Journal of Experimental Psychology: General

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Online First Publication, June 13, 2022. http://dx.doi.org/10.1037/xge0001245

AMERICAN PSYCHOLOGICAL ASSOCIATION

Journal of Experimental Psychology: General

ISSN: 0096-3445

https://doi.org/10.1037/xge0001245

The Emergence of Bifurcated Structure in Children's Language

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Human language is unique among animal communication systems, in part because of its dual patterning in which meaningless phonological units combine to form meaningful words (phonological structure) and words combine to form sentences (lexicosyntactic structure). Although dual patterning is well recognized, its emergence in language development has been scarcely investigated. Chief among questions still unanswered is the extent to which development of these separate structures is independent or interdependent, and what supports acquisition of each level of structure. We explored these questions by examining growth of lexicosyntactic and phonological structure in children with normal hearing (n = 49) and children with hearing loss who use cochlear implants (n = 56). Multiple measures of each kind of structure were collected at 2-year intervals (kindergarten through eighth grade), and used to construct latent scores for each type of structure. Growth curve analysis assessed (a) the relative independence of development for each level of structure; (b) interactions between these two levels of structure in real-time language processing; and (c) contributions to growth of each level of structure made by auditory input, socioeconomic status (as proxy for linguistic experience), and speech motor control. Findings suggested that phonological and lexicosyntactic structure develop largely independently. Auditory input, socioeconomic status, and speech motor control help shape these language structures, with the last two factors exerting stronger effects for children with cochlear implants. Only for children with cochlear implants were interdependencies in real-time processing observed, reflecting compensatory mechanisms likely present to help them handle the disproportionately large phonological deficit they exhibit.

Keywords: language evolution, language acquisition, phonological, syntactic, cochlear implants

Supplemental materials: https://doi.org/10.1037/xge0001245.supp

In 1960, an article appeared in *Scientific American* that by any definition may be considered seminal. The focus of this article was on design features of human language that the author (Hockett) viewed as making human communication distinct from the systems used by other animal species to communicate. Although 13 features were described, the one that has received the most attention in the intervening years is the feature labeled *Duality of Patterning*. According to this feature, human language attains its broad semantic scope through this unique bilevel combinatorial structure in which meaningless elements (largely phonemes) can be combined to create novel lexical items, and meaningful lexical units can be combined to generate sentences. This design feature, along with the 12 others, has primarily been the purview of evolutionary linguists who seek to understand how these unique features arose in communication among humans (e.g., de Boer et al., 2012; Ladd, 2012; Pinker & Bloom, 1990; Studdert-Kennedy, 1998; Wacewicz & Żywiczyński, 2015). Our interest in this structural feature was sparked by the pattern of results emerging from a longitudinal study we have been conducting with deaf children and age-matched peers with normal hearing (e.g., Nittrouer, 2010; Nittrouer & Caldwell-Tarr, 2016; Nittrouer et al., 2018). Deaf children who received cochlear implants very early in life, along with intensive spoken-language intervention, show evidence of acquiring vocabulary skills and syntactic knowledge close to that of their normal-hearing peers (i.e., within one standard deviation of the normal-hearing mean), but their sensitivity to phonological structure and their abilities to use that structure in further language processing are much more seriously impaired (i.e., close to two standard deviations below normal-hearing means). This unequal developmental pattern compelled us to question the extent to which lexicosyntactic and phonological structure are independently acquired. Related questions arose regarding the foundations of development of each level of structure and how children function in their everyday exchanges if they are disproportionately impaired with one level of structure. Combined, these are the questions that motivated the analyses reported here.

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This work was supported by Grants R01 DC006237 and R01 DC015992 from the National Institute on Deafness and Other Communication Disorders, the National Institutes of Health, to Susan Nittrouer. The authors thank staff, students, and families who participated in the collection of these data. We have no known conflicts of interest.

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Duality of Patterning in the Evolution of Language

Unlike the evolution of physical traits, the evolution of language cannot be studied through examination of artifacts because there are no ancient linguistic artifacts to be collected. Consequently, there exists widespread speculation regarding how human language came to be so different from the communication systems of other animals. Nonetheless, several principles appear consistently across the several models of language evolution that have been proposed and those principles contributed to the original conceptualization of the Duality of Patterning.

One commonality across models of language evolution is the idea that words came first, and only later did a well-defined level of phonological structure emerge (Falk, 2004; Sandler et al., 2011; Studdert-Kennedy, 1998). According to this idea, vocal calls among humans became standardized within communities, thereby acquiring the status of words (i.e., labels for objects or actions). As long as these communal lexicons were small, individual words could remain highly distinctive in acoustic structure. As lexicons increased in size, however, constituent words came to be more similar in sound. This factor, in turn, exerted pressure on those lexicons to refine the level of representation as a way of maintaining distinctiveness, resulting in standardization of word-internal phonological structures.

Another commonality across models of language evolution is the idea that the levels of structure apparent in human language evolved across many generations, with each successive generation building on the constructions they acquired from the last (Falk, 2004; Senghas et al., 2004). That is, each new generation of speakers of an emerging language needed to reconstruct for themselves the structures they inherited from the previous generation. Out of each iterative reconstruction emerged more sophisticated structures that then served as models for the subsequent generation.

Although it is patently true that origins cannot be examined for languages currently spoken across the globe to provide evidence to support the principles described above, there is another source of evidence to be gathered from natural languages; this evidence comes from signed languages. Many signed languages currently used in communities with high proportions of deaf people have evolved only recently, because many of these communities have only recently been formed. For example, Nicaraguan sign language is a newly evolved language that stemmed from a focused effort on assembling deaf children living in rural areas of the country for the purpose of creating a school. The first cohort of students brought with them to their new school their own “home signs.” These were manual gestures that each child had developed in coordination with family members to communicate. From the assembled individual sets of gestures gradually emerged a standardized set of gestures, used by the collective group of students. But a full-blown Nicaraguan Sign Language did not appear with that first cohort, or even the next couple cohorts. It took several generations of students for the language to achieve the levels of lexicosyntactic and phonological sophistication prototypical of more mature languages, spoken and signed (Senghas et al., 2004). Furthermore, analyses of signed utterances revealed that early generations of signers conflated phonological features that later generations of signers clearly distinguished and independently manipulated.

The emergence of yet another sign language supported the observation that phonological structure in languages emerges only through progressive refinement of lexical structure, rather than existing as a primitive. Sandler et al. (2011) described the development of a new Israeli Sign Language that emerged in a newly established community where a large number of residents share a gene causing deafness. These investigators specifically tracked the emergence of phonological structure and were able to show that it appeared relatively late in the evolution of the sign language. And again, it was found that the mature language required several generations to unfold with lexicosyntactic structure predating phonological.

These two proposals—that lexicosyntactic structure emerges prior to phonological structure and that each generation of language users must reconstruct the ambient language for themselves —helped to shape hypotheses for the analyses reported here. Specifically, evidence that a language can exist and its users function reasonably well with only lexicosyntactic structure suggested that the two levels of structure described in the Duality of Patterning may emerge independently, and if only one level were to develop fully—or close to fully—it would most likely be lexicosyntactic structure. Thus, the analyses described in this paper were explicitly designed to address three questions:

1. Do lexicosyntactic and phonological structure emerge independently in language development?

2. If lexicosyntactic structure is disproportionately better developed than phonological structure, how do language users handle functions typically requiring keen access to phonological structure?

3. What supports development of each level of structure?

Emergence of Structure

The question of what comes first, meaningless phonological elements or meaningful words, has been the stuff of considerable controversy for as long as language development has been studied. For some developmental psycholinguists, the phoneme-sized phonetic unit is a primitive, likely present at birth, but certainly emerging as an intact cognitive and perceptual structure over the first year of life (e.g., Eimas et al., 1971; Kuhl et al., 2006; Lasky et al., 1975; Streeter, 1976; Tsao et al., 2006; Werker, 1991; Werker & Tees, 1984; Zhao et al., 2021). According to this view, a universal, language-independent set of phonemes is modified as a consequence of language experience, with those segments that are not part of the infant’s first language disappearing from the repertoire while those that are part of that first language remain and are strengthened. This process purportedly unfolds over the second half of the first year of life, endowing the infant with the adult set of phonemic elements specific to one’s native language by 12 months of age, just about the time first words appear in production. Thus, the capacity to execute and coordinate articulatory gestures to instantiate phonological units in one’s own productions would emerge later, largely after the phonological units—especially phonemes—of the child’s language have been well established as cognitive structures. With word-internal units present as primitives, linguistic structures emerge through combinatorial advances only, with infants and children learning how these primitive elements can be combined through statistical learning to form words (e.g., Saffran, 2020). One challenge to this account from an evolutionary perspective is that it places all possible phonemic segments within the infant at birth, as a sort of corollary to Universal Grammar (Chomsky, 1965), and so at the birth of human language. It is difficult to see how this perspective leaves room for the emergence of novel phonological units.

An alternative account to the one described above is that meaningful words are the initial level of linguistic organization for the infant, and those words are void of internal, phonological structure (Ainsworth et al., 2016; Menn, 1978; Menn & Vihman, 2011; Menyuk et al., 1986; Metsala & Walley, 1998; Ventura et al., 2007; Vihman, 1996). For example, Walley (1993, p. 292) proposed that these early words consist of "individual salient characteristics or overall acoustic shape." According to this view, the infant's entry to language is through parsing sections of broad acoustic shapes that recur frequently in the ambient language from the ongoing speech stream, and attaching meaning to those parsed sections (Nittrouer, 2006); the child's entry to language is through the desire to find meaning in the sound of speech. This characterization of early words is supported by the work of Charles-Luce and Luce (1990) showing that the lexicons of young children are comprised of maximally distinct (in acoustic terms) entries. Children begin to learn how to combine these early words, even before they have discovered word-internal elements, thus developing knowledge of simple lexicosyntactic structure involving word order and (salient) bound morphemes. As the lexicon grows, the child also begins to recognize word-internal elements, so phonological representations begin to emerge as cognitive structures (Anthony et al., 2003). According to this view, however, this is a protracted learning process, with children becoming increasingly sensitive to those word-internal elements over the first decade or so of life (Liberman et al., 1974; Nittrouer, 2020; Walley et al., 1986). The lexicon is also continuing to grow, and children become increasingly capable of understanding and using complex syntactic structures, patterns that raise questions regarding whether growth of these linguistic structures occurs in parallel or scaffolded fashion.

