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Asynchronies in Auditory and Language Development Obscure Connections to Phonological Deficits in Children

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ABSTRACT

Purpose: For half a century, psycholinguists have been exploring the idea that developmental language disorders may have their roots in suprathreshold auditory dysfunctions, but results are inconclusive. Typical studies focus on relationships between temporal processing abilities and measures of various language skills at the time of testing, a proximal account. This study expanded that focus by testing three novel hypotheses: (a) Spectral processing impairments may be more responsible for language-learning deficits than temporal processing impairments. (b) Phonological sensitivity is likely the specific language skill most strongly affected by auditory (dys)functions. (c) Poor auditory functioning observed at young ages may wholly or partly recover, reducing the magnitude of relationship between those recovered functions and persistent language skills at older ages.

Method: Sixty-six children (31 boys, 35 girls) 7–10 years of age participated: 36 with typical language and 30 with reading or speech disorder; from this sample two subsamples were designated: younger (7–8 years) and older (9–10 years) children. Four auditory measures were obtained of spectral modulation detection (0.5 and 2.0 cycles per octave) and temporal modulation detection (16 and 64 Hz). Four language measures were obtained, two lexicosyntactic and two phonological.

Results: Younger children showed deficits in all auditory skills, but most strongly for spectral modulation detection at 0.5 cycles per octave; that measure was the only one for which older children showed deficits. Spectral modulation detection was the auditory function most strongly correlated with a language skill, and that language skill was phonological sensitivity.

Conclusions: Early impairments in suprathreshold auditory functions, especially spectral processing, interfere with language acquisition at early stages, especially phonological sensitivity. Although auditory functions can recover to some extent, impairments in language skills persist, indicating that a distal account may more appropriately explain the relationship.

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Language is a uniquely human and highly complex behavior. Nonetheless, it surely emerged through evolutionary processes that cobbled together capacities common to all mammals, including suprathreshold auditory functions. Consequently, it is reasonable to suspect problems in auditory functions (exclusive of raised thresholds) when children encounter difficulties learning language, and no proposal has garnered more attention than the proposal that deficits in the processing of temporal structure are responsible for the difficulties some children face in acquiring language (e.g., Abrams et al., 2009; Boets et al., 2006; Casini et al., 2018; Farmer & Klein, 1995; Gaab et al., 2007; Goswami, 2011; Lorenzi et al., 2000; Tallal, 1980; Van Ingelghem et al., 2001). However, as reasonable as that proposal may seem prima facie, it has generated considerable controversy over several decades because of repeated failures to replicate the essential finding (e.g.,

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Cacace et al., 2000; Marshall et al., 2001; Nittrouer, 1999; Rosen & Manganari, 2001; Studdert-Kennedy, 1995), leaving Rosen (2003) to conclude that the proposal that language or reading deficits are causally related to rapid auditory processing is "…almost certainly wrong." (p. 509). The study reported here was undertaken on the premise that any weaknesses in past work examining potential relationships between auditory functions and language acquisition may have arisen from several methodological restrictions, including (a) the auditory functions examined, which focused almost exclusively on temporal processes; (b) the language skills examined, which have varied across studies and often have not been specified on principled grounds; and (c) the selection of subjects, which often included older children. To explore these proposed weaknesses, the current study (a) examined both temporal and spectral processing tasks, (b) systematically measured both lexicosyntactic and phonological language abilities, and (c) included children slightly younger than those typically studied.

Developmental Language Disorders and Auditory Dysfunction

Fifty years ago, Tallal and colleagues embarked on a series of experiments examining potential auditory bases of language deficits. That work was conducted with children who had developmental language disorders, and involved nonspeech, complex tones of different durations across each trial, presented at different rates across trials. The chore for the child was to recall the order of presentation of the tones. Results showed that the children in the language-disordered groups were poorer at recalling the temporal order of tones than children with typical language, but only when those tones were presented in rapid succession, that is, shorter tones with briefer interstimulus intervals (Tallal, 1980; Tallal et al., 1985; Tallal & Piercy, 1973, 1974). The primary language deficit ascribed to the children in those studies was one of poor speech perception, specifically, difficulty recognizing phonemic structure (Tallal et al., 1993). This led to a narrowed focus on children with dyslexia (De Martino et al., 2001; Gaab et al., 2007; Pasquini et al., 2007). The explanation provided by these investigators for why the observed deficit in temporal processing—poor serial-order recall for rapidly presented tones—on the part of children with dyslexia could lead to poor speech perception was that recognition of individual phonemes depends on formant transitions between adjacent segments. Formant transitions consist of rapidly changing spectral structure. These authors contended that the presentation of brief, steady-state tones in rapid succession in their paradigm was an appropriate analog of that rapid spectral change in speech signals. Thus, the proposal was that the speech-perception deficit demonstrated by children diagnosed with dyslexia is based on their inabilities to recover rapidly changing spectral structure, a problem labeled as a temporal processing disorder. With that proposal serving as the foundation for much of the research on this topic, the focus was put squarely on temporal structure in speech signals (Habib, 2021).

Since the early work of Tallal, other investigators have attempted to replicate, extend, or otherwise address the principal finding and theoretical account. Of particular note, several investigators have suggested that it is actually the rate of amplitude change, rather than spectral change, that presents challenges to children or adults with dyslexia (Goswami et al., 2002; Hämäläinen et al., 2005; Pasquini et al., 2007). More recently, Goswami (2011) has identified areas of the central nervous system responsible for processing temporal structure in general, suggesting that lesions in these areas explain why some individuals have difficulty processing temporal structure across sensory modalities. This proposal of a temporal sampling framework to account for the processing of temporal structure and the problems of dyslexia arises from work in several laboratories. For example, as early as 2001, Van Ingelghem et al. (2001) tested children with dyslexia and with typical reading abilities using gap detection tasks in both the auditory and visual domains. They found that children with dyslexia required longer gaps in both domains to recognize those gaps, as compared to children with typical reading abilities. Tests of word and nonword reading were also administered, and scores on those tests correlated with gap detection thresholds in both domains. In general, theories regarding temporal processing deficits as a source of developmental reading problems have remained central to the search for the basis of dyslexia, or more specifically, for the phonological deficit so frequently cast as the core source of reading difficulties (e.g., Ramus et al., 2003; Snowling, 2000; Vellutino et al., 2004; but cf. Castles & Friedmann, 2014). Outcomes, however, have not always supported a relationship between deficits in temporal processing and problems recognizing the phonological units of spoken and written language, raising doubts regarding the temporal deficit hypothesis (Marshall et al., 2001; Mody et al., 1997; Rosen & Manganari, 2001). Work by others has examined language disorders more broadly in search of underlying temporal processing deficits (Basu et al., 2010; Leonard et al., 1992; Marler & Champlin, 2005), with similar uncertainty regarding outcomes across studies (Rosen, 2003). Nonetheless, the model of temporal processing deficits as causal to language deficits remains central to exploration in this area (Casini et al., 2018). We suggest that the uncertainty across studies may be due to either the age of subjects included in those studies, with some including children old enough that temporal processing abilities would have matured in spite of earlier delays, or the auditory function proposed as causal to language delays, temporal processing.

