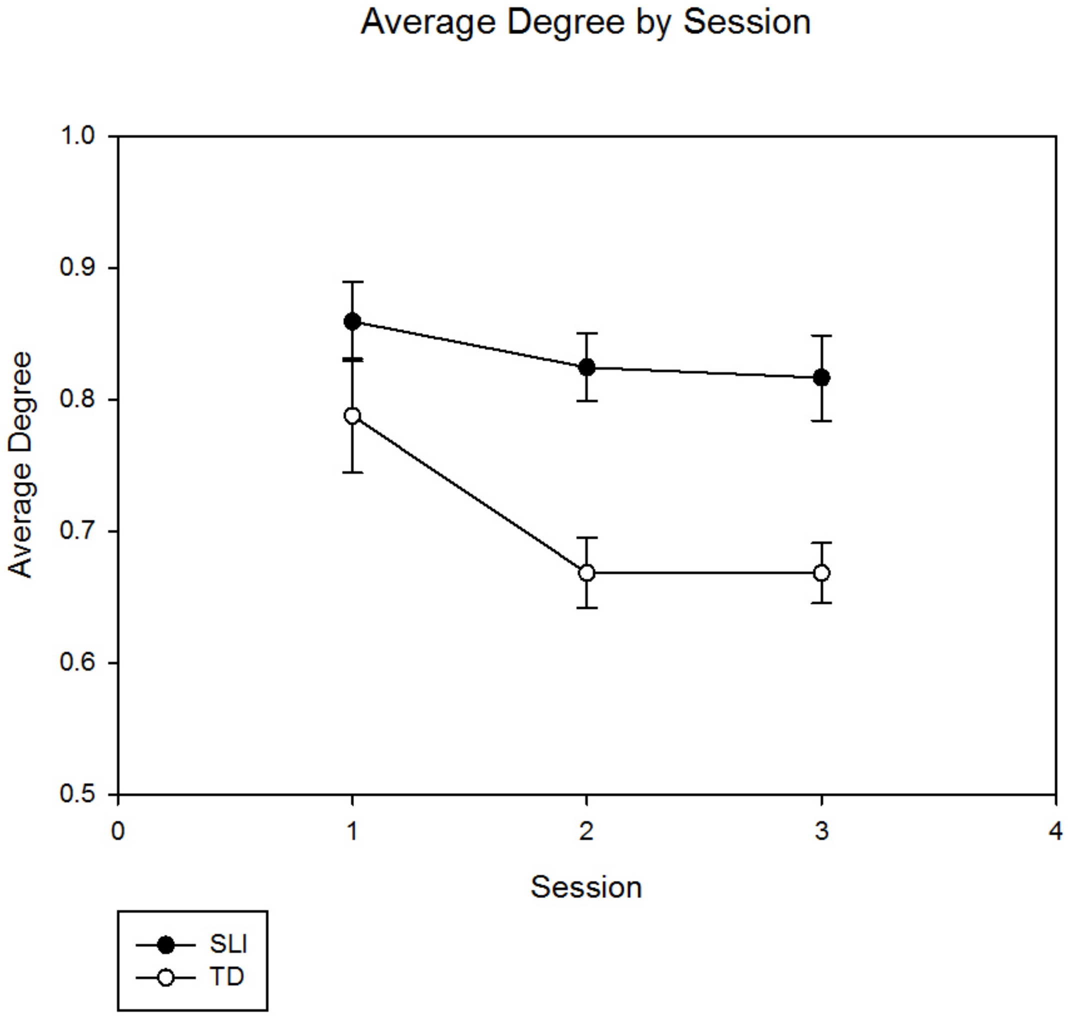


Figure 9. Average Degree by Session

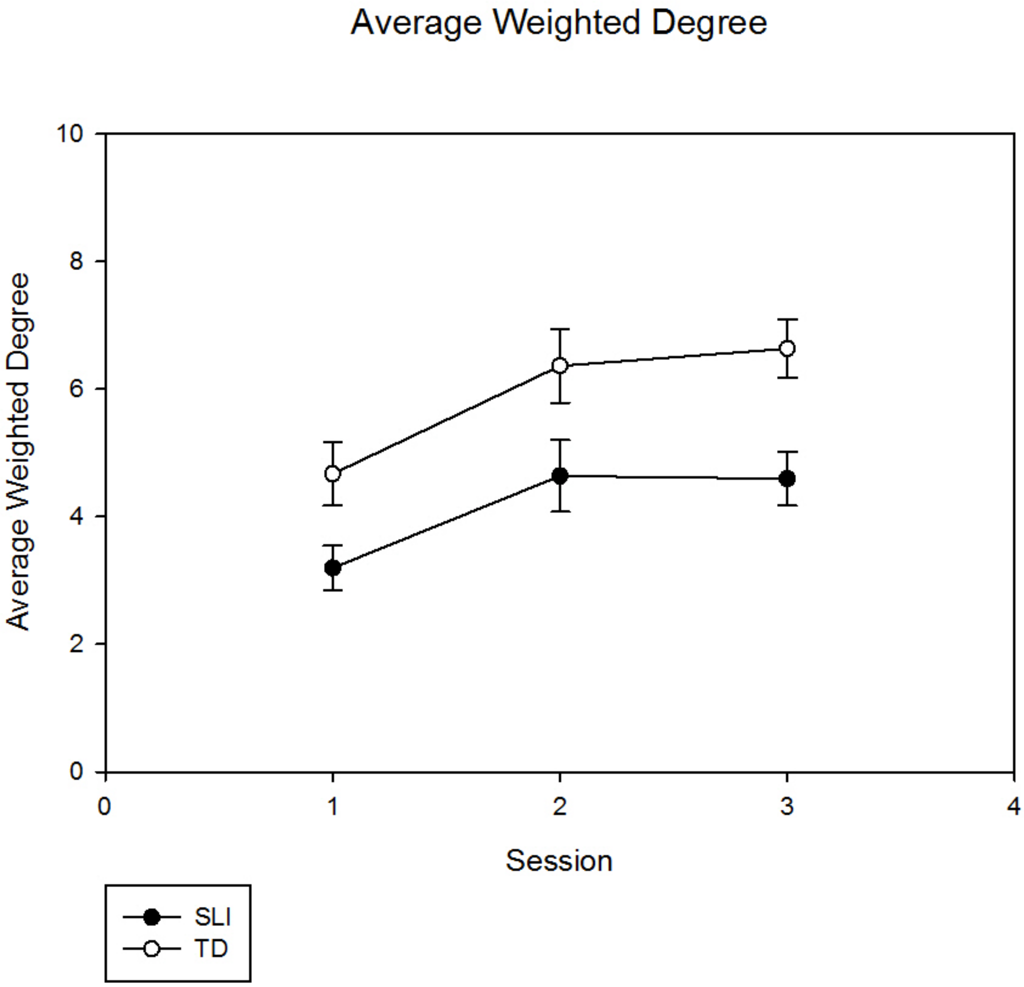


Figure 10. Average Weighted Degree by Session

Word Effects

A one-way ANOVA was used to assess differences in the six nonword stimuli at session one for PCC and ISP measures. For PCC, children with SLI demonstrated a word effect, *F*(5,18)=6.03, *p*<.01. Post-hoc analyses revealed that "f^ʃpəm" was no different from the other 5 words (*p*>.18), whereas the remaining stimuli were different from each other (p<.04). It is an important reminder that these words were counter-balanced across children. No significant word differences in PCC were observed in typically developing children, $F(5,18)=0.82$, $p=.55$. No word differences were found for the ISP in either children with SLI, $F(5,18)=0.25$, $p=.93$, or typical controls, $F(5,18)=0.78$, $p=.58$.

Correlations

Segmental Accuracy (PCC) x Segmental Variability (ISP)

One fundamental research question was to explore the relationship between segmental accuracy and variability. Correlation analyses revealed no significant relationships between these two measures at any of the time points (p>.05). However, as shown in Table 5, while non-significant, correlations increased as a result of more protracted learning, suggesting that even if children do not make large gains in production accuracy, they appear to become increasingly entrenched in their speech production patterns as indicated by increased stability of their errors.

Table 5. Correlations: PCC x ISP

	Session 1	Session 2	Session 3
PCC x ISP (SLI)	-.14	-.20	-.49
PCC x ISP (TD)	-.34	-.39	-.55

Segmental Accuracy (PCC) and Segmental Variability (ISP) x Networks

As predicted, for children with SLI and typical peers, segmental accuracy was not closely correlated with the number of nodes, edges, or weighted degree. Not surprisingly, segmental variability measures were highly correlated (*p*<.05) with the networks measures (see Tables 6 and 7; significant correlations are marked with *).

Table 6. Correlations: PCC x Networks Measures

PCC x Networks	**Session 1**	**Session 2**	**Session 3**
SLI			
Nodes	-.35	.04	-.30
Edges	-.27	-.06	-.54
Weighted Degree	.24	-.15	.16
TD			
Nodes	-.39	-.29	-.46
Edges	-.33	-.3	-.46
Weighted Degree	.46	.25	.31

Table 7. Correlations: ISP x Networks Measures

ISP x Networks	**Session 1**	**Session 2**	**Session 3**
SLI			
Nodes	*.70	*.78	*.69
Edges	*.79	*.78	*.71
Weighted Degree	*-.78	*-.66	*-.60
TD			
Nodes	*.85	*.70	*.85
Edges	*.86	*.72	*.85
Weighted Degree	*-.77	*-.80	*-.78