Thus, two alternative accounts have been proposed regarding the relationship between development of lexicosyntactic and phonological structure. According to one account, phonological units exist before meaningful words are acquired. According to the other account, it is the very existence of meaningful words that propels the child to discover phonological structure. Of course, a third possibility is that these two systems develop in parallel, with a relatively large degree of independence. That possibility was examined in the analyses reported here.

A Possible Role of Speech Motor Control

The acquisition of precisely executed and timed articulatory actions is viewed by many developmental psychologists as contributory to the acquisition of refined phonological representations, rather than deriving from the preexistence of such representations (Best et al., 2016; Goodell & Studdert-Kennedy, 1991; Nittrouer et al., 2018; Studdert-Kennedy, 1987; Vihman, 1996, 2017). Infants' earliest productions follow what has been termed the "everything moves at once" principle (Kent, 1983). In these productions, the infant moves from a closed vocal tract to an open configuration, generating what can be described as an open syllable. Analyses of these early utterances reveal that the quality of the vowel is determined by the place of the initial (consonantal) constriction, such that bilabial constrictions are typically followed by low, mid vowels and alveolar constrictions (i.e., tongue tip to alveolar ridge) are followed by high, front vowels (MacNeilage & Davis, 1991). These patterns flow from the simple fact that when there is a constriction at the lips, the tongue body can rest undisturbed on the floor of the oral cavity, so that when the lip closure is released the tongue is in a low position. When the tongue tip is raised and fronted to form the consonant closure, as it does for an alveolar constriction, the tongue body is also raised and fronted, evoking a high-front vowel on release of closure. Gradually the child moves away from this rudimentary pattern of production and learns to control independently the constrictions made by different articulators. As this independent control emerges there ensues a period during which the child appears to attempt all component gestures of a word, but struggles to impose the temporal coordination required to generate the sequence of phonological elements comprising the word being attempted (Ferguson & Farwell, 1975; Goodell & Studdert-Kennedy, 1991). The gradual acquisition of precisely coordinated motor actions coincides with the emergence of refined phonological representations as cognitive structures, leading to suggestions that these coordinated articulatory structures help to define those representations (Best et al., 2016; Browman & Goldstein, 1986; Lindblöm, 2000; Studdert-Kennedy, 2002). Vihman (1996, 2017) refers to the link between what the child hears and what the child can produce as the "articulatory filter," and suggests that the young child's attention to inputs consisting of motor routines within the child's productive repertoire is a driving force in the development of phonological representations. That suggestion was examined in the current analyses by exploring the relationship between speech motor control and phonological sensitivity.

How Units at Each Level of Structure Differ

Characteristics regarding the physical representation of lexical and phonemic elements can further differentiate the lexicosyntactic and phonological levels of language structure. Words, especially if monosyllabic, are readily recognizable structures in visible displays of acoustic speech signals. In almost all languages, syllables consist of some consonantal constriction at the start and some vocalic nucleus thereafter. Depending on the language, the initial consonantal structure might be restricted to a single constriction or may be permitted to consist of a cluster with two or more constrictions at different places in the vocal tract, manners of production, or voicing features. Languages also differ with respect to whether consonantal constrictions are allowed at the ends of syllables. If final consonants are permitted, there may be restrictions on what kinds of constrictions are allowed; it may be that only continuants can serve as syllable-final consonants, for example. Regardless of those details, syllables are generally discernable as amplitude prominences with amplitude minima on either side. Multisyllabic words can be recognized as consisting of adjacent syllables, differing in amplitude, so in stress pattern across the word. A typical rate of speech is on the order of two or three words per second, depending on the numbers of syllables in each word. This rate leaves the individual units of analysis (words or syllables) readily perceptible as separate elements. When it comes to phonemes, however, it is not uncommon to talk at a rate of greater than 10 phonemes per second. The reader can easily demonstrate this by recording the time required to say a sentence such as *The quick, brown fox jumped over the lazy dog*, at a comfortably fast rate. Most talkers are able to maintain intelligibility of this sentence when it is produced in under 3 seconds; more than three words per second. There are 30 phonemes in the sentence, indicating that more than 10 phonemes are transmitted per second. Although temporal modulation experiments demonstrate that listeners can recognize the presence of modulation at this rate in a constant signal, say of band-limited noise, early experiments attempting to develop acoustic alphabets found that combining acoustically distinct patterns of such brief duration was unworkable. Sequences of these stable but distinct acoustic segments blurred into an indiscernible buzz at rates of anything greater than roughly seven or eight Hertz (Shankweiler & Fowler, 2015).

Thus, there is a clear and impenetrable limit on how brief separate acoustic segments can be and still be recognized as distinct entities when combined in sequence. Human speech production evades this limit by what might be termed parallel transmission. Articulatory gestures affiliated with adjacent phonemes are produced in a highly overlapping manner, but one that requires precision in relative timing, displacement, and velocity (i.e., phasing) of these gestures (Browman & Goldstein, 1986; Kelso et al., 1986). Of course, the price paid for this highly intertwined execution of gestures is that the resulting acoustic signal lacks discreteness at the phoneme level, and any acoustic structure associated with individual phonemes varies across contexts depending on the sequence of phonemes being produced. What this all means is that the units of relevance to lexicosyntactic structure may be viewed as being more salient in the physical signal of speech than are the units of phonological structure. This fact suggests that sophisticated auditory functions are more important for accessing phonological structure, rather than lexicosyntactic structure. That suggestion was examined in the current analyses.

The Current Study

The goal of the study reported in this article was to examine the emergence of lexicosyntactic and phonological structure in children's language processing. A central question was whether development at one level of structure significantly impacts emergence of structure at the other level. Specifically, do burgeoning lexicons impose pressure that encourages the child to discover word-internal phonological structure, as a way to represent and access items in the mental lexicon more efficiently? Or does the gradual refinement of phonological representations support growth of the lexicon, as well as syntactic complexity through expanded working memory capacity? These alternative possibilities were examined by testing a sample of children with normal hearing who were developing spoken language on a typical timetable. A variety of tasks were administered to assess both lexicosyntactic knowledge and phonological sensitivity as thoroughly as possible. These tasks were administered at each of five times, starting at the initiation of formal schooling and continuing to the start of high school (every other year, from kindergarten to the end of eighth grade). From these observed measures, two latent variables were derived at each test age: one each for lexicosyntactic and phonological abilities. The relative independence in development of these abilities was examined using growth curve analyses. Specifically, scores at earlier ages for each latent measure were entered into the growth curve models we constructed. We then measured the extent to which the same latent variable supported continued growth of that variable, and the extent to which the other latent variable supported growth of that latent variable, in a cross-lagged manner.

In addition to investigating independence in development of each level of structure, we examined the magnitude of effects imposed by demographic factors on the growth of each latent variable. The first factor of interest was simply the age at testing. This analysis allowed us to assess how rapidly growth occurred for each level of structure, lexicosyntactic and phonological. We also examined the effects of gender and socioeconomic status on growth of both lexicosyntactic and phonological latent scores. Socioeconomic status is associated with variation in the amount and type of language input a child hears in the early years (Hart & Risley, 1995; Huttenlocher et al., 2002; Hoff, 2003; Nittrouer & Burton, 2005; Rodríguez et al., 2009), so can serve as a sort of proxy for linguistic experience. Where children with hearing loss are concerned, there is also evidence that the quality of treatment received for that hearing loss is associated with socioeconomic status (Noblitt et al., 2018). Therefore, this seemed an important factor to consider in acquisition of lexicosyntactic and phonological structure.

The role of auditory functioning in the acquisition of these two latent variables was examined by administering the same tests of lexicosyntactic knowledge and phonological sensitivity as those administered to typically developing children to a sample of children born with severe-to-profound hearing loss who all received cochlear implants early in life. Cochlear implants can restore normal sensitivity to users, meaning these individuals are able to detect sound at the same intensity levels as listeners with normal hearing, but the quality of those signals is highly degraded. This degradation means that the acoustic structure that helps to define linguistic elements (mostly phonemes) is not readily available to users of cochlear implants. We hypothesize that this situation presents a more significant challenge to children in discovering the phonological structure comprising words than in developing serviceable lexical representations. That hypothesis is based on the proposal that words can be recognized with less refined acoustic structure, such as the kind of broad structure that facilitates infants' initial parsing of words from the ongoing acoustic speech signal. It is proposed that the recognition of phonological units, especially phonemes, depends on more detailed properties of the acoustic speech signal—the kind of structure that is degraded in the processing of a cochlear implant.

When it comes to children with cochlear implants, of course, any deficits in either lexicosyntactic knowledge or phonological sensitivity could also be attributable to periods of auditory deprivation early in life, before they received their cochlear implants. Effects of early auditory deprivation could be an *alternative* source of deficit, compared with signal degradation, or it could be an *additional* source of deficit. In either case, we examined the effect of early auditory deprivation by using age of receiving a cochlear implant as a predictor variable, as well as preimplant auditory thresholds.

