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Research Article

An Application of Network Science to Phonological Sequence Learning in Children With Developmental Language Disorder

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Purpose: Network science has been a valuable tool in language research for investigating relationships between complex linguistic elements but has not yet been applied to sound sequencing in production. In the present work, we used standard error-based accuracy and articulatory kinematic approaches as well as novel measures from network science to evaluate variability and sequencing errors in speech production in children with developmental language disorder (DLD; aka *specific language impairment*).

Method: Twelve preschoolers with DLD and 12 age-matched controls participated in a 3-day novel word learning study. Transcription and articulatory movement data were collected to measure accuracy and variability of productions, and networks of speech productions were generated to analyze syllable co-occurrence patterns.

Results: Results indicated that children with DLD were less accurate than children with typical language at the segmental level. Crucially, these findings did not align with performance at the articulatory level, where there were no differences in movement variability between children with DLD and those with typical language. Network analyses revealed characteristics that were not captured by standard measures of phonetic accuracy, including a larger inventory of syllable forms, more connections between the forms, and less consistent production patterns.

Conclusions: Network science provides significant insights into phonological learning trajectories in children with DLD and their typically developing peers. Importantly, errors in word production by children with DLD do not surface as a result of weakness in articulatory control. Instead, results suggest that speech errors in DLD may relate to deficits in sound sequencing.

The application of network science to theoretical and empirical questions in psychology and linguistics has been growing exponentially. In its most basic terms, network science provides a quantitative approach to characterizing the relationships (i.e., edges) between entities of interest (i.e., nodes) as well as graphic visualizations of the relationship structure. This approach has proven to be especially relevant to the study of language, particularly from the perspective of modeling language as a complex system (Cong & Liu, 2014; M. Vitevitch, 2014; Zipf, 1949). The fundamental question motivating a network analysis is simple—to explore the relationship between two entities such as individual people or, in the case of language, words, grammatical morphemes, syllables, or sounds. It is perhaps due to this simplicity that network science has become a compelling analytic tool in a variety of linguistic and psycholinguistic disciplines. A network science approach has been implemented to address problems in language research, such as those related to semantic word mapping (Sigman & Cecchi, 2002), syntactic dependencies (Ferrer i Cancho, Solé, & Köhler, 2004), morphological complexity (Liu & Xu, 2011), phonological networks (Chan & Vitevitch, 2009; M. S. Vitevitch, 2008), sound mapping (Mukherjee, Choudhury, Basu, & Ganguly, 2008), and lexical modeling in typical and atypical learners (Beckage, Smith, & Hills, 2011; Brooks, Maouene, Sailor, & Seiger-Gardner, 2017; Hills, Maouene, Maouene, Sheya, & Smith, 2009; Li, Farkas, & MacWhinney, 2004). In the present work, we focus on the sequencing and variability of novel sound and syllable production in typical and atypical language learners. For a more comprehensive list of ongoing work in these areas, see http://www.cs.upc.edu/~rferrericancho/linguistic_and_cognitive_networks.html

Network science is particularly appealing for modeling the organization and structure of developmental phenomena

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in typical and atypical language learners, as it highlights the importance of quantitative results as well as qualitative visual representations of structural changes. In early development, this method has been applied to multiple language domains. For instance, Barceló-Coblijn, Corominas-Murtra, and Gomila (2012) analyzed the relationship between syntactic and lexical growth using networks of word relationships in 3-year-old Dutch, German, and Spanish speakers. They observed abrupt shifts in network structure from treelike networks to networks populated by local hubs, indicating an increase in interconnectivity as grammatical elements emerged. The structural change revealed by a network analysis provides evidence for lexical acquisition as a driving force in syntactic growth.

Phonological effects on lexical development in toddlers have also been investigated using a network approach. Carlson, Sonderegger, and Bane (2014) found that a word's phonological features and position within a network can predict the emergence of a lexical item. In semantic organization, Hills and colleagues (2009) constructed networks based on children's early word inventories. They found that children's semantic networks are governed by different principles of expansion than those of adults. These studies represent a growing trend in cognitive and linguistic research of using network science, an interdisciplinary methodological framework, to address long-standing problems regarding the structure of language—in the present case, as applied to characterizing developmental transitions and variable processes in early childhood.

Extending the implementation of network science beyond typical developmental processes, a network approach is also beginning to be applied to the study of atypical speech and language. For example, network analysis has been used to quantify the connection between children's vocabulary growth and their semantic network structure. Beckage and colleagues (2011) applied network science to reveal differences in structural organization in how late talkers and typically developing (TD) children expand their semantic networks, identifying weaker patterns of network organization in late talkers as compared with children with typical language. In the area of semantic acquisition, Brooks et al. (2017) applied a network approach to model lexical–semantic organization in children with specific language impairment as compared with children with typical language. They observed striking differences in connection patterns between the two groups, suggesting that children with specific language impairment construct relatively weak and unspecified lexical representations. Network science has also been used to investigate organizational differences in syntactic complexity of children's language production, revealing potentially distinguishing characteristics in speech and language production among disorders such as specific language impairment, Down syndrome, Fragile X syndrome, and Williams syndrome (Barceló-Coblijn, Benítez-Burraco, & Irurtzun, 2015). These studies underscore the value of network science as a powerful tool for examining atypical language use, with implications for clinical intervention approaches (M. S. Vitevitch & Castro, 2015).

One example of the application of network science to clinical intervention comes from work on individuals who stutter. Using a network analysis to quantify the relationships among key items from the Overall Assessment of the Speaker's Experience of Stuttering-Adult, Siew, Pelczarski, Yaruss, and Vitevitch (2017) identified potential behaviors and attitudes that may serve as intervention targets. This extension of network science provides an example of its potential for clinical treatment, in this case in the identification of specific goals with the highest potential for impact on an individual client.

In the area of phonology, much of the work within network science has focused on lexical and phonological interactions in perception and production in adults, especially as related to phonological neighborhoods (e.g., Chan & Vitevitch, 2009; M. S. Vitevitch, 2008). To date, network science has not been applied to normal versus disordered phonological development, where a central question is how children acquire sound sequences, especially when learning novel words. We propose that network science may also be a relevant tool for assessing the organization of sound sequences as novel words are produced by young learners.

In the current work, we apply network science to children with typical language as well as children with developmental language disorder (DLD, aka *specific language impairment*). Children with DLD are diagnosed based on deficits in language performance in the absence of neurological, hearing, or cognitive impairments (Leonard, 2014). Deficits in sound production are also often observed in many children with DLD in both real words (Conti-Ramsden, Crutchley, & Botting, 1997; Deevy, Weil, Leonard, & Goffman, 2010; Shriberg & Kwiatkowski, 1994; Shriberg, Tomblin, & McSweeny, 1999; Sices, Taylor, Freebairn, Hansen, & Lewis, 2007) and when producing unfamiliar or novel word strings, such as in nonword repetition tasks (C. Dollaghan & Campbell, 1998; C. A. Dollaghan, 1987; Heisler, Goffman, & Younger, 2010).

Sound production errors in children with DLD have often been related to deficits in working memory (e.g., Gathercole & Baddeley, 1990), although more recent evidence suggests that speech production of nonwords relies on many facets of speech and language processing beyond working memory (e.g., Coady & Evans, 2008). In nonword repetition tasks, few studies have examined the specific characteristics of the sound errors produced (see Burke & Coady, 2015, for a review), and those that do have emphasized the segment (however, see Kapalková, Polišenská, & Vicenová, 2013, for a focus on syllable and word levels). In summary, few qualitative or quantitative analyses have been applied to characterize children's error patterns in nonword learning tasks, leaving a gap in our understanding of the mechanisms underlying speech errors when children engage in a nonword repetition task.

Potential Sources of Speech Sound Errors in DLD

In children with DLD, speech sound errors have generally been interpreted as a comorbidity that is not tied mechanistically to the disorder (e.g., Shriberg et al., 1999). However, very little is known about the nature of the sound errors observed or how speech production errors may be integrated into the language deficit profile. A standard approach to assessing the sources of speech production errors in children with DLD is by characterizing substitutions and omissions at the segmental level or phonological processes that describe specific patterns observed at the segment (e.g., fronting) or syllable (e.g., cluster reduction, weak syllable deletion) levels.

We suggest that speech errors that have been documented in children with DLD may be difficult to characterize using standard approaches, such as segmental accuracy, or the application of phonological processes. For example, within our data sets, a child with DLD may produce the target novel word "p^btəm" in the following ways: "b^bməm," "p^fəm," and "p^gtə." In this example, each production has two accurate consonants. If we were to rely on a metric of consonant accuracy to describe this child's speech, it would appear that the child is 50% accurate with every production. All of the target sounds are in the child's phonetic inventory, and no systematic phonological patterns are obvious. Standard measures do not incorporate the variable substitutions and omissions observed as this child attempts to organize a sequence of syllables. Whereas variability of speech sounds and word forms is a core feature of analytic approaches to early phonological learning in toddlers (Ferguson & Farwell, 1975; Sosa, 2015; Sosa & Stoel-Gammon, 2006), rarely is variability considered in novel word learning in preschool-aged children.