Average degree presented a unique dissociative pattern of correlation with accuracy and variability measures as a function of session (Table 8; significant correlations are marked with *). A node’s degree represents the number of other variants to which it is connected, where a higher degree indicates more variability. Children with SLI showed no significant correlation (*p*>.05) between segmental accuracy and average degree until session 3, where the degree increased as accuracy decreased. This is consistent with the correlation trend (reported above) between the PCC and ISP by the end of session 3. However, we found the opposite effect for typical learners, who demonstrated a strong correlation between segmental accuracy and degree only at session 1 (*p*<.05).

This dissociation was also evident in segmental variability, which was highly correlated with average degree until session 3 for children with SLI. For typically developing children, this relationship was significant in sessions 2 and 3, but not in session 1. This suggests that typically developing and language impaired children demonstrate differential relationships between segmental accuracy and variability (as measured by the degree) at different time points in their learning.

Table 8. PCC and ISP x Average Degree

PCC x Average Degree	**Session 1**	**Session 2**	**Session 3**
SLI	.09	-.32	*-.76
TD	*-.68	-.29	-.31
ISP x Average Degree			
SLI	*.63	*.65	.49
TD	.38	*.74	*.79

DISCUSSION

The purpose of this study was to characterize novel speech sound acquisition in preschoolers with SLI and typical language over multiple sessions using standard and non-standard approaches to measuring accuracy and variability. The first aim was to analyze speech production patterns of nonwords using classic methods such as segmental accuracy (PCC) and segmental variability (ISP). A second aim was to determine the extent to which differences in segmental accuracy and variability related to kinematic performance (STI). Finally, the third aim was to introduce a novel networks methodology and explore relationships between these networks components and standard accuracy and variability measures.

We predicted that, as compared to typical learners, children with SLI would demonstrate lower segmental accuracy and higher segmental and kinematic variability. Results from standardized articulation testing (BBTOP) revealed that 10 out of 12 (83%) of children with SLI participating in this study also demonstrated performance of greater than 1 standard deviation below the mean--these children met criteria for speech impairment. All participants with typical language scored within 1 standard deviation of the mean. This is a strikingly high proportion of co-occurring speech and language impairment in this population and is consistent with a growing body of literature documenting a high occurrence of speech sound errors in children with SLI (Conti-Ramsden, Crutchley, & Botting, 1997; Deevy, Wisman Weil, Leonard, & Goffman 2010; Shriberg & Kwiatkowski, 1994; Shriberg, Tomblin, & McSweeny, 1999; Sices, Taylor, Freebairn, Hansen, & Lewis, 2007).