Another goal of the current study was to examine the extent to which the development of motor control for speech production facilitates the acquisition of lexicosyntactic knowledge and phonological sensitivity. The hypotheses behind this assessment were (a) speech motor control should facilitate the acquisition of sensitivity to phonological structure more than it facilitates the acquisition of knowledge about lexicosyntactic structure, and (b) this facilitation should be greater for children with auditory deficits, because it could compensate for impoverished auditory signals. This goal was accomplished by measuring the quality of spoken language production (i.e., speech intelligibility) in these children with normal hearing or cochlear implants and using those scores as predictors in regression analyses for performance at later ages on tasks of lexicosyntactic knowledge and phonological sensitivity. It was predicted that early speech motor control would more strongly predict later language abilities for children with cochlear implants than for children with normal hearing, and that phonological sensitivity would be better predicted than lexicosyntactic knowledge.

Finally, we examined the independence of real-time lexical and phonological processing across childhood. This question is different from the one of scaffolding that was examined with the cross-lagged analysis described above. In this analysis of independence in real-time processing, we correlated lexicosyntactic and phonological latent scores at each test age, across test ages. Even if one type of language structure did not strongly promote the acquisition of the other type of structure across developmental ages, it could be that the two types of skills and knowledge interacted in real-time processing. This would happen, for example, because working memory abilities have been found to be related to comprehension of complex syntactic structures in children (Bar-Shalom et al., 1993; Byrne, 1981; Nittrouer & Burton, 2005; Smith et al., 1989). Sentences with complex syntax are often long, so it is necessary to be able to store the entire string in a memory buffer long enough to parse the syntactic structures. Interdependence in real-time processing might be greater for children with cochlear implants than for children with normal hearing, if children with cochlear implants need to use more holistic word structures to perform tasks typically performed with word-internal phonological structure; for example, they may need to store verbal material as whole words in working memory, if they are unable to recover discrete phonemic units accurately, in a rapid manner (Nittrouer et al., 2017).

In summary, the series of analyses reported in this article were designed to examine the relationship between the emergence of phonological and lexicosyntactic structure in children's language, as well as to investigate the contributions of auditory perceptual functions, linguistic experience, and oral motor control for speech to the emergence of both levels of linguistic structure. Four specific hypotheses could be made:

1. *The emergence of mature lexicosyntactic and phonological structure across childhood would show evidence of a fair degree of independence.* This hypothesis is based on evidence that in the evolution of languages lexicosyntactic structure can exist in the absence of phonological structure, as well as the contradictory accounts of the order of acquisition for individual children. Perhaps the two levels of structure actually develop in parallel.

2. *Auditory deficits will more severely impact the acquisition of phonological structure than of lexicosyntactic structure.* This hypothesis is based on the notion that holistic lexical forms can be acquired without access to details for the acoustic input, but that is not so for phonological structure.

3. *Linguistic experience and speech motor control both support language development, with linguistic experience supporting acquisition of both lexicosyntactic and phonological structure, but with speech motor control having a stronger impact on phonological structure.* This hypothesis arises from evidence that children who lack linguistic experience show deficits in acquisition of both levels of structure. Proprioceptive feedback from speech motor control should be most important for development of phonological sensitivity.

4. *Children with poor phonological sensitivity—which should be largely children with cochlear implants in this study—will need to rely on lexicosyntactic knowledge to a greater extent to perform language functions that are typically performed with phonological elements.* Although a less effective strategy evoking less efficient processing, this strategy is necessary when phonological sensitivity is lacking.

Method

Participants

Data are reported for 105 children: 49 children with normal hearing (22 male) and 56 children with moderate-to-profound hearing loss who used cochlear implants (28 male). These children were tested at regular, 2-year intervals between the summer after completing kindergarten to the summer after completing eighth grade. All children had participated since infancy in a longitudinal study designed to track the development, largely in spoken language, of children with hearing loss, compare it with that of children with normal hearing, and identify facilitative factors in that development (Nittrouer, 2010). Greater detail regarding demographics of these children and linguistic input to them can be found elsewhere (e.g., Nittrouer, 2010; Nittrouer & Caldwell-Tarr, 2016).

In general, these children came from 20 different states in the United States. This diversity in geographic location was deliberately implemented as a way of avoiding any idiosyncratic effects that might be associated with specific intervention programs for children with hearing loss. At the time that children and their families enrolled in the study, the children, their parents, and their intervention programs needed to meet certain criteria. All children were born between August 2002 and June 2004. This spread in birthdates meant that testing was distributed across two summers at each grade level. None of the children had any condition, other than hearing loss in the case of the children with CIs, that on its own could impose a risk to language acquisition. All children had parents with normal hearing and came from homes where only English was spoken to them.

Other information regarding these children was also gathered. The Leiter International Performance Scale – Revised (Roid & Miller, 2002) was administered as a test of nonverbal cognitive functioning in both second and eighth grade. Children were required to obtain a standard score of 70 or higher to be included in the study. At second grade, mean standard scores (and *SD*s) were 105 (14) and 100 (18) for children with normal hearing and cochlear implants, respectively. This difference was not significant, $t(103) = 1.83$, $p = .070$. At eighth grade, mean scores were 106 (13) and 101 (15) for children with normal hearing and cochlear implants, respectively. This difference was not significant, $t(103) = .21$, $p = .210$.

Socioeconomic status (SES) was assessed using an index that ranks occupational status and highest educational level attained for each parent on scales from 1 to 8, from lowest to highest (Nittrouer & Burton, 2005). It is based on the methods of Hollingshead (1957), but with occupations updated to reflect more modern jobs. These scores are multiplied together for each parent separately, and the highest value obtained is used as the SES metric for the family. Scores of 30 and higher indicate that at least one parent had a four-year university degree or more, and a job commensurate with that level of education. *M* SES was 35 (13) and 33 (11) for children with normal hearing and cochlear implants, respectively. This difference was not significant, $t(103) = .64$, $p = .524$.

Table 1 provides treatment information for the children with cochlear implants. No child had a comorbid condition that would put the child at risk for language delay for reasons other than a hearing loss, and no child had an etiology that would suggest a progressive loss. All children with cochlear implants were required to be in early intervention programs that met certain criteria. Before the age of 3 years, the children and their parents had to be receiving intervention at least once per week, but in fact the median number of intervention sessions per week was three. The base criterion of at least one intervention session remained in place after children turned 3 years of age, but in fact most of the children began attending half- or full-day preschool programs focused on providing intervention to children with hearing loss. All of the intervention these children received needed to be provided by someone with a Master's degree or higher in a specialty related to pediatric hearing loss; in general, that meant teacher of the deaf or speech-language pathologist. Finally, all parents had to have made the decision to have their child with hearing loss grow up with spoken language as their first mode of communication, a criterion that ensured that parents were actively promoting spoken language in the home.

Table 1
Mean and Median Scores and Standard Deviations (SDs) for Treatment Information for Children With Cochlear Implants (CIs)

Measure	*M*	*Mdn*	*SD*
Age at identification (months)	6.7	4.0	7.2
Age at hearing aids (months)	8.1	5.0	6.4
Age at first implant (months)	21.4	15.0	16.3
Preimplant better-ear PTA (dB HL)	101	102	17
Aided two-ear PTA at eighth grade (dB HL)	20	20	5

Note. Pure-tone average thresholds (PTAs) are given in dB hearing level and are for the three speech frequencies of 500, 1,000, and 2,000 Hz.

Not all children were able to be tested at every test age. The primary reason for reduced numbers at some ages was that the project was between grants. This happened twice: at kindergarten and at sixth grade. At kindergarten, the earliest born children were missed in testing, as funding was unavailable the summer just after they completed kindergarten. At sixth grade, the latest-born children were missed, as funding was unavailable the summer they completed sixth grade. Otherwise, there were a few instances in which individual children missed testing at one time point, usually owing to a family situation. All testing took place over the summer months (see Procedures below), so opportunities for testing were constrained. Reasons for children not being able to attend a test session included a parent being ill or having to care for an ill relative, a prolonged family trip out of the country, or the impending wedding of a family member. Thus, although not every child was tested at each test age the source of missing data was nothing that could bias the overall results. Table 2 shows numbers of children tested at each age, and median and range of ages of children at the time of each test.

Materials

Assessments at each test age consisted of five to nine measures each for lexicosyntactic and phonological abilities. The exact set of measures varied slightly across test ages, because not every measure was an equally sensitive metric of skill at each test age. Some measures would have most children scoring very poorly (near the 'floor') at young ages, whereas other measures would have most children scoring extremely well (near the 'ceiling') at older ages. Therefore, measures of each construct were adjusted across test ages to obtain maximum variability in performance. Broad categories of measures are described here, with more detailed descriptions offered in Supplemental Materials 1. Readers may contact the first author to obtain the exact recorded materials used in this study.

Five broad categories of lexicosyntactic abilities were examined at every age tested.

1. A measure of vocabulary was obtained. This measure is essential to assessing children's lexical knowledge.

2. A measure was obtained of children's abilities to comprehend the syntactic structures that they hear (i.e., auditory comprehension).

3. Generative syntax was assessed by collecting narrative samples at each test age, transcribing those samples, and submitting transcripts to Systematic Analysis of Language Transcripts (SALT; Miller & Iglesias, 2010, 2016). For four of the five test ages, four measures of generative syntax were obtained: mean length of utterance (MLU), number of conjunctions, number of pronouns, and number of different words. At fourth grade, however, the narrative samples were insufficient in length to provide robust and reliable indicators for the count measures. Therefore, only MLU was used in the construction of the latent lexicosyntactic measure at fourth grade.

Table 2
Number of Participants (N), Median Age (in Months), and Range of Ages for Each Group Separately at Each Test Age

	Normal Hearing			Cochlear Implant		
Age group	*N*	*Mdn*	Range	*N*	*Mdn*	Range
Kindergarten	19	78	72–85	27	79	72–94
Second	49	101	93–108	56	103	92–119
Fourth	47	125	114–132	55	128	116–145
Sixth	29	147	138–156	32	149	139–161
Eighth	45	173	162–179	50	176	164–189

4. Global language-production abilities were assessed at each age tested by using a rubric to analyze children's narrative samples. This rubric assessed children's abilities to produce connected and organized linguistic networks at a level higher than the sentence.