Why a Newly Proposed Emphasis on Spectral Processing

Recent outcomes for another population of children with language-learning challenges for a different reason have identified a new suspect as the potential source of disorder for children struggling to acquire sensitivity to phonological structure. Children born with severe-to-profound hearing loss who receive cochlear implants and appropriate early intervention are achieving levels of language proficiency not previously imagined. However, advancement in these abilities is uneven across skill areas as a function of the type of language structure involved. Skills based on global lexical and syntactic (here termed "lexicosyntactic") structure have fared much better than have skills based on refined phonological structure (Nittrouer, Muir, et al., 2018). Children with cochlear implants display a disproportionately large deficit in recognizing word-internal (phonological) structure, along with the language-processing problems that are predicted by that specific phonological deficit: Such problems include verbal, or phonological, working memory (Alt et al., 2022; Brady et al., 1983; Pennington et al., 1991; Swanson, 2012); novel word learning (Alt et al., 2017; Rasamimanana et al., 2020; Snowling et al., 1986); and reading of unfamiliar words in decontextualized materials (Bruck, 1993; Mody et al., 1997). These phonologically related deficits likely arise because cochlear implants provide a spectral representation of speech that is highly impoverished; although temporal structure may be somewhat degraded, it is less severely impacted than spectral structure. Support for that proposal comes from an experiment examining spectral processing and phonological awareness in adolescents with cochlear implants. In that experiment, spectral processing was measured using a test of spectral modulation depth detection, meaning the extent of amplitude change from peak to valley in the spectrum required for the adolescent to recognize that there is modulation imposed on the spectrum. A low rate of modulation was used (0.5 cycles per octave [cpo]); this modulation rate is similar to that of the first few formants of voiced speech. For adolescents with cochlear implants, detection thresholds (in dB) were significantly correlated with phonological sensitivity, $r = -.452$, whereas no relationship was found between those thresholds and lexicosyntactic skills, $r = -.138$ (Nittrouer et al., 2021). These findings support the proposal that spectral processing should be explored, with the idea that weaknesses in this processing may be responsible for the phonological deficits children with dyslexia (and normal hearing) face.

Developmental Asynchrony and the Acquisition of Phonological Sensitivity

There are principled reasons for offering the hypothesis that younger children would show stronger relationships between auditory and language functions than older children, along with proposing that the strongest relationships would involve spectral modulation detection on one side and phonological sensitivity on the other. The early years of language acquisition involve myriad changes at several levels. It is generally accepted by developmental psycholinguists that children's earliest lexical representations are holistic in nature, unanalyzed with respect to phonological structure (Jusczyk, 1992, 1993; Menn, 1983; Menyuk & Menn, 1979; Nittrouer, 2006; Vihman & Velleman, 1989; Waterson, 1971). When it comes to syntactic knowledge, children appear to begin learning about syntactic structures such as word classes through a process sometimes termed "prosodic bootstrapping," even before many lexical representations are well formed (Mintz, 2003; Morgan & Demuth, 1996). Thus, early language acquisition can be characterized as involving broadly specified lexical representations combined according to equally broad rules. It is not until roughly the end of the preschool years that children begin acquiring keen access to phonological structures (Ainsworth et al., 2016), a developmental process that involves perceptual learning and extends through the elementary grades. Initially, typically developing children attend most strongly to the relatively slow spectral undulations associated with global word forms, and only later does that perceptual attention, or weight, shift to more static spectral cues, such as consonant noise spectra (Mayo & Turk, 2005; Nittrouer, 1992; Parnell & Amerman, 1978), and temporal cues, such as duration of vocalic segments (Greenlee, 1980; Nittrouer, 2005; Wardrip-Fruin & Peach, 1984). Presumably, these developmental shifts in perceptual weight require access to the detailed acoustic structure that will serve as the focus of mature attentional strategies.

However, keen sensitivity to acoustic structure is also developing through at least the first decade of life, for both temporal modulation (Buss et al., 2019; Cabrera et al., 2019; Hall & Grose, 1994) and spectral modulation (Allen & Wightman, 1992; DiNino & Arenberg, 2018; Horn et al., 2017; Peter et al., 2014). Accordingly, any delay in the development of those auditory functions could hinder developmental shifts in the weighting strategies required for emerging phonological representations. Work with both animal models (Caras & Sanes, 2015) and children (Hautus et al., 2003) has shown that even when deficits in auditory functions are present early in life, development can occur that eventually brings these functions into the normal range. This situation could lead to disparities in the developmental time course of auditory and language (especially phonological) skills, if those language skills remain impaired due to early auditory deficits. This is the situation that Bishop and Snowling (2004) termed a distal relationship between auditory and language abilities. If such a situation exists, it would make it difficult to identify the relationship between these two sorts of abilities in older children because their auditory functioning may have developed, without concomitant language development. This proposed model was central to the current study.

Current Study

Three hypotheses were tested in this study. Hypothesis 1 was that deficits in spectral processing abilities would more clearly define children with language delays than would deficits in temporal processing. Hypothesis 2 was that language skills based on sensitivity to phonological structure in the speech signal would be more strongly impacted by auditory dysfunctions than would lexicosyntactic knowledge and skills. The bases for these two hypotheses were related. Since the discovery of Liberman et al. (1974) showing that sensitivity to word-internal phonological structure emerges gradually over the first decade or so of life, models of language development have evolved to suggest that children can have reasonably sized vocabularies and rather good command of syntactic rules but nonetheless lack sensitivity to phonological structure (Peterson et al., 2009; Van der Lely, 2005; Wagner & Torgesen, 1987). Work involving children with severe-to-profound hearing loss who receive cochlear implants demonstrates a similar asymmetry in language skills: These children are found to have close-to-typical lexicosyntactic skills, but disproportionately large deficits in phonological sensitivity (Nittrouer, Muir, et al., 2018). Thus, phonological sensitivity and related skills appear to be most impacted by auditory processing deficits, and spectral processing deficits are predicted to be most strongly responsible.