Results from the accuracy analysis of the nonwords used in the study also demonstrated significant group differences in segmental accuracy with the SLI group showing lower PCC scores. Nonword repetition performance in children with SLI has been well studied and reveals consistently weaker performance than that observed in typical peers, especially as the syllable length increases (Dollaghan & Campbell 1998; Gathercole, Willis, Baddeley, & Emslie, 1994; Montgomery, 1995). This study provides evidence that children with SLI perform significantly more poorly in their production of two-syllable nonwords. It is notable that these nonwords included relatively complex syllable structure, with a low frequency consonant cluster in the medial position. Over the course of three sessions, children in both groups made very few gains in production accuracy, only improving from 65-67% in the SLI group, and 85-89% in the typical group. This suggests that even with three sessions of practice via direct imitation of nonwords, accuracy does not substantially improve.

Such striking group differences in segmental accuracy warranted analysis of segmental variability, especially since children with SLI were demonstrating multiple errors in their attempts at the nonword targets. It may be that a child would produce the same sound errors over three sessions, or alternatively she may demonstrate variation in errors over time. Importantly, this variation in errors would not necessarily be reflected in segmental accuracy, and thus a measure specific to variability was required.

As with phonetic accuracy, significant group differences were observed in the ISP scores, where children with SLI were more variable than typical peers. Although the ISP has not yet been applied to speech errors in children with SLI, this replicates findings of segmental variability as a prominent feature in speech errors in SLI using a type-token ratio (Heisler, Goffman, & Younger, 2010). This measure of variability revealed an important distinction in learning trajectories as compared with segmental accuracy, with significant differences between sessions 1 and 2, as well as sessions 1 and 3 in both groups, suggesting that with repeated practice of nonwords, variability decreases. As discussed above, little improvement was observed in segmental accuracy as measured by PCC.

One interpretation of this finding is that more stable production patterns do not necessarily align with gains in production accuracy. More work is needed to determine the scope of segmental variability in children with SLI. For example, variability may be reduced when nonwords are attached to referents in word learning. However, consideration of variability in speech production in children with SLI may have strong clinical implications. As discussed previously, variability is a prominent feature in children with childhood apraxia of speech. In these children, intervention often incorporates principles of motor learning in order to increase consistency and accuracy of productions (ASHA, 2007). Given the role of variability in the speech of children with SLI, it is important to consider whether similar intervention approaches may be beneficial. It is unclear whether the variability observed in children with SLI emerges from the same source as those with childhood apraxia of speech. However, it appears that consideration of phonological components of production, especially variability, merit attention in diagnostic and intervention phases.

Interestingly, there was no significant correlation between segmental accuracy and segmental variability at any time point. However, visual inspection of the data from this small group of children with SLI showed that by session 3 the relationship between PCC and ISP scores strengthened (-.14 at session 1, -.2 at session 2, -.49 at session 3). This trend merits further attention, and suggests that over time segmental accuracy and variability interact. Overall, children change minimally in accuracy, but variability decreases. By session 3, when more entrenched learning has occurred, children with SLI who produce more segmental errors reduce variability and settle on these errorful productions. Over time, a pattern of stability and consistency emerges, regardless of whether or not the productions are accurate.

One interpretation of this finding is outlined by Thelen and Smith (2006) in their dynamic systems view of human development. They postulate that development is multiply determined by a number of factors including genetics and epigenetics, behavior, and physiology. Importantly, the interaction between these processes changes over time and presents a continually evolving landscape; one component of development cannot be isolated without considering its interactions with other developmental processes. They further explain that each system has a *basin of attraction*, which may be behaviorally, genetically, or physiologically determined. This can be visualized as a valley in a particular landscape. Now, imagine a ball rolling along the landscape. In a landscape with shallow troughs or valleys, reduced energy is required for the ball to continue rolling. However, for deeper valleys, the ball may become stuck and deeply entrenched. Furthermore, as the ball rolls along the valley floor more frequently, it interacts with the landscape itself and creates a deeper, more traversed pattern. For the present study, the ball represents a novel production, and the valley a basin of attraction. A more flexible system allows the child to produce more variations without becoming entrenched and rigid in production. However, once a pattern becomes well established, more energy is required to emerge from the valley, or the production pattern. In this sense, segmental variability could be perceived as a positive feature in learning, and may simply represent an exploratory production pattern before settling on one particular production. However, as discussed earlier, a child could indeed settle on an inaccurate production, and thus the dissociation between segmental accuracy and variability becomes clear.

Children with SLI showed significantly more segmental variability in both the networks measures and the ISP scores, as well as decreased segmental accuracy. Surprisingly, this was not instantiated in movement variability, as both groups of children demonstrated similar performance during this novel word-learning task. Therefore, the mechanisms underlying segmental accuracy and variability must arise from factors beyond the scope of articulatory movement. The lack of relationship across transcription and movement is consistent with previous findings demonstrating a dissociation between motor variability and segmental variability (Goffman, Gerken, & Lucchesi, 2007), and motor variability and segmental accuracy (Benham & Goffman, 2014).

The final purpose of this study was to present a network analysis approach as a way to visualize and quantify the interactions between word forms. The ISP is limited in that it is a single value associated with segmental variability across productions of the same target and may not capture changes in the structure of production variability. The graphics associated with network analysis provide compelling qualitative information about the nonwords produced, and how they interact with each other.

The group differences observed in all networks components, as well as in the ISP, strengthen the argument that variability is an important component of production to consider in children with SLI. At the core of both network and ISP analyses is the number of forms produced as well as the consistency of those productions, so it is not surprising that there was such a high degree of correlation between both measures. However, average degree demonstrated a different profile of correlation. This finding further highlights evidence of dissociations between accuracy and variability, but future work is needed to explore this relationship more in depth. Furthermore, learning trajectories for average degree demonstrated structural differences in the nonword networks in children with SLI, suggesting yet another layer of variability to their speech production patterns. All measures, including ISP, nodes, edges, degree, and weighted degree, demonstrated that children with SLI were significantly more variable than their typical peers. All quantitative measures were also correlated. However, more qualitative analysis, as discussed below, suggests that network analysis has the potential to capture components of structure that more unitary approaches such as the ISP and PCC do not.

