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A developmental account of the role of sequential dependencies in typical and atypical language learners

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ABSTRACT
The Gerken lab has shown that infants are able to learn sound patterns that obligate local sequential dependencies that are no longer readily accessible to adults. The Goffman lab has shown that children with developmental language disorder (DLD) exhibit deficits in learning sequential dependencies that influence the acquisition of words and grammar, as well as other types of domain general sequences. Thus, DLD appears to be an impaired ability to detect and deploy sequential dependencies over multiple domains. We meld these two lines of research to propose a novel account in which sequential dependency learning is required for many phonological and morphosyntactic patterns in natural language and is also central to the language and domain general deficits that are attested in DLD. However, patterns that are not dependent on sequential dependencies but rather on networks of stored forms are learnable by children with DLD as well as by adults.

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Introduction

Learning language involves detecting and making use of sequential information, both stochastic (/sp/ is a more frequent sequence in English than /sv/, although the latter occurs in words like *Sven* and *svelte*) and absolute (*she likes ice cream* is grammatical but **she like ice cream* is not in some English dialects). Indeed, a recent study with bonobos and adult humans suggests that being able to discriminate among sequences of two stimuli is a uniquely human ability and perhaps a reason for human linguistic prowess (Lind et al., 2023). In keeping with the apparent importance of sequence learning in language, numerous studies suggest that learning novel phonological (and relatedly morphosyntactic) sequences is especially implicated in children with developmental language disorder (DLD). In this article, we present a developmentally motivated account of linguistic and non-linguistic deficits in DLD that relies on recent data on developmental changes in sequence learning in typically developing immature language learners vs. adults.

Part 1 presents evidence that the types of linguistic sequences that are learnable change over development from infancy to adulthood (Gerken & Knight, 2015; Gerken et al., 2021; Gerken & Quam, 2017; Gerken et al., 2019; Goffman & Gerken, 2020). Part 2 presents evidence that DLD is not a disorder of language, speech, or motor skill, but rather an impaired ability to detect and use sequential dependencies across multiple domains. Part 3 elucidates how these two initially separate lines of research have resulted in a new and integrated research agenda that has implications for understanding typical and atypical development.

Part 1. Sequence learning in typical development

A number of studies of language learning in the lab by typically developing infants and children, on the one hand, and adults on the other suggest that younger and older learners approach linguistic input differently. For example, Hudson, Kam et al. (2009) found that 5- to 7-year-olds "clean up" input generated from a stochastic grammar; adults given the same input "probability match" and produce the same distribution of forms as their input. This research

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clearly demonstrates that younger and older learners approach structured input with different biases and processing abilities.

In a similar vein, we have been pursuing for some time a line of research on phonotactic learning by 11-month-olds and adults (Gerken & Knight, 2015; Gerken et al., 2021; Gerken & Quam, 2017; Gerken et al., 2019). We will describe this research, which uses infant attention and adult grammaticality judgements as the dependent measures, later in this section. As noted in the Introduction, we have found over multiple studies that 11-month-olds are able to learn a complex sequential dependency that adults are apparently unable to learn. Dell and colleagues (2021) recently reported that the developmental effect we had observed in our lab was also present in slip-of-the tongue studies carried out by Dell and others. Dell and colleagues (2021) suggested some of the same developmental mechanisms that we have considered (e.g., Goffman & Gerken, 2020), as well as some we have not. Both the infant~adult differences that we have observed, and the child~adult differences discussed by Dell and colleagues, suggest important differences in how younger vs. older learners approach linguistic sequential dependencies. Our ongoing research attempts to characterize these differences and the underlying mechanism, with an ultimate goal of viewing the sequential dependency learning deficit observed in DLD within this developmental framework.

We now review data from several published experiments on phonological sequence learning by several populations: typically developing infants, toddlers, and preschoolers, and adults with and without a history of developmental language disorder. The phonological sequences are of two types: One type is 2nd order dependencies in which the segments that occur in one position are dependent on the segments that occur in another position. These dependencies are expressed by an "iff" relation. The segment dependencies can either be arbitrary as in 1a and 1b in which the onset and coda each depends on the vowel (e.g., Warker & Dell, 2006), or they can be based on phonetic feature relations such as 2a-b and 3a-b in which the two consonants must share a feature (e.g., Gerken & Knight, 2015; Gerken et al., 2021; Gerken & Quam, 2017; Gerken et al., 2019; Goffman & Gerken, 2020). Note that the 2nd order dependencies like 2a-b and 3a-b are typical of morphological rules. For example, in the English past tense, the voicing of the final segment of the stem determines the voicing of the past tense ending, which surfaces as either /t/ or /d/, a point to which we will return in Part 3.

1a. /f/ must be an onset and /s/ must be a coda iff the vowel is /æ/
1b. /f/ must be a coda and /s/ must be an onset iff the vowel is /ɪ/
2a. Iff C1 is voiced, then C2 is voiced OR
2b. Iff C1 is voiceless, then C2 is voiceless
3a. Iff C1 is labial, then C2 is labial OR
3b. Iff C1 is coronal, then C2 is coronal

The second type of phonological sequence under consideration involves a family resemblance (FR) relation, with legal sequences containing at least two out of three features, as illustrated in 4a-c.

4a. C_1 is voiced
4b. V_1 is front
4c. C_2 is voiced

Finally, we will also make reference to 1st order or single-feature categories, illustrated in 5.

5. /f/ must be an onset

Note that to learn the second-order dependencies in 1-3, the learner needs to detect the dependency *within* a word. Put another way, noticing that, *across the whole set of input*, many words begin with /f/ and many words end with /f/ will not permit the correct generalization in 1a-b. Similarly, noticing that many words begin in a voiced consonant and many words end in a voiced consonant in 2a-b would not allow learners to distinguish between a new grammatical word in which C_1 and C_2 are voiced vs. an ungrammatical word in which C_1 but not C_2 is voiced. However, both the FR rule in 4 and the single-feature rule in 5 allow learners to accrue rule-relevant information across the set of input. Thus, the accumulation of many *independent* observations that there are many voiced C_1's, many front vowels, and many voiced C_2's is sufficient to allow generalization to new words that fit the FR rule.

Focusing first on infants and toddlers, two published studies using the headturn preference procedure (Kemler Nelson et al., 1995) demonstrated that 11-month-olds are able to learn the sequences generated by 2a-b and 3a-b (Gerken & Knight, 2015; Gerken & Quam, 2017). Sample words for 2a-b might be *pota, tapa, biza, deva,* and for 3a-b might be *poba, taza, bipa, desa*.

The procedure for the two studies was the same: Each infant sat on their caregiver's lap in a soundproof booth with a centre light, two side lights over two speakers, and a camera trained on the infant's face. During familiarization, the infant hears some number of CVCV nonwords generated by the relevant rule (different groups of infants were familiarized with stimuli generated by 2a-b vs. 3a-b, and different numbers of familiarization words were played in different experiments). During this phase, the centre light flashed until the observer watching the infant on a monitor outside the booth and blind to the experimental condition judged the infant to be looking at it, at which point a light on the left or right would begin flashing. When the infant looked first at the side light and then away for 2 sec., the centre light would resume flashing, and the cycle would begin again. In this phase, the auditory stimulus continued to play, even when the side light stopped flashing. The familiarization phase lasted approximately 2 min. During the test phase, infants heard lists of new words that were consistent with the rules in 2a-b on half of the trials and with 3a-b on the other half. Infants all received the same test trials no matter which stimuli they received during familiarization (2a-b or 3a-b). The testing procedure was similar to the one in familiarization, except that the auditory stimulus stopped playing when the infant looked away from the flashing light for 2 sec. Thus, infants controlled how long they listened to each of the test trials, and significant differences between how long they listened to consistent vs. inconsistent test trials were taken to indicate that infants learned the relevant sequential dependency. Learning is further indicated if infants who were familiarized with 2a-b show the opposite listening preference at test than infants familiarized with 3a-b.

Using this method, Gerken and Knight (2015) showed that infants were able to learn the patterns in 2a-b and 3a-b from just four non-repeated familiarization words, so long as those four words were a representative sample of the range of consonants and vowels (the remainder of the 2 min familiarization session was taken up with music to familiarize infants with the lights and speakers). Gerken and Quam (2017) showed that infants were able to learn the patterns in 2a-b and 3a-b from 24 familiarization words so long as the stimuli order did not contain "local spurious generalizations" (e.g., 3 words in a row that started with *p*). Because infants in these two studies heard test stimulus lists of words that combined the two halves of each rule (i.e., words in which C_1 and C_2 were both voiced and C_1 and C_2 were both voiceless all occurred in the same consistent test stimulus list), one concern in interpreting infants' behaviour as showing learning is that they may have learned only one half of each rule and still showed a listening difference between consistent and inconsistent test items. More recent versions of this paradigm presented voiced and voiceless consistent words on different test trials, and both 11-month-old infants and 20-month-old toddlers discriminated both 2a-type and 2b-type test words from inconsistent test words (Gerken et al., 2022).

Moreover, the finding that immature humans can learn this kind of 2nd order sequential dependency isn't limited to attention/preference data. In a recent experiment, one group of typically developing 4-year-olds listened to and produced nonwords over the course of 6 sessions separated by at least a day. The nonwords for the experimental group were generated by the 2nd order sequential dependency rule in 2a, while another (control) group heard and produced words that did not all adhere to a single rule. Even in the first session of learning, children in the OR rule group, matched for performance on speech and language measures, showed higher accuracy than those in the control condition. Thus, 4-year-old children who are TD appear to show sensitivity to a 2nd order sequential dependency rule in their production systems (Scoppa et al., 2022).

Interestingly, a substantial literature shows that adults with normal language and adults with DLD do not easily learn these 2nd order sequential dependencies, although they readily learn family resemblance (FR) patterns like those generated by the requirements in 4a-c. Moreton and colleagues categorized cross-linguistic morpho-phonological patterns into the classic Shepard et al. system, including single feature rules, 2nd order dependencies (of which the Exclusive OR rule is a subset), and FR patterns (Moreton, 2008, 2012; Moreton & Pater, 2012; Moreton et al., 2015; Moreton & Pertsova, 2014; Shepard et al., 1961). They found that single feature categories like 5 above were most frequent, followed by 2nd order dependencies like 2a-b and 3a-b, with FR (4a-c) less frequent than the other two. Moreton and colleagues also found that FR patterns, despite being relatively infrequent, are readily learned by adults while 2nd order dependencies are not. The task they used was a familiarization-then-judgement task in which adults were familiarized with a set of positive examples and then asked to rate how similar new consistent and inconsistent test nonwords were to the familiarization set.

Gerken et al. (2019) used a similar familiarization-then-judgement task with adults, but on the same stimuli (2a-b and 3a-b) presented to infants by Gerken and Knight (2015). They, like Moreton and colleagues, found that adults were unable to learn the sequential dependencies. A subsequent study using a familiarization-then-judgement task with the voicing sequential dependency in 2a-b and very similar (yet not sequentially dependent) stimuli generated by the FR requirements in 4a-c showed that both adults with typical language and adults with DLD showed significant learning of the FR pattern, but not the sequential dependency pattern, with a significant effect of 2nd order vs. FR on the rate of correct responding. Note that the FR pattern was instantiated in the same consonant features as 2a-b plus an additional vowel feature, such as the pattern illustrated in 4a-c. Thus, it does not appear that adults have difficulty encoding the phonological features that are used in the 2nd order sequential dependency rule, since the same features (consonant voicing) are also used in the FR pattern. Importantly for our discussion of DLD in Parts 2 and 3, adults with DLD were able to learn the FR pattern and to the same degree as adults with typical language (and not the 2nd order sequential dependency pattern, Gerken et al., 2021).