Finally, Hypothesis 3 was that there would be a developmental asynchrony for auditory and language skills, such that differences in auditory functions between children with typical language and those with language deficits would be larger in magnitude for younger than for older children, but that group differences in those language abilities themselves would be similar for younger and older children. This prediction was explicitly predicated on the idea that older children with language deficits may have made improvements in any auditory dysfunction they experienced at younger ages, but the language-learning challenges imposed by those early auditory deficits would persist. For the purpose of this study, the cut point between younger and older children was set at roughly the end of third grade, when children typically turn 9 years of age. Children 7–8 years of age served as the young cohort and children 9–10 years of age served as the older cohort. This age boundary was selected because it marks a critical point in reading acquisition—the transition from third to fourth grade. This particular transition is associated with mounting expectations of reading proficiency as the school curriculum changes from “learning to read to reading to learn.” Around this time, there is heightened concern on the part of parents and educators if children are struggling in their reading acquisition. Consequently, diagnostic testing for dyslexia typically accelerates starting in fourth grade. Our fundamental hypothesis was that any auditory dysfunction that underlies phonological deficits would have taken its heaviest toll before this age, so possibly before a diagnosis of dyslexia was suspected or made.

Method

Participants

Sixty-six children between the ages of 7;0 (years; months) and 10;11 participated in this study. Thirty-six of the children in this study had never been suspected as having and had never been diagnosed as having a reading or speech sound disorder (SD); these children formed the typical-language (TYPL) group. Thirty of the children had been diagnosed by a speech-language pathologist with a reading disorder (RD), an SD, or both. For the purpose of this study, the three children with dual diagnoses were categorized as RD. The mean age of children in both the TYPL and the RDSD groups was 9;0. Seventeen of the 36 children in the TYPL group were male (47%), and 14 of the 30 children in the RDSD group were male (47%). When the age range is split between children 7–8 years of age and children 9–10 years of age, numbers remain even: 18 children with TYPL were in each of the 7- to 8-year-old and 9- to 10-year-old cohorts, and 15 children with RDSD were in each of the age cohorts.

The disorder of primary interest in this study was RD. This disorder is commonly described as arising from a core phonological deficit (Ramus et al., 2003; Vellutino et al., 2004), making it likely that the range of variability in phonological measures would be enhanced by the inclusion of these children. Furthermore, children with dyslexia have served as a primary focus of investigations into potential relationships between auditory functions and language processes. Nonetheless, the search for participants was broadened to include children with SD. The hypothesis in this study was that there is an asynchrony in the emergence of linguistic and nonspeech auditory skills, especially for children with phonologically based disorders, such that auditory functions may eventually develop, albeit later than typical, but language skills, especially phonological sensitivity, remain impaired. Accordingly, any relationship between auditory and language functions may be missed if only children older than 8 years of age are included in testing. Unfortunately, dyslexia is not commonly diagnosed until after the age of 8 years. Thus, in order to have a sufficient number of 7- to 8-year-old children, we decided to include those with diagnoses of SD as well. The reason we expanded the search specifically to include children with diagnoses of SD—here meaning poor speech production accuracy—rather than other sorts of developmental language disorders, is that SD is known to be highly comorbid with RD (Bird et al., 1995; Cabbage et al., 2018; Hayiou-Thomas et al., 2017). Although not all children diagnosed with SD early in life go on to receive diagnoses of RD (Peterson et al., 2009), SD, like RD, has been found to be associated with deficits in phonological sensitivity (Raitano et al., 2004; Rvachew & Grawburg, 2006). It has also been suggested that SD arises from underlying deficits in processing acoustic signals (Ramus et al., 2013). Consequently, SD was a reasonable diagnosis to include in the current study when recruiting subjects likely to have language-related deficits involving phonological sensitivity. Another possibility would have been to recruit children with diagnoses of specific language impairment, which can be comorbid with dyslexia, but children with specific language impairment in the absence of dyslexia are unlikely to show deficits in phonological sensitivity or processing (Catts et al., 2005).

All children in this study passed hearing screenings consisting of pure tones at the frequencies of 0.5, 1.0, 2.0, 4.0, and 6.0 kHz presented to each ear separately at 20 dB hearing level. A child needed to pass at all frequencies, in both ears, to be included in the study. No child had any diagnosed medical condition that would be expected to put a child at risk for developmental language delays.

Socioeconomic status (SES) was assessed using a two-factor scale on which occupation and highest educational attainment are ranked from 1 to 8, from lowest to highest. These scores are multiplied together, and the product serves as the SES index. A SES index was computed for each parent, and the highest value was used as the family SES (Nittrouer & Burton, 2005). A SES score of 30 indicates that the parent had a 4-year university degree and a job commensurate with that level of education. Although an attempt was made to match SES across groups, a slight discrepancy was found: Mean SES for the TYPL group was 42 (SD = 14), and mean SES for the RDSD group was 33 (SD = 14), $t(64) = 2.69$, $p = .009$. The range of SES was similar for children in both the TYPL and RDSD groups and indicated a range from skilled laborers to high-level professionals. Because the mean SES for both groups was over 30, indicating that most parents had university educations, and the ranges were similar, the mean difference between groups was not considered problematic. Differences in language acquisition associated with SES are typically found when children in abject poverty are compared to middle-class children (B. Bernstein, 1971; Farah et al., 2006; Perkins et al., 2013; Wild et al., 2013). Nonetheless, given any indication of a relationship between SES and language acquisition meant it was appropriate to examine SES as a possible covariate in analyses of language outcomes in this study.

Equipment

Materials for the measures of syntactic comprehension, phonological sensitivity, and phonological processing were recorded using an AKG C535 EB microphone, a Shure M268 amplifier, and a Creative Laboratories soundcard. Hearing screenings were performed with a Welch Allyn RM262 audiometer and TDH-39 headphones. All testing took place in a soundproof booth. Acoustic stimuli were presented through a computer, with a Creative Labs Sound Blaster soundcard, a Samson C-Que 8 amplifier, and AKG-K141 headphones. Stimuli for the measures of syntactic comprehension, phonological sensitivity, and phonological processing were presented in audio–video format, with the video shown on a computer monitor; audio signals were presented through the same AKG-K141 headphones mentioned above. Data collection for all measures other than the four auditory measures was video- and audio-recorded using a SONY HDR-XR550V video recorder. Children wore Sony FM transmitters that sent the signals to the video recorder to ensure good sound quality on the recordings. These recordings allowed scoring to be performed at a later time by independent observers.