Based on the findings from this study, what the networks analysis offers that the ISP does not lies in the qualitative information provided. For instance, target nodes such as “f^ʃ” and “b^p” were eliminated from the network by the end of session 3 in children with SLI but not in children with typical language. Both nodes were present in sessions 1 and 2, yet by the end of the study, children had replaced these forms with others. There is no articulatory account that could explain the disappearance of these nodes, as all children had “b” and “p” and “f” in their phonetic inventories. Almost all children had the “ʃ” in their inventories, so even if one child produced “f^ʃ,” this would have appeared in the group network. Interestingly, other word forms that included “ʃ” were documented in session 3, such as “^ʃ”, “lɛʃ,” and “m^ʃ,” suggesting that the phonetic capability was present, yet there was something intrinsically problematic about the sequence of these phonemes that was not amenable to consistent production patterning.

Overall, the finding that children with SLI show particular difficulties with the stable sequencing of syllables and segments is consistent with some current accounts of SLI. It has been suggested that sequential learning may form a core deficit associated with SLI (Hsu & Bishop, 2014; Ullman & Pierpont, 2005; Vuolo, Goffman, & Zelaznik, in revision). The present data suggest that such sequential factors may contribute to deficits in sound learning. Interestingly, two of the children with SLI did not show speech sound impairments as measured by the standardized articulatory measure (BBTOP). However, they behaved similarly in network configuration as children with SLI that did show speech impairments (Table A, participants 7 and 8 in the Appendix, marked with *). This further supports the notion that speech impairments in children with SLI are not determined by articulatory resources, but rather the ability to sequence sounds in a complex manner.

Limitations and Future Directions

One obvious limitation of this study was the small sample size included. In addition to increasing sample size, it would also be particularly relevant to include a third experimental group of children with speech sound disorders and no language impairment. This may provide insight into specific mechanisms of language impairment as they relate to sound acquisition and learning over time.

All analyses were based on broad phonemic transcription. This could be perceived as a limitation as it consists of a categorical approach to classifying sounds (i.e., distortions of one phoneme are assigned to the same phonemic category). While this approach does not account for discrete patterns of marking sounds that are not apparent perceptually (e.g., covert contrasts), we believe that broad transcription was well suited for this study. The broad transcription analysis provided children with SLI the most advantage in terms of grouping variations of a sound into one category. And yet even with this advantage, their speech was significantly less accurate and more variable than that of their typical peers.

Most centrally for future work, while the networks analyses provided striking qualitative visualizations of speech patterning in children with SLI and their typical peers, it is crucial to incorporate additional quantitative methods. Specifically, these methods will target the structural components of the network, such as the distribution and layout of the edges and nodes, and how these patterns of distribution shift over periods of protracted learning. The networks results provided meaningful information about the components of the network (e.g., the number of different forms and how they interacted with other forms), but we did not predict that there would be such a strong correlation between these components and the ISP. Future efforts will focus on this relationship and attempt to discern whether the networks analyses provide novel quantitative information not accounted for by the ISP measure.

An additional follow-up to this experiment includes a detailed analysis of the types of word forms that become the most stable by the end of session 3. This could be driven by frequency, phonotactic constraints or by other attributes such as place, manner, and voicing. Children with SLI have demonstrable difficulty acquiring novel phonological forms, yet the patterns of acquisition are largely understudied. Do children with SLI settle on sound patterns that are comparable in place or voicing distinctions? Or show preferences in the manner of articulation? Potentially, one could also manipulate word frequency, similarity, phonotactic frequency (Munson, 2001), and neighborhood density, (Storkel, 2001, 2004). These manipulations may highlight patterns of interactivity and word interference, and would have significant therapeutic implications related to factors such as sound target selection and frequency of therapy.

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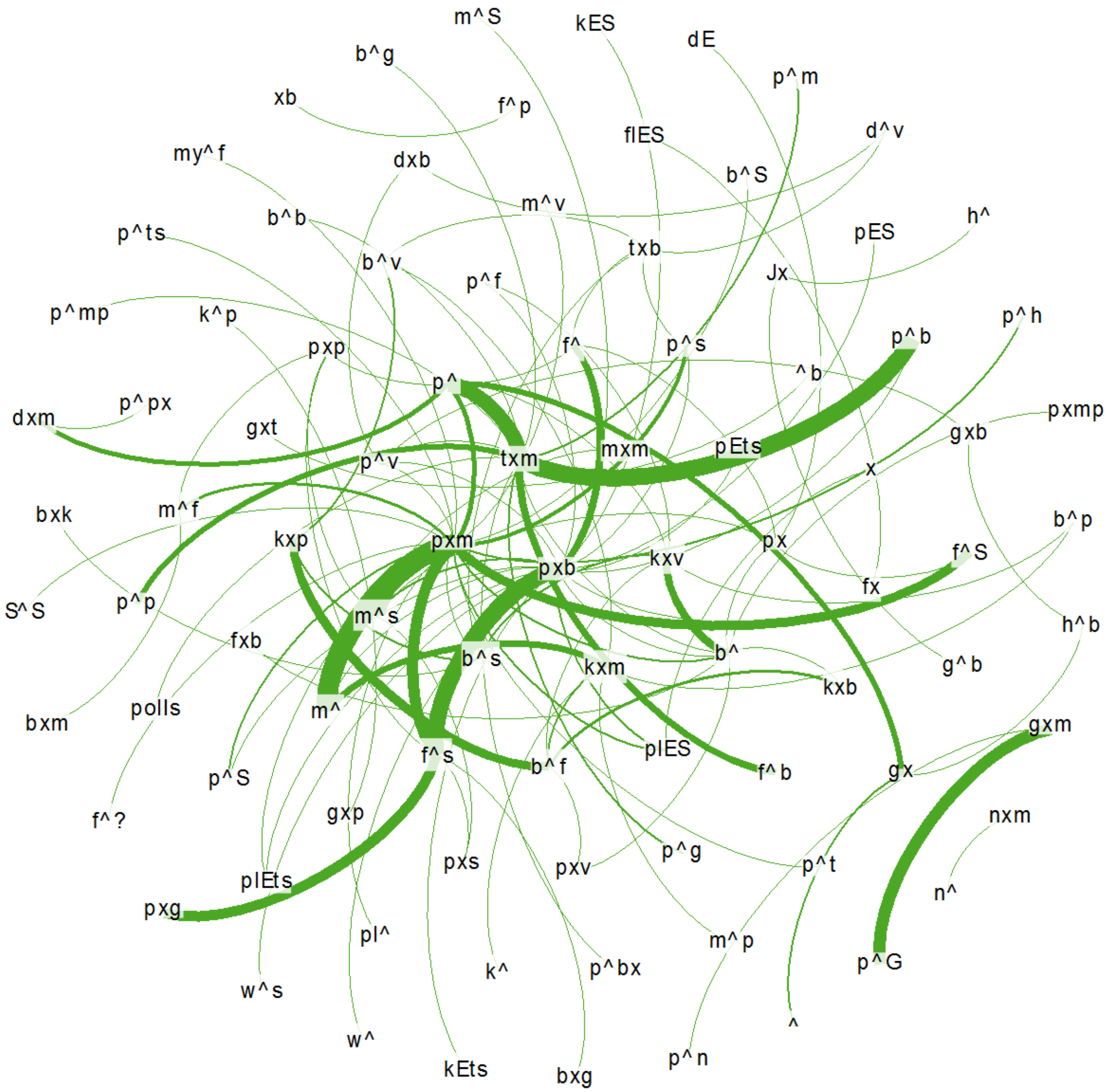
APPENDICES