At this point, we are faced with an intriguing developmental difference in the learning of 2nd order sequential dependencies—younger learners seem to readily learn these dependencies, whereas adults do not. Adults, on the other hand, seem adept at learning FR patterns in which an aggregate of features, not their dependencies, determine if a nonword fits the pattern. One difference in the methodology in the infant~child experiments and the adult experiments reported thus far is that the latter studies may tap implicit learning, whereas the judgement task may tap more explicit learning.

However, this explanation is not supported by a large set of experiments recently summarized by Dell and colleagues (Dell et al., 2021). The work by Dell and colleagues that is of most relevance here comes from a slip-of-the tongue induction task using 2nd order dependencies, such as the one in 1a-b (Dell et al., 2021; Smalle et al., 2017; Warker, 2013; Warker & Dell, 2006). To learn these sequential dependencies, participants are asked to say sequences like *hin ming kig sif* and *kas fam hag nang*. Evidence that participants have learned the 2nd order dependencies is that, when they make slips of the tongue, /f/ is more likely to slip into onset positions when the vowel is /æ/, and /s/ is more likely to slip into onset positions when the vowel is /ɪ/ (e.g., Warker & Dell, 2006). While adults appear to show immediate learning of 1st order dependencies (e.g., /f/ is always an onset and /s/ is always a coda), they do not appear to show learning of 2nd order dependencies like those in 1a-b until the second day of training (suggesting sleep-based consolidation is required, Anderson & Dell, 2018). Thus, when tested immediately, as has been done in the familiarization-then-judgement work described above, adults do not show learning of the second order dependency, although they show other learning, all of this in an arguably highly implicit task.

Moreover, work using the SOT task also shows a developmental effect: nine-year-old children tested using the same paradigm show the same degree of learning of 2nd order dependencies as do adults. However, unlike adults, children show learning right away (suggesting that consolidation is not required, Smalle et al., 2017). This work supports the growing body of evidence that younger learners are more adept at learning 2nd order sequential dependencies than are adults.

Clearly the parallel that we are drawing between evidence of delayed adult learning in the SOT studies reviewed by Dell and colleagues (2021) and the failure of adults to learn in the familiarization-then-judgement studies reported here must be further explored. One obvious first step would be to present adults with a list of nonwords generated by the 2nd order sequential dependency in 2a on day 1, but not ask for grammaticality judgements until day 2. Pilot data from our lab using this approach continued to show no evidence of learning. However, Dell and colleagues (2021) express some belief that the requirement for consolidation seen in the college-aged adult 2nd order SOT studies may be specific to syllable production: *Thus during Day 1, the mini-grammar is being created, but is not used to speak. On Day 2, the mini-grammar is now available for the production system whenever the experimental context is present.* If sleep-related consolidation only occurs for production tasks, we must address how learning a 2nd order sequential dependency might be differentially affected by production versus perceptual judgements.

Finally, one finding in the literature fails to support the observation that adults find 2nd order sequential dependencies to be very difficult to learn. In a study by Onishi and colleagues (Onishi et al., 2002), adult participants merely listened to (did not produce) a set of words and non-words that exhibited 2nd order dependencies similar to those in 1a-b. In a subsequent speeded repetition task, participants repeated syllables that fit the 2nd order dependencies faster than those that did not. That is, using production speed instead of SOT's *per se*, this study suggests that college-aged adults learn a 2nd order dependency on day 1. This study provides the only evidence for immediate 2nd order sequential dependency learning by adults, and we are currently trying to replicate it. We will return to the implications of this study in Part 3.

In summary, the developmental data from our labs (e.g., Gerken et al., 2019; Scoppa et al., 2022) show a potentially important parallel to the developmental data described by Dell and colleagues (Dell et al., 2021; Smalle et al., 2017). Together, these parallel lines of research suggest that there is likely to be a real developmental difference in 2nd order sequential dependency (OR rule) learning between typically developing infants and children on the one hand and adults on the other.

We will explore possible explanations for this difference in Part 3. We suggest that findings from children and adults with DLD, which appears to entail a deficit in the learning and use of sequential dependencies (in English, particularly those that involve tense and agreement) and which we discuss in Part 2, will contribute to our understanding of this developmental difference. In the remainder of Part 1, we lay out a hypothesized order of difficulty of learning 1st order and 2nd order rules (e.g., examples 5 and 1-3, above respectively) and family resemblance patterns (4 above) for immature vs. mature learners. With respect to 1st order (or single feature) rules, there is ample reason to believe that college-aged adults find such rules readily learnable in judgement tasks (e.g., Moreton et al., 2015). The FR pattern can also be viewed as a complex 1st order dependency encompassing two or three single-feature rules (e.g., C_1 voiced, vowel front, C_2 voiced). There is no contextual dependency marked by an "iff" relation like the rules in 1a-b, 2a-b, and 3a-b. Thus, we view the finding that FR patterns are readily learnable by adults, including adults with DLD, as evidence that, as noted earlier, college-aged adults are able to learn feature-based patterns. Although learning that two or three single-feature rules apply to the same word may be harder than learning only a simple single-feature rule, the learning mechanism may be the same. Developmentally, previous research on 1st order rules suggests that both 9 and 16.5-month-olds readily learn these patterns (e.g., /b/ must be an onset, Chambers et al., 2003; Saffran & Thiessen, 2003). No published studies exist on linguistic FR pattern learning by infants; however, ongoing research in our lab suggests that 11-month-olds do not show any evidence of learning FR patterns, while 20-month-olds show some evidence of learning. If this pattern persists, it would support the view that FR patterns are complex 1st order dependencies that require memory and cognitive resources available to toddlers, but no special processing mechanisms. Moreover, both 1st order and FR patterns are learnable across species (e.g., Smith et al., 2012).

We argued at the beginning of this section that 2nd order sequential dependencies require noticing a relation between segments *within* a word. In contrast, FR patterns could be discovered by independently tallying the relevant features *across* a set of input words. That is, discovering FR patterns requires computations over sets of stored forms. We have argued elsewhere (Goffman & Gerken, 2020; Gerken et al., 2021) that the lexicon may serve as a storage medium: As adults attempt lexical access, the pattern of spreading activation in the lexicon might allow the relevant features of the FR pattern to emerge as highly activated. Because adults with DLD appear to have normally organized lexicons that would allow such spreading activation, they too are able to learn FR patterns. We return to the view that stored forms are particularly important for children and adults with DLD in Parts 2 and 3.

In contrast with FR patterns, 2nd order sequential dependencies have been documented as extremely difficult (perhaps impossible) for adults to learn without overnight sleep-based consolidation. Out of the many studies reviewed here, only one found learning of a 2nd order dependency on day 1 (Onishi et al., 2002). Second order sequential dependencies are also not learnable by any non-humans that have been thus far examined (e.g., Smith et al., 2012). Although there are fewer studies on 2nd order sequential dependency learning by infants and children, there are enough studies involving enough different methods to suggest that immature learners have a learning advantage (Gerken & Knight, 2015; Gerken & Quam, 2017; Scoppa et al., 2022; Smalle et al., 2017). Before leaving this section, it is perhaps important to point out that, although adults generally fail to learn 2nd order dependency or OR rules, these are the 2nd most frequent morpho-phonological rules cross-linguistically; 1st order rules are more frequent, but FR patterns are less frequent. Therefore, an immature learning mechanism that allows for the robust learning of 1st and 2nd order rules contributes to their frequency in the language. The idea that immature learning mechanisms contribute to language learnability, and thereby the ultimate form language takes, is consistent with the "Less is More" hypothesis by Newport and colleagues (Goldowsky & Newport, 1993; Hudson Kam, 2005; Kam et al., 2009).

Let us now turn to sequential dependency learning in DLD. In Section 2 we make the case that the ability to learn sequential dependencies underlies the very deficits that define DLD. Further, these deficits are domain general and influence the acquisition of words and grammar, but also other types of sequences.

Part 2. Sequence learning in children with developmental language disorder

In this section, we address how disorders, with a focus on DLD, inform the theoretical account we are pursuing. Language disorders, such as aphasia (e.g., Dell et al., 2007), have long provided an important source of data that contribute to understanding mechanisms of language processing and production. In Section 1, we presented data suggesting that sequential 2nd order rules are learnable by infants and children, but not by adults. In this section, we argue that these very sequential rules are challenging for children with DLD. Two primary hallmarks of DLD are deficits in grammar (e.g., Rice & Wexler, 1996) and in the production of novel sequences of syllables, or nonword repetition (e.g., Dollaghan & Campbell, 1998). Additionally, and central to our account, deficits extend beyond language to cognition and action (e.g., Hill, 2001). Indeed, insights into the learning of sequential dependencies, such as the Exclusive OR rule, are drawn from other, non-linguistic, domains (e.g., Shepard et al., 1961). We turn here to evidence for our hypothesis that domain general deficits in learning sequential dependencies form a core and mechanistic component of DLD. We argue that the sequential dependencies that are so readily learnable by infants but not by adults underlie the deficits that are characteristic of DLD.

Findings from the Gerken lab and others demonstrate that the complexity of sequences may influence the time course of learning, with single features acquired more readily than family resemblance relations. Further, distinct processes may underlie aspects of sequential dependency learning, as in the linguistically relevant OR rule. Here we present the case that pattern learning involving sequential dependencies, which are so central to language, are domain general. We have initiated studies, in collaboration with the Gerken lab, focused on the influence of specific sequential dependencies on learning non-linguistic as well as linguistic patterns. We argue that children with DLD show a sequential pattern learning deficit, but only in those aspects of sequence learning that rely on dependencies.

The results from this line of research increasingly indicate that DLD is not constrained to language, but rather a domain general impairment in the ability to detect and use sequential dependencies across multiple domains. Our claim is that these sequential patterns are exploited for language, but that they are not language specific; we also suggest that a domain general approach, motivated initially by work in DLD, has implications for language learning in typical development. In DLD, we posit that domain general sequence pattern learning deficits that incorporate dependencies characterize the disorder. In Part 3, we turn to how the profile of unaffected and impaired sequential patterns attested in DLD link to our developmental model, including the current status of our hypothesis and the research agenda that it invites.

We first describe DLD (AKA specific language impairment; SLI) and discuss why this language disorder informs accounts of language processing and production. DLD is classically defined as an impairment in language that is not explained by other perceptual, motor, or cognitive factors (Leonard, 2014a; Rice et al., 1995). Children with language weaknesses were initially characterized by their specific language impairment. Thus, DLD was construed as a modular deficit specific predominantly to morphosyntactic aspects of language (e.g., Rice & Wexler, 1996; Gopnik, 1997). However, following the accrual of empirical evidence it has become clear that children with DLD show other deficits, such as in motor skills (e.g., Bishop & Edmundson, 1987; Brumbach & Goffman, 2014; Hill, 2001; Sack et al., 2022; Vuolo et al., 2017), nonword repetition (e.g., Dollaghan & Campbell, 1998), and word form learning (e.g., Benham et al., 2018; McGregor et al., 2020).