Stimuli and Task-Specific Procedures

Four measures of language abilities were obtained, and four measures of nonspeech, auditory abilities were obtained. For the language measures, both lexicosyntactic and phonological skills were assessed. The measures of lexicosyntactic skills consisted of a vocabulary measure (lexical) and a measure of auditory comprehension of syntactic structure. One measure of phonological skills evaluated sensitivity to word-internal phonemic structure, and the other measure evaluated phonological processing abilities. When it came to the auditory measures, spectral modulation detection was assessed at two modulation rates and temporal modulation detection was assessed at two modulation rates.

Lexicosyntactic Measures

Vocabulary. The Expressive One-Word Picture Vocabulary Test (Martin & Brownell, 2011) was used to assess vocabulary knowledge. In this task, children were shown a series of pictures and had to label each one in turn. Testing stopped after six consecutive errors. Raw scores were used in further analyses to capture developmental changes.

Syntactic comprehension. The Sentence Comprehension of Syntax subtest from the Comprehensive Assessment of Spoken Language–Second Edition (Carrow-Woolfolk, 2017) was administered to assess syntactic knowledge. Items are of two types in this subtest. For the first 42 items, children are shown an easel with four pictures on it. They hear a sentence and must select the picture that represents the action described in the sentence. For items 43 to 56, pairs of sentences that differ in syntactic structure are presented. After each pair of sentences is presented, the child must say whether the sentences have the same meaning or not. The basal score is four consecutive correct items and testing stops after five consecutive errors. Again, raw scores were used in further analyses.

Phonological Measures

Phonological sensitivity. Scores from a final consonant choice task were used to assess phonological sensitivity. In this task, the child is presented with a target word via a video of a talker shown on the computer monitor, and must repeat it. After the child repeats the target word, the video-recorded talker presents three words. The child must select the word that ends in the same sound as the target. There are 48 items in the testing portion of this task that are sequenced from simplest to hardest, and there are six items presented first as practice. Testing is discontinued after six consecutive errors. A MATLAB program controls testing and keeps track of responses. Percent correct scores were found to be normally distributed and were used in further testing.

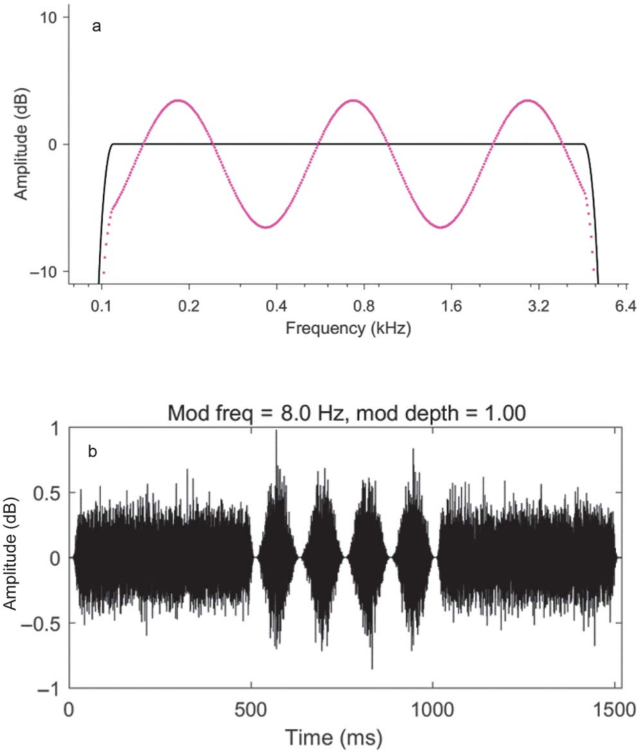
Phonological processing. Scores from a phoneme deletion task were used to assess children's abilities to manipulate phonological structure. In this task, the child is presented with a nonword via the same videotaped talker who presented items for the final consonant choice task. The child must repeat the nonword (e.g., Say "plig"). Then the child is presented, via the videotaped talker, with instructions on how to manipulate the nonword, a manipulation that results in a real word (e.g., Now say "plig" without the *l* sound). There are 32 items in total that are sequenced from simplest to hardest, and there were six practice items. Testing is discontinued after six consecutive errors. A MATLAB program controls testing and keeps track of responses. Percent correct scores were found to be normally distributed and were used in further testing.

Auditory Measures

Spectral modulation. Stimuli for measuring spectral modulation depth detection were generated with procedures similar to those of Henry et al. (2005) and Won et al. (2007). For each stimulus, 800 sinewave components were generated and were spaced logarithmically between 0.1 and 5.0 kHz. The starting phases of the individual components were chosen randomly for each stimulus on each trial. This pattern of a flat spectrum served as the standard stimuli. For the modulated (target) stimuli, a sinusoidal-in-dB envelope was imposed on the sinewave components, such that the amplitudes of the individual components were set according to the depth of the envelope at that location. Starting phase of these envelopes varied from trial to trial, ensuring that peaks and values were not at the same spectral locations across trials. Next, the amplitudes of the components were shaped in two additional ways. First, the amplitudes of the lowest-frequency components were shaped to increase gradually, and the amplitudes of the highest-frequency components were shaped to decrease gradually, to eliminate audible artifacts at the edges. Second, the amplitudes of all components were adjusted by an amount that followed the long-term average spectrum of speech, as reported by Byrne et al. (1994). Duration of each waveform was 500 ms, with 150-ms cosine-squared ramps. Figure 1a displays a standard stimulus as the black line and the target stimulus as the pink line. Modulation depth for these stimuli describes the difference in dB from peak to trough, and the largest depth was 30 dB; this was the value used in training, and it served as the initial depth for testing. Step size in this study was initially 4 dB but changed to 2 dB after the first four reversals. Smaller (positive) thresholds represent better spectral modulation detection.

The modulation rates of 0.5 and 2.0 cpo were selected based on outcomes of Davies-Venn et al. (2015). In that study with adults who either had normal hearing or hearing loss, it was found that the listeners with hearing loss performed similarly to those with normal hearing at low rates of modulation, including 0.5 cpo, but had significantly higher thresholds at high rates of modulation, including 2.0 cpo. This difference in outcomes likely reflects differences in the mechanisms underlying spectral processing at different rates (Eddins & Bero, 2007; Horn et al., 2017; Jahn et al., 2022). At higher rates, modulation detection may best be described as measuring spectral resolution largely associated with auditory filter bandwidths. This is a very peripheral phenomenon and something that would be affected by sensorineural hearing loss.