Appendix A: Enlarged Networks Plots



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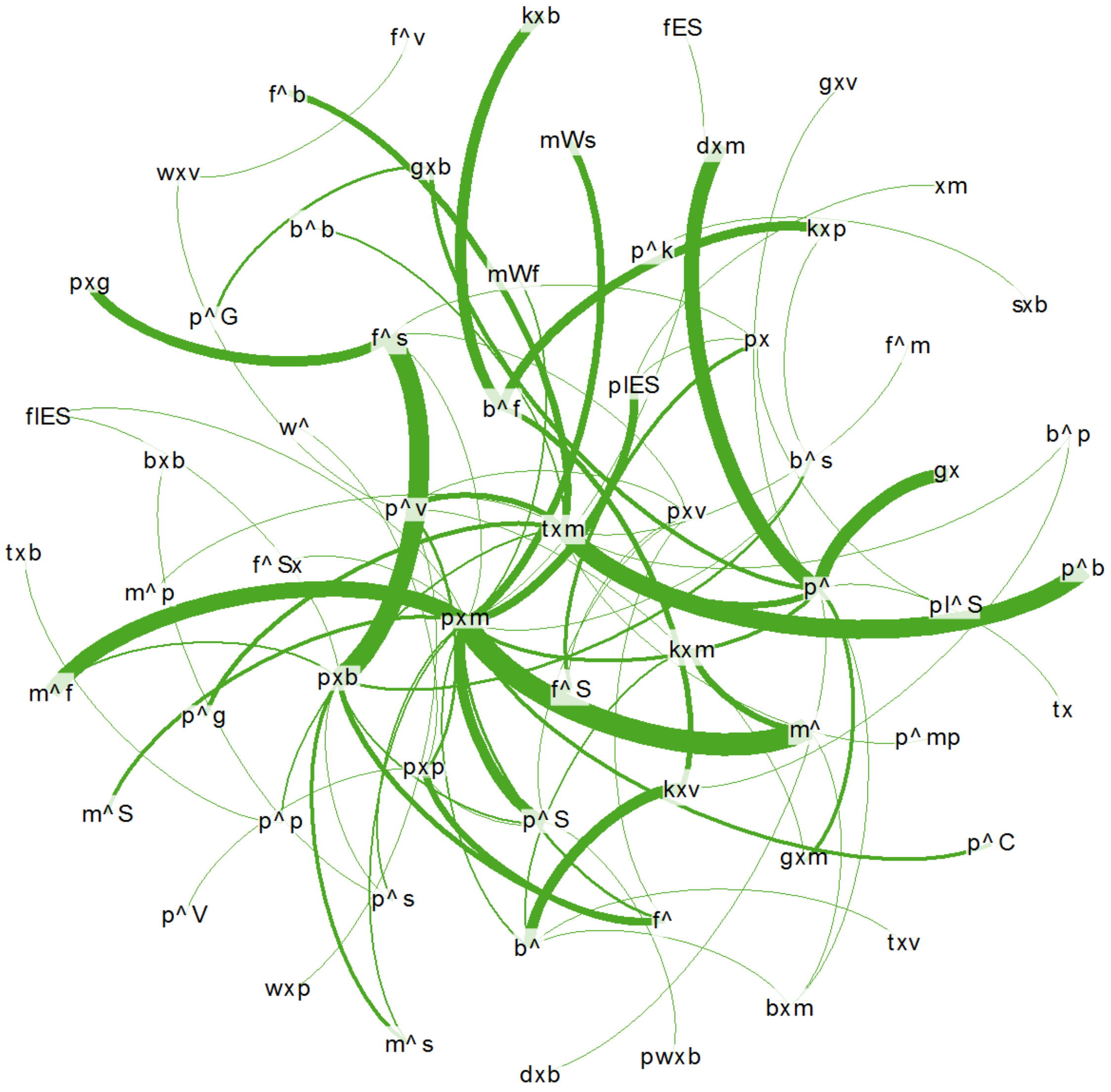