Some theoretical accounts of DLD

DLD, termed SLI at the time, was initially viewed as a modular linguistic deficit, with particular weaknesses in morphosyntax, specifically in tense and agreement (e.g., Leonard, 2014a; Rice & Wexler, 1996). Indeed, deficits aligned with morphosyntactic processing are core. However, many findings have emerged showing that other features are prominent in the deficit profile, such as in memory (e.g., Montgomery et al., 2021) and motor skill (e.g., Hill, 2001). The frequently attested motor deficits in DLD have variously been explained as spurious noise (Hill, 2001; Leonard & Deevy, 2020) or as mechanistically related to the disorder, perhaps most prominently illustrated in the procedural deficit hypothesis (PDH; Ullman & Pierpont, 2005; Ullman et al., 2020).

The PDH is a unifying account in which the frequently attested and domain general behavioural deficits that characterize DLD are proposed to result from neurobiological abnormalities that underlie procedural learning (Ullman & Pierpont, 2005; Ullman et al., 2020). The PDH makes reference to two memory systems that are part of standard theories of memory: the declarative and procedural systems. The procedural memory system is implicated in phonological, morphological, and syntactic rule learning (e.g., Ullman et al., 2020), as well as in statistical learning (Evans et al., 2009) and non-linguistic timing and serial reaction time tasks (e.g., Lum et al., 2014). Procedural deficits arise due to abnormalities in the basal ganglia and associated circuitry. Procedural learning occurs without conscious awareness and relates to the hallmark morphosyntactic deficits that characterize DLD as well as to other linguistic and non-linguistic features of the disorder. Thus, this is a common mechanisms account.

Unlike procedural memory, declarative learning mechanisms are relatively unaffected in DLD and may provide compensation for procedural deficits. The declarative memory system is responsible for explicit knowledge, which includes many features of the lexicon (Ullman et al., 2020). Thus, aspects of the lexicon are predicted to be unaffected, even when matching for age. The primary anatomic structure implicated is the hippocampus.

In relation to our own more constrained hypothesis, it is important to point out that children with DLD do not show deficits in some non-sequential procedural tasks. For example, children with DLD, when compared with age-matched TD peers, show no deficits on a pursuit rotor task (Hsu & Bishop, 2014). In addition, metronomic timing tasks are not affected (Vuolo et al., 2017; Zelaznik & Goffman, 2010). Children with DLD show similar manual timing ability to their age-matched TD peers. Thus, non-sequential procedural tasks appear to be unaffected in children with DLD.

Our hypothesis is that children with DLD show deficits in learning sequential dependencies. This hypothesis is related to the PDH, but narrower in scope and explicitly reliant on behavioural findings from typical lifespan development, as described in Section 1. We argue that sequential dependencies, which are indeed procedural, are the core of the deficit that deeply affects language, but also transcends to non-linguistic domains. Work from our lab has focused specifically on sequential pattern learning deficits that link documented difficulties in language and action. Importantly, some aspects of language and motor skill, even those that are procedural, are learnable by children (and adults) with DLD (e.g., Gerken et al., 2021; Hsu & Bishop, 2014; Vuolo et al., 2017); only specific features are challenging. As will be shown in the evidence section below, we now argue that a general cognitive deficit that underlies language and action profiles in DLD is specific to sequential pattern learning.

Critically, our results conceptually align with the developmental shifts identified in Section 1. Learning sequential dependencies are affected, while other types of learning, such as related to FR prototypes and crystallized wholes (as discussed in the following sections) are not. While memory factors clearly contribute to DLD (e.g., Montgomery et al., 2021), they cannot fully explain the attested deficits. As was shown in the studies reviewed above on typical development and will be shown below in relation to DLD, length and computational complexity do not explain all aspects of the findings.

In considering the nature of DLD, it is important to address the cross-linguistic features of the deficit. As shown by Leonard (2014b) and others, DLD affects every language that has been studied, but is attested differently based on the structure of that language. For example, in English, tense and agreement errors are prominent, while in Spanish, articles and clitics are more vulnerable (Bedore & Leonard, 2001). The cross-linguistic results show that DLD is not related to specific grammatical features, such as tense and agreement, but rather to another aspect of computation. Leonard (2014b) suggests that computational factors likely underlie how DLD will be realized in a particular language. In our developmentally motivated account, we posit that the particular computations that underlie cross-linguistic and domain general deficits in DLD are in the capacity to learn sequential dependencies and second order rules.

Findings related to the domain general deficits in sequential dependencies have potential to tap into vulnerabilities that place a child or adult at high risk for DLD, regardless of language or dialect being learned. We position our results in a developmental context. The data reviewed in Section 1 show that infants learn complex second order rules that adults cannot without sleep consolidation, while family resemblance or prototype rules are readily learnable by adults, but only beginning to be learned by toddlers. Thus, we argue that a developmentally attested computation related to the acquisition of novel dependent sequences is central to domain general (and language and dialect general) deficits that are core to DLD.

Review of empirical support

That children with DLD show deficits that extend to action motivated the routine testing of motor skill in children with DLD and the incorporation of direct measures of motion into our language production and our manual studies. These studies have always included typically developing (TD) age matched peers. To summarize findings to date, children with DLD show a motor impairment (e.g., Brumbach & Goffman, 2014; Sack et al., 2022; Vuolo et al., 2017; Zelaznik & Goffman, 2010), but it appears to be constrained to manual (and speech production) tasks that involve sequencing, especially dependency relations (Vuolo et al., 2017; Goffman et al., 2023). Phonological and morphosyntactic aspects of language are inherently sequential and dependent. The typical developmental framework is essential for explaining why, even when memory demands such as length are controlled, children with DLD show a profile of deficits in which novel phonological and morphosyntactic learning are affected but aspects of learning, such as those that involve prototypes or crystallized word forms, are not. Those aspects of language that can be learned as first order or FR rules are not affected in children with DLD. Overall, this work has implications for understanding typical development and aligns with findings from Gerken and colleagues, showing distinct developmental trajectories across infants' and children's capacity to learn different kinds of sequences that are relevant for lexical, phonological, and morphosyntactic processing.

In this framework, we turn to studies of children with DLD that have been conducted in our lab, many of these initially viewed through the lens of motor development. To foreshadow, as these empirical data have accrued, it has become evident that it is not language or motor learning per se that is implicated in DLD, but rather that these children show deficits in the detection and implementation of sequential patterns and dependencies across domains. In Part 3, we revisit the developmental constructs of disjunctive OR and FR, and how the different learning trajectories of each may characterize the deficits attested in children with DLD. We also discuss our research agenda going forward.

Methodological approaches to studying manual and speech production.

Variability and accuracy are key indices of production learning in spoken language and manual domains. Spatiotemporal variability is measured across repeated productions of a target and indexes the replicability of a movement trajectory in association with a goal, such as the production of a word or a sentence or, in the manual domain, a sign or a patterned hand motion or musical sequence. We established a methodology for assessing pattern variability in speech production, the spatiotemporal index (STI; Smith et al., 1995). This method is ideally suited to assess shifts in automaticity as people learn. In Figure 1, we show one example from upper and lower lip and jaw motion (production of a sentence) and in Figure 2 one from the hands (production of a patterned hand motion sequence in a serial reaction time task). We first transcribe productions for accuracy. In speech, this is phonetic accuracy. In manual sequences, such as novel sign and hand patterns, we turn to accuracy of handshape, path, and location and of replication of the target motion sequence.

Spatiotemporal variability is assessed across groups, such as younger and older children (e.g., Goffman & Smith, 1999; Smith & Goffman, 1998; Smith & Zelaznik, 2004) and disordered and typical children (e.g., Goffman, 1999; Saletta et al., 2018). We also evaluate within subject comparisons across learning conditions (e.g., prosody, Goffman, 1999; sentence retrieval vs. imitation, Saletta et al., 2018; Vuolo & Goffman, 2018). Because we are interested in motion patterning, and not differences in rate or loudness, we first time- and amplitude-normalize the trajectories associated with multiple productions of the same manual or articulatory target. These normalized records are shown in Figures 1 and 2. We operationalize differences in variability by taking standard deviations at 2% intervals across the overlying motion trajectories and sum the resulting 50 standard deviations. This sum is the spatiotemporal index, or the STI, which shows the *stability* of the motor implementation of an articulatory or manual target. In Figure 1, we show multiple productions of the sentence “Buy Bobby a puppy”. Children with DLD often (though not always) show a higher STI, indicating that they are using a more variable movement pattern on each rendition of the production than their age-matched peers. Similarly, Figure 2 shows movement variability as children learn a hand motion sequence. For details about this method, see Smith et al. (1995) and Smith et al. (2000). Together, accuracy and variability measures index learning.

We also transcribe speech production errors and segmental variability as children learn. Children with DLD have long been characterized by their difficulties with processing and producing grammar. Their speech production errors are also hallmark, as demonstrated by their difficulties in nonword repetition tasks (e.g., Dollaghan & Campbell, 1998) and in word form learning (e.g., Benham & Goffman, 2022; McGregor et al., 2020). Children with DLD produce increased phonetic errors in their speech compared to their age matched TD peers. In their acquisition of a novel word form, they also show high levels of phonetic variability in comparison to their peers. For example, a child with DLD may produce the target novel word [p^vgəb] as [^bgə], [^gə], [^bgə], [p^bgə], [^bgət], [p^gə], [g^bgə], [h^dʒə]. Children with DLD routinely show higher levels of intra-word variability during novel word learning than their TD peers (e.g., Benham et al., 2018). In transcription, reliability is calculated by including a second trained transcriber. In motion capture, we apply an algorithm for formalizing that we are selecting replicable onset and offset points in the kinematic record (see Goffman & Smith, 1999; Smith et al., 1995).