5. Reading comprehension for written material was assessed at each age tested to assess children's abilities to comprehend language material at a level above the sentence in reading; it was a measure of literacy.

Three broad categories of phonological abilities were examined at every age tested, with a fourth category examined at three of the five test ages.

1. Phonological awareness was assessed at every test age, using three instruments at each age. The ability to explicitly recognize and manipulate word-internal structure is a sensitive indicator of precision in phonological representations. However, sensitivity to word-internal structure develops gradually across childhood, up to puberty, so different instruments were administered at the younger test ages than at the older test ages.

2. Verbal working memory was assessed at every test age. One of the most important language skills that is dependent on having keen access to phonological structure is verbal working memory (Baddeley & Hitch, 2019). For this reason, this skill was assessed.

3. Word recognition in reading was assessed at every test age. The goal of reading is usually comprehension, which can often be strongly supported by the reader's familiarity with events being described in the text, along with syntactic constraints. There are times, however, when readers must rely more strongly on their sensitivity to phonological structure to recognize the words they are reading. This situation typically happens while reading words that are somewhat unfamiliar or reading text that is not highly contextualized; both these situations exist with academic reading material, or expository text.

4. Nonword repetition was examined at three of the five test ages, excluding kindergarten and fourth grade. Although words can be stored in the lexicon with holistic representations—especially words used in everyday communication—the learning of novel words is greatly facilitated by having ready access to word-internal structure—especially for less-common words, such as those that might be used in technical or academic communications. Nonword repetition simulates novel word learning, so it was examined in this study.

Confirmatory factor analysis demonstrated that each test administered loaded highly on the construct it was presumed to be measuring: lexicosyntactic or phonological skills. Table 3 displays factor loadings for each measure obtained at eighth grade for the children with normal hearing. Because this was the oldest age tested these scores represent loadings at the most mature level of language functioning we obtained, and because these loadings are for the children with normal hearing they represent typical functioning. These loadings reveal that three factors are actually obtained that each account for at least 10% of total variance explained across the set of measures. In this case, Factor 1 explains 28.5% of total variance, Factor 2 explains 24.5% of total variance, and Factor 3 explains 10.7% of total variance. The measures that we a priori described as phonological in nature all clearly loaded on Factor 1. The measures we a priori described as lexicosyntactic in nature loaded on either Factor 2 or Factor 3. These outcomes support the construction of latent phonological and lexicosyntactic variables using the measures described above for each. Combining measures that loaded on Factors 2 and 3 is reasonable on conceptual grounds and allows for the construction of two latent variables fitting the descriptions offered by the Duality of Patterning.

One measure of speech motor control was used to assess how strongly it predicted acquisition of lexicosyntactic and phonological structure. The measure came from the Children's Speech Intelligibility Measure (CSIM; Wilcox & Morris, 1999). In this task, the child imitated 50 words presented in audio-video modality on a computer monitor. These word imitations were recorded and later separated

Table 3
Loadings of Observed Measures on Three Factors in Principal Components Analysis

Measure	#1	#2	#3
Phonological sensitivity-processing			
Final consonant choice	**.765**	.110	.005
Backwards words	**.772**	.130	.184
Pig Latin	**.794**	.224	−.007
Word recognition in reading	**.636**	.240	.141
Nonword repetition	**.723**	.065	.225
Immediate serial recall	**.814**	.059	.068
Digit span forward	**.721**	−.267	.289
Generative syntax			
Mean length of utterance	.155	**.876**	.292
Conjunctions	.055	**.686**	−.132
Pronouns	.118	**.817**	.143
Number of different words	.140	**.732**	.232
Other lexicosyntactic skills			
Expressive vocabulary	.107	.128	**.781**
Sentence comprehension	.307	.089	**.701**
Ambiguous sentences	.404	.169	**.568**
Reading comprehension	−.015	.060	**.767**
Narrative rubric score	.044	.407	**.412**

Note. Bolded values are the highest factor loadings for each measure.

into individual waveform files. The 50 imitated words produced by each child were presented to two naïve adult listeners, who had to judge what the child said. Mean percent correct word judgements across the two listeners served as the dependent measure for speech motor control. Although this measure was obtained at each test age, except for eighth grade, we selected scores from second-grade testing for use in these analyses. This test age included scores from all children whose data are included in this study, before they had necessarily reached mature speech motor control.

Procedures

All procedures were approved by the Institutional Review Board of the University of Florida.

Because the children involved in this longitudinal study came from disparate geographic locations, they traveled with their parents to the laboratory for testing during the summer after the designated grade level; for example, second-grade testing occurred in the summer after the children completed second grade. This testing occurred over two-day sessions, with between four and six children present. Children were tested in carefully planned one-hour sessions (four on the first day and two on the second day), with 1-hour play breaks between each. All testing took place in sound booths or sound-attenuated rooms.

University students doing the testing were trained during the spring preceding summer testing by laboratory staff. To ensure that every student tester was highly skilled and procedures were consistent across testers, each student tester had to practice with ten children whose data were not included in the analyses reported here.

Procedures for all measures were designed to rely as little as possible on testers presenting stimuli or scoring at the time of testing. That meant that video recordings were made of all stimulus materials that would in a typical clinical setting involve a clinician presenting the materials to a child via live voice. These videos were then presented on a monitor at the time of testing. In this way we ensured that all children saw and heard exactly the same test material.

All test sessions were video recorded so children's responses could be reviewed or scored later. For some measures, responses were scored by the tester at the time of testing. For these responses, another staff member reviewed them later with the recordings of the test session available to ensure that scoring had been performed accurately. An example of this situation involved responses to the phonological awareness task where the experimenter simply had to mark whether the response was correct or not. More complex responses were only scored later. Examples of these responses included the narrative samples, which required transcribing. For these materials, two staff members did the scoring independently, and their responses were compared. In all cases good reliability was obtained between scorers.

Analyses

Latent scores were computed using the lexicosyntactic and phonological measures obtained at each test age. These latent lexicosyntactic and phonological scores were used in growth curve analyses to test the four hypotheses described in the Introduction. All data will be made available on request to the first author.

Model

We used hierarchical modeling to explore the growth of lexicosyntactic and phonological skills across time. Specifically, we assigned each individual at each test age a score for both the latent lexicosyntactic and phonological variables at that point in time. We assumed that all of the observed measures that are lexicosyntactic in nature are a function of the latent lexicosyntactic variable, and all observed phonological measures are a function of the latent phonological variable. Consequently, the latent scores can be derived from the combination of observed scores. This model is depicted in Figure 1 and described in equations (1) and (2) below, where O_{itj}^{lex} is the j^{th} observed lexicosyntactic measure for child i at time t, and O_{itj}^{phon} is the j^{th} observed phonological measure for child i at time t. Additionally, let L_{it}^{lex} be the latent lexicosyntactic score for child i at time t, with L_{it}^{phon} representing the corresponding latent phonological score.

$$O_{itj}^{lex} = \theta_{0j}^{lex} + \theta_{1j}^{lex} L_{it}^{lex} + \epsilon_{itj}^{lex} \tag{1}$$

$$O_{itj}^{phon} = \theta_{0j}^{phon} + \theta_{1j}^{phon} L_{it}^{phon} + \epsilon_{itj}^{phon} \tag{2}$$

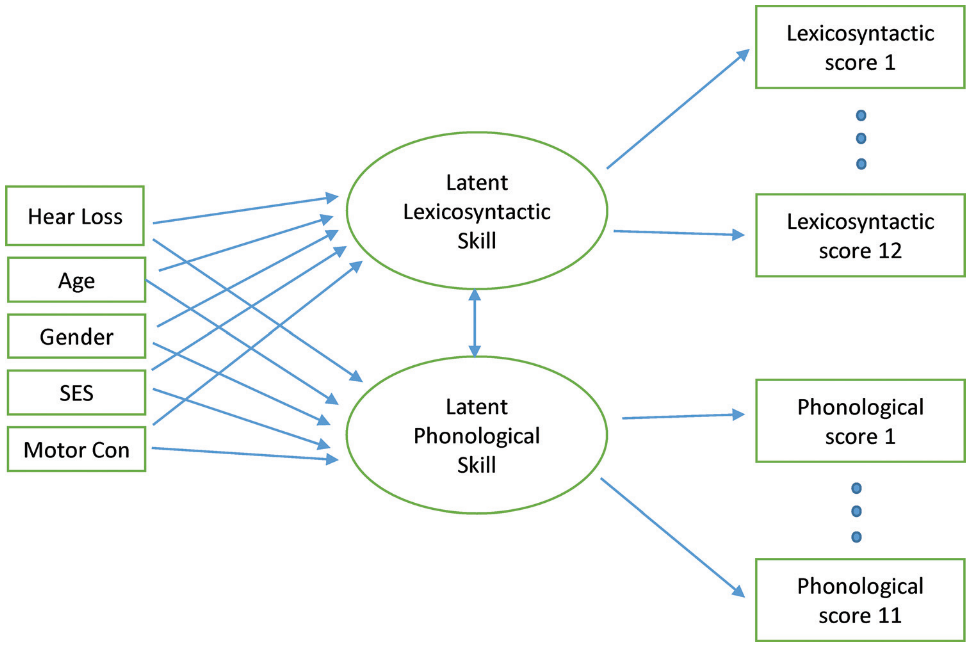
The error terms ϵ_{itj}^{phon} and ϵ_{itj}^{lex} are assumed to follow a normal distribution. This first stage of the model related the observed outcome measures to the latent scores, whereas the second stage of our hierarchical model related the latent scores to independent variables, largely demographic and audiological. Specifically, we allowed the latent scores for both lexicosyntactic and phonological skills to depend on hearing loss, SES, gender, test age, and the child's speech motor control, as measured with the CSIM. This is depicted in equations (3) and (4):

$$\begin{aligned} L_{it}^{lex} = {} & \alpha_0^{lex} + \alpha_1^{lex} HL_i + \alpha_2^{lex} SES_i + \alpha_3^{lex} Gender_i + \alpha_4^{lex} Test\,age_i \\ & + \alpha_5^{lex} CSIM_i + \alpha_6^{lex} HL_i * Test\,age_i + \alpha_7^{lex} HL_i * SES_i \\ & + \alpha_8^{lex} HL_i * CSIM_i + \gamma_{it} \end{aligned} \tag{3}$$

$$\begin{aligned} L_{it}^{\text{phon}} = {} & \alpha_0^{phon} + \alpha_1^{phon} HL_i + \alpha_2^{phon} SES_i + \alpha_3^{phon} Gender_i \\ & + \alpha_4^{phon} Test\,age_i + \alpha_5^{phon} CSIM_i + \alpha_6^{phon} HL_i * Test\,age_i \\ & + \alpha_7^{phon} HL_i * SES_i + \alpha_8^{phon} HL_i * CSIM_i + \delta_{it} \end{aligned} \tag{4}$$