We propose that sound and sequence variability is important in characterizing how novel phonological sequences are organized and acquired, even in older children. In this study, we assess two sources of variability that we hypothesize to be implicated in children with DLD: articulatory variability and phonological variability (as measured by network science). These both relate to a central hypothesis that the source of speech production errors in children with DLD relates to a broader sequential learning deficit (e.g., Goffman, 2015; Hsu & Bishop, 2014; Saletta, Gladfelter, Vuolo, & Goffman, 2015; Ullman & Pierpont, 2005; Vuolo, Goffman, & Zelaznik, 2017).

In one prominent approach, the procedural deficit hypothesis (Ullman & Pierpont, 2005), children with specific language impairment are said to have deficits in the neural circuitry supporting procedural learning. This domain-general learning mechanism underlies the coordination and sequencing of linguistic (e.g., phonology) and nonlinguistic (e.g., motor action) elements. Motor and linguistic involvement has been demonstrated in bimanual coordination (Vuolo et al., 2017) and the acquisition of novel hand gestures (Goffman, Barna, Cai, & Feld, 2018), which invoke sequential learning processes. However, other findings diverge from a strictly procedural account, as children with DLD perform similarly to typical peers in nonsequential procedural learning tasks such as pursuit rotor (Hsu & Bishop, 2014) or unimanual timing (Vuolo et al., 2017), implicating the sequential–organizational component as the locus of impairment.

Variable speech production errors may be a result of impaired articulatory control. Many children with DLD indeed demonstrate global motor deficits (e.g., Bishop, 2002; Brumbach & Goffman, 2014; Hill, 2001; Vuolo et al., 2017). These motor deficits often extend to the articulatory domain and have been documented as increased spatiotemporal variability (e.g., Brumbach & Goffman, 2014; Goffman, 2004). Spatiotemporal variability may contribute in important ways to the speech sound variability observed in children with DLD (Kent, 1992). However, segmental accuracy and articulatory variability do not always align (Goffman, Gerken, & Lucchesi, 2007), suggesting that motor skills and phonological outcomes may not have a dependent relationship.

In contrast to an articulatory account, children with DLD may have higher-order phonological deficits that result in poorly organized sequences of sounds and syllables. Network science, in conjunction with articulatory analysis, provides a powerful approach for the assessment of mechanisms underlying sequential sound pattern learning in children with DLD.

This Study

To summarize, none of the existing standard approaches explain the instabilities observed in how children with DLD organize sound sequences as novel words are acquired, nor do they inform how accuracy and variability relate across phonological and motor levels. Given the limitations of standard error analyses, research in the field of child speech production is in need of novel methodologies that assess the organization and interplay of productions as a holistic and interconnected system. We propose network science as a promising approach for exploring patterns of organization, variability, and systematicity in speech production in children with and without DLD as they acquire novel words over time. In addition, we incorporate a standard analysis of phonetic accuracy as well as a measure of articulatory stability to better understand the factors contributing to short-term phonological learning in young typical and atypical language learners.

Crucially, network science affords multiple levels of analysis, from the individual network elements at the micro level to network-wide, structural properties at the macro level (M. Vitevitch, 2014). The scope of this study is to examine individual network entities and their connections at the micro level, described in detail below. This approach characterizes patterns of variability within the context of a child's entire production set as they produce novel disyllabic sequences. Using network science to characterize these multisyllabic interactions has the potential to contribute to our understanding of how sequences of sounds are initially organized and represented over time in children acquiring novel words.

The aim of the present work is to assess, using network science along with articulatory movement and standard speech production error analysis, whether children with DLD produce systematic errors beyond segments when confronted with a novel phonological sequence. We discuss these findings within the framework of two hypothesized sources of speech error: articulatory deficits and sequential deficits related to procedural learning. We incorporate three levels of analysis to address the nature of children's speech production errors as they acquire novel words. These three levels include the following:

1. Standard analysis of phonetic accuracy
2. Analysis of articulatory movement variability
3. A novel application of network science to assess the organization and sequencing of multisyllabic phonological strings

On the basis of observed variability of speech sounds, we hypothesize that children with DLD will demonstrate relatively more disorganized sound sequences than their typical peers, as characterized by a higher number of network elements (i.e., nodes and edges) and a lower degree of stability (i.e., edge weight), described in detail below. We also predict that the networks will show organizational shifts over the course of learning and will in fact be a better indicator of phonological learning than standard measures of how accurately sound segments are produced.

To assess the role of articulatory stability in phonological learning, we incorporate a measure of kinematic movement. If children with DLD are less stable in their productions than their typical peers, one possible interpretation is that articulatory factors may significantly contribute to impaired speech production. However, if articulatory performance does not distinguish children with DLD from their typical peers, the source of impairment may not reside at the level of motor implementation but rather in the ability to organize sequences of sounds, consistent with a deficit in sequence learning. Studies of nonword repetition usually are based on a single fast-mapped production of a nonword. In the current study, we were interested in how phonetic accuracy, articulatory movement variability, and network organization change over the course of learning. Therefore, we obtained multiple productions over 3 days. There were two major predictions. First, consistent with the procedural deficit hypothesis, we expected that children with DLD would show more errors in their productions, especially characterized by articulatory and network instabilities. We also predicted that deficits in sequential organization would persist over time, with slower learning trajectories observed in children with DLD in comparison with their age-matched peers.

Method

Participants

Twenty-four preschoolers participated, aged 4;0–6;0 years;months. This study includes the data from 12 children who met exclusionary and inclusionary criteria for DLD (Leonard, 2014) and 12 who were TD (DLD: five girls, mean age = 5;3 years;months, *SD* = 0.51 years; TD: six girls, mean age = 5;0 years;months, *SD* = 0.52 years). Children with DLD were recruited for a summer clinical and research program using flyers, newspaper ads, and referrals from local educators. Table 1 shows performance on key behavioral assessments. The Structured Photographic Expressive Language Test–Preschool: Second Edition (Dawson et al., 2005) was used to assess language performance. Children with a standard score of 87 or less on this assessment met criteria for the group with DLD (Greenslade, Plante, & Vance, 2009). All children passed a hearing screening, with 20 dB HL pure tones presented bilaterally at 500, 1000, 2000, and 4000 Hz; demonstrated typical nonverbal IQ scores as measured by the Columbia Mental Maturity Scale (Burgemeister, Blum, & Lorge, 1972); and had no history of neurological impairment. In addition, all participants performed within normal limits on the structural assessment of the Robbins and Klee (1987) oral motor protocol to rule out any anatomic deficits that could account for speech errors. All children were monolingual English speakers.

It is important to note that the participants for the group with DLD were identified based on language performance. However, prior studies (e.g., Alt, Plante, & Creusere, 2004; Deevy et al., 2010; Gray, 2006) indicate that preschool-aged children with DLD often present with a co-occurring speech deficit. As an additional measure, participants were administered the Bankson-Bernthal Test of Phonology (BBTOP; Bankson & Bernthal, 1990) to assess speech performance. Performance on the BBTOP was not used as an exclusionary criterion for either group. However, 83% (10/12 children) of the participants with DLD fell greater than 1 *SD* below the mean on this assessment (a standard score of 85 or below on the Consonant Inventory subtest), meeting diagnostic criteria for speech impairment. For most analyses, all children with DLD were collapsed into a single group. However, two children with DLD who showed typical speech production abilities were also analyzed separately in a post hoc follow-up to provide exploratory evidence regarding the contribution of language deficits alone to the organization of phonological networks. All children in the control group performed within typical limits on the BBTOP. Participant and parental consent were obtained before initiating any research activity. Approval from the

Table 1. Group performance on behavioral assessments.

	DLD			TD		
Assessment	***M***	***SD***	**Range**	***M***	***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

Note. Standard scores are presented for these three tests. DLD = developmental language disorder; TD = typically developing; CMMS = Columbia Mental Maturity Scale; SPELT-P2 = Structured Photographic Expressive Language Test–Preschool: Second Edition; BBTOP-CI = Bankson–Bernthal Test of Phonology-Consonant Inventory.

institutional review board was obtained from Purdue University.