Figure 1. Stimuli for the spectral modulation task on top (a), with the black line representing a standard stimulus and the pink line representing a target (modulated) stimulus. Stimuli for the temporal modulation task on the bottom (b), with standard stimuli on each side and a target (modulated) stimulus in the center.



At lower rates, modulation detection may best be described as dependent on the ability to recognize patterns of amplitude change across a broad range of frequencies. This is a more central phenomenon, and one that would not necessarily be affected by sensorineural hearing loss. Where development is concerned, spectral resolution appears to reach mature status earlier in life than pattern recognition, with the latter apparently continuing to develop past the age of 10 years (Horn et al., 2017; Jahn et al., 2022).

Temporal modulation. Stimuli for measuring temporal modulation detection consisted of broadband noise (0.05 to 8.0 kHz), which is the most common signal in experiments on temporal modulation. Sinusoidal amplitude modulation was applied in the time domain. Stimuli had 20-ms cosine-squared ramps. Modulation depth (m) varied between 0 and 1 and is described in dB derived from 20×log(m). Here, more negative thresholds represented better temporal modulation detection. Figure 1b displays a target stimulus between two standard stimuli.

Based on pilot testing, two modulation rates were selected for use in this study, 16 and 64 Hz. In that testing, the modulation rates of 4, 16, 64, 128, and 512 Hz were used. The lowest rate (4 Hz) appeared to be difficult for some children, apparently because there was an inadequate sample of that modulation in the 500-ms stimuli. Thus, that modulation rate was eliminated. Thresholds at the highest two rates did not appear to be sensitive to differences across listeners, so they were eliminated, as well. As with spectral modulation detection, different mechanisms appear to be responsible for modulation detection at low and high modulation rates. Temporal modulation detection thresholds at low modulation rates are generally thought to reflect integration of information across time in service to pattern recognition, whereas at high modulation rates, thresholds reflect temporal resolution (Walker et al., 2019). In children with normal hearing, temporal resolution thresholds reach adult values around 4 years of age, and thresholds for temporal pattern recognition reach adult values around 9 years of age (Hall & Grose, 1994). Although the modulation rates of 16 Hz and 64 Hz are neither extremely low nor extremely high, these rates seemed good choices for the reasons described above. Initial depth was 0 dB (maximum depth), with a step size of 2 dB for the first four reversals, and 1 dB thereafter.

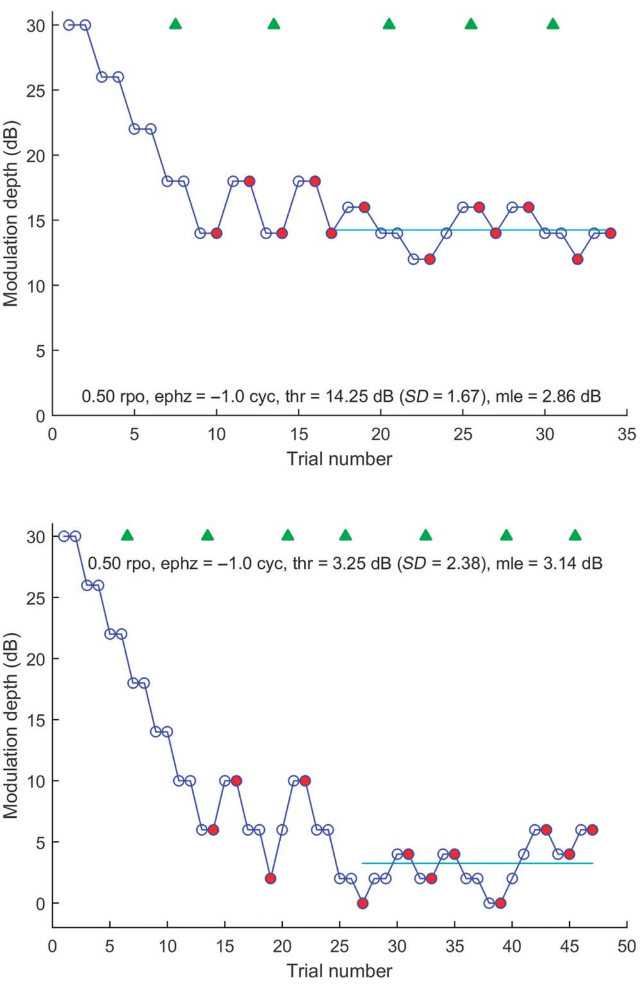
Procedures. The same procedure was used to obtain detection thresholds for both the spectral and temporal modulation stimuli. This was a two-down, one-up adaptive procedure (Levitt, 1971) using a three-interval, forced-choice task. MATLAB scripts controlled testing and kept track of responses. One of two displays was presented on the monitor during testing. In one—the "robot" game—three cartoon robots were shown on the monitor, with the numerals 1 to 3 beneath them. The robots would pulse (increase in size and return to normal) in sequence as each of the three stimuli was presented. The child's task was to point to the robot perceived as making a different sound and say its numeral. That robot would then pulse again. Robots changed on each trial. The other display—the "meow-meow-woof" game—consisted of three cat faces, with the numerals 1 to 3 beneath them. They would pulse in sequence as each of the three stimuli was presented. The child was told that one of the cats was really a dog in disguise and the child would know because it made a different sound. When the child selected the cat perceived as making a different sound, the cat's face would change to a dog's face. The experimenter entered the child's responses into the computer. Pretest training was used to introduce the adaptive task. This training always utilized target stimuli with the largest modulation depths. For the first few presentations, the experimenter would provide feedback, but children needed to respond to nine out of 10 consecutive stimuli without feedback to proceed to testing. Each child was given a maximum of 30 trials in which to reach this criterion. If the child did not, the child would have been dismissed. No child failed to reach the criterion for any set of stimuli. Twelve reversals were obtained in all testing. Step size was larger for the first four reversals and decreased for the last eight reversals. Thresholds were computed as the means of the last eight reversals. For each rate of spectral and temporal modulation, two tests were conducted on two different days separated by no more than 2 weeks. The means across each pair of tests (for the same modulation rate of spectral or temporal stimuli) served as the threshold used in further analyses. A video demonstration of the spectral and temporal modulation tasks is available in Supplemental Materials S1 and S2.