We assumed that γ_{it} and δ_{it} jointly follow a multivariate normal distribution with correlation ρ. Of most interest to us in the analysis of both groups was how the trajectories varied over time for children with normal hearing and for children with cochlear implants, and how independent variables influenced those trajectories. We fit this model within the Bayesian paradigm using the Stan software (Stan Development Team, 2021), and all results were found using Markov chain Monte Carlo (MCMC) sampling. Additional information regarding the selection of prior

Figure 1
Model of Latent Variables Analysis



Note. The two latent variables analyzed in this report are shown in the middle of the figure. Independent variables presumed to influence these latent variables are shown to the left, and separate, observable measures deriving from these latent variables are on the right. See the online article for the color version of this figure.

distributions, details of MCMC sampling, and convergence criteria can be found in Supplemental Materials 2. We have also provided both the R and Stan scripts required to estimate the aforementioned model in Supplemental Materials 3. Because we are using Bayesian inference, all uncertainty assessments are provided by 95% Bayesian credible intervals instead of traditional confidence intervals used in frequentist analyses.

In this model, hearing loss was treated as a dichotic variable. Although the children with cochlear implants had different degrees of hearing loss prior to getting cochlear implants, their hearing levels were essentially rendered the same in severity by getting cochlear implants; none of these children had any residual hearing after implantation.

Test age was included as an independent variable, to investigate growth of proficiency with each level of language structure across childhood. Gender was included as an independent variable and treated as binary. SES was included, because it could index variability in quantity and quality of early linguistic experience, as well as in quality of treatment for hearing loss. Finally, speech motor control was included, because we hypothesized that sensorimotor feedback may facilitate the acquisition of phonological units, in particular, and especially for children with cochlear implants, all of whom have diminished auditory feedback.

In our analyses, we first analyzed the groups together, examining the effects of the independent, fixed variables depicted on the left of Figure 1 with the proposed latent growth curve model. Furthermore, we examined the interaction terms of hearing loss with test age, SES, and speech motor control to see whether these variables had different effects across these groups. Next, we performed similar analyses for each group separately to examine growth of these two levels of language structure when auditory input was typical and when it was impoverished. These analyses could help us identify the source of any interactions observed. For children with normal hearing, the model used replicated the one used in the analyses involving all children. For children with cochlear implants, two additional independent variables were added: age of receiving a first cochlear implant and preimplant auditory thresholds. Adding these variables allowed us to examine whether the development of lexicosyntactic or phonological skill was affected by either the duration of time with a cochlear implant or the amount of hearing available prior to receiving that cochlear implant. Details of these expanded models are available in Supplemental Materials 2.

Still another modification to the model was that we allowed the latent variables at a previous time point to affect latent scores at a current time point so that we could understand whether one latent measure tends to drive the other. This is effectively a latent cross-lagged analysis, and it could help identify if there is a scaffolding to the development of these two measures.

Finally, we examined the relationship between these two latent measures of lexicosyntactic and phonological structure at discrete time points. This analysis was done to see whether they interact in real-time processing. We hypothesized that there would be stronger interaction for children with cochlear implants, who were likely to show disproportionately large phonological deficits.

Results

Across-Groups Outcomes

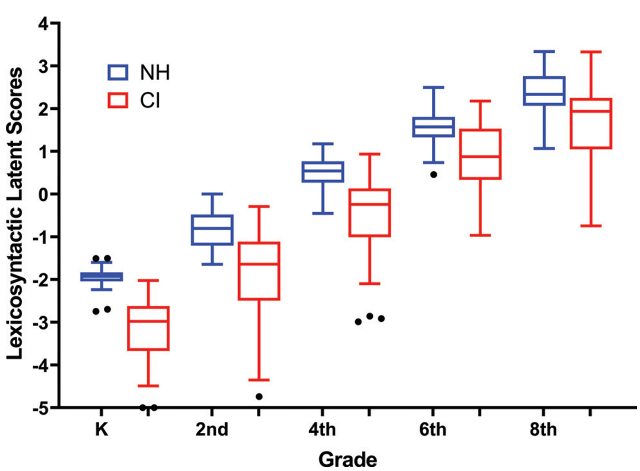
Using Tukey box and whisker plots, Figure 2 displays average latent lexicosyntactic scores and Figure 3 displays average latent phonological scores, for children with normal hearing and those with cochlear implants. Both groups show substantial growth on both sets of skills, but differences between groups are apparent at all test ages. Furthermore, these group differences appear larger for phonological scores than for lexicosyntactic scores. Analyses of the latent scores provided insights into the growth of these skills for both groups.

Table 4 displays α coefficients for each effect examined, along with 95% credible intervals. These are across-groups effects, except the effect of hearing loss is also displayed. It can be seen that hearing loss had an effect on both latent variables, but the effect was stronger for phonological scores than for lexicosyntactic scores. Thus, as Figures 2 and 3 illustrate, children with cochlear implants performed more poorly, relative to children with normal hearing, on phonologically based skills than on lexicosyntactic skills.

Test age had strong effects on both the latent lexicosyntactic and phonological scores, indicating that children performed better as they got older. This effect was larger for latent lexicosyntactic scores than phonological scores. Gender did not have an effect on either latent score, but SES had a positive effect of equivalent magnitude across the two latent scores. Speech motor control also had a positive effect, of relatively equal size, on the two scores.

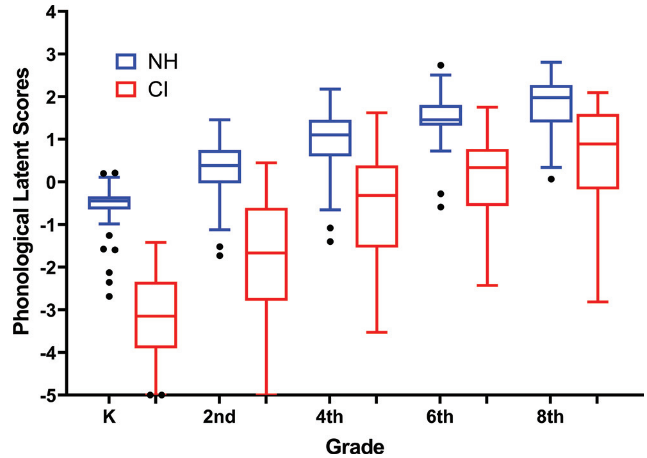
Two of the three interaction terms had credible intervals that did not contain zero for either latent measure: Hearing Loss × Test Age and Hearing Loss × SES. These results reveal that children with cochlear implants showed more rapid growth in these measures than children with normal hearing, and that SES had a stronger effect on outcomes for children with cochlear implants than for children with normal hearing. The Hearing Loss × Motor Control interaction was not significant for the lexicosyntactic latent measure but was strongly positive for phonological awareness, indicating that the effect of speech motor control on phonological awareness is more pronounced for children with cochlear implants.

Figure 2
Growth of Latent Lexicosyntactic Scores



Note. Mean scores for each group at each test age are shown using Tukey box and whisker plots. See the online article for the color version of this figure.

Figure 3
Growth of Latent Phonological Scores



Note. Mean scores for each group at each test age are shown using Tukey box and whisker plots. See the online article for the color version of this figure.

Children With Normal Hearing

We applied the latent growth curve model with cross-lagged components to children with normal hearing only. Coefficients illustrating how the independent variables relate to the latent measures from this analysis are shown in Table 5. These effects are slightly different when examined for this group alone, rather than across groups. Test age was again found to have a larger effect on lexicosyntactic scores than on phonological scores. SES retained its strong effect for lexicosyntactic scores but did not have a strong effect on phonological scores for this group. And for these children with normal hearing, speech motor control had no effect on either latent score.

Cross-Lagged Effects

In this analysis, the effects of each score from the earlier test age were allowed to affect scores at later ages. Table 6 shows these estimates of cross-lagged effects for children with normal hearing only. In each case, the first β coefficient (β1) is the estimate of the effect that each latent score had on the same score at later ages, across test ages. The second β coefficient (β2) is the estimate of the effect that the other latent score had on that score at later ages, across test ages. Thus, we see that each latent variable affected growth of the skill measured by that variable across time, but neither affected the growth of skill represented by the other variable. For these children, acquisition of lexicosyntactic and phonological skills was largely independent, rather than scaffolded.