Stimuli

The stimuli were six trochaic CVCCVC nonwords. This data set was extracted from a larger study on how semantic attributes affect word learning in children with DLD as well as children with typical language (Gladfelter & Goffman, 2017; Gladfelter, Goffman, & Steeb, 2018). However, in this study, only the nonwords that were not assigned a semantic referent in the larger study were included for analysis. Therefore, the focus of this study was on the production of novel nonwords over time.

One set of two nonwords was quasirandomly assigned to each child. The nonword set remained constant throughout the three sessions, with assignment equally distributed across children so that four children in each group produced each nonword set. The nonword sets were /f^ʃpəm/ and /p^vgəb/, /m^fpəm/ and /b^pkəv/, and /p^btəm/ and /f^spəb/. The stimuli were controlled for neighborhood density and phonotactic probability, because both of these factors also influence word and sound learning (Munson, 2001; Storkel, Armbrüster, & Hogan, 2006). There is evidence that short-term learning is more likely to be observed in low neighborhood density and low phonotactic frequency forms (Gladfelter & Goffman, 2013; Heisler & Goffman, 2016; Storkel, 2001). For this reason, stimuli were composed of syllables with low neighborhood density and low positional phonotactic probability of the medial consonant cluster. Neighborhood density and phonotactic probability were calculated using the child online phonotactic probability and neighborhood density calculator (Storkel & Hoover, 2010). The neighborhood density of each syllable ranged from 0 to 15 neighbors ($M = 6.3$, $SD = 4.3$). The positional biphone frequency of the medial cluster ranged from 0 to 0.0081 ($M = 0.0014$, $SD = 0.0032$). In addition, stimuli were constrained such that labial consonants were present in the initial, medial, and final positions to demarcate nonword onset and offset points for kinematic analysis of lip movement.

Procedure

Participants were seated approximately 8 feet in front of a 76.2-cm Dell monitor, which was used to present PowerPoint slides containing visual images (described below) and audio playback of the stimuli. Novel words were recorded in a child-directed 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 that were used to obtain visual attention and facilitate optimal data capture, as the motion capture system was positioned directly above the monitor. Children engaged in an imitative production and listening task in which they produced each of the nonwords 12 times in direct imitation per session over the course of three sessions. The two nonwords were quasirandomly ordered, with no more than two productions in a row of the same nonword. To be certain the children slept between exposures and consolidation could occur, the sessions occurred at least 24 hr apart but no more than 1 week apart (Diekelmann & Born, 2010; McGregor, 2014).

Data Capture

For transcription analysis, a high-quality audio signal was recorded using a Marantz CD recorder and a Shure Beta 87 microphone. Video was recorded with a Panasonic DVD camcorder. The 3D Investigator (Northern Digital Inc.) motion capture system was used to record movement of the lips and jaw during speech production. One infrared light-emitting diode 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 (Gladfelter & Goffman, 2017; Heisler & Goffman, 2016). These served as reference points to subtract head movement. 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 16,000 samples per second.

Analyses

Transcription

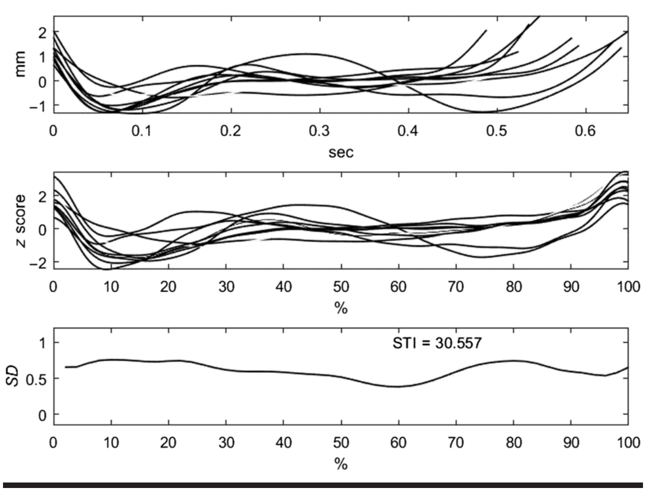
Trained research assistants used audio and video recordings to broadly phonetically transcribe the children's productions. Productions that were disfluent, contained yawning, whispering, laughter, sighing, or long pauses between syllables (2 *SD*s or greater than the mean word duration) were excluded from the analysis. Interrater reliability was calculated between two coders using a sample of 20% of all productions quasirandomly selected and distributed equally across experimental groups. The reliability of the two coders was 93% agreement. Transcription data were used for the segmental accuracy and network analyses, each further described below.

Segmental accuracy. To calculate segmental accuracy, the number of consonants produced correctly was divided by the total number of target consonants (160 consonants per session) and multiplied by 100 to yield a percentage. For this analysis, percent consonants correct (PCC) was calculated for the first 20 productions (10 for each word) for each child by session. Because the objective was to assess accuracy of segments that were in the child's phonetic inventory, segments that were never produced throughout the entire experimental novel word learning 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. This was done so as not to penalize children for errors on sounds on the nonword task that did not appear in their phonetic inventories. One participant with DLD did not have [s] in his phonetic inventory, and the nonword pair that he was assigned to produce was p^btəm/f^spəb. Therefore, the [s] was excluded from the PCC analysis. Sixty consonants over the course of three sessions were removed for this participant, out of 5,760 total consonants in the group with DLD. This represents a minimal data loss with 1% of phonemes not amenable to the analysis. For all other participants, the consonants included in the nonwords were within their phonetic inventories.

Kinematic variability. The spatiotemporal index (STI; A. Smith, Goffman, Zelaznik, Ying, & McGillem, 1995) was used to measure variability of articulatory movements of the jaw, upper lip, and lower lip across multiple productions of each target nonword. Productions without an initial or final labial consonant, as well as words that contained an extra syllable, were excluded from the articulatory movement analysis. Productions that were excluded from the transcription analysis were also discarded from the kinematic analysis. A minimum of five and a maximum of 10 productions were used for each nonword.

To calculate the STI, the onsets and offsets of each target nonword were extracted from lower lip movement based on peak velocity. Movement onsets and offsets were selected by visually inspecting the velocity record for local minima and maxima. An algorithm was used to establish the value based on the point at which velocity was highest within a 100-ms window of the point selected by the experimenter. As shown in Figure 1, the extracted movement trajectories (top panel) were then linearly time-normalized by setting each extracted record to a time base of 1,000 points and using a cubic spline algorithm to interpolate between points. Trajectories were amplitude-normalized by setting the mean to 0 and the standard deviation to 1. Productions were normalized in time and amplitude to rule out differences in rate and loudness because the overall goal was to assess spatiotemporal patterning within each production set (shown in middle panel). After normalizing the data, standard deviations were computed at 2% intervals in relative time across the records and then summed. The sum of the 50 standard deviations is the STI; a higher value reflects greater movement variability (bottom panel; see Goffman et al., 2007; A. Smith & Goffman, 1998; A. Smith et al., 1995; A. Smith & Zelaznik, 2004).

Figure 1. Spatiotemporal index (STI). The top panel shows 10 productions of the same nonword extracted from a child's continuous speech signal. In the middle panel, the productions are normalized in time and amplitude, and the sum of the standard deviations is shown in the bottom panel to yield the STI.



Network analysis. To facilitate computer-based analyses, the transcriptions were converted to Klattese (Klatt, 1987), a computer-readable version of the International Phonetic Alphabet. For this approach, we emphasized the syllable rather than the segmental level to evaluate how children, both TD and those with DLD, acquire novel syllable sequences. Productions were divided into first and second syllables. For most cases, each syllable was treated as one consonant–vowel–consonant unit. However, some children omitted a medial consonant, as in the case of /f^pəb/. In this case, we assumed they were omitting the coda of the first syllable and that the onset of the second syllable was preserved. Therefore, the syllable boundary would be as follows: /f^/ for the first syllable and /pəb/ for the second syllable.

Before describing the network analysis, it is necessary to first define the essential elements and how they relate to each other. The two primary elements of a network are nodes and edges. A *node* is an agent or entity, and an *edge* represents the relationship between the two nodes. In other words, a node is connected to another node through an edge. Applied to this study, a node is defined as a consonant–vowel–consonant syllable, and an edge can be thought of as one production of a nonword, linking the two syllables in a child's production. For example, if the child produced the nonword "f^ʃpəm," the nodes "f^ʃ" and "pəm" would be connected by an edge. Edges can either be undirected (bidirectional) or directed (unidirectional). In the case of "f^ʃ" and "pəm," the edge connecting the two nodes is not reciprocal, meaning that "pəm" → "f^ʃ" is qualitatively different from "f^ʃ" → "pəm." Given that we are interested in the particular order in which syllables are produced, edges are represented in a directed manner, indicating the flow of one syllable to the next. This is represented graphically as an arrow from one node to another. Related to edges is the measure of edge weight. A more frequently occurring edge has more weight or strength to the connection between two nodes. This is graphically depicted as the thickness of the edge, where a thicker edge represents a more frequent connection pattern. Applied to this study, if a child produced "f^ʃ" → "pəm" nine times and "f^m" → "pəm" once, the edge between "f^ʃ" → "pəm" would be thicker than that between "f^m" → "pəm."