Sequencing and timing via the lens of manual production

We now present findings that show why we view sequential learning as domain general. Children with DLD show weak gross and fine motor skills. The aim of this work was to determine if the motor deficit attested in DLD is a general weakness or is constrained to specific aspects of processing. Further, we asked whether the learning profile aligns across language and manual domains. To set the stage for this section, two findings are relevant. First, children with DLD as a group show generalized weaknesses on standardized tests of motor skill, including in

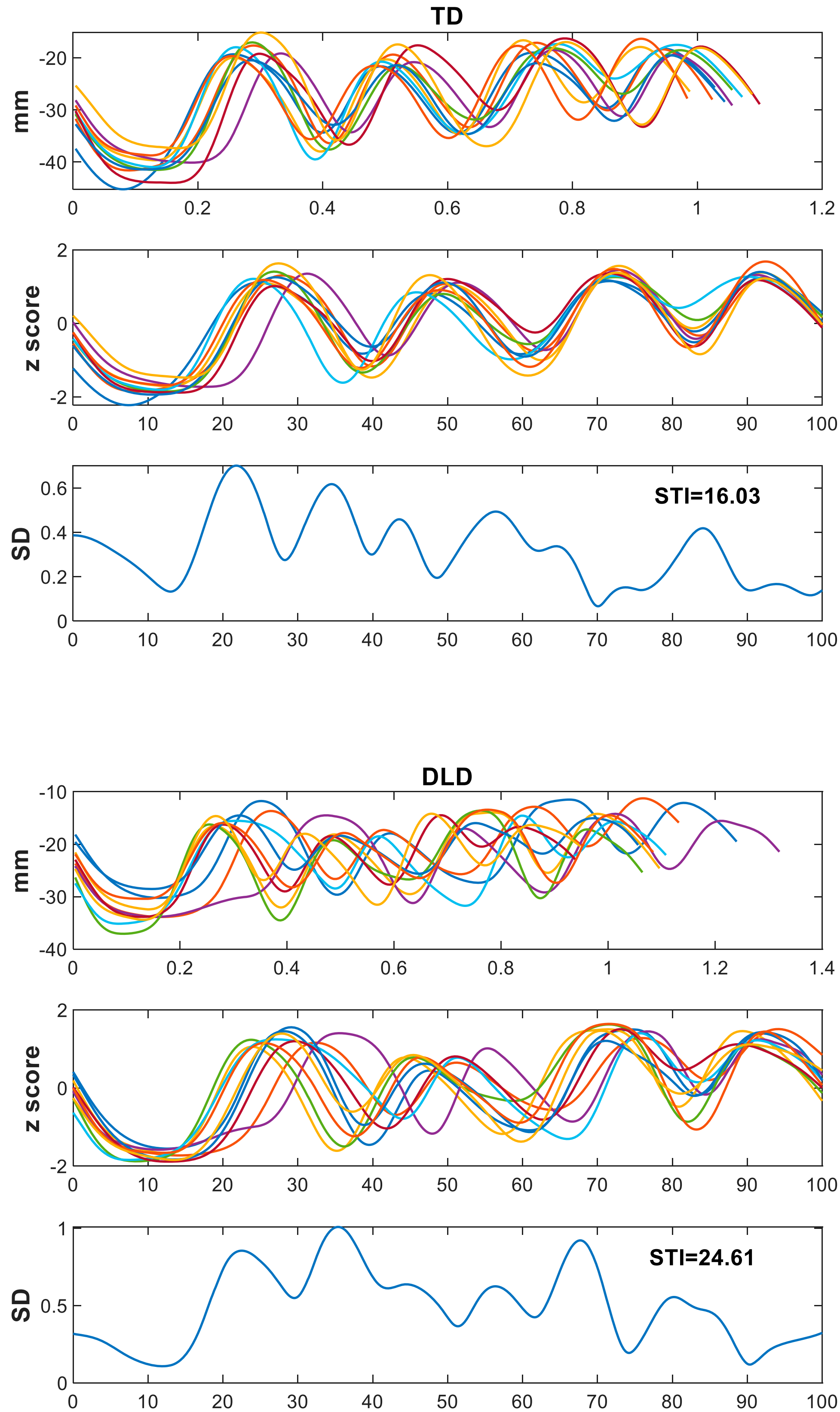

Figure 1. Methodological approach to assessing articulatory variability. 10 productions of the sentence "Buy bobby a puppy" from a child with typical development (TD) and a child with developmental language disorder (DLD). The top panels are non-normalized productions. The middle panels are time- and amplitude-normalized. The bottom panels illustrate the spatiotemporal index (STI). Details further explained in the text.

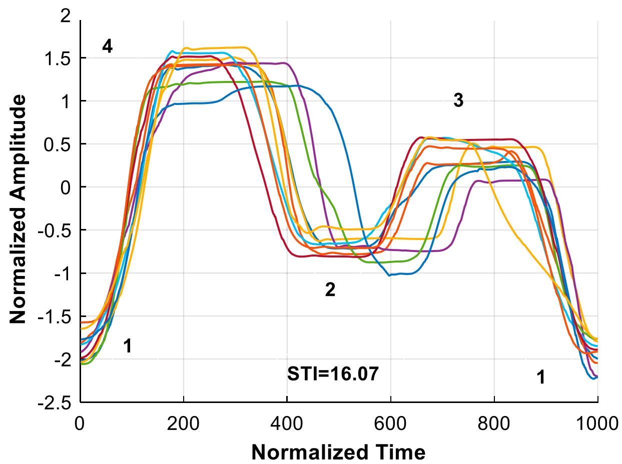

Figure 2. Methodological approach to assessing manual variability. 10 amplitude- and time-normalized productions of a patterned sequence of hand motion performing button presses in a serial reaction time task. The target buttons are 1-4-2-3-1.

Table 1 Summary of profile of manual motor and language abilities that do not show differences (i.e., are spared; left columns) and that do show differences (i.e., are affected; right columns) between children with developmental language disorder (DLD) and their typically developing (TD) peers.

Domain	No difference between DLD and TD	Difference between DLD and TD
Manual Motor	• Manual tap after each click of metronome (note that there is a dependency that is not represented sequentially) • Unimanual signs • Manual signs in which both hands move in the same way	• Tapping rhythmic sequences, or groupings (e.g., 3 beats, pause, 3 beats) in which taps depend on pauses and vice versa • Bimanual signs in which the motion of one hand depends on the other
Language	• Single syllables • Practiced and crystallized phrases that function as a unit	• Rhythmic grouping of syllables in which the physical properties of strong/stressed syllables depend on (contrast with) weak/unstressed syllables • Sentence production that is not practiced or includes the insertion of varying words

manual skill and balance (Brumbach & Goffman, 2014; Hill, 2001; Sanjeevan & Mainela-Arnold, 2017, 2019; Vuolo et al., 2017). Second, in a small sample size longitudinal study we found that it was performance in motor skill, not language or speech skill, that predicted language outcomes two years later (Sack et al., 2022). This was true for children with DLD, but not their TD peers. In the next sections, we present finer grained findings on the relationship between motor and language skill in DLD and in typical development. Note that we find systematic profiles of strengths and weaknesses that align across manual motor and language domains. These relationships are illustrated in Table 1.

Thus far, we have studied three central constructs that relate to manual production. These include timing, rhythmic grouping, and sequencing. In the timing studies, we assessed performance on a simple metronomic tapping task (Vuolo et al., 2017; Zelaznik & Goffman, 2010). Tapping to a metronome is the quintessential cerebellar timing task; individuals with a cerebellar lesion have difficulty with producing a stable timed sequence following entrainment to a metronome (Spencer et al., 2003). Because the cerebellum had been implicated in the PDH and timing deficits may be a contributor to rhythmic grouping deficits, we conducted two studies on timing, one including 4- and 5-year-old children with DLD and their TD peers (Vuolo et al., 2017) and a second with 7- to 8-year-old children (Zelaznik & Goffman, 2010). Children were asked to tap to a metronome, with an inter-beat interval of 600 msec. Following a series of 16 entrainment beats, they were asked to continue tapping for 32 more beats (this task was made child friendly by use of a trumpeting elephant puppet to signal the end of a trial). The variability of these continuation intervals was the focus of study. We found that children with DLD were similar to their TD peers in the variability of their timing performance in this metronomic task (see Table 1). This was an important result because it demonstrated that not all aspects of manual motor skill are implicated, and that timing deficits are not core to DLD. Note that no sequencing is required in this task, just one tap following another after entrainment to the metronome.

Rhythmic grouping. The ability to group rhythmic elements is core to language processing and production. Syllables are grouped into prosodic words which are grouped into phrases, etc., and typically developing toddlers appear to use canonical rhythmic groupings to organize their earlier multi-syllabic and multi-word productions (Gerken, 1994; 1996). As a test of prosody in the manual domain, we assessed the production of simple musical sequences in a drumming and a clapping task (Kreidler et al., 2023). In this experiment 57 4- and 5-year-old children (36 with DLD) were asked to, in imitation, clap and drum a simple musical sequence (drawn from Drake, 1993), consisting of three beats, a pause, and three more beats. Children with DLD showed more errors and more variable musical sequences than their peers with TD. In addition, they were especially likely to include errors in both the pre-pausal and post-pausal rhythmic groupings. This task goes beyond simple timing in that it incorporates grouping structure—three beats, pause, three beats. In terms of sequential dependencies, pauses are dependent on having produced three beats, and three beats are in turn dependent on just having produced a pause. Rhythmic sequence groupings inherently include dependency relations.

This result provides evidence that rhythmic grouping is affected in a manual task. As will also be observed in the language results, the production of single elements is not affected, but when these are arranged in a temporally organized sequence that incorporates dependency relations, children with DLD show difficulty. Manual grouping skill is correlated with performance in language, but not in fine motor or speech domains; thus, this deficit appears to pattern with language ability. Based on the evidence presented thus far, children with DLD show rhythmic grouping, but not timing, deficits. Table 1 summarizes these results.

Sequencing. In another line of experiments related to manual skill, we turned to the acquisition of form components of novel signs (Factor & Goffman, 2022; Goffman et al., 2023). In this work, we asked children with DLD and their TD peers to learn novel signs, some of which were nonwords and some associated with a visual referent. The central hypothesis in these studies was that the word form and articulatory implementation deficits that characterize spoken language learning in DLD would extend to the manual domain. A core feature of sign is path, or motion; thus, as in speech, the motor system is implicated. We studied a group of 55 4- and 5-year-old children (34 with DLD) and found that those with DLD show phonological deficits in their productions of novel signs, regardless of whether practiced as words or nonwords (Goffman et al., 2023). In this task, children were exposed to four novel signs, two of them iconic words and two presented as nonwords. Children imitatively produced each sign multiple times and phonetic accuracy and hand motion stability were measured. For example, in producing a bimanual novel and iconic sign associated with the referent "empanada maker", the child may use the incorrect handshape (e.g., open hand instead of closed hand) or path (e.g., one hand moving towards midline and one hand held still, rather than both moving simultaneously towards midline). Children with DLD produced significantly more errors than their age-matched peers on the sign language phonological features of handshape, path, and hand orientation. These manual phonological errors mirror those that occur in the language domain. That is, the word form errors that characterize children with DLD as they learn new spoken words also appear as they learn novel signs.

While the above analyses relied on perceptually based transcription, we also directly measured the spatiotemporal stability of the path movements associated with target signs using motion capture. The hand motion results were more complex than the accuracy results. First, hand motion variability did not correlate with standard measures of fine motor skill (Goffman et al., 2023); manual motor deficits do not account for differences in motion variability as children acquire and produce novel signs. Second, only those novel signs that obligated bimanual oppositional control showed higher levels of variability in children with DLD. Relatedly, in an earlier experiment (Vuolo et al., 2017) we found that, while timing was not affected in single hand tapping, when two hands were incorporated in a bimanual clapping task, children with DLD showed higher levels of timing variability than their TD peers. We conclude that word form learning deficits cross to the manual domain and, further, that hand motion deficits only occur when coordination and sequencing demands are high. As summarized in Table 1, the coordination of two hands, whereby movement of one hand occurs in relation to the other, may be viewed as a manual dependency; what one hand does is dependent on what the other hand does. Thus, this deficit appears related to the implementation of a sequential dependency, with only bimanual and coordinated hand movements affected.