Attentional Control Checks

Cognitive factors such as short-term memory and general attention have been cited as potential contributors to children's performance on psychoacoustic tasks (Banai & Ahissar, 2004; Moore et al., 2010; Petley et al., 2021). To address these potentially confounding effects, we implemented three procedures to minimize them and assess any remaining influence. The first step taken was to develop test procedures to maintain children's attention, but not distract them from the task at hand. The second step was to establish pretest criteria for participation: Children had to demonstrate that they could readily perform the task when signal uncertainty was lowest. Thirdly, to assess children's sustained attention during testing, we presented probe trials at random intervals of five to seven stimuli. These trials consisted of target stimuli with the largest modulation depth, so the same targets as those used in training. Children generally heard six to eight of these stimuli over the course of each test. They could respond to no more than two of them incorrectly, or their data for that test would be eliminated from analysis. Figure 2 displays recorded tracks for two children for the 0.5-cpo stimuli. The track on the top is from a child with a relatively high (poor) threshold, and the one on the bottom is from a child with a low (good) threshold. The green triangles at the top indicate the probe trials and show that both children responded correctly to all these trials. Only one child in the study failed to reach criterion on one test, but the child's other test for those stimuli showed no misses. Because all other data across the two test sessions were unmarked by peculiarities, in this instance, the threshold from the one good test was used in further analyses.

Finally, we computed two metrics of variability around thresholds with the reasoning that a child who was not paying attention to the task would show more widely varying tracks. The first of these metrics was simply the standard deviation of the last eight reversals. The second was the mean length of excursion, which was the mean difference between all adjacent pairs of the last eight reversals. For each auditory measure, the means of these metrics across the two test sessions were used in analyses. None of these values showed a significant correlation with age, and none showed a significant difference across the language groups. Thus, these assessments indicate that the steps taken to minimize cognitive effects on responding were successful.

Figure 2. Adaptive tracks for two children for spectral modulation detection at 0.5 cycles per octave. The track on top reveals a higher threshold than the track on the bottom. Red circles mark reversals and green triangles indicate correct responses on the catch trials. rpo = ripples (cycles) per octave; ephz = envelope phase; thr = threshold; mle = mean length of excursion.



General Procedures

All procedures were approved by the institutional review board of the authors' institution. Participants were recruited through flyers distributed to schools and clinics.

Testing took place in two sessions of 70–90 min each. In the first session, informed consent was obtained from the parent and assent was obtained from the child. The hearing screening was performed next and then testing began. All acoustic stimuli were presented at a level of 68 dB sound pressure level. For the spectral modulation tasks, level roved by 3 dB across trials. Testing for all measures except vocabulary was done under headphones.

In each of the two testing sessions, all four auditory tasks were administered. The order of presentation of these four tasks was randomized across children, with the provision that spectral and temporal modulation tasks alternated. The four language tasks were randomly distributed across testing session, with one lexicosyntactic and one phonological measure obtained at each session. These language tasks were inserted in the test session between the first and second auditory tasks and the third and fourth auditory tasks. Responses for the four auditory tasks were entered directly into the computer during testing. The lexicosyntactic tasks were scored on paper forms at the time of testing by the experimenter, and testing was also video-recorded. Later, a second experimenter reviewed the paper forms and the recordings to ensure accuracy. If the second scorer noticed a mistake, it was corrected at that time. Responses for the phonological tasks were recorded by the experimenter at the time of testing using the MATLAB routines, and children were also video-recorded taking these tests. A second experimenter later checked the responses entered at the time of testing against the video recordings. Any errors could be corrected at that time.

Data Analysis and Reporting

Data were entered into a database by one experimenter, and data entry was checked by a second experimenter. All analyses were performed with SPSS Version 28.

Raw scores on the vocabulary and sentence comprehension tasks were submitted to principal components analysis to derive one standardized latent measure of lexicosyntactic abilities. Similarly, percent correct scores from the two phonological measures were submitted to principal components analysis to derive one standardized latent measure of phonological abilities. These latent standardized scores were used in further analyses.

The four auditory measures represent modulation detection thresholds in dB. Initial data screening revealed that thresholds for spectral modulation at 2.0 cpo were highly and positively skewed. These values are reported as dB for interpretability, but an inverse transform was performed on the values and used for analyses. Thresholds across the two spectral modulation tasks or the two temporal modulation tasks were not combined based on the premise that mechanisms underlying modulation detection for either spectral or temporal modulation likely differ depending on modulation rate.

Results

Cross-Age Results

To test the first two hypotheses, outcomes were examined without dividing children into the 7- to 8-year-old and 9- to 10-year-old cohorts. Hypothesis 1, proposing that stronger group differences would be observed for spectral rather than temporal processing, was tested using univariate analysis of covariance (ANCOVA) on each of the four auditory measures (two of spectral modulation depth detection and two of temporal modulation depth detection) to determine if there were differences between the two groups. Age (in months) was used as a covariate because modulation depth detection could be expected to develop across the age range used in this study. Table 1

Table 1. Outcomes of analyses of covariance performed on auditory measures, comparing scores for children in the TYPL group (36) and children in the RDSD group (30) using age as a covariate.

Auditory measure	***df***	***F***	***p***	**η^2**
Spectral modulation 0.5 cpo				
Age	1, 63	15.64	< .001	.199
Reading group	1, 63	13.47	< .001	.176
Spectral modulation 2.0 cpo				
Age	1, 63	5.08	.028	.075
Reading group	1, 63	0.90	.347	.014
Temporal modulation 16 Hz				
Age	1, 63	5.28	.025	.077
Reading group	1, 63	3.90	.053	.058
Temporal modulation 64 Hz				
Age	1, 63	12.98	< .001	.171
Reading group	1, 63	4.70	.034	.069

Note. TYPL = typical language; RDSD = reading disorder or speech disorder.

Table 2. Outcomes of analyses of covariance performed on latent language measures, comparing scores for children in the TYPL group (36) and children in the RDSD group (30) using age and socioeconomic status (SES) as covariates.

Language measure	*df*	*F*	*p*	η^2
Latent lexicosyntactic score				
Age	1, 62	17.75	< .001	.223
SES	1, 62	6.13	.016	.090
Reading group	1, 62	27.93	< .001	.311
Latent phonological score				
Age	1, 62	3.91	.052	.059
SES	1, 62	4.68	.034	.070
Reading group	1, 62	54.09	< .001	.466

Note. Latent scores are standardized values. TYPL = typical language; RDSD = reading disorder or speech disorder.

shows results. As expected, age had a significant effect on scores for all four auditory measures. And as predicted according to Hypothesis 1, the largest group difference after controlling for age, indexed by the effect size (η^2), was observed for spectral processing, but only at the low modulation rate (0.5 cpo).