The production set for each child was uploaded to NodeXL (M. A. Smith et al., 2009), an open-source network software program, to render graphic depictions of a production set and analyze specific network properties. For each child, one network was constructed for each individual session to obtain individual values. See Figure 2 for a depiction of the conversion process for a sample of 10 productions of the nonword /f^ʃpəm/ into a network layout. For this study, the goal was to track the organization and systematic patterning of syllable sequences. To that end, the following

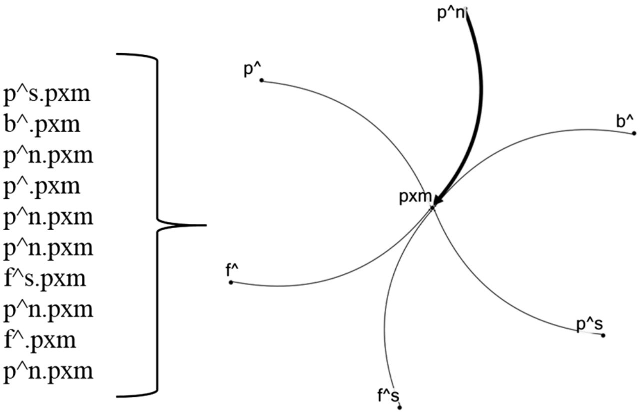


Figure 2. A sample of multiple productions of a single target, /f^ʃpəm/, visually depicted in network format. The period (.) indicates a syllable boundary.

three network attributes were selected: (a) number of nodes, (b) number of distinct edges, and (c) edge weight. The number of nodes represents the number of syllable forms produced, whereas the number of edges provides insight into how the syllable forms co-occur within a child's production set. By controlling the number of productions for all participants (i.e., 40 productions per session), the total number of edges for each child is the same because each edge represents one production. However, the number of distinct edges indicates the number of different nonword forms produced, which will be the focus for the edge analysis in this study. Edge weight was also selected to demonstrate the frequency of a connection pattern. This is calculated by dividing the number of productions by the number of edges. Again, given that the number of productions was controlled for each participant, the analysis of edge weight is a redundant measure statistically; however, it informs the way in which the connection patterns are distributed graphically.

The above-mentioned network elements address quantitative and visual properties of the network. We were also interested in the qualitative shifts in production patterns over the time course of the three sessions. For example, a child may produce the same number of connection patterns (i.e., edges) in Sessions 1 and 2; however, the nodes they are connecting may be different despite being quantitatively equal. To further detail these connection patterns and their shifts over time, we calculated a Jaccard index (see Figure 3) for each participant. This index accounts for the distribution of each production, or edge, across all three sessions as a proportion of all productions. This metric has been used in network science to track qualitative differences among social connections. For instance, Saramäki and colleagues (2014) were interested in the social network structure of phone calls made by students in the transition between high school and college. Analyses revealed that the overall size of the social network did not change but the members of the network did (Saramäki et al., 2014). This method is applicable to our study as it captures qualitative variations in the production network structure. For example, it is important to ascertain the number of distinct connection patterns, or edges, in a child's production network. Equally important is an assessment of how the network connections—the edges themselves—change, which is revealed by the Jaccard index. To calculate this index, the number of common edges between Sessions 1 and 2 was divided by the total number of distinct edges in Sessions 1 and 2, using the following equation:

$$J(1,2) = \frac{|1 \cap 2|}{|1 \cup 2|} = \frac{|1 \cap 2|}{|1| + |2| - |1 \cap 2|} \tag{1}$$

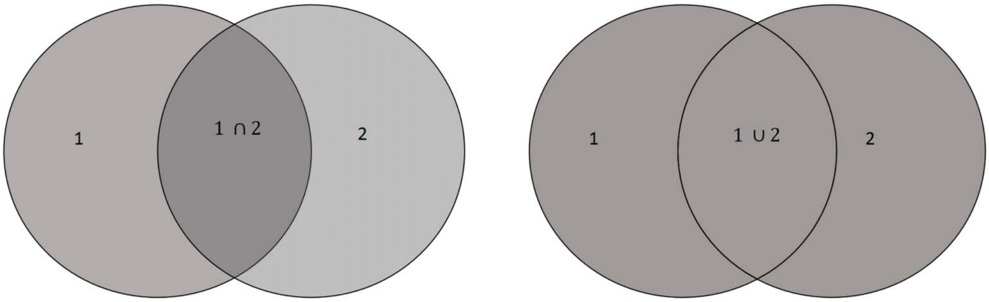
Analogous equations were used for Sessions 1 and 3 and Sessions 2 and 3.

It is necessary to clarify that all dependent variables were calculated for each participant as the basis for the statistical analysis but are represented graphically as a group of either participants with DLD or TD participants. Each figure will specify whether the graphic depiction is for a group or an individual. Group figures (DLD or TD) consist of 480 productions per session. The number of productions for an individual participant is 40 per session. The means and standard deviations of all dependent variables by session for both groups are provided in Table 2; because the Jaccard index crosses sessions, descriptive data are included in the Results section.

Statistical Analyses

For omnibus tests, the statistical design was a mixed, repeated-measures analysis of variance with group (DLD and TD) as the between-subjects factor and session as the within-subjects factor. Analysis of variance requires an assumption of sphericity, with degrees of freedom sometimes adjusted for a possible violation (e.g., Kirk, 2013). We followed a sequential procedure that only uses adjustment when it cannot be avoided (e.g., Kirk, 2013, p. 310). If an F is not significant with conventional degrees of freedom, the hypothesis it tests is not rejected. If an F is significant with conservative (lower-bound) degrees of freedom, the hypothesis it tests is rejected. If neither of the preceding occurs, a test is done with degrees of freedom adjusted with the Greenhouse–Geisser estimator of eccentricity (Geisser & Greenhouse, 1958). No interactions between group and session were significant so no tests of such interactions are reported. To provide details about network measures, tests of differences between pairs of sessions were done with paired t tests. Such tests were considered a family for each dependent variable, with familywise error rate of 0.05. For each dependent variable, there are three pairs of sessions to test. With the Bonferroni adjustment for three tests, each pair of sessions was tested at level .05/3 = .0167. The unadjusted significance level is reported. (Conclusions of tests turned out to be the same, with or without adjustment.) Although the omnibus tests of session are redundant with the tests of pairs of sessions, some readers may be interested in the omnibus tests, so we report them.

Figure 3. Graphical representation of the Jaccard index for Sessions 1 and 2. In the diagram on the left, the darkest gray region is 1 ∩ 2. In the diagram on the right, the entire gray region is 1 ∪ 2.



Results

This study employed three analyses to reveal phonological and articulatory indices of novel word acquisition over the course of three sessions. The first analysis was speech production accuracy. For this, we used the standard approach of measuring consonant accuracy. Next, we wanted to explore how movement variability may affect speech production using direct measures of lip movement. We predicted that neither of these analyses would be sufficient to reveal patterns of how children with typical and atypical language organize their productive phonologies as they learned novel words. We therefore applied a novel approach to phonological learning using measures from network science. Results are presented for each analysis below. Means and standard deviations for each measure are reported in Table 2. Error bars in all figures denote standard error.

Segmental Accuracy (PCC)

There was an overall main effect of group, $F(1, 22) = 14.69$, $p = .001$, $MSE = 0.052$, $\eta_p^2 = .400$. Children with DLD demonstrated lower segmental accuracy than typical peers at all three time points. On the basis of the Greenhouse–Geisser adjustment, the effect of session was nonsignificant, $F(1.365, 30.032) = 3.54$, $p = .058$, $MSE = 0.003$, $\eta_p^2 = .139$. Children with DLD averaged 65% consonants correct at Session 1 and 67% at Session 3, and typical children averaged 85% at Session 1 and 89% at Session 3 (see Figure 4). Overall, children with DLD were consistently weaker in segmental accuracy than their typical peers, and neither group made significant changes in accuracy over time.

Kinematic Variability (STI)

There was no main effect of group, $F(1, 22) = 0.648$, $p = .430$, $MSE = 77.666$, $\eta_p^2 = .029$, or session, $F(2, 44) = 2.224$, $p = .120$, $MSE = 13.989$, $\eta_p^2 = .092$ (see Table 2 for means and standard deviations and Figure 5 for a visual representation of the data). Visual inspection suggests that children with DLD converge with typical peers by Session 2 (see Figure 5), indicating that variability normalizes with learning.