Together, the manual results have demonstrated that children with DLD show a motor deficit, but one that is specific to only some aspects of processing. Deficits are observed when there are rhythmic grouping and complex sequencing demands. While we are continuing this line of work, for example via pattern learning manipulations of the serial reaction time task, thus far we conclude that the motor profile shows many shared features across language and action domains, with deficits in learning *rhythmic groupings and sequentially organized* and dependent manual actions.

Sequencing via the lens of language production.

A major premise of our work in language production is well expressed by Veit and colleagues (2021) in reference to their research on birdsong: "The flexible control of sequential behaviour is a fundamental aspect of speech, enabling endless reordering of a limited set of learned vocal elements (syllables or words)". This distinction between crystallized units, such as practiced syllables, words, and phrases, and ever reorganized units that are dependent sequences characterizes the aspects of speech motor skill that are spared compared with those that are affected in children with DLD (See Table 1 for a summary).

The initial hypothesis motivating our work in DLD was that the well documented gross and fine motor deficits would also affect speech motor skill. However, a more nuanced set of findings emerged. As in the manual domain (see Table 1), the profile of speech motor deficits in DLD is generally predictable and associated with those aspects of production aligned with the organization, grouping, and implementation of sequential dependencies. The ability to sequence patterns that incorporate dependencies is impaired in children with DLD; the speech motor deficit, like the manual motor deficit, is not general.

To assess speech motor skill, we incorporate parameters of articulatory movement, such as duration, amplitude, and velocity and, most frequently and usefully, motor variability and stability (Smith et al., 1995). As discussed in the methodological approaches section above, speech motor variability has proven an important index of learning, with shifts in articulatory variability providing evidence of developmental change, of disorder, and of within individual differences across specific tasks.

As initially hypothesized, a primary result is that children with DLD often show speech motor deficits along with their language impairment. When producing novel non-words (e.g., Goffman, 1999; Heisler et al., 2010) and sentences (e.g., Benham & Goffman, 2022; Brumbach & Goffman, 2014), children with DLD often (though not always) show higher articulatory variability than their age matched TD peers. The development of speech motor skill is protracted, with adult like stability not attained until adolescence (Smith & Zelaznik, 2004; Walsh & Smith, 2002). The simple interpretation of findings may be that children with DLD are immature and that this affects both their language and their articulatory motion. However, children with DLD are actually similar to their age matched peers in some speech motor tasks, such as in the production of familiar words (e.g., Goffman & Westover, 2013) and well-practiced, crystallized sentences (Saletta et al., 2018). We argue that only specific aspects of speech motor skill are implicated in DLD and, as in the manual domain, these occur when producing sequential patterns, often those that incorporate dependencies.

This section is organized as follows. In considering the speech motor developmental profile in children who are defined by their language impairment, we first report on those aspects of speech motor skill that are **not** affected in children with DLD. We then turn to tasks in which children with DLD show significant weaknesses in contrast to their TD peers. We close out this section with findings that focus on the organization of phonetic segments in novel nonword and word learning. Together, these results demonstrate that a deficit in specified aspects of grouping and organizing speech production units into temporally structured and dependent sequences is a crux of the deficit.

Aspects of speech motor skill that are unaffected in DLD. Many argue that the constituent units of speech production that are amenable to reorganization are syllables (though, in the context of novel word learning, sounds and features share similar sequencing properties). The primary aspects of speech motor skill that are unaffected in children with DLD are those that, following from the birdsong example, are learned and relatively crystallized vocal elements. The first type of element is the syllable. In studies of the production of weak and strong syllables in prosodically varying contexts, one analysis was of the spatiotemporal variability of the individual syllables (Goffman, 1999; Goffman et al., 2007). When single weak or strong syllables were extracted from a prosodic string, such as the syllables [f^f] and [fᵊf] in the sequences ['f^fᵊf] and [fᵊ'f^f], weak syllables showed more spatiotemporal variability than strong syllables. Further, children showed more variability than adults (Goffman, 1999). However, the age-matched TD and DLD cohorts showed no group differences. While spatiotemporal variability clearly is differentiated based on syllable weight, in the production of single syllables that presumably require no sequential organization, group differences in speech motor skill are not observed.

Children with DLD also do not show deficits in spatiotemporal organization when producing multi-movement articulatory series (sentences and nonword strings) that presumably do not obligate sequential reordering. When repeatedly producing the same sentence, *Mom pats the puppy*, over multiple sessions, children with DLD show articulatory variability that rapidly converges to levels that are similar to their TD peers (Saletta et al., 2018). In a nonword repetition task, in which strings of two to four syllables that contain no prosodic variation (i.e., all are trochaic) are repeated, segmental errors are copious, yet children with DLD show no spatiotemporal deficits (Benham et al., 2018; Vuolo & Goffman, 2020). As with the repeated sentence production task, group differences in spatiotemporal variability quickly disappear (Benham & Goffman, 2022; Richtsmeier & Goffman, 2015). These are examples of temporal sequences that become crystallized with practice and appear to no longer obligate sequential reordering or dependent relations. Notably, the crystallization process is accelerated in both children with DLD and their TD peers when a visual referent (or semantic cue) is added to a nonword form (Gladfelter & Goffman, 2018; Heisler et al., 2010). That is, pairing a novel word string to a visual referent strengthens speech motor learning and rapid crystallization of a word form. Children with DLD showed similar sensitivity to the inclusion of a semantic referent as their TD peers.

In summary, we found that, in practiced (or crystallized) chunks, including in two to four syllable nonword strings and in practiced sentences, deficits are not observed. It is in sequences of units that obligate reordering and reorganization that spatiotemporal organization breaks down. The locus of difficulty appears to be in the capacity to implement these flexible and dependent sequences, not in the speech motor system itself.

Aspects of speech motor skill that are impaired in DLD. The speech motor deficit in DLD emerges when units are organized into larger temporal sequences, or, relying on the birdsong constructs, when flexible control of sequential behaviour is required. Language is inherently sequential and many form based aspects of language are characterized by dependencies amongst units. The three examples we include here are: rhythmic grouping and prosody, relatively novel (as opposed to practiced and repeated) sentence production, and novel word production (see Table 1).

Rhythmic grouping and prosody. Prosodic levels of the phonological hierarchy are where elements are concatenated into sequences that vary systematically in prominence, or stress. Thus, prosody provides a prime example of units that are flexible and amenable to regrouping. Prosodic weight is the epitome of a dependency, since strong and weak syllables are defined in relation to one another. A weak syllable only exists in contrast to a strong one.

In a series of studies, we aimed to determine how prosodic categories were instantiated in the rhythmic organization of speech production. A predictable developmental trajectory of articulatory variability was observed, with adults showing the most stable movement patterns and children with DLD the least; young typical children were in the middle (Goffman, 1999; 2004; Goffman et al., 2007). Interestingly, iambic words were more stable than trochaic for all groups (Goffman, 1999). In all prosodic sequences, children with DLD show relatively high levels of spatiotemporal variability (Goffman, 1999; Goffman, 2004). When assessing temporal and spatial contributions to the control of motion, temporal deficits are robust (Goffman, 1999; Goffman, 2004; Goffman et al., 2006; Goffman et al., 2007). Most notably, weak syllables are longer in duration for children with DLD (Goffman, 1999; 2004; Goffman et al., 2006), and may be produced with greater amplitude (Goffman, 2004; Goffman et al., 2006). In sum, children with DLD show deficits in their organization of prosodic sequences.

Sentence production. The generation of sentences is a key sequential task. Sequential dependencies define morphosyntax. Thus, if our hypothesis is correct, children with DLD should show difficulties in the spatiotemporal organization of sentences. As we previously discussed, when repeating the same sentence, group differences disappear with practice. That is, in a sentence repetition task, in one session of practice, in which children repeatedly produce the same sentence, children with DLD show higher spatiotemporal variability than their TD peers (e.g., Benham et al., 2023; Saletta et al., 2018). However, by a second learning session, with consolidation, children with DLD show crystallization and converge to typical levels of variability.

As another approach to assessing how children with and without DLD produce sequences associated with a sentence, we vary the lexical items within a sentence frame; these tasks may be viewed as highly scaffolded syntactic priming (Brumbach & Goffman, 2014; Saletta et al., 2018; Vuolo & Goffman, 2018). Children hear a sentence and see an associated picture that incorporates the same syntactic frame (e.g., a simple SVO) structure, such as "Mouse washes the bird". Their task is to produce the same sentence frame, but with different lexical items inserted, such as "Mom pats the puppy" or "Monkey pushes the baby". When varying words are inserted, crystallization cannot occur, and all children show relatively high spatiotemporal variability. Children with DLD are especially sensitive to the active reorganization that is required in this task and show markedly higher spatiotemporal motion variability than their TD peers (Brumbach & Goffman, 2014; Saletta et al., 2018). This effect has been shown in two word phrases (e.g., *mommy pops*; Vuolo & Goffman, 2018), sentences containing prepositions and particles (e.g., *jump over the block*, *tip over the block*; Brumbach & Goffman, 2014), and a simple SVO sentence (e.g., *Mom pats the puppy*; Saletta et al., 2018). In all of these studies, children with DLD showed significant deficits in organizing a spatiotemporal sequence associated with a phrase or sentence. Practiced frames are not facilitative when new elements need to be inserted into phrases or sentences. Importantly, crystallization can occur both when sequences are short (e.g., a word or phrase) or relatively long (e.g., a sentence). Memory does not appear to be the primary factor driving crystallization.

As an added note, one of these studies (Vuolo & Goffman, 2018) also incorporated a group of children with speech sound disorders. These children, characterized by their speech, not their language, impairment did not show deficits in spatiotemporal organization. This provides additional evidence that the spatiotemporal deficit that emerges when sequential organization is obligated is aligned with language and not with speech variables.

Novel word production: Sequencing of segments and features. Thus far, the focus has been exclusively on how sequential organization is instantiated in movement. Transcription of children's errors has provided another source of evidence that the organization of sequential dependencies is implicated in DLD. Here again we focus on variability, but now based on transcription of children's production errors. All of these studies share that children are being asked to acquire novel word forms, sometimes linked to a referent and sometimes as nonwords. The relevant observation for the present purposes is that children with DLD show remarkably variable errors in their productions (e.g., Benham et al., 2018; Benham & Goffman, 2022). Systematic phonological or phonetic analyses do not capture their errors. We suggest that, in the early stages of acquiring a new word form, children cannot rely on the crystallization of elements that emerge with practice. Thus, the learning of the segments and features associated with new word forms provides another example of deficits in sequential pattern learning. Speech errors do not occur because children with DLD are unable to produce the target sounds; in fact, these sounds are in their phonetic inventory (e.g., Benham et al., 2018; Benham & Goffman, 2022; Goffman & Westover, 2013). What is striking, and indicative of a deficit in learning sequential dependencies, is that children with DLD show high levels of segmental and syllable co-occurrence variability as they learn novel word forms. For example, a child with DLD, when learning the novel word form [f^ʃpəm] in an imitated context produced the following: [p^ʃpəm], [p^ʔpəm], [kɛtʃpəm], [^ʃpəm], [flæʃpəm], [fl^ʃpəm], [ʃ^ʔpəm], [hɛʃpəm]. Children with TD also show some variability in their errors, with productions such as: [ʃ^pəm], [f^ʃəpəm], and [f^ʃpəm] for the target [f^ʃpəm]. Notably, TD children's errors are generally much closer to and systematically aligned with the target (Benham et al., 2018).