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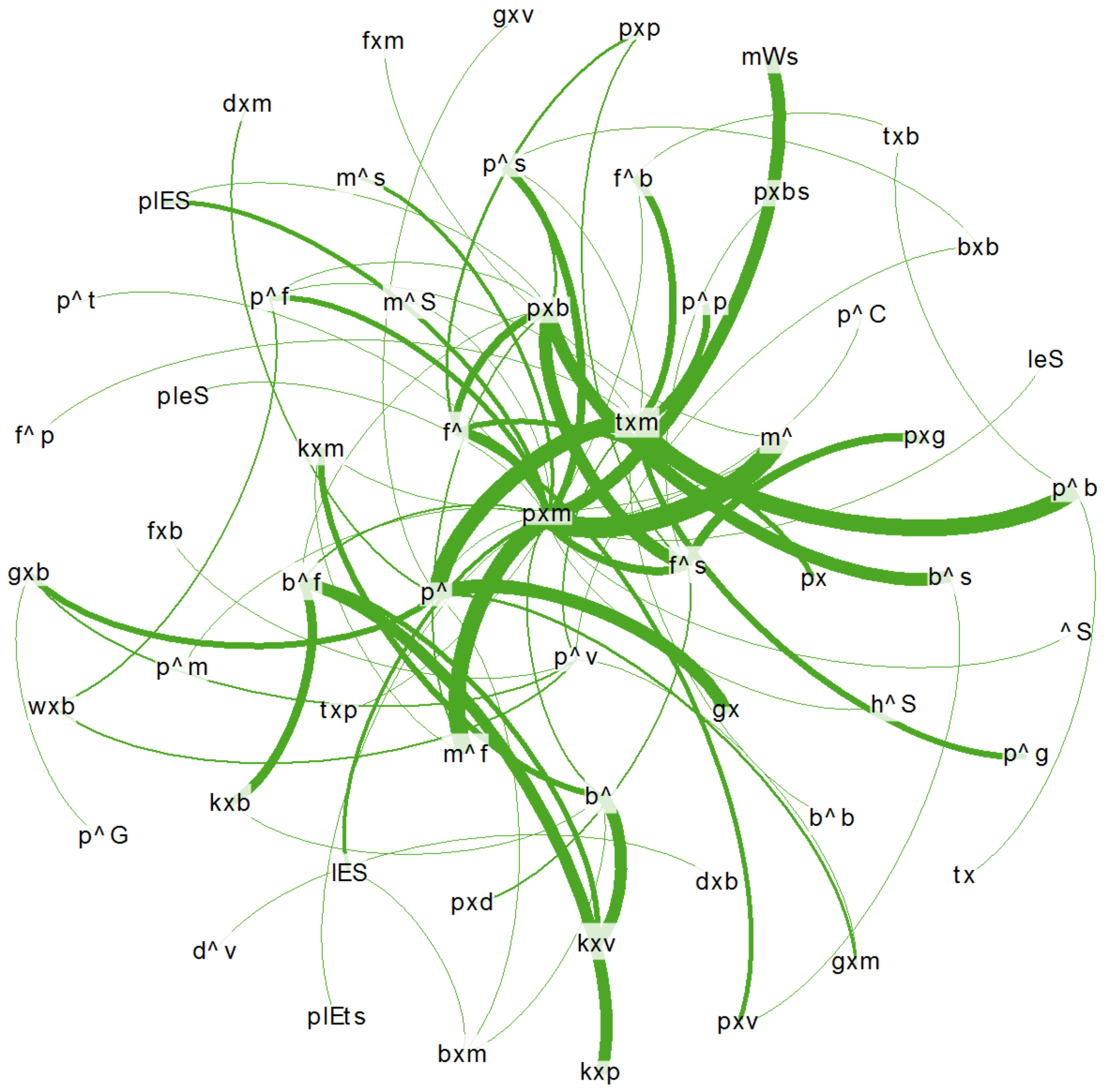