Network Analysis

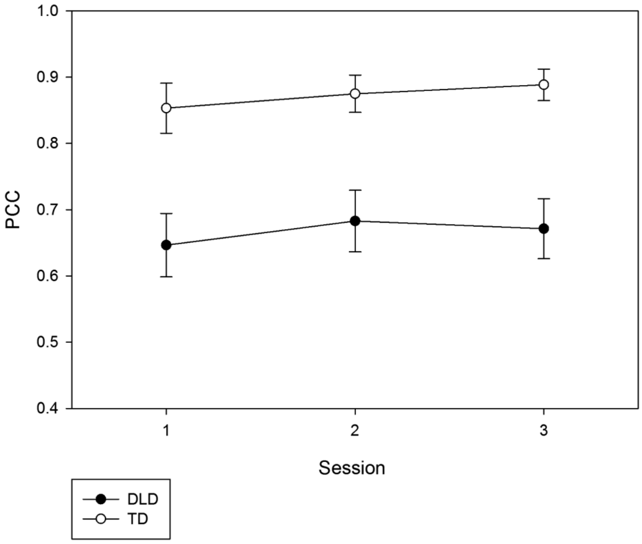
Figure 6 shows group network visualizations from all the children with DLD and typical language, and Figure 7 depicts the two participants with DLD and no speech impairment. To interpret these results, recall that the network analyses highlight patterns of variability and stability, not accuracy. This means that a child who was consistently inaccurate would have similar outcomes as a child who was consistently accurate in her productions. To better frame the network results, ranges of a completely stable and unstable

Table 2. Means and standard deviations of all variables.

	Session 1		**Session 2**		**Session 3**	
	DLD	**TD**	**DLD**	**TD**	**DLD**	**TD**
Variable	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**
PCC	0.65 (0.17)	0.85 (0.13)	0.68 (0.16)	0.88 (0.10)	0.67 (0.16)	0.89 (0.08)
STI	23.87 (6.92)	20.78 (3.35)	20.38 (6.69)	19.85 (5.70)	22.39 (7.39)	21.00 (4.51)
Nodes	14.17 (5.44)	9.75 (4.29)	9.58 (2.84)	6.75 (1.76)	9.42 (2.54)	6.33 (1.44)
Edges	12.33 (4.94)	7.83 (3.88)	8.08 (3.09)	4.67 (1.67)	7.83 (2.82)	4.33 (1.44)
Edge weight	3.88 (1.90)	6.38 (3.23)	5.85 (2.88)	10.14 (5.06)	5.81 (2.23)	10.37 (4.01)

Note. Descriptive statistics for the Jaccard index are given in the text. DLD = developmental language disorder; TD = typically developing; PCC = percent consonants correct; STI = spatiotemporal index.

Figure 4. Percent consonants correct (PCC) performance by session. DLD = developmental language disorder; TD = typically developing.

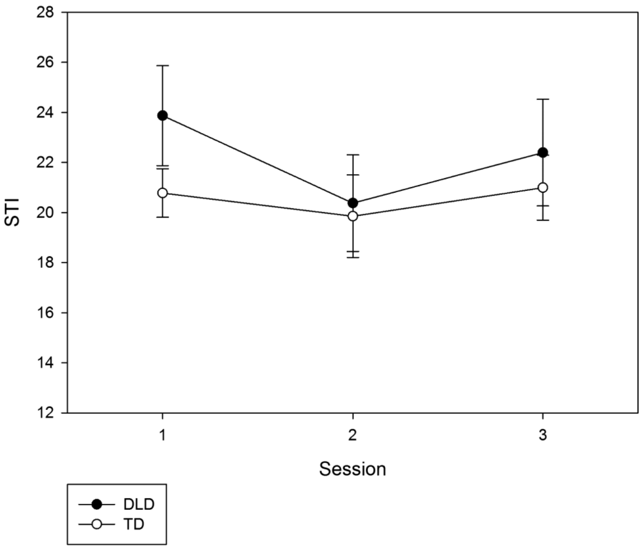


network are described. In a completely stable network, a child would have four nodes, one for each syllable of the two target nonwords, two distinct edges (i.e., two different nonwords), and a maximum edge weight of 10 (i.e., each nonword produced 10 times). Conversely, in a completely unstable network in which the child produces each nonword differently every time, a child would have 80 nodes, 40 distinct edges, and a maximum edge weight of 1.

Nodes

There was a main effect of group, $F(1, 22) = 11.34$, $p = .003$, $MSE = 18.838$, $\eta_p^2 = .340$, with children with DLD producing more nodes than typical peers (DLD: $M = 11.06$, $SD = 4.34$; TD: $M = 7.61$, $SD = 3.13$). With the lower-bound degrees of freedom, a session effect was observed, $F(1, 22) = 16.59$, $p = .001$, $MSE = 15.010$, $\eta_p^2 = .430$. With paired t tests, there was a significant difference between Sessions 1 and 2, $t(23) = 4.209$, $p < .001$, $SE = 0.901$, $d = .859$, and Sessions 1 and 3, $t(23) = 4.417$, $p < .001$, $SE = 0.925$, $d = .902$, but not Sessions 2 and 3, $t(23) = 0.696$, $p = .493$, $SE = 0.419$, $d = .142$. The learning trajectory indicates that both groups showed a decrease in nodes over time and that the primary drop in number of nodes occurred after Session 1 (see Figure 8). The number of nodes stabilized between Sessions 2 and 3 (see Table 2 for means and standard deviations). It is important to note that all target nodes were represented in the networks in the TD group, but by Session 3, the target nodes "f^S" and "b^p" disappeared from the DLD network, meaning that no child with DLD produced either of these two nodes. This is despite the fact that these four segments were within their productive inventories.

Figure 5. Spatiotemporal index (STI) performance by session. DLD = developmental language disorder; TD = typically developing.



Edges

There was a main effect of group, $F(1, 22) = 14.61$, $p < .001$, $MSE = 17.847$, $\eta_p^2 = .399$, where children with DLD produced more edges than typical peers (DLD: $M = 9.42$, $SD = 4.19$; TD: $M = 5.61$, $SD = 2.97$). With the lower-bound degrees of freedom, a session effect was observed, $F(1, 22) = 18.26$, $p < .001$, $MSE = 13.073$, $\eta_p^2 = .454$. With paired t tests, there was a significant difference between Sessions 1 and 2, $t(23) = 4.638$, $p < .001$, $SE = 0.800$, $d = .947$, and Sessions 1 and 3, $t(23) = 4.579$, $p < .001$, $SE = 0.870$, $d = .938$, but not Sessions 2 and 3, $t(23) = 0.669$, $p = .51$, $SE = 0.436$, $d = .137$ (see Figure 8). Learning trajectories were similar to nodes in that both groups showed an initial drop in the number of edges between Sessions 1 and 2, but there were no significant changes between Sessions 2 and 3.