Similar to the crystallization that occurs when sentences are practiced, words also show sharp increases in stability following consolidation in a second session of practice (Benham et al., 2018; Benham & Goffman, 2022). Group differences persist, but learning trajectories are similar across groups. It appears that it is in this initial mapping phase that the deficit is most prominent. As with sentence production, as a novel phonological sequence becomes established as a word form, consolidation and crystallization occur quite rapidly.

To return to Table 1, in this section we have made the case that children with DLD show domain general deficits in the manual motor and language domains, and that these deficits link to sequences that obligate dependencies. Many aspects of motor skill that do not require such dependencies are spared.

Part 3. Possible mechanisms and existing questions

In this section, we elaborate on our current theoretical account, including new preliminary findings, and discuss what evidence is needed moving forward. The integration of work on typical and atypical development has resulted in a new research agenda. Parts 1 and 2 illustrated two points that we believe are related: Part 1 demonstrated that infants and children learn 2nd order dependencies or OR patterns more readily than adults. This observation is supported by the SOT data reviewed by Dell et al. (2021), in which college-aged adults, but not 9-year-olds or older adults, require sleep consolidation to show learning of 2nd order dependencies. It is also supported by the data showing that 11- and 20-month-olds readily learn OR patterns, while college-aged adults do not (Gerken & Knight, 2015; Gerken & Quam, 2017; Gerken et al., 2019; Gerken et al., 2021; Goffman & Gerken, 2020). Finally, the developmental change in OR learning is supported by a production study mentioned in Part 1 in which 4-year-olds with TD seem to learn the same OR pattern that college-aged adults fail to learn (Cullinan et al., 2022). Taken together, the data suggest that sometime between age 9 years and adulthood, 2nd order dependency and OR pattern learning become more difficult in both perception and production.

Part 2 presented a host of studies from Goffman and colleagues, demonstrating that children with DLD have a domain general difficulty with sequential dependencies. Children with DLD do not show deficits in producing non-sequenced single units (single taps, single syllables) or, importantly, in producing what we are calling crystallized forms, which can range from single familiar words to entire well-practiced sentences. This latter point involving stored or crystallized forms is at the heart of our current hypothesis regarding both the developmental differences in 2nd order dependency learning and the pattern of spared and affected abilities in children with DLD. We will return to it shortly.

We are now in a position to offer a possible theoretical framework that integrates the data on developmental changes in OR and FR pattern learning as well as the pattern of preserved and impaired abilities in DLD (Goffman & Gerken, 2020; Gerken et al., 2021). As already noted, we believe that the construct of crystalized vs. productive forms serves a key role in this framework. On our account, the word-form lexicon serves as a repository for crystalized word forms. Let us be clear at this point by what we mean by "crystallized". Crystallized forms may *not* be monolithic entities with no internal units. Rather, even though they may be composed of smaller units, sequential dependencies among these units are not represented. Thus, in the word-form lexicon, words might be composed of position specific features, segments, or biphones (or even syllables, with well-established syllables entered into a syllabary; Levelt & Wheeldon, 1994). Phonotactic patterns, such as the relative frequency of /t/ and the lack of /ŋ/ in syllable onsets emerge from word forms in the lexicon. That is, the lexicon serves to aggregate over the phonological information that is represented in individual words. Recall from Part 1 that aggregating over individual features allows for the detection of generalizations about single features (e.g., lots of English words start with /t/), but not dependency relations. On our view, college-aged adults attempt lexical access on the OR pattern rules, and since the dependency between C_1 and C_2 that makes up the OR pattern does not emerge from the pattern of activation in the lexicon, adults are not able to detect the pattern. Dell et al. (2021) make a similar claim about how ingrained lexical knowledge, and particularly knowledge about how to produce the syllables that compose the words of the lexicon, constrain adults from learning 2nd order dependencies within those syllables. Dell et al. (2021) suggest sleep consolidation allows adults to make use of new "contextual" relations in their 2nd order dependencies; different onsets and codas occur in the context of /æ/ vs. /ɪ/ used in their experiments.

Partly because we have not yet determined whether adults can learn our OR pattern after sleep, and partly because the dependency in our OR pattern is between the two consonants themselves, not between the consonants and a context-cuing vowel, our take on how the lexicon prevents OR pattern learning has been somewhat different than that of Dell and colleagues (2021). We suggest that frequency information about individual phonological features, phonemes, and perhaps biphones in particular syllable positions is implicit in the lexical network in activation patterns between words. This view appears to be consistent with the Dell et al. account, in which they describe a mini-grammar that contains newly learned phonotactic patterns that, through sleep consolidation, can be used to drive production. We understand the Dell et al. account to be saying that the particular biphones resulting from the two vowel contexts (e.g., fæ, æs, sɪ, ɪf) might gain sufficient strength through sleep consolidation to control production.

However, if activation over the lexicon simply offers up the frequency of features, segments, and biphones, the words used in our OR pattern do not allow a mini-grammar of the sort described by Dell et al. to emerge. That is because the features "cancel" each other over the set of familiarization words. More specifically, during familiarization, learners hear a large number of words with the following syllable position~feature relations: C_1 voiced, C_2 voiced, C_1 voiceless, C_2 voiceless. If they are simply tracking the independent frequency of occurrence of features in positions, there are an equal number of voiced and voiceless consonants in the C_1 and C_2 positions. To learn the OR pattern, they must somehow discover that the voicing of C_2 depends on the voicing of C_1. That sort of dependency information, we suggest, is not a type of information offered up by the phonotactics of the lexicon. If phonotactic patterns emerge from some sort of tally of features, segments, and biphones by syllable position, our OR pattern should not be learnable even after sleep, because such a tally alone does not reveal the dependency. Clearly the role of sleep in sequential dependency learning is one that needs a great deal more exploration.

Note that a simple tally of activated features, segments, and biphones by syllable position in the lexicon *would* allow adults to learn the FR pattern described in Part 1 if adults are attempting lexical access during familiarization. In the FR pattern described in Part 1, C_1 voiced, C_2 voiced, V_1 front are the most frequent features across the set of familiarization words. As noted in Part 1, learning the FR pattern is similar to learning a single feature pattern, except that a count must be kept over three syllable positions instead of just one. These features are independent of each other, meaning that there is no dependency relation among them. When the count of frequent features reaches two or more, the test word is consistent with the familiarization pattern.

To summarize thus far, we are suggesting that because college-aged adults have a well-established word-form lexicon, which they attempt to access when encountering words with new phonotactic patterns, they cannot readily learn new phonotactic patterns that involve segment or feature dependencies (the 2nd order dependencies discussed by Dell and colleagues and our OR pattern) that are not consistent with their existing lexicon. This account, we think, is similar to the one offered by Dell and colleagues. However, adults can learn patterns that involve a simple segment or feature tally (1st order dependencies and our FR pattern), perhaps because the relevant segments and features activate a neighboruhood of the lexicon (e.g., words starting with /f/).

Can the lexical framework just outlined account for the developmental effects in phonotactic pattern learning that have been observed? And importantly, what does the particular pattern of strengths and weaknesses attested in DLD children predict about how they might learn 2nd order dependencies like those studied by Dell and colleagues, and the OR and FR patterns that have been studied by Gerken and colleagues? We will attempt to address these questions now. With respect to the differences in OR and FR pattern learning between infants/toddlers and college-aged adults, we suggest that differences in the size of and dependency on the word-form lexicon are responsible. Infants and toddlers have considerably smaller lexicons than adults. Moreover, we suggest that, because they are still rapidly learning new words and have sparse lexical neighbourhoods, they might still listen to spoken language as a sequence of sounds, not just a sequence of words. Listening to our OR familiarization words as a sequence of sounds might allow the voicing dependency that exists between C_1 and C_2 to be detected. Further, young learners might focus on more local information than older learners, rather than on the larger statistical landscape. Evidence for this is that 11-month-olds are misled by local spurious generalizations, such as three contiguous nonwords starting with /p/ (Gerken & Quam, 2017).

With respect to FR patterns, we know that infants are able to detect single feature patterns (e.g., only certain consonants appear in onset position; Chambers et al., 2003; Saffran & Thiessen, 2003). On our view that FR patterns are simply a set of single feature patterns, all that is required to learn FR patterns is the ability to sum over the single features. Such an ability is likely to improve with age, which is consistent with our preliminary data: 11-month-olds show no hint of learning an FR pattern, but 20-month-olds may learn it. As noted in Part 1, we also have preliminary production data from TD 4-year-olds suggesting that they also learn the OR voicing pattern (Cullinan et al., 2022).

Turning to children with DLD, there is good evidence that these children have relatively normal lexical organization and, if anything, make greater use of phonotactic probabilities than their TD peers (Quémart & Maillart, 2016). Indeed, Ullman's PDH suggests that children with DLD compensate for their morpho-syntactic deficits by relying on lexical knowledge (Ullman & Pullman, 2015). If single feature and FR patterns require the same segment, biphone, and feature tallying mechanism that produces implicit phonotactic knowledge, then we predict that children with DLD should be able to learn single feature and FR patterns relatively well.

An interesting question arises when considering how children with DLD might perform on the 2nd order dependencies that are at the heart of the work of Dell et al. (2021) vs. our OR voicing pattern. As noted above, the 2nd order dependencies in which C_1 and C_2 are dependent on the vowel might be represented as biphones. If the implicit phonotactic knowledge of children with DLD included not only single segments and features but also biphones, then they might be able to learn such second order dependencies. If they are very reliant on their stored word-form lexicon and the phonotactic patterns therein, they, like college-aged adults, might require sleep for 2nd order dependency learning to be detected. In contrast, our OR voicing pattern cannot easily be represented as biphones, but rather involves a sequential dependency between the voicing values of C_1 and C_2. If children with DLD depend more heavily on their word-form lexicons than do their TD peers, and if children with DLD have particular difficulty detecting and employing sequential dependencies, we predict that they should *not* be able to learn the OR voicing pattern that appears to be learned by their TD pre-school peers.

We already know that children with DLD show difficulties in producing stable and accurate novel and phonologically complex (CVCCVC) word forms comprised of low frequency and low neighbourhood density syllables (Benham et al., 2018; Benham & Goffman, 2022). That is, children and adults with DLD have difficulty entering new material (words or manual sequences) into their lexicon or other memory store (Benham & Goffman, 2022; Goffman et al., 2023; McGregor et al., 2020). It may be that forms that have not yet been crystallized, for example via a high frequency syllabary, obligate sequential processing. We also have begun to test children with DLD on both the OR and FR patterns that have been used with infants and toddlers and are also incorporating the sorts of 2nd order dependencies discussed by Dell et al. (2021), because our current lexically-based account suggests differences in learnability of these dependencies vs. the OR pattern. Thus, our current research agenda emphasizes how children who are TD and DLD learn 2nd order and FR patterns in both spoken and manual domains.