Although not explicitly related to one of the main hypotheses, ANCOVAs were also performed on the two latent language measures. For these analyses, SES was included as a covariate, along with age. SES can serve as a proxy of sorts for variability in home language environment, which can affect language development. Table 2 shows outcomes of these analyses and reveals that language ability (TYPL or RDSD) explained a significant amount of variance in performance on both language measures, even after age and SES were controlled. In fact, effects of language ability are larger for both latent language measures than for any of the auditory measures, including spectral modulation at 0.5 cpo. These results demonstrate that we were successful in assembling subject groups that met the definitions for those groups as either typical language or language disordered.

Support for Hypothesis 1 not only required that larger deficits be found for children with RDSD but also that spectral processing be found to explain more variability in the language measures than temporal processing. To test that aspect of the hypothesis, partial correlation coefficients were computed between each latent language measure and each measure of modulation detection. For these analyses, both age and SES were controlled. Table 3 displays results. Significant coefficients are highlighted. This table shows that just one auditory measure—spectral modulation detection at 0.5 cpo—explained a significant amount of variability in the latent lexicosyntactic scores, after controlling for age and SES. For latent phonological scores, three of the four auditory measures explained a significant amount of variability—all of them except temporal modulation detection at 16 Hz—but spectral modulation detection at 0.5 cpo had the largest *r* value. Thus, this aspect of Hypothesis 1 is largely supported. The correlation coefficients shown on Table 3 also offer support for Hypothesis 2, that phonological sensitivity would be more strongly related to auditory functions than lexicosyntactic skills.

Results by Age Cohort

The cross-ages analyses described above provided insights into differences between the TYPL and the RDSD groups for both auditory and language abilities. A central goal of this study, however, was to see if these group differences and these relationships between auditory and language abilities differ depending on age. Specifically, Hypothesis 3 was that there would be a developmental asynchrony for auditory and language skills, such that differences in auditory functions between children with typical language and those with language deficits would be larger in magnitude for younger than for older children, but that group differences in those language abilities would be similar in magnitude for younger and older children. Evidence of this asynchrony in auditory and language development would support the notion of a distal relationship between the two developmental phenomena. To test that hypothesis, children needed to be categorized as belonging to the 7- to 8-year-old or the 9- to 10-year-old age cohort.

Figure 3 displays Tukey box and whisker plots for the four auditory measures for each language-ability

Table 3. Partial correlation coefficients between each latent language measure and each auditory measure, controlling for age and SES.

Language measure	SMD 0.5		SMD 2.0		TMD 16		TMD 64	
	r	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Latent lexicosyntactic score	**–.372**	**.003**	.116	.359	–.196	.122	–.213	.091
Latent phonological score	**–.471**	**< .001**	**.292**	**.019**	–.216	.087	**–.400**	**.001**

Note. Highlighted values represent coefficients with $p < .05$. When Bonferroni corrections are applied, only the coefficient for latent phonological scores and SMD 2.0 ceases to be significant. SES = socioeconomic status; SMD = spectral modulation detection; TMD = temporal modulation detection.

Figure 3. Tukey box and whisker plots for the four auditory measures obtained in this study. These plots display the median as the center line, the interquartile range as the box, and 1.5*interquartile range as the whiskers. Scores outside of this range are displayed as individual points. Higher thresholds indicate poorer processing abilities. TYPL = typical language; RDSD = reading disorder or speech disorder.