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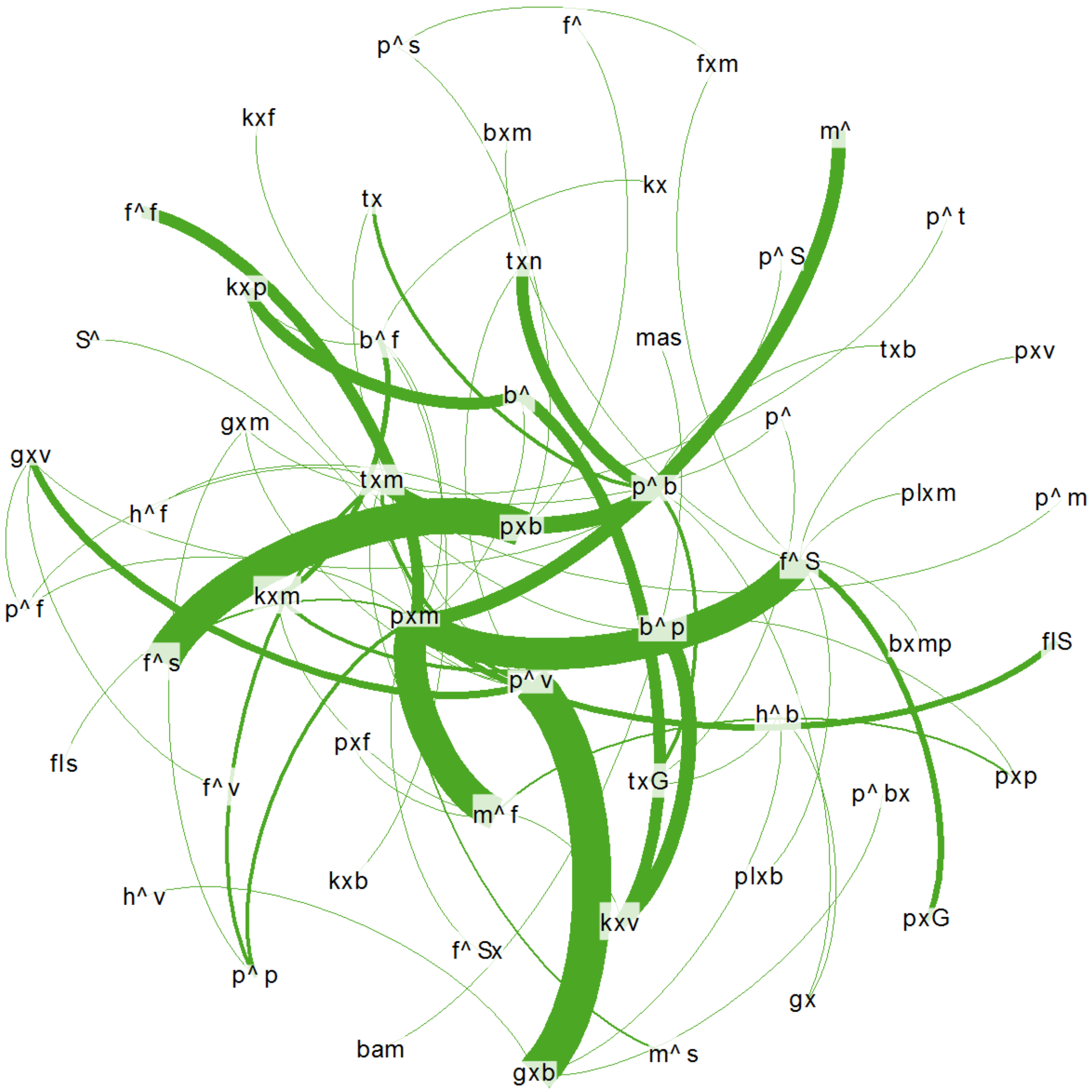
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txG
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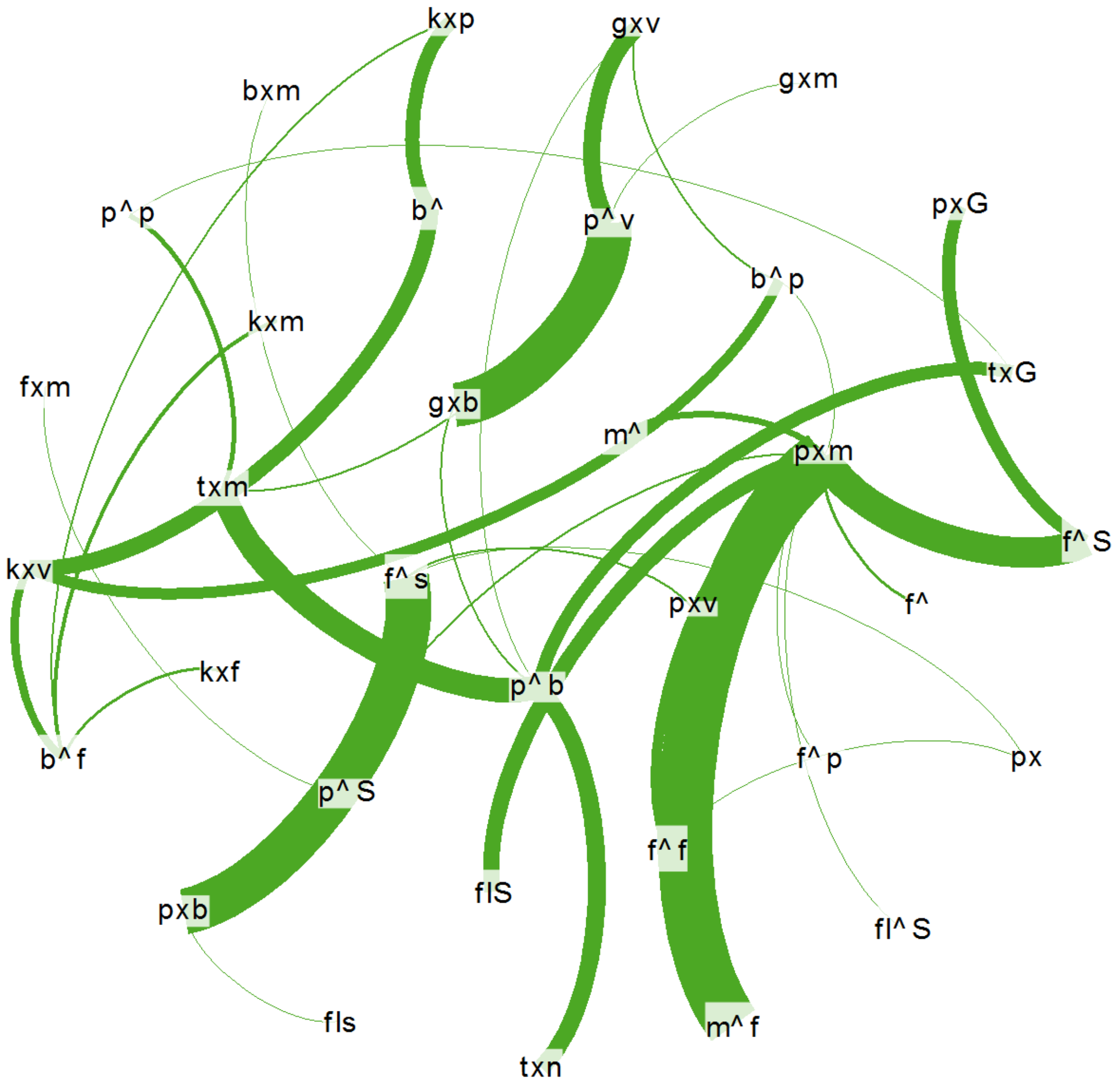
TD: Session 1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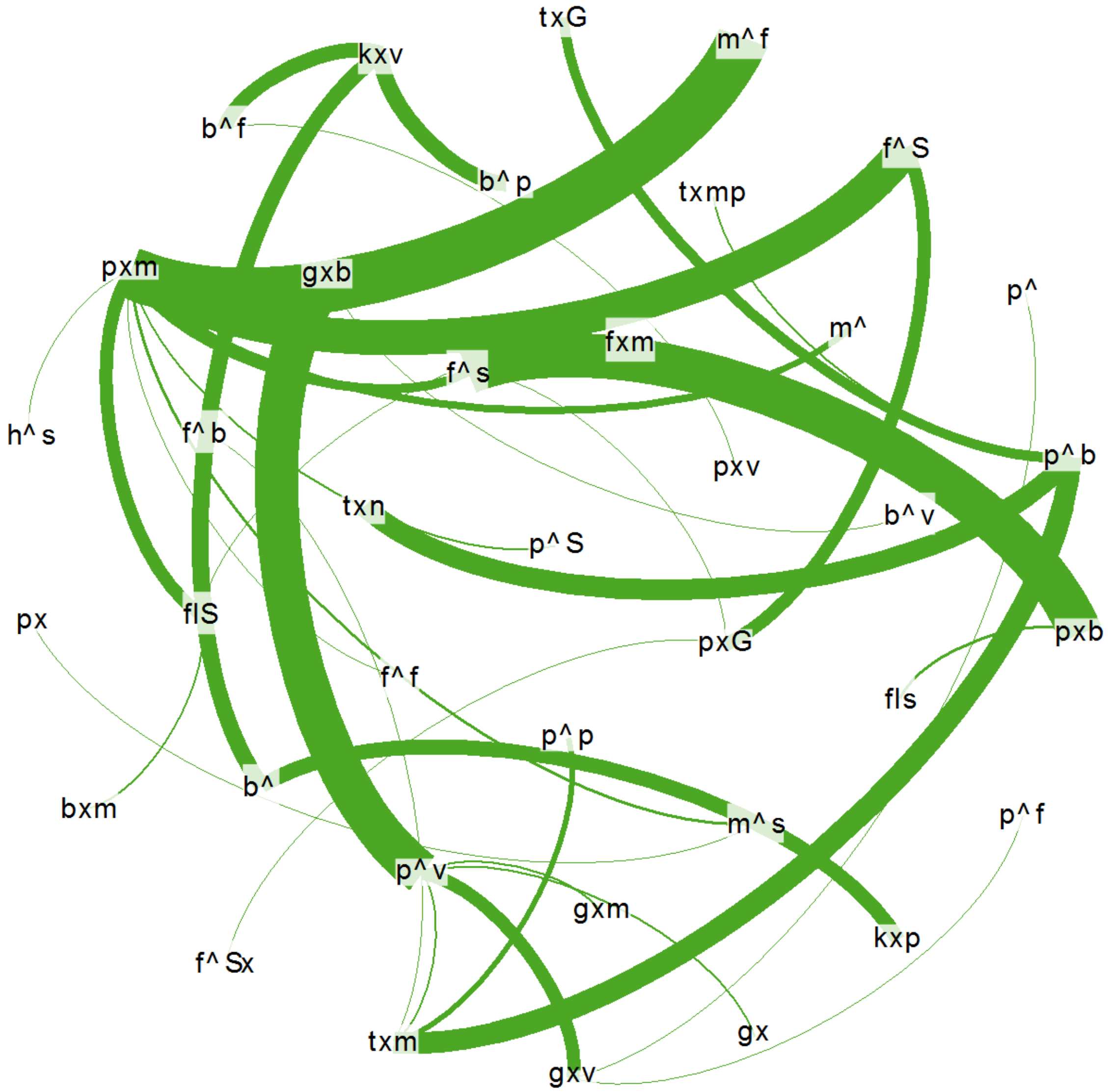
TD: Session 2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txn
b^v
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px
flS
pxG
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f^f
fls
p^p
bxm
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gxm
kxp
f^Sx
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gx
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TD: Session 3