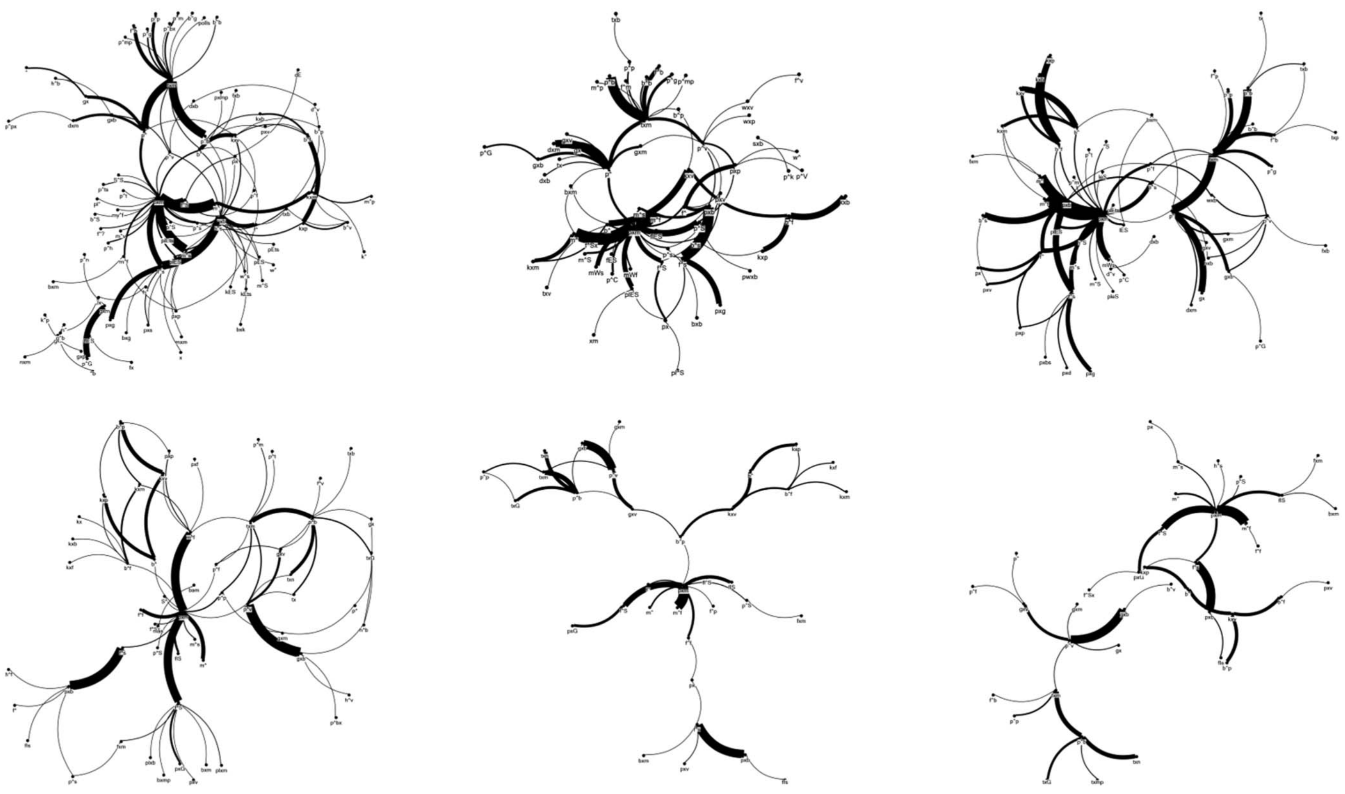
Edge Weight

There was a main effect of group, $F(1, 22) = 14.641$, $p = .001$, $MSE = 17.579$, $\eta_p^2 = .400$, where the TD group had a higher edge weight than the group with DLD (DLD: $M = 5.18$, $SD = 2.49$; TD: $M = 8.96$, $SD = 4.45$). There was also a session effect, with the lower-bound degrees of freedom, $F(1, 22) = 8.039$, $p = .010$, $MSE = 16.925$, $\eta_p^2 = .268$. With paired t tests, there was a significant difference between Sessions 1 and 2, $t(23) = -3.271$, $p < .01$, $SE = 0.877$, $d = .668$, and Sessions 1 and 3, $t(23) = -3.658$, $p < .01$, $SE = 0.810$, $d = .747$, but not Sessions 2 and 3, $t(23) = -0.115$, $p = .910$, $SE = 0.825$, $d = .023$. Results indicate a primary increase in edge weight between Sessions 1 and 2 and no significant changes between Sessions 2 and 3, indicating that the frequency of productions increased in the initial learning between the first two sessions (see Figure 8).

Jaccard Index

In the above networks measures, learning showed a substantial improvement primarily between Sessions 1

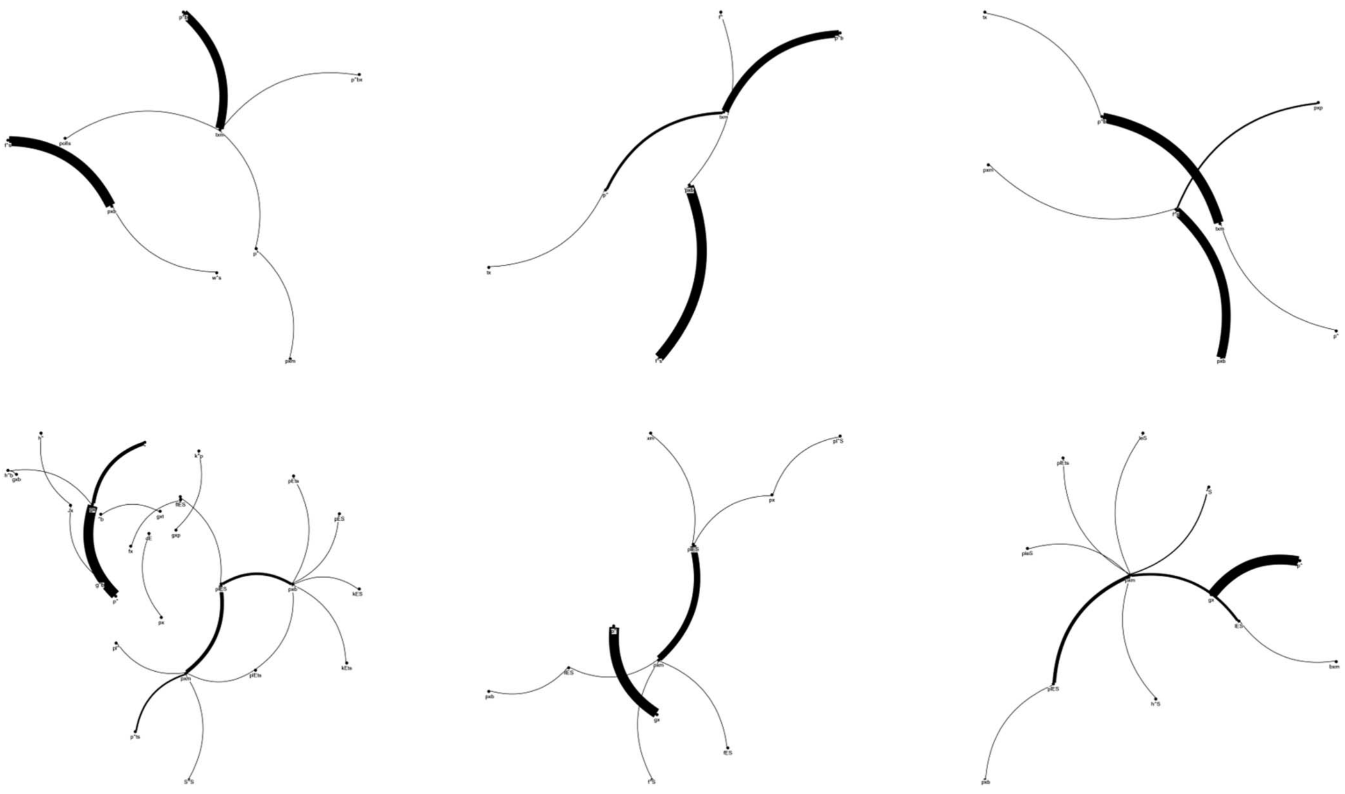
Figure 6. Network visualizations for the group with developmental language disorder (top) and the typically developing group (bottom). Nodes correspond with the syllable sequence, and edges are depicted as the lines connecting nodes when two nodes were produced in succession. A thicker line indicates a more frequent pattern of production. Sessions 1–3 appear from left to right. Networks of children with developmental language disorder have more different syllables (nodes) and more different productions (edges).



and 2 and an apparent stabilization between Sessions 2 and 3. The Jaccard index was used to further explore learning beyond the initial production experience. Specifically, this measure was implemented to assess proportional changes in how specific connection patterns (i.e., edges) were represented over time. As shown in Figure 9, there was a main effect of group, $F(1, 22) = 5.80$, $p = .025$, $MSE = 0.037$, $\eta_p^2 = .209$, where the TD group had a higher Jaccard index than the group with DLD, indicating that syllable co-occurrence patterns were more consistent over time in children with typical language than those with DLD (see Figure 9; DLD: $M = 0.28$, $SD = 0.14$; TD: $M = 0.39$, $SD = 0.19$). The mean proportion of shared edges between Sessions 1 and 2 was 0.24 ($SD = 0.08$) for the group with DLD and 0.34 ($SD = 0.11$) for the TD group; there were a mean of 0.38 ($SD = 0.19$) between Sessions 2 and 3 for the group with DLD and 0.48 ($SD = 0.19$) for the TD group and a mean of 0.21 ($SD = 0.09$) between Sessions 1 and 3 for the group with DLD and 0.34 ($SD = 0.23$) for the TD group.