Table 4

Across Both Groups, Coefficients and 95% Credible Intervals for the Effects of Independent Variables on Growth Curves for Latent Lexicosyntactic and Phonological Scores, and Interactions of Hearing Loss (HL) With Other Relevant Variables

	Lexicosyntactic		Phonological	
Variable	α	95% Interval	α	95% Interval
Hearing loss	−0.748	[−1.06, −0.419]	−1.222	[−1.551, −0.898]
Test age	1.653	[1.469, 1.852]	0.764	[0.661, 0.873]
Gender	0.082	[−0.03, 0.197]	0.023	[−0.089, 0.134]
Socioeconomic status (SES)	0.389	[0.268, 0.51]	0.301	[0.193, 0.415]
Motor control	0.446	[0.227, 0.662]	0.338	[0.123, 0.54]
HL × Age	0.109	[0.022, 0.193]	0.176	[0.088, 0.261]
HL × SES	0.201	[0.093, 0.312]	0.177	[0.071, 0.289]
HL × Motor Control	0.154	[−0.077, 0.375]	0.298	[0.076, 0.53]

Real-Time Processing Effects

Finally, we evaluated the correlation of the separate latent scores to see how strongly related skills represented by these scores were in real-time processing at discrete test ages. This correlation is represented in our model by ρ. For these children with normal hearing, ρ= .29 (−.001, .56), meaning that just less than ten percent of variance in either score was explained by the value of the other latent score. This finding suggests that processing for each level of language structure is relatively independent of processing for the other level of structure.

Children With Cochlear Implants

Similar analyses as those described above for children with normal hearing were performed on latent scores of children with cochlear implants only. Outcomes are shown in Table 7. Here, however, age of receiving a first cochlear implant and preimplant, better-ear pure-tone average thresholds were included as additional independent variables. Some differences can be seen for children with cochlear implants, compared to children with normal hearing. The effect of test age was not as strong for the latent lexicosyntactic scores for these children as for the children with normal hearing (α = 2.348 vs. 3.546), suggesting that growth of lexicosyntactic skills was slightly slower. On the other hand, growth of phonological skills for these children with cochlear implants was similar to that of children with normal hearing. For these children with cochlear implants, SES had an effect on both lexicosyntactic and phonological skills, as did speech motor control. On the other hand, neither the age of receiving a first cochlear implant nor pre-implant, better-ear auditory thresholds had effects on these scores.

Cross-Lagged Effects

Table 8 displays the estimates of earlier latent scores on each latent score. Here we see similar effects as those found for children with normal hearing. The effect of previous lexicosyntactic scores on future lexicosyntactic scores was extremely strong, with similar effects seen for phonological latent scores. However, neither phonological nor lexicosyntactic scores affected future values of the other score. Thus, the development of each level of language structure for these children with cochlear implants was largely independent of development on the other level of structure.

Real-Time Processing Effects

Finally, we examined the correlation of the separate latent scores to see how strongly related these scores were at discrete test ages. For these children with cochlear implants, ρ = .71 (.54, .85). Thus, roughly 50% of variance in either score was accounted for by the other latent score, considerably more than was found for the children with normal hearing.

Discussion

The purpose of the analyses reported here was to examine growth across much of childhood for the two levels of language structure described by the Duality of Patterning (Hockett, 1960), one termed lexicosyntactic and the other phonological. This design feature is a hallmark of human language, and as such has continued to spark speculation and investigation into its purpose and

Table 5

For Children With Normal Hearing Only, Coefficients and 95% Credible Intervals for the Effects of Independent Variables on Growth Curves for Latent Lexicosyntactic and Phonological Scores

	Lexicosyntactic		Phonological	
Variable	α	95% Interval	α	95% Interval
Test age	3.546	[2.534, 5.048]	1.147	[0.915, 1.399]
Gender	0.174	[−0.235, 0.623]	0.045	[−0.314, 0.387]
Socioeconomic status	0.602	[0.171, 1.071]	0.333	[−0.024, 0.712]
Motor control	0.05	[−0.344, 0.423]	−0.017	[−0.345, 0.311]

Table 6

For Children With Normal Hearing, Estimates of Cross-Lagged Effects

	Lexicosyntactic		Phonological	
Variable	β	95% Interval	β	95% Interval
Same factor (β_1)	0.86	[0.53, 1.13]	0.87	[0.69, 1.03]
Other factor (β_2)	0.11	[−0.01, 0.25]	−0.08	[−0.40, 0.23]

Table 7
For Children With Cochlear Implants (CIs) Only, Coefficients and 95% Credible Intervals for the Effects of Independent Variables on Growth Curves for Latent Lexical and Phonological Scores

	Lexicosyntactic		Phonological	
Variable	α	95% Interval	α	95% Interval
Test AGE	2.348	[1.971, 2.787]	1.242	[1.004, 1.506]
Gender	0.22	[−0.129, 0.566]	0.108	[−0.191, 0.404]
Socioeconomic status	0.617	[0.268, 0.959]	0.408	[0.116, 0.714]
Motor control	1.251	[0.85, 1.668]	1.136	[0.796, 1.514]
Age of first CI	0.003	[−0.46, 0.461]	0.043	[−0.345, 0.463]
Preimplant threshold	−0.141	[−0.591, 0.273]	−0.284	[−0.659, 0.084]

origins, long past its original description (e.g., Berent et al., 2017; de Boer et al., 2012; Nowak & Komarova, 2001; Roberts & Galantucci, 2012). In this study, we examined the relative independence of development for these two levels of language structure, as well as factors that support development of each level of structure. In particular, the inclusion of children who use cochlear implants allowed us to examine the extent to which auditory inputs with high resolution are required for acquisition of each level of language structure. Similarly, we included a measure of speech motor control, to examine the contributions of that motor control for speech production to the emergence of each level of structure. SES was included, as a way to investigate the role of early linguistic experience.

Independence of Development

The major finding of these analyses was that lexicosyntactic and phonological structure emerge over the course of childhood in a relatively independent manner, thus supporting the first hypothesis proposed in the Introduction. We began tracking this development as these children were leaving the preschool years and entering formal educational environments. The lexical restructuring model suggests that it is around this age that we would expect sensitivity to and the ability to manipulate word-internal phonological structure to begin emerging in earnest; for that reason, we had not assessed it prior to kindergarten for the children in this longitudinal study. From kindergarten through eighth grade, growth was observed for both levels of structure. These children were 14 years of age—or very close to it—when they were tested at eighth grade. Although estimates vary slightly, this age is typically considered the end of what is termed the sensitive or critical period for first language acquisition (Flege et al., 1995; Hartshorne et al., 2018; Lenneberg, 1967; Werker & Tees, 2005).

The Role of High-Quality Auditory Inputs

The underlying factors that contribute to the acquisition of lexicosyntactic and phonological structure were evaluated by the analysis reported here. First, we assessed the contribution made by having a high-quality acoustic signal available. This assessment was achievable by the inclusion of children with cochlear implants who had generally had those implants for most of their lives. Cochlear implants can restore auditory sensitivity to the normal range, as we saw for these children, who all had good aided thresholds. Nonetheless, the signals available through cochlear implants are highly degraded, and those degraded signals were found to take a greater toll on the acquisition of sensitivity to phonological structure than to lexicosyntactic structure. Thus, the second hypothesis proposed in the Introduction was supported: the quality of the auditory input is more important for acquisition of phonological structure than lexicosyntactic.

Human language is unique among animal communication systems, but our auditory processing abilities are not. All mammalian auditory systems function similarly, with the range of audible frequencies varying across species. Hallmarks of this processing include the ability to recognize fine-grained structure (i.e., resolution) in both the spectral and the temporal domain, as well as the ability to integrate across broad spectral and temporal signal sections to recognize patterns. These processing abilities clearly subserved the evolution of language and are essential to its acquisition—especially where phonological structure is concerned. Lexicosyntactic structure can apparently be acquired with less-refined auditory inputs.

Linguistic Experience and Speech Motor Control

Another factor examined by us for a potential effect on development of lexicosyntactic or phonological structure was SES. This factor was examined as a sort of proxy for the quantity and quality of linguistic experience the child likely had. Earlier studies have consistently reported that better language skills are associated with higher SES, and that is what we found, with one exception: We did not find an effect of SES on latent phonological scores for the children with normal hearing, although an effect was observed for latent lexicosyntactic scores. For children with cochlear implants, effects of SES were found for the development of both lexicosyntactic and phonological structure. Thus, these findings largely supported the third hypothesis described in the Introduction.

Another factor that might contribute to acquisition of lexicosyntactic and phonological structure examined by us was speech motor control. The phoneme—a primary phonological structure—has been described as a perceptuomotor unit (Studdert-Kennedy, 1987), meaning that phonemes are defined by both acoustic properties and properties derived from proprioceptive input arising from speech production. Accordingly, learning to produce speech skillfully should facilitate language acquisition, especially for phonological structure. And because refined phonological representations are supported by both auditory and proprioceptive input, it is reasonable to suggest that children for whom auditory input is restricted may rely to a greater extent on proprioceptive feedback. In

Table 8
Estimates of Cross-Lagged Effects for Children With Cochlear Implants

	Lexicosyntactic		Phonological	
Variable	β	95% interval	β	95% interval
Same factor (β_1)	0.84	[0.62, 1.05]	0.87	[0.62, 1.1]
Other factor (β_2)	0.13	[−0.04, 0.31]	−0.04	[−0.34, 0.24]

these analyses, that is precisely what was found, further supporting the third hypothesis. In fact, for children with normal hearing, speech motor control was not found to have any effect on the acquisition of either lexicosyntactic or phonological structure. For children with cochlear implants, however, the ability to produce speech so as to be intelligible was found to have a stronger effect on the acquisition of both lexicosyntactic and phonological structure than any other factor, except age. This is a critical insight into language acquisition for children with diminished auditory input. In fact, speech motor control had a stronger effect than either factor associated with the treatment for hearing loss: age of receiving a first cochlear implant and auditory thresholds prior to implantation.