The work included in this paper began as two independent lines of research asking two distinct questions. One line was focused on typical learners and identified developmental differences between infants and adults. The second line emphasized domain general deficits that affect language and action in children with DLD. We have melded these areas together into what is emerging as a coherent account of typical and atypical development that is focused on explaining what is and is not learnable during particular phases of development or in developmental disorders, here DLD. The domain general components of our account have a rich history, and were discussed by Lashley (1951), who stated "Temporal integration is not found exclusively in language; the coordination of leg movements in insects, the song of birds, the control of trotting and pacing in a gaited horse, the rat running the maze, the architect designing a house, and the carpenter sawing a board present a problem of sequences of action which cannot be explained in terms of successions of external stimuli". Further, the primary categories of learning we propose, crystallization and the flexible reordering of sequential elements, are consistent with work on bird song (Veit et al., 2021). Thus, the two primary types of learning that we suggest have a long and domain general history.

We propose two primary types of learning that are hallmarks of two stages of normal development. The first is the detection of sequential dependencies in the input. These sequential dependencies play an important role in phonology, morphology, and syntax and are readily learned by normally developing infants and children. Note that these are the domains that are hallmark deficits in DLD. The second type of learning emphasizes a restricted set of units that occur in crystallized stored forms, which are loosely aligned with words, but other forms (like frequent phrases) may also be learned in this way. Words stored in the lexicon give rise to phonotactic patterns, including some 2nd order dependencies that can be represented as biphones. Unlike the OR dependency, 2nd order dependencies that can be represented as biphones might still be learned in adulthood, but as discussed by Dell and colleagues (2021), require sleep consolidation. With respect to children with DLD, we propose that they have difficulty with sequential dependencies, which we believe explains at least some of their phonological and morpho-syntactic weaknesses. Moreover, although children with DLD have difficulty initially learning new word forms, once they have stable representations of these forms, their word-form lexicon appears to be structured like that of TD children. Therefore, we propose, consistent with the PDH, that children with DLD are highly dependent on stored word-forms in the lexicon, which might allow them to learn some 2nd order dependencies that can be represented as biphones or other phonotactic patterns. This idea is supported by the finding that adults with DLD are able to learn FR, but not OR, rules (Gerken et al., 2021). We are presently testing this idea in preschool and young school aged children with DLD, with the prediction that FR rules will be learnable, but those relying on sequential dependencies, such as the OR rule, will not be. We propose that, during childhood, people with DLD never focus on sequential dependencies and thus rely on other learning mechanisms, such as crystallized or stored forms.

In sum, the work on normal and disordered language development presented here provides a new framework for looking at potentially differentiable components of language and how these develop, as well as many new studies for testing the framework.

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References

Anderson, N. D., & Dell, G. S. (2018). The role of consolidation in learning context-dependent phonotactic patterns in speech and digital sequence production. *Proceedings of the National Academy of Sciences*, *115*(14), 3617–3622. https://doi.org/10.1073/pnas.1721107115

Bedore, L. M., & Leonard, L. B. (2001). Grammatical morphology deficits in Spanish-speaking children with specific language impairment. *Journal of Speech, Language, and Hearing Research*, *44*(4), 905–924. https://doi.org/10.1044/1092-4388(2001/072)

Benham, S., & Goffman, L. (2022). A longitudinal study of the phonological organisation of novel word forms in children with developmental language disorder. *International Journal of Speech-Language Pathology*, *24*(2), 212–223. https://doi.org/10.1080/17549507.2021.1975816

Benham, S., Goffman, L., & Schweickert, R. (2018). An application of network science to phonological sequence learning in children with developmental language disorder. *Journal of Speech, Language, and Hearing Research*, *61*(9), 2275–2291. https://doi.org/10.1044/2018_JSLHR-L-18-0036

Benham, S., Wisler, A., Berlin, J., Wang, J., & Goffman, L (2023). Acoustic and kinematic methods of indexing spatiotemporal stability in children with developmental language disorder. *Journal of Speech, Language, and Hearing Research*, *66*(8S), 3026–3037. https://doi.org/10.1044/2022_JSLHR-22-00290

Bishop, D. V. M., & Edmundson, A. (1987). Specific language impairment as a maturational lag: Evidence from longitudinal data on language and motor development. *Developmental Medicine & Child Neurology*, *29*(4), 442–459. https://doi.org/10.1111/j.1469-8749.1987.tb02504.x

Brumbach, A., & Goffman, L. (2014). Interaction of language processing and motor skill in children with specific language impairment. *Journal of Speech, Language, and Hearing Research*, *57*(1), 158–171. https://doi.org/10.1044/1092-4388(2013/12-0215)

Chambers, K. E., Onishi, K. H., & Fisher, C. L. (2003). Infants learn phonotactic regularities from brief auditory experience. *Cognition*, *87*(2), B69–B77. https://doi.org/10.1016/s0010-0277(02)00233-0

Cullinan, M., Gerken, L. A., Glickman, S., Benham, S., & Goffman, L. (2022). *The acquisition of a rule-based sound sequence in typically developing 4- to 6-year-old children*. Poster presented at The symposium on research in child language disorders. Madison, WI.

Dell, G. S., Kelley, A. C., Hwang, S., & Bian, Y. (2021). The adaptable speaker: A theory of implicit learning in language production. *Psychological Review*, *128*(3), 446–487. https://doi.org/10.1037/rev0000275.

Dell, G. S., Martin, N., & Schwartz, M. E. (2007). A case-series test of the interactive two-step model of lexical access: Predicting word repetition from picture naming⋆. *Journal of Memory and Language*, *56*(4), 490–520. https://doi.org/10.1016/j.jml.2006.05.007

Dollaghan, C., & Campbell, T. F. (1998). Nonword repetition and child language impairment. *Journal of Speech, Language, and Hearing Research*, *41*(5), 1136–1146. https://doi.org/10.1044/jslhr.4105.1136

Drake, C. (1993). Reproduction of musical rhythms by children, adult musicians, and adult nonmusicians. *Perception & Psychophysics*, *53*(1), 25–33. https://doi.org/10.3758/BF03211712

Evans, J. L., Saffran, J. R., & Robe-Torres, K. (2009). Statistical learning in children with specific language impairment. *Journal of Speech, Language, and Hearing Research: JSLHR*, *52*(2), 321–335. https://doi.org/10.1044/1092-4388(2009/07-0189)

Factor, L., & Goffman, L. (2022). Phonological characteristics of novel gesture production in children with developmental language disorder: Longitudinal findings. *Applied Psycholinguistics*, *43*(2), 333–362. https://doi.org/10.1017/S0142716421000540

Gerken, L. A. (1994). Young children′s representation of prosodic phonology: Evidence from English-speakers′ weak syllable productions. *Journal of Memory and Language*, *33*(1), 19–38. https://doi.org/10.1006/jmla.1994.1002

Gerken, L. A. (1996). Prosodic structure in young children's language production. *Language*, *72*(4), 683–712. https://doi.org/10.2307/416099

Gerken, L. A., Figueroa, M., & Goffman, L. (2022). 11-Month-Olds can learn A phonological pattern that adults cannot. Paper presented at the poster presented at The symposium on research in child language disorders, Madison, WI.

Gerken, L. A., & Knight, S. (2015). Infants generalize from just (the right) four words. *Cognition*, *143*, 187–192. https://doi.org/10.1016/j.cognition.2015.04.018

Gerken, L. A., Plante, E., & Goffman, L. (2021). Not all procedural learning tasks are difficult for adults with developmental language disorder. *Journal of Speech, Language, and Hearing Research*, *64*(3), 922–934. https://doi.org/10.1044/2020_JSLHR-20-00548

Gerken, L. A., & Quam, C. (2017). Infant learning is influenced by local spurious generalizations. *Developmental Science*, n/a-n/a. https://doi.org/10.1111/desc.12410

Gerken, L. A., Quam, C., & Goffman, L. (2019). Adults fail to learn a type of linguistic pattern that is readily learned by infants. *Language Learning and Development*, *15*(4), 279–294. https://doi.org/10.1080/15475441.2019.1617149

Gladfelter, A., & Goffman, L. (2018). Semantic richness and word learning in children with autism spectrum disorder. *Developmental Science*, *21*(2). https://doi.org/10.1111/desc.12543

Goffman, L. (1999). Prosodic influences on speech production in children With specific language impairment and speech deficits. *Journal of Speech, Language, and Hearing Research*, *42*(6), 1499–1517. https://doi.org/10.1044/jslhr.4206.1499

Goffman, L. (2004). Kinematic differentiation of prosodic categories in normal and disordered language development. *Journal of Speech, Language, and Hearing Research*, *47*(5), 1088–1102. https://doi.org/10.1044/1092-4388(2004/081)

Goffman, L., Factor, L., Barna, M., Cai, F., & Feld, I. (2023). Phonological and articulatory deficits in the production of novel signs in children with developmental language disorder. *Journal of Speech, Language, and Hearing Research*, *66*(3), 1051–1067. https://doi.org/10.1044/2022_JSLHR-22-00434

Goffman, L., & Gerken, L. A. (2020). An alternative to the procedural~declarative memory account of developmental language disorder. *Journal of Communication Disorders*, *83*), doi:https://doi.org/10.1016j.jcomdis.2019.105946

Goffman, L., Gerken, L. A., & Lucchesi, J. (2007). Relations between segmental and motor variability in prosodically complex non-word sequences. *Journal of Speech, Language, and Hearing Research*, *50*(2), 444–458. https://doi.org/10.1044/1092-4388(2007/031)

Goffman, L., Heisler, L., & Chakraborty, R. (2006). Mapping of prosodic structure onto words and phrases in children's and adults' speech production. *Language and Cognitive Processes*, *21*(1-3), 25–47. https://doi.org/10.1080/01690960400001820

Goffman, L., & Smith, A. (1999). Development and phonetic differentiation of speech movement patterns. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(3), 649–660. https://doi.org/10.1037/0096-1523.25.3.649

Goffman, L., & Westover, S. (2013). Interactivity in prosodic representations in children. *Journal of Child Language*, *40*(5), 1032–1056. https://doi.org/10.1017/S0305000912000505

Goldowsky, B. N., & Newport, E. (1993). Modeling the effects of processing limitations on the acquisition of morphology: the less is more hypothesis. In E. Clark (Ed.), *The proceedings of the 24th annual child language research forum* (pp. 124–139). CSLI.

Gopnik, M. (1997). Language deficits and genetic factors. *Trends in Cognitive Science*, *1*, 1–15. https://doi.org/10.1016/S1364-6613(97)01005-X

Heisler, L., Goffman, L., & Younger, B. (2010). Lexical and articulatory interactions in children's language production. *Developmental Science*, *13*(5), 722–730. https://doi.org/10.1111/j.1467-7687.2009.00930.x

Hill, E. L. (2001). Non-specific nature of specific language impairment: a review of the literature with regard to concomitant motor impairments. *International Journal of Language & Communication Disorders*, *36*(2), 149–171. https://doi.org/10.1080/13682820010019874

Hsu, J., & Bishop, D. V. M. (2014). Sequence-specific procedural learning deficits in children with specific language impairment. *Developmental Science*, *17*(3), 352–365. https://doi.org/10.1111/desc.12125

Hudson Kam, C. L., & Newport, E. L. (2005). Regularizing unpredictable variation: The roles of adult and child learners in language formation and change. *Language Learning and Development*, *1*(2), 151–195.