A session effect was also observed, with lower-bound degrees of freedom, $F(1, 22) = 9.08$, $p < .01$, $MSE = 0.038$, $\eta_p^2 = .292$. The Jaccard index identifies shared edges between two sessions; therefore, using paired *t* tests to assess differences over time, effects represent the difference between two pairs of sessions. Recall that nodes, edges, and edge weight all decreased by Session 2, with no differences between Sessions 2 and 3. However, session effects based on the Jaccard index demonstrate that the proportion of same edges increased between Sessions 2 and 3, although to a lesser extent in children with DLD (see Figure 9). In other words, children do not add new network elements (nodes and edges) to their production systems over time. Rather, they reconfigure the nodes and eventually settle on a preferred production pattern, as indicated by an increase in the proportion of same edges used between Sessions 2 and 3. Performance across Sessions 1 to 2 was similar to performance across Sessions 1 to 3, $t(23) = 0.513$, $p = .613$, $SE = 0.032$, $d = .105$, highlighting the disorganization in edges at initial production experience with the novel sequences. However, performance across Sessions 2 to 3 differed from both other pairings: Session pairs 1 and 2 and Session pairs 2 and 3, $t(23) = -3.535$, $p = .002$, $SE = 0.039$, $d = .721$, and Session pairs 1 and 3 and Session pairs 2 and 3, $t(23) = 3.467$, $p = .002$, $SE = 0.044$, $d = .708$, again suggesting that the significant learning occurs between Sessions 2 and 3. In other words, learning for both groups of children continues beyond the initial exposure and can be characterized by stabilization

Figure 7. Two children in the group with developmental language disorder with typical performance on the Bankson-Bernthal Test of Phonology: Participants 1 (top) and 2 (bottom). Nodes correspond with the syllable sequence, and edges are depicted as the lines connecting nodes when two nodes were produced in succession. A thicker line indicates a more frequent pattern of production. Note that neither child stabilized on a single production with both showing multiple variations of the same form. Sessions 1–3 appear from left to right.



on a preferred phonological pattern; however, children with DLD produce the same connection patterns to a lesser degree than children with typical language.

Discussion

In this study, we examined the trajectory of novel phonological learning in children with and without DLD at multiple levels including segmental accuracy, articulatory variability, and organization of syllable sequences. This was accomplished using a standard analysis tied to the segment (i.e., PCC) and nonstandard approaches associated with larger sequences (i.e., STI, network measures). To summarize, when imitating novel words, children with DLD were significantly less accurate at segment production than typical peers. Importantly, both groups demonstrated limited changes in the accuracy of their productions over time. Using a novel framework for detecting production patterning, a network approach revealed that children with DLD were highly variable and disorganized in their speech production system when sequencing novel phonological strings. Furthermore, both groups demonstrated similar patterns of learning over time: After the initial production experience, network organization stabilized and then continued to maintain a relatively consistent structure, with qualitative changes evident over time. Despite these striking group differences in segmental accuracy and variability, experimental groups could not be distinguished by performance in kinematic variability, suggesting that the source of errors is not an unstable speech motor system. We will first position these results within a developmental framework and then discuss how our findings relate to other sources of deficit in DLD.

Motor Contributions to Variability

In early development, variable speech outcomes are described within the context of an unstable and ever-changing motor and phonological system (Vihman, 1996). Over the first few years of life, young children undergo significant changes in anatomical structure and motor control, which has been hypothesized to account for variable phonetic outcomes (Browman & Goldstein, 1992; Kent, 1992). Therefore, the first factor we evaluated as a contributor to variable speech production was motor performance. We approached this analysis from the perspective of variability rather than articulatory precision, as motor variability is a hallmark of early development (A. Smith & Goffman, 1998; A. Smith & Zelaznik, 2004; Walsh & Smith, 2002). In keeping with this perspective, we examined multiple levels of variability

Figure 8. Nodes (top), edges (middle), and edge weight (bottom) by session. DLD = developmental language disorder; TD = typically developing.

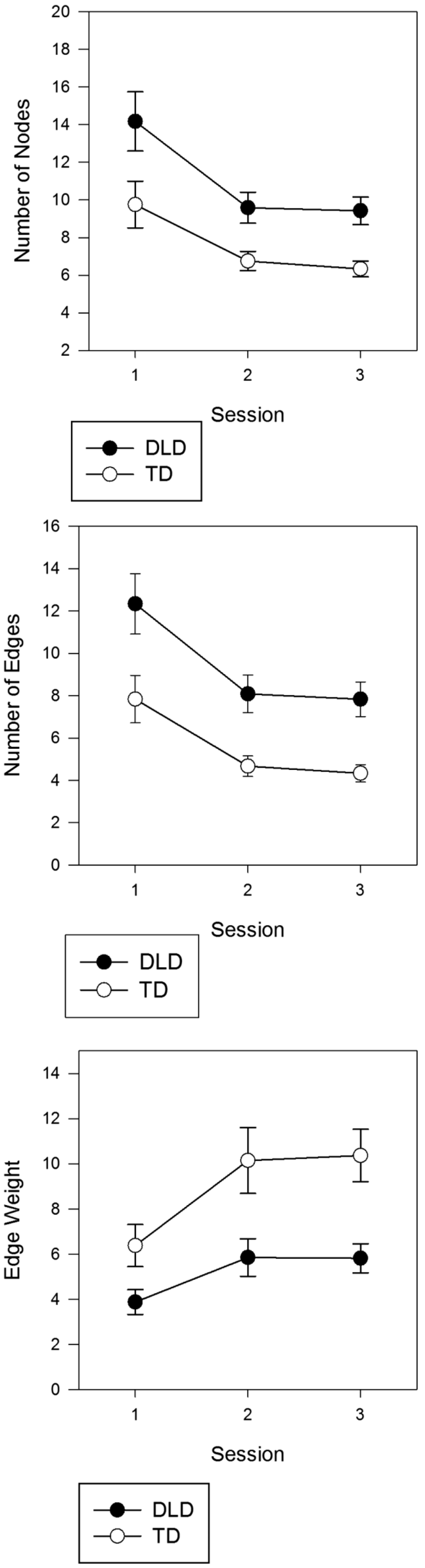
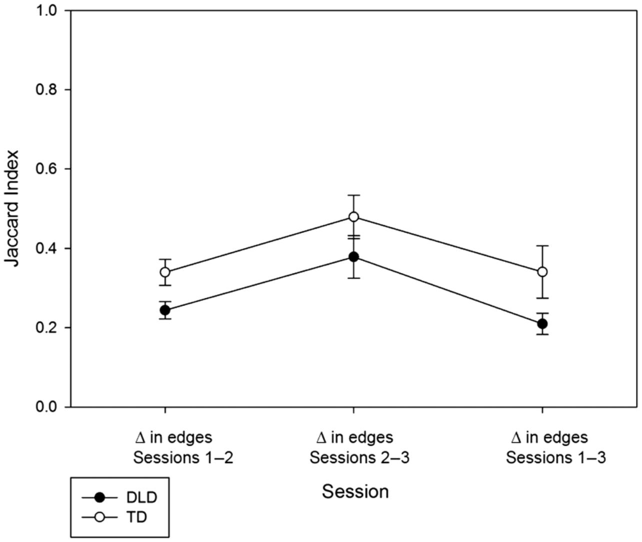


Figure 9. Jaccard index representing the change in edges over time. DLD = developmental language disorder; TD = typically developing.



in the speech production system, motivated by developmental work positing that "the study of early speech should distinguish two kinds of variability: one, the variability in phonetic organization; and two, the variability in motor performance" (Kent, 1992, p. 80). We contend that this approach is of particular relevance to children with DLD as they often demonstrate high variability in both the segmental and motor domains, especially as applied to novel nonwords (e.g., Goffman, 1999; Goffman et al., 2007).

In our kinematic analysis, there were no significant group differences in the articulatory consistency of nonword production, despite striking discrepancies in segmental and syllable productions. In this task, children with DLD and those with typical language performed similarly in their motor implementation of novel word forms but varied significantly in their ability to organize phonological sequences. Many scholars have described a tight association between segments and articulatory gestures, especially in early development (Browman & Goldstein, 1992; Kent, 1992). However, our findings support the idea that this coupling across segments and articulatory gestures is not observed in the context of novel phonological learning in preschool-aged typical learners and learners with language impairment. This finding is consistent with previous reports of a dissociation between motor and phonological levels as children with DLD learn novel words (Benham & Goffman, 2014; Goffman et al., 2007; Heisler et al., 2010). Taken together, these results indicate that a motor contribution is insufficient to explain differences in variable organization of syllable sequences.

Phonological Characterization of Variability

Beginning with Ferguson and Farwell's (1975) classic study of early phonological development, it has been evident that young children produce emerging wordlike forms with a high degree of within-child variability (see also Sosa & Stoel-Gammon, 2012). For example, an individual child on a single day may produce the target word “bottle” as *baːɹ*, *baɪu,* and *baju*. In typical development, these word forms predominantly stabilize over the second year of life. Children’s error patterns become far more systematic and are often described in terms of processes or phonological patterns (e.g., gliding of liquid consonants, simplification of clusters, and/or deletion of final consonants). However, this approach to error analysis that relies on systematic and relatively rule-governed errors does not characterize the variable speech production of very young children. Crucially, young learners are thought to store speech representations that extend beyond individual segments. There is evidence that representational units are initially stored holistically and become refined (or segmental) as the lexicon expands and a greater need for differentiation arises (Gierut, 2016; Metsala & Walley, 1998). A holistic motor score likely underlies these broader word-level units, leading to increased production variability. As such, analyses at the segmental level cannot fully capture the organization of these initial sound representations and how these representations relate to motor gestures.