Appendix B: Individual Performance on Networks Measures

Table B.1: SLI Performance on Networks Measures (* denotes participants who scored within the typical range on the BBTOP articulation testing)

	Session 1				**Session 2**				**Session 3**			
SLI	Nodes	Edges	Degree	Weight	Nodes	Edges	Degree	Weight	Nodes	Edges	Degree	Weight
1	17	18	1.06	2.35	15	15	1.00	2.67	13	12	0.92	3.08
2	7	5	0.71	5.71	12	11	0.92	3.33	10	9	0.90	4.00
3	8	6	0.75	4.88	4	3	0.75	10.00	5	4	0.80	8.00
4	16	16	1.00	2.50	13	11	0.85	3.08	7	5	0.71	5.71
5	13	11	0.85	3.08	9	8	0.89	4.44	11	12	1.09	3.64
6	14	11	0.79	2.86	8	6	0.75	5.00	11	8	0.73	3.64
*7	9	7	0.78	4.44	7	5	0.71	5.71	8	6	0.75	5.00
*8	28	22	0.79	1.43	11	9	0.82	3.64	12	10	0.83	3.33
9	13	12	0.92	3.08	7	5	0.71	5.71	7	5	0.71	5.71
10	16	14	0.88	2.50	11	9	0.82	3.64	12	10	0.83	3.33
11	14	13	0.93	2.86	9	7	0.78	4.44	7	5	0.71	5.71
12	15	13	0.87	2.67	10	9	0.90	4.00	10	8	0.80	4.00
Mean	14.17	12.33	0.86	3.20	9.67	8.17	0.82	4.64	9.42	7.83	0.82	4.60
SD	5.44	4.94	0.10	1.21	2.99	3.27	0.09	1.95	2.54	2.82	0.11	1.46

Table B.2: TD Performance on Networks Measures (* denotes participants who scored within the typical range on the BBTOP articulation testing)

	Session 1				**Session 2**				**Session 3**			
TD	Nodes	Edges	Degree	Weight	Nodes	Edges	Degree	Weight	Nodes	Edges	Degree	Weight
*1	6	4	0.667	6.667	4	2	0.5	10	7	5	0.714	5.714
*2	5	3	0.6	8	7	5	0.714	4.714	5	3	0.6	8
*3	8	7	0.875	5	4	2	0.5	10	5	3	0.6	8
*4	11	9	0.818	3.636	7	5	0.714	5.714	7	5	0.714	5.714
*5	11	11	1	3.636	7	5	0.714	5.714	5	3	0.6	8
*6	8	6	0.75	4.375	6	4	0.667	6.667	6	4	0.667	6.667
*7	6	4	0.667	6.667	8	6	0.75	5	7	5	0.714	5.714
*8	11	7	0.636	3.636	5	3	0.6	8	4	2	0.5	10
*9	13	10	0.769	3.077	8	6	0.75	5	6	4	0.667	6.667
*10	21	17	0.81	1.905	9	6	0.667	4.444	7	5	0.714	5.714
*11	8	6	0.75	5	6	4	0.667	6.667	8	6	0.75	5
*12	9	10	1.111	4.444	9	7	0.778	4.444	9	7	0.778	4.444
Mean	9.75	7.83	0.79	4.67	6.67	4.58	0.67	6.36	6.33	4.33	0.67	6.64
SD	4.29	3.88	0.15	1.73	1.72	1.62	0.09	2.00	1.44	1.44	0.08	1.59