Kam, H., Newport, C. L., & L, E. (2009). Getting it right by getting it wrong: When learners change languages. *Cognitive Psychology*, *59*(1), 30–66. https://doi.org/10.1016/j.cogpsych.2009.01.001

Kemler Nelson, D., Jusczyk, P. W., Mandel, D. R., Myers, J., Turk, A. E., & Gerken, L. A. (1995). The headturn preference procedure for testing auditory perception. *Infant Behavior and Development*, *18*, 111–116.

Kreidler, K., Vuolo, J., & Goffman, L. (2023). Manual rhythmic grouping in children with developmental language disorder. epub ahead of print.

Lashley, K. S. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior; the Hixon Symposium* (pp. 112–146). Wiley.

Leonard, L. B. (2014a). *Children with specific language impairment*. MIT press.

Leonard, L. B. (2014b). Specific language impairment across languages. *Child Development Perspectives*, *8*(1), https://doi.org/10.1111/cdep.12053

Leonard, L. B., & Deevy, P. (2020). Retrieval practice and word learning in children with specific language impairment and their typically developing peers. *Journal of Speech, Language, and Hearing Research*, *63*(10), 3252–3262. https://doi.org/10.1044/2020_JSLHR-20-00006.

Levelt, W. J. M., & Wheeldon, L. (1994). Do speakers have access to a mental syllabary? *Cognition*, *50*(1-3), 239–269. https://doi.org/10.1016/0010-0277(94)90030-2

Lind, J., Vinken, V., Jonsson, M., Ghirlanda, S., & Enquist, M.. (2023). A test of memory for stimulus sequences in great apes. *PLoS ONE*, *18*(9), e0290546. https://doi.org/10.1371/journal.pone.0290546

Lum, J. A. G., Conti-Ramsden, G., Angela, T., Morgan, A. T., & Ullman, M. T. (2014). Procedural learning deficits in specific language impairment (SLI): A meta-analysis of serial reaction time task performance. *Cortex*, *51* (100), 1–10. https://doi.org/10.1016/j.cortex.2013.10.011

McGregor, K. K., Arbisi-Kelm, T., Eden, N., & Oleson, J. (2020). The word learning profile of adults with developmental language disorder. *Autism & Developmental Language Impairments*, *5*, 239694151989931–19. https://doi.org/10.1177/2396941519899311

Montgomery, J., Gillam, R., & Evans, J. (2021). A new memory perspective on the sentence comprehension deficits of school-age children with developmental language disorder: Implications for theory, assessment, and intervention. *Language, Speech, and Hearing Services in Schools*, *52*(2), 449–466. https://doi.org/10.1044/2021_LSHSS-20-00128

Moreton, E. (2008). Analytic bias and phonological typology. *Phonology*, *25*(1), 83–127. https://doi.org/10.1017/S0952675708001413.

Moreton, E. (2012). Inter- and intra-dimensional dependencies in implicit phonotactic learning. *Journal of Memory and Language*, *67*(1), 165–183. https://doi.org/10.1016/j.jml.2011.12.003

Moreton, E., & Pater, J. (2012). Structure and substance in artificial-phonology learning, part II: Substance. *Language and Linguistics Compass*, *6*(11), 702–718. https://doi.org/10.1002/lnc3.366

Moreton, E., Pater, J., & Pertsova, K. (2015). Phonological concept learning. *Cognitive Science*, *40*(1), 1–66.

Moreton, E., & Pertsova, K. (2014). Pastry phonotactics: Is phonological learning special? In H.-L. Huang, E. Poole, & A. Rysling (Eds.), *Proceedings of the 43rd annual meeting of the northeast linguistic society* (pp. 1–14). Graduate Linguistics Students' Association.

Onishi, K. H., Chambers, K. E., & Fisher, C. (2002). Learning phonotactic constraints from brief auditory experience. *Cognition*, *83*(1), B13–B23. https://doi.org/10.1016/S0010-0277(01)00165-2

Quémart, P., & Maillart, C. (2016). The sensitivity of children with SLI to phonotactic probabilities during lexical access. *Journal of Communication Disorders*, *61*, 48–59. https://doi.org/10.1016/j.jcomdis.2016.03.005

Rice, M., Wexler, K., & Cleave, P. (1995). Specific language impairment as a period of extended optional infinitive. *Journal of Speech, Language, and Hearing Research*, *38*(4), 850–863. https://doi.org/10.1044/jshr.3804.850

Rice, M. L., & Wexler, K. (1996). Toward tense as a clinical marker of specific language impairment in English-speaking children. *Journal of Speech, Language, and Hearing Research*, *39*(6), 1239–1257. https://doi.org/10.1044/jshr.3906.1239

Richtsmeier, P. T., & Goffman, L. (2015). Learning trajectories for speech motor performance in children with specific language impairment. *Journal of Communication Disorders*, *55*, 31–43. https://doi.org/10.1016/j.jcomdis.2015.02.001

Sack, L., Dollaghan, C., & Goffman, L. (2022). Contributions of early motor deficits in predicting language outcomes among preschoolers with developmental language disorder. *International Journal of Speech Language Pathology*, *24*(4), 362–374. https://doi.org/10.1080/17549507.2021.1998629

Saffran, J. R., & Thiessen, E. D. (2003). Pattern induction by infant language learners. *Developmental Psychology*, *39*(3), 484–494. https://doi.org/10.1037/0012-1649.39.3.484

Saletta, M., Goffman, L., Ward, C., & Oleson, J. (2018). Influence of language load on speech motor skill in children with specific language impairment. *Journal of Speech, Language, and Hearing Research*, *61*(3), 675–689. https://doi.org/10.1044/2017_JSLHR-L-17-0066

Sanjeevan, T., & Mainela-Arnold, E. (2017). Procedural motor learning in children with specific language impairment. *Journal of Speech, Language, and Hearing Research*, *60*(11), 3259–3269. https://doi.org/10.1044/2017_JSLHR-L-16-0457

Sanjeevan, T., & Mainela-Arnold, E. (2019). Characterizing the motor skills in children with specific language impairment. *Folia Phoniatrica et Logopaedica*, *71*(1), 42–55. https://doi.org/10.1159/000493262

Scoppa, M., Gerken, L. A., Glickman, S., Benham, S., & Goffman, L. (2022). *The acquisition of a rule-based sound sequence in typically developing 4- to 6-year-old children*. Paper presented at the Poster presented at The Symposium on Research in Child Language Disorders, Madison, WI.

Shepard, R. N., Hovland, C. I., & Jenkins, H. M. (1961). Learning and memorization of classifications. *Psychological Monographs: General and Applied*, *75*(13). https://doi.org/10.1037/h0093825

Smalle, E. H. M., Muylle, M., Szmalec, A., & Duyck, W. (2017). The different time course of phonotactic constraint learning in children and adults: Evidence from speech errors. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(11), 1821–1827. https://doi.org/10.1037/xlm0000405.

Smith, A., & Goffman, L. (1998). Stability and patterning of speech movement sequences in children and adults. *Journal of Speech, Language, and Hearing Research*, *41*(1), 18–30. https://doi.org/10.1044/jslhr.4101.18

Smith, A., Goffman, L., Zelaznik, H., Ying, G., & McGillem, C. (1995). Spatiotemporal stability and patterning of speech movement sequences. *Experimental Brain Research*, *104*(3), 493–501. https://doi.org/10.1007/BF00231983

Smith, A., Johnson, M., McGillem, C., & Goffman, L. (2000). On the assessment of stability and patterning of speech movements. *Journal of Speech, Language, and Hearing Research*, *43*(1), 277–286. https://doi.org/10.1044/jslhr.4301.277

Smith, A., & Zelaznik, H. N. (2004). Development of functional synergies for speech motor coordination in childhood and adolescence. *Developmental Psychobiology*, *45*(1), 22–33. https://doi.org/10.1002/dev.20009

Smith, J. D., Berg, M. E., Cook, R. G., Murphy, M. S., Crossley, M. J., Boomer, J., Spiering, B., Beran, M. J., Church, B. A., Ashby, F. G., & Grace, R. C. (2012). Implicit and explicit categorization: A tale of four species. *Neuroscience & Biobehavioral Reviews*, *36*(10), 2355–2369. https://doi.org/10.1016/j.neubiorev.2012.09.003

Spencer, R. M. C., Zelaznik, H. N., Diedrichsen, J., & Ivry, R. B. (2003). Disrupted timing of discontinuous but not continuous movements by cerebellar lesions. *Science*, *300*(5624), 1437–1439. https://doi.org/10.1126/science.1083661

Ullman, M. T., Earle, F. S., Walenski, M., & Janacsek, K. (2020). The neurocognition of developmental disorders of language. *Annual Review of Psychology*, *71*, 389–417. https://doi.org/10.1146/annurev-psych-122216-011555

Ullman, M. T., & Pierpont, E. I. (2005). Specific language impairment is not specific to language: The procedural deficit hypothesis. *Cortex*, *41*(3), 399–433. https://doi.org/10.1016/S0010-9452(08)70276-4

Ullman, M. T., & Pullman, M. Y. (2015). A compensatory role for declarative memory in neurodevelopmental disorders. *Neuroscience & Biobehavioral Reviews*, *51*, 205–222. https://doi.org/10.1016/j.neubiorev.2015.01.008

Veit, L., Tian, L. Y., Monroy Hernandez, C. J., & Brainard, M. S. (2021). Songbirds can learn flexible contextual control over syllable sequencing. *Elife*, *1*(10), e61610. https://doi.org/10.7554/eLife.61610.

Vuolo, J., & Goffman, L. (2018). Language skill mediates the relationship between language load and articulatory variability in children with language and speech sound disorders. *Journal of Speech, Language, and Hearing Research*, *61*(12), 3010–3022. https://doi.org/10.1044/2018_JSLHR-L-18-0055

Vuolo, J., & Goffman, L. (2020). Vowel accuracy and segmental variability differentiate children with developmental language disorder in nonword repetition. *Journal of Speech, Language, and Hearing Research*, *63*(12), 3945–3960. https://doi.org/10.1044/2020_JSLHR-20-00166

Vuolo, J., Goffman, L., & Zelaznik, H. N. (2017). Deficits in coordinative bimanual timing precision in children With specific language impairment. *Journal of Speech, Language, and Hearing Research*, *60*(2), 393–405. https://doi.org/10.1044/2016_JSLHR-L-15-0100

Walsh, B., & Smith, A. (2002). Articulatory movements in adolescents. *Journal of Speech, Language, and Hearing Research*, *45*(6), 1119–1133. https://doi.org/10.1044/1092-4388(2002/090)

Warker, J. A. (2013). Investigating the retention and time course of phonotactic constraint learning from production experience. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *39*, 96–109.

Warker, J. A., & Dell, G. S. (2006). Speech errors reflect newly learned phonotactic constraints. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(2), 387–398. https://doi.org/10.1037/0278-7393.32.2.387

Zelaznik, H. N., & Goffman, L. (2010). Generalized motor abilities and timing behavior in children With specific language impairment. *Journal of Speech, Language, and Hearing Research*, *53*(2), 383–393