We considered these phonological characteristics of very early development to help understand speech error patterns in preschoolers with and without DLD. Our central hypothesis was that network science would be a powerful tool for characterizing the process of novel phonological learning in typical and atypical language learners. Speech deficits in children with DLD have been widely documented, especially in novel word learning tasks (e.g., C. Dollaghan & Campbell, 1998; C. A Dollaghan, 1987), but the source of production errors has not been established (e.g., Coady & Evans, 2008; Shriberg et al., 2009). Crucially, little attention has been devoted to the finding that these production errors are not confined to novel words. Many preschoolers with DLD also perform poorly on standardized measures of speech production (e.g., the BBTOP, as used in the current study). There is evidence that a large proportion of 4- to 6-year-old children with DLD (e.g., 86% in Deevy et al., 2010; 83% in this study, but see Shriberg et al., 1999, for a conflicting view about school-age children) perform significantly below their typical peers on these measures. This is clinically problematic, as the speech production deficit has not yet been mechanistically related to the language deficit. Further complicating our understanding of the speech deficit in children with DLD is the manner in which errors are classified. Error assessment typically occurs at a single time point and imposes presumed systematicities and precategorized constraints on the segment (i.e., phonological processes). This motivated the development of a method that would consider the organization of phonological sequences (i.e., syllables) instead of the accuracy of segments as a critical productive unit, especially given the role that holistic phonological representations play in early development (Ferguson & Farwell, 1975).

This analytic approach proved to be successful at characterizing a disorganized and variable speech production system in children with DLD as compared with typical peers. Importantly, this novel application of a network science approach revealed that learning trajectories and variability characterized the speech production of children with DLD. Analyses of the stability of articulatory movement and the accuracy of segments were less informative. Children with DLD exhibited a larger inventory of syllables (i.e., nodes) and syllable connections (i.e., edges) as well as a lower frequency of repeated connections (i.e., edge weight) than children with typical language. Within the context of very early speech development, a highly variable productive system is not a novel finding. What is compelling, however, is that preschoolers with DLD maintain these features of instability from early developmental periods (e.g., multiple variations of the same target sequences, simplified syllable structures) to a greater extent than children with typical language. For instance, children with DLD exhibited a puzzling disappearance of the target nodes “b^p” and “f^ʃ.” By the third session, none of the children with DLD produced these nodes, despite confirming that the phonemes were a part of their phonetic inventories. This is perhaps indicative of a weakened or destabilized representation, often characteristic of a “U-shaped” phonological trajectory, or even the emergence of an alternative productive pattern (Ferguson & Farwell, 1975). These features suggest a highly unpredictable and mutable system that does not readily converge on one particular form.

Phonological Learning Trajectories

Results also demonstrated an important difference in phonological learning trajectories measured by network science and segmental accuracy. In terms of nodes, edges, and edge weight, both groups of children made significant increases in production stability after the first session, with no difference between the second and third sessions. This suggests that a second production experience with novel sound sequences significantly reduced variability with limited effects on production accuracy. Taken a step further, consistency of production, rather than accuracy, may be a relevant clinical focus in speech assessment and intervention of children with DLD. Although sound accuracy is an important clinical outcome in populations with disordered speech, the narrow range of performance as evidenced in this study does not specify where learning may occur or highlight any systematicities in sound production. It is intriguing to consider what these analyses reveal about the learning mechanisms observed in both groups of children. Considering the relationship between the segmental analysis (PCC) and the syllable sequencing analysis (networks), it is evident that, over time, both groups stabilize on a preferred network size, as shown in the decreasing number of edges over time (e.g., Figure 8). However, children with DLD are still significantly less accurate at the segmental level, even by Session 3. This may suggest that children with DLD more heavily weight the process of stabilization on a particular form, even the wrong one, rather than acquiring the target segments.

One crucial difference between groups revealed by network science was the representation of syllable connections over time. We used the Jaccard index to characterize the qualitative variations in connection patterns between sessions. Children with DLD not only produced a higher number of syllable connections, but they were also more variable in the actual sequence produced. In other words, they produced fewer of the same nonword forms over the course of three sessions than children with typical language. However, both groups of children demonstrated an increase in edge representation across sessions, providing further evidence that stabilization and consistency of form production were important factors in their learning, regardless of whether these forms were accurately produced. These sparsely distributed syllable connections also suggest that production variability is indeed an important marker of the speech systems of children with DLD, which has not yet been captured by classic approaches to speech error analysis.

In the initial exposure to a novel word (Session 1), it is apparent that children with DLD do not configure novel phonological sequences as efficiently as children with typical language: Children with DLD are more variable and less accurate. Whereas both groups of children appear to settle on preferred production patterns in Sessions 2 and 3 (although children with DLD to a lesser degree), there may be factors inherent in the initial process of organizing and building representations for children with DLD that prevent them from efficiently forming a stable and accurate production upon repeated exposures. If a deficit in procedural learning were the primary underlying mechanism affecting their errors, we would have observed a less positive change in learning trajectories. However, results from this study suggest that there may be other variables affecting performance beyond a purely sequential deficit. Future directions will explore aspects of the words themselves (e.g., lexical, semantic, and phonological features) to determine which factors affect learning trajectories in the acquisition of a novel word.

The primary research question of this study was to apply a novel networks methodology to characterize phonological learning in typical and atypical language learners. Although articulatory performance on standardized articulation measures was not used for exclusionary criteria, 10 of 12 of our participants with DLD demonstrated impaired speech performance. The aim of this study was not to specifically compare children with DLD with speech impairment with those without speech impairment but rather to implement an alternative error analysis to speech production in a population with atypical language. However, given the results from this study, one compelling follow-up direction would be to explicitly target these two groups of children and determine whether their performance aligns more closely to a phonological deficit or rather a deficit in sequential learning.

As an exploratory approach to this question, we examined the individual performance of the two children with DLD who were within typical limits on the standardized speech assessment (see Figure 7). We cannot make significant generalizations based on the data from two participants; however, their production networks are more closely aligned with the patterning of children with DLD with speech deficits than those with typical language. These two children with language but not speech impairment demonstrate multiple variations of the target forms both in the number of different syllables produced as well as how they are sequenced. Further investigation is required on a larger sample of children who present with DLD but no speech deficits to isolate specific contributions from speech and language levels. However, these results, along with evidence from the sequence learning literature, lead us to predict that children with DLD with no apparent speech disorder would also maintain these features of variability, consistent with a sequential learning deficit.

In terms of clinical practice, this study highlights several key considerations applicable to the assessment and intervention of preschool-aged children with DLD. Importantly, results from this study suggest that speech production variability is a critical feature of novel sound organization in children with DLD. However, articulatory and motor explanations were insufficient to explain the observed variability in children with DLD. Instead, results indicate that stable phonological sequences in early sound mapping, rather than other motor and speech sound components, may be appropriate directions for clinical investigation in children with DLD.

It is important to interpret these findings within the constraints of the networks methodology. Butts (2009) outlines potential limitations and assumptions when constructing networks, primarily that the nodes, edges, and time scale at which the relationships are unfolding are defined by the investigator. In this study, we predefined what the nodes and edges represented. Therefore, results may not reflect the psycholinguistic reality of the child's representation of the word form. This has potential implications for the size of the network and the number of network elements, such as nodes and edges. In future work, analyses of relationships occurring at other units (e.g., sound and/or feature) may be particularly informative.

In our study, network science provided rich qualitative and quantitative measurements of the changing inventory of syllable forms and connection patterns beyond phonetic accuracy or articulatory variability. We also highlight that this approach has significant potential for identifying discrete contributions of speech and language deficits to novel word production. In fact, network science has been used to investigate a similar question concerning shared symptoms between mental disorders such as major depression and generalized anxiety disorder (Borsboom & Cramer, 2013). Using such an approach, it is possible to determine causal links between symptoms to differentiate between complex psychological disorders. Extending this methodology to speech and language science may be especially relevant for children who exhibit co-occurring speech and language deficits. Network science is a promising tool for moving the field forward to identify and differentiate the involvement of multiple factors that contribute to communication disorders.

Conclusion

In summary, network science successfully captured the variations in how children with typical and atypical language productively organize novel phonological sequences over time, more so than a segmental error analysis. Variations in speech production cannot be attributed solely or even predominantly to motor contributions. Results suggest that a deficit in sequential learning may contribute to performance in children with DLD, although similarities in learning trajectories between children with DLD and TD children indicate the need to explore other factors that may mediate learning.

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