Real-Time Processing

Although the acquisition of lexicosyntactic and phonological structure was found to be independent of each other, there was nonetheless some interaction when it came to real-time language processing. For children with normal hearing, it was found that roughly 10% of the variance in real-time language processing was shared across the two levels of structure, and there are reasonable explanations for this observed interaction. For example, although prowess recognizing and using phonological structure is most facilitative for tasks such as novel word learning or reading of unfamiliar words, the ability to recover phonological structure and use it to rapidly code verbal material into a short-term memory (STM) buffer is facilitative of syntactic learning, as well as online processing of complex syntactic structure. Thus, some interaction during real-time processing would be expected between these two levels of language structure.

But children with cochlear implants were found to display stronger interactions during real-time language processing, as the fourth hypothesis proposed. Roughly half of the variance in language processing abilities was shared between lexicosyntactic and phonological structure. We suggest that the reason for this greater interaction rests with the disproportionately large phonological deficits exhibited by children with cochlear implants. Those language processes that typical language users perform largely by extracting and using phonological structure pose challenges for children with cochlear implants, owing to their phonological deficits. As a result, these children are forced to perform the same operations using larger linguistic units, such as whole words, which might be seen as a "brute force" approach. Although doable, this approach requires that greater cognitive resources be expended to perform the task and performing those tasks takes longer to accomplish (Nittrouer et al., 2017).

Summary

Language is truly a triumph of human evolution. With language we are able to talk about events that happened in the past, make plans for the future, and contemplate abstract ideas. Although there are many features of human language that distinguish it from other systems of animal communication, its bifurcated structure consisting of meaningful units at one level and meaningless units at another level is surely one of its most important features, a feature that supports the nearly infinite generativity that language allows. But despite widespread recognition of this Duality of Patterning across the community of scientists studying language, little attention has heretofore been directed to investigating how it emerges in the individual child. In this study, we traced the emergence of that bifurcated structure across childhood, exploring the relative independence of each level of structure, the factors that support development of each level of structure, and how these two levels of linguistic structure interact during real-time processing. Results provided support for four hypotheses:

1. Lexicosyntactic and phonological structure emerge across childhood in a fairly independent manner.
2. Auditory deficits more severely impact the acquisition of phonological structure than lexicosyntactic structure.
3. Linguistic experience and speech motor control both support development of both levels of structure, especially under conditions of auditory impairment.
4. Children with poor phonological sensitivity—which were the children with cochlear implants in this study—rely on lexicosyntactic knowledge to a greater extent than peers with typical language to perform language functions typically performed with phonological elements.

Context

In 2003 we initiated the longitudinal study with the children whose data form this report. At that time, those children were infants. We followed them through preschool, with the primary objective of describing language acquisition for a new generation of deaf children, those who received the novel treatment of cochlear implants. As our optimistic colleagues had all expected, the children with cochlear implants in our study—who all had been recipients of state-of-the-art behavioral interventions, as well—were demonstrating language skills remarkably similar to those of their same-age peers with normal hearing. Thus, it would seem that the field had solved the problem of childhood deafness: A child born with severe-to-profound sensorineural hearing loss could be expected to progress through childhood unscathed by that hearing loss, if a cochlear implant were provided. But then these children reached school age, and we began to explore their language skills in more depth. In particular, we began to administer tests of phonological awareness and memory, and suddenly we were uncovering chinks in their linguistic armor. We observed a strong divide between their skills with lexicosyntactic and phonological structure; that sparked our interest in the traditional notion of Duality of Patterning in language.

References

Ainsworth, S., Welbourne, S., & Hesketh, A. (2016). Lexical restructuring in preliterate children: Evidence from novel measures of phonological representation. *Applied Psycholinguistics*, *37*(4), 997–1023. https://doi.org/10.1017/S0142716415000338

Anthony, J. L., Lonigan, C. J., Driscoll, K., Phillips, B. M., & Burgess, S. R. (2003). Phonological sensitivity: A quasi-parallel progression of word structure units and cognitive operations. *Reading Research Quarterly*, *38*(4), 470–487. https://doi.org/10.1598/RRQ.38.4.3

Baddeley, A. D., & Hitch, G. J. (2019). The phonological loop as a buffer store: An update. *Cortex*, *112*, 91–106. https://doi.org/10.1016/j.cortex.2018.05.015

Bar-Shalom, E. G., Crain, S., & Shankweiler, D. (1993). A comparison of comprehension and production abilities of good and poor readers. *Applied Psycholinguistics*, *14*(2), 197–227. https://doi.org/10.1017/S0142716400009553

Berent, I., Bat-El, O., & Vaknin-Nusbaum, V. (2017). The double identity of doubling: Evidence for the phonology-morphology split. *Cognition*, *161*, 117–128. https://doi.org/10.1016/j.cognition.2017.01.011

Best, C. T., Goldstein, L. M., Nam, H., & Tyler, M. D. (2016). Articulating what infants attune to in native speech. *Ecological Psychology*, *28*(4), 216–261. https://doi.org/10.1080/10407413.2016.1230372

Browman, C. P., & Goldstein, L. M. (1986). Towards an articulatory phonology. *Phonology Yearbook*, *3*, 219–252. https://doi.org/10.1017/S0952675700000658

Byrne, B. (1981). Deficient syntactic control in poor readers: Is a weak phonetic memory code responsible. *Applied Psycholinguistics*, *2*(3), 201–212. https://doi.org/10.1017/S0142716400006512

Charles-Luce, J., & Luce, P. A. (1990). Similarity neighbourhoods of words in young children's lexicons. *Journal of Child Language*, *17*(1), 205–215. https://doi.org/10.1017/S0305000900013180

Chomsky, N. (1965). *Aspects of the theory of syntax*. MIT Press.

de Boer, B., Sandler, W., & Kirby, S. (2012). New perspectives on duality of patterning: Introduction to the special issue. *Language and Cognition*, *4*(4), 251–259. https://doi.org/10.1515/langcog-2012-0014

Eimas, P. D., Siqueland, E. R., Jusczyk, P., & Vigorito, J. (1971). Speech perception in infants. *Science*, *171*(3968), 303–306. https://doi.org/10.1126/science.171.3968.303

Falk, D. (2004). Prelinguistic evolution in early hominins: Whence motherese? *Behavioral and Brain Sciences*, *27*(4), 491–503. https://doi.org/10.1017/S0140525X04000111

Ferguson, C. A., & Farwell, C. B. (1975). Words and sounds in early language acquisition. *Language*, *51*(2), 419–439. https://doi.org/10.2307/412864

Flege, J. E., Munro, M. J., & MacKay, I. R. (1995). Factors affecting strength of perceived foreign accent in a second language. *The Journal of the Acoustical Society of America*, *97*(5 Pt. 1), 3125–3134. https://doi.org/10.1121/1.413041

Goodell, E. W., & Studdert-Kennedy, M. (1991). *Articulatory organization of early words: From syllable to phoneme.* Proceedings of the XIIth International Congress of Phonetic Sciences, 4, 166–169.

Hart, B., & Risley, T. R. (1995). *Meaningful differences in the everyday experience of young American children*. Brookes.

Hartshorne, J. K., Tenenbaum, J. B., & Pinker, S. (2018). A critical period for second language acquisition: Evidence from 2/3 million English speakers. *Cognition*, *177*, 263–277. https://doi.org/10.1016/j.cognition.2018.04.007

Hockett, C. F. (1960). The origin of speech. *Scientific American*, *203*(3), 89–96. https://doi.org/10.1038/scientificamerican0960-88

Hoff, E. (2003). The specificity of environmental influence: Socioeconomic status affects early vocabulary development via maternal speech. *Child Development*, *74*(5), 1368–1378. https://doi.org/10.1111/1467-8624.00612

Hollingshead, A. B. (1957). *The two factor index of social position*. Yale University Press.

Huttenlocher, J., Vasilyeva, M., Cymerman, E., & Levine, S. (2002). Language input and child syntax. *Cognitive Psychology*, *45*(3), 337–374. https://doi.org/10.1016/S0010-0285(02)00500-5

Kelso, J. A. S., Saltzman, E. L., & Tuller, B. (1986). The dynamical perspective on speech production: Data and theory. *Journal of Phonetics*, *14*(1), 29–59. https://doi.org/10.1016/S0095-4470(19)30608-4

Kent, R. D. (1983). The segmental organization of speech. In P. F. MacNeilage (Ed.), *The production of speech* (pp. 57–89). Springer-Verlag. https://doi.org/10.1007/978-1-4613-8202-7_4

Kuhl, P. K., Stevens, E., Hayashi, A., Deguchi, T., Kiritani, S., & Iverson, P. (2006). Infants show a facilitation effect for native language phonetic perception between 6 and 12 months. *Developmental Science*, *9*(2), F13–F21. https://doi.org/10.1111/j.1467-7687.2006.00468.x

Ladd, D. R. (2012). What is duality of patterning, anyway? *Language and Cognition*, *4*(4), 261–273. https://doi.org/10.1515/langcog-2012-0015

Lasky, R. E., Syrdal-Lasky, A., & Klein, R. E. (1975). VOT discrimination by four to six and a half month old infants from Spanish environments. *Journal of Experimental Child Psychology*, *20*(2), 215–225. https://doi.org/10.1016/0022-0965(75)90099-5

Lenneberg, E. H. (1967). *Biological foundations of language*. Wiley. https://doi.org/10.1080/21548331.1967.11707799

Liberman, I. Y., Shankweiler, D., Fischer, F. W., & Carter, B. (1974). Explicit syllable and phoneme segmentation in the young child. *Journal of Experimental Child Psychology*, *18*(2), 201–212. https://doi.org/10.1016/0022-0965(74)90101-5

Lindblöm, B. (2000). Developmental origins of adult phonology: The interplay between phonetic emergents and the evolutionary adaptations of sound patterns. *Phonetica*, *57*(2-4), 297–314. https://doi.org/10.1159/000028482

MacNeilage, P. F., & Davis, B. L. (1991). Acquisition of speech production: Frames, then content. In M. Jeanerod (Ed.), *Attention & Performance XIII* (pp. 453–476). Erlbaum.

Menn, L. (1978). Phonological units in beginning speech. In A. Bell & J. B. Hooper (Eds.), *Syllables and segments* (pp. 157–172). North-Holland Publishing Company.

Menn, L., & Vihman, M. M. (2011). Features in child phonology: Inherent, emergent, or artefacts of analysis? In N. Clements & R. Ridouane (Eds.), *Where do phonological features come from?* (pp. 259–302). John Benjamins. https://doi.org/10.1075/lfab.6.10men

Menyuk, P., Menn, L., & Silber, R. (1986). Early strategies for the perception and production of words and sounds. In P. Fletcher & M. Garman (Eds.), *Language Acquisition* (2nd ed., pp. 198–222). Cambridge University Press. https://doi.org/10.1017/CBO9780511620683.012

Metsala, J. L., & Walley, A. C. (1998). Spoken vocabulary growth and the segmental restructuring of lexical representations: Precursors to phonemic awareness and early reading ability. In J. L. Metsala & L. C. Ehri (Eds.), *Word recognition in beginning literacy* (pp. 89–120). Erlbaum Publishers.

Miller, J., & Iglesias, A. (2010). *Systematic analysis of language transcripts (SALT)* (Research Version 2010). SALT Software, LLC.

Miller, J., & Iglesias, A. (2016). *Systematic analysis of language transcripts (SALT)* (Research Version 16). SALT Software, LLC.

Nittrouer, S. (2006). Children hear the forest. *The Journal of the Acoustical Society of America*, *120*(4), 1799–1802. https://doi.org/10.1121/1.2335273

Nittrouer, S. (2010). *Early development of children with hearing loss*. Plural Publishing.

Nittrouer, S. (2020). The duality of patterning in language and its relationship to reading in children with hearing loss. *Perspectives of the ASHA Special Interest Groups*, *5*(6), 1400–1409. https://doi.org/10.1044/2020_PERSP-20-00029

Nittrouer, S., Caldwell-Tarr, A., Low, K. E., & Lowenstein, J. H. (2017). Verbal working memory in children with cochlear implants. *Journal of Speech, Language, and Hearing Research*, *60*(11), 3342–3364. https://doi.org/10.1044/2017_JSLHR-H-16-0474

Nittrouer, S., Muir, M., Tietgens, K., Moberly, A. C., & Lowenstein, J. H. (2018). Development of phonological, lexical, and syntactic abilities in children with cochlear implants across the elementary grades. *Journal of Speech, Language, and Hearing Research*, *61*(10), 2561–2577. https://doi.org/10.1044/2018_JSLHR-H-18-0047

Nittrouer, S., & Burton, L. T. (2005). The role of early language experience in the development of speech perception and phonological processing abilities: Evidence from 5-year-olds with histories of otitis media with effusion and low socioeconomic status. *Journal of Communication Disorders*, *38*(1), 29–63. https://doi.org/10.1016/j.jcomdis.2004.03.006

Nittrouer, S., & Caldwell-Tarr, A. (2016). Language and literacy skills in children with cochlear implants: Past and present findings. In N. Young & K. Kirk (Eds.), *Pediatric cochlear implantation: Learning and the brain* (pp. 177–197). Springer. https://doi.org/10.1007/978-1-4939-2788-3_11

Noblitt, B., Alfonso, K. P., Adkins, M., & Bush, M. L. (2018). Barriers to rehabilitation care in pediatric cochlear implant recipients. *Otology & Neurotology*, *39*(5), e307–e313. https://doi.org/10.1097/MAO.0000000000001777

Nowak, M. A., & Komarova, N. L. (2001). Towards an evolutionary theory of language. *Trends in Cognitive Sciences*, *5*(7), 288–295. https://doi.org/10.1016/S1364-6613(00)01683-1

Pinker, S., & Bloom, P. (1990). Natural language and natural selection. *Behavioral and Brain Sciences*, *13*(4), 707–727. https://doi.org/10.1017/S0140525X00081061

Roberts, G., & Galantucci, B. (2012). The emergence of duality of patterning: Insights from the laboratory. *Language and Cognition*, *4*(4), 297–318. https://doi.org/10.1515/langcog-2012-0017

Rodríguez, B. L., Hines, R., & Montiel, M. (2009). Mexican American mothers of low and middle socioeconomic status: Communication behaviors and interactive strategies during shared book reading. *Language, Speech, and Hearing Services in Schools*, *40*(3), 271–282. https://doi.org/10.1044/0161-1461(2008/07-0053)

Roid, G. H., & Miller, L. J. (2002). *Leiter international performance scale—Revised (Leiter-R*). Stoelting Co.

Saffran, J. R. (2020). Statistical language learning in infancy. *Child Development Perspectives*, *14*(1), 49–54. https://doi.org/10.1111/cdep.12355

Sandler, W., Aronoff, M., Meir, I., & Padden, C. (2011). The gradual emergence of phonological form in a new language. *Natural Language and Linguistic Theory*, *29*(2), 503–543. https://doi.org/10.1007/s11049-011-9128-2

Senghas, A., Kita, S., & Ozyürek, A. (2004). Children creating core properties of language: Evidence from an emerging sign language in Nicaragua. *Science*, *305*(5691), 1779–1782. https://doi.org/10.1126/science.1100199

Shankweiler, D., & Fowler, C. A. (2015). Seeking a reading machine for the blind and discovering the speech code. *History of Psychology*, *18*(1), 78–99. https://doi.org/10.1037/a0038299

Smith, S. T., Macaruso, P., Shankweiler, D., & Crain, S. (1989). Syntactic comprehension in young poor readers. *Applied Psycholinguistics*, *10*(4), 429–454. https://doi.org/10.1017/S0142716400009012

Stan Development Team. (2021). Stan. Modeling Language Users Guide and Reference Manual, Version 2.28. https://mc-stan.org

Streeter, L. A. (1976). Language perception of 2-month-old infants shows effects of both innate mechanisms and experience. *Nature*, *259*(5538), 39–41. https://doi.org/10.1038/259039a0

Studdert-Kennedy, M. (1987). The phoneme as a perceptuomotor structure. In A. Allport, D. G. MacKay, W. Prinz, & E. Scheerer (Eds.), *Language perception and production: Relationships between listening, speaking, reading, and writing* (pp. 67–84). Academic Press

Studdert-Kennedy, M. (1998). Introduction: The emergence of phonology. In J. R. Hurford, M. Studdert-Kennedy, & C. Knight (Eds.), *Approaches to the evolution of language: Social and cognitive bases* (pp. 169–176). Cambridge University Press.

Studdert-Kennedy, M. (2002). Mirror neurons, vocal imitation, and the evolution of particulate speech. In M. Stamenov & V. Gallese (Eds.), *Mirror neurons and the evolution of brain and language* (pp. 207–227). John Benjamins; https://doi.org/10.1075/aicr.42.17stu

Tsao, F. M., Liu, H. M., & Kuhl, P. K. (2006). Perception of native and non-native affricate-fricative contrasts: Cross-language tests on adults and infants. *The Journal of the Acoustical Society of America*, *120*(4), 2285–2294. https://doi.org/10.1121/1.2338290

Ventura, P., Kolinsky, R., Fernandesa, S., Queridoa, L., & Morais, J. (2007). Lexical restructuring in the absence of literacy. *Cognition*, *105*, 334–361. https://doi.org/10.1016/j.cognition.2006.10.002

Vihman, M. M. (1996). *Phonological development: The origins of language in the child*. Blackwell.

Vihman, M. M. (2017). Learning words and learning sounds: Advances in language development. *British Journal of Psychology*, *108*(1), 1–27. https://doi.org/10.1111/bjop.12207

Wacewicz, S., & Żywiczyński, P. (2015). Language evolution: Why Hockett's design features are a non-starter. *Biosemiotics*, *8*(1), 29–46. https://doi.org/10.1007/s12304-014-9203-2

Walley, A. C. (1993). The role of vocabulary development in children's spoken word recognition and segmentation ability. *Developmental Review*, *13*(3), 286–350. https://doi.org/10.1006/drev.1993.1015

Walley, A. C., Smith, L. B., & Jusczyk, P. W. (1986). The role of phonemes and syllables in the perceived similarity of speech sounds for children. *Memory & Cognition*, *14*(3), 220–229. https://doi.org/10.3758/BF03197696

Werker, J. F. (1991). The ontogeny of speech perception. In I. G. Mattingly & M. Studdert-Kennedy (Eds.), *Modularity and the motor theory of speech perception* (pp. 91–109). Erlbaum.

Werker, J. F., & Tees, R. C. (1984). Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. *Infant Behavior and Development*, *7*(1), 49–63. https://doi.org/10.1016/S0163-6383(84)80022-3

Werker, J. F., & Tees, R. C. (2005). Speech perception as a window for understanding plasticity and commitment in language systems of the brain. *Developmental Psychobiology*, *46*(3), 233–251. https://doi.org/10.1002/dev.20060

Wilcox, K., & Morris, S. (1999). *Children's speech intelligibility measure*. The Psychological Corporation.

Zhao, T. C., Boorom, O., Kuhl, P. K., & Gordon, R. (2021). Infants' neural speech discrimination predicts individual differences in grammar ability at 6 years of age and their risk of developing speech-language disorders. *Developmental Cognitive Neuroscience*, *48*, 100949. https://doi.org/10.1016/j.dcn.2021.100949

Received July 25, 2021
Revision received March 7, 2022
Accepted March 28, 2022 ■