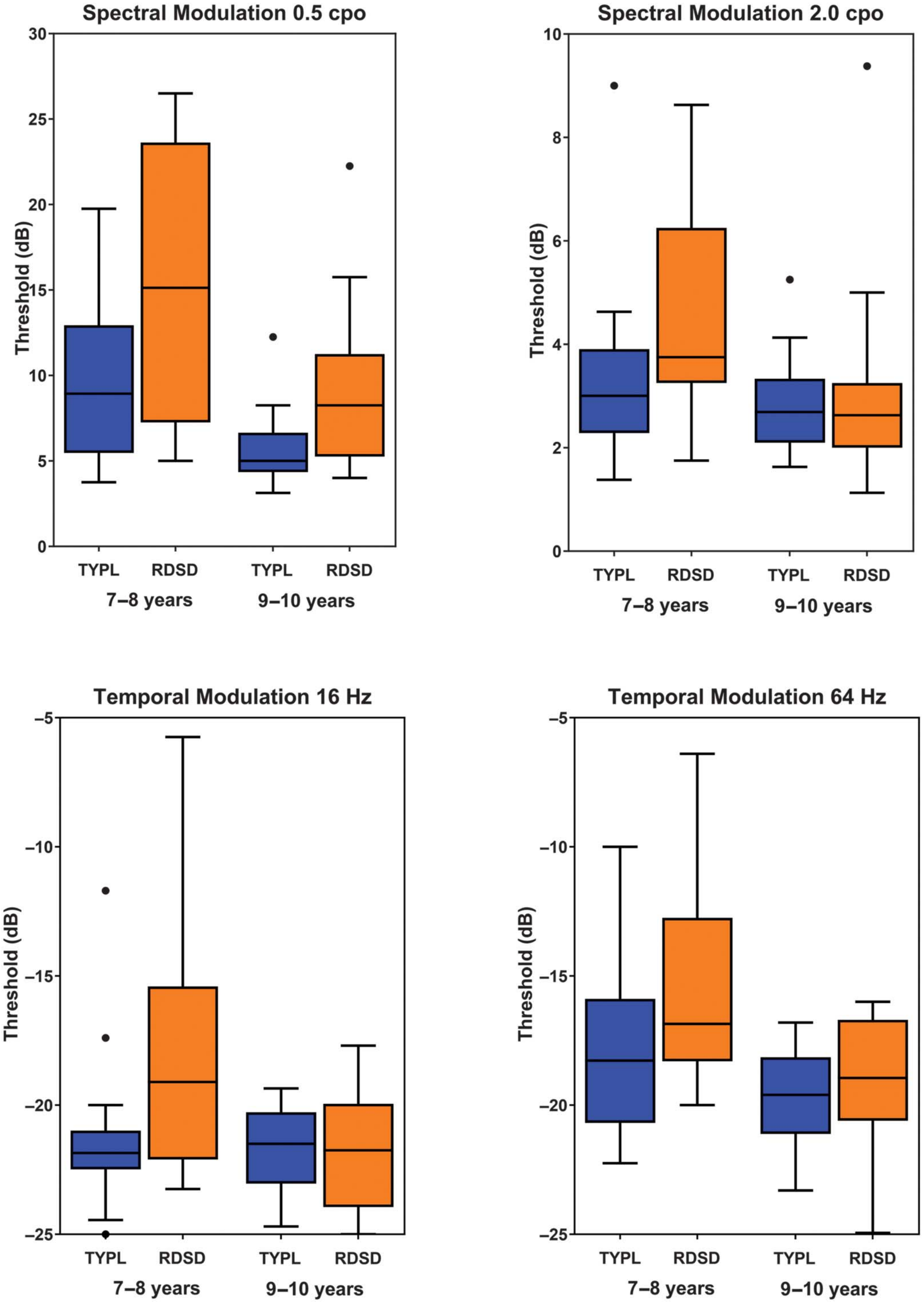


Table 4. Outcomes of independent-samples *t* tests performed on auditory measures, comparing scores for children in the TYPL group and children in the RDSD group, separately for 7- to 8-year-old and 9- to 10-year-old children.

Auditory measure	*df*	*t*	*p*	*d*
7- to 8-year-old children				
Spectral modulation, 0.5 cpo	31	–2.58	.015	–0.90
Spectral modulation, 2.0 cpo	31	1.87	.071	0.65
Temporal modulation, 16 Hz	31	–2.47	.019	–0.86
Temporal modulation, 64 Hz	31	–2.26	.031	–0.79
9- to 10-year-old children				
Spectral modulation, 0.5 cpo	31	–2.96	.006	–1.04
Spectral modulation, 2.0 cpo	31	–0.357	.724	–0.13
Temporal modulation, 16 Hz	31	0.287	.776	0.10
Temporal modulation, 64 Hz	31	–0.687	.497	–0.24

Note. Cohen's *d*s represent effect sizes for differences between scores of children with TYPL and children with RDSD. TYPL = typical language; RDSD = reading disorder or speech disorder.

group separately, for each age cohort. Higher thresholds indicate poorer processing abilities. Independent-samples *t* tests and Cohen's *d*s were computed to test Hypothesis 3 because this procedure allowed a comparison of effect sizes across groups, something that would not be available otherwise. Table 4 displays results of these *t* tests performed on each measure. Here, we find significant differences ($p < .05$) for three of the four measures for the 7- to 8-year-old children. For the 9- to 10-year-old children, however, a significant difference is found only for spectral modulation detection at the low rate of 0.5 cpo. Figure 3 also reveals there is a reduction in range of scores for the 9- to 10-year-old children, compared to the 7- to 8-year-old children. Overall, the first part of Hypothesis 3 is supported: Larger group differences are observed for the auditory measures in the 7- to 8-year-old children, compared to the 9- to 10-year-old children.

Figure 4 displays Tukey box and whisker plots for the two latent language measures for children with TYPL

Figure 4. Tukey box and whisker plots for the four auditory measures obtained in this study. These plots display the median as the center line, the interquartile range as the box, and 1.5*interquartile range as the whiskers. Scores outside of this range are displayed as individual points. Higher thresholds indicate poorer processing abilities. TYPL = typical language; RDSD = reading disorder or speech disorder.

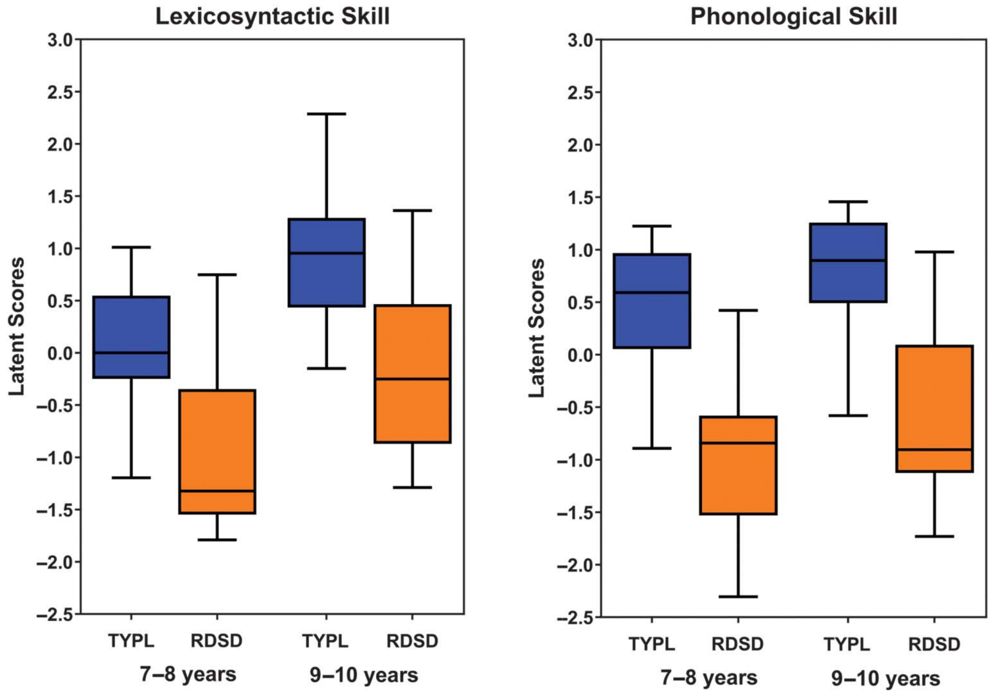


Table 5. Outcomes of independent-samples *t* tests performed on latent language measures, comparing scores for children in the TYPL group (18) and children in the RDSD group (15), separately for 7- to 8-year-old and 9- to 10-year-old children.

Language measure	*df*	*t*	*p*	*d*
7- to 8-year-old children				
Latent lexicosyntactic score	31	4.67	< .001	0.68
Latent phonological score	31	5.89	< .001	0.68
9- to 10-year-old children				
Latent lexicosyntactic score	31	4.48	< .001	0.74
Latent phonologic score	31	5.69	< .001	0.72

Note. Cohen's *d*s represent effect sizes for differences between scores of children with TYPL and children with RDSD. TYPL = typical language; RDSD = reading disorder or speech disorder.

and for those with RDSD in both the 7- to 8-year-old and the 9- to 10-year-old cohorts. Lower scores indicate poorer abilities. Overall, differences across the TYPL and RDSD groups remain similar for the 7- to 8-year-old and 9- to 10-year-old cohorts. Table 5 displays the results of independent-samples *t* tests performed on each of these measures, for children in each age cohort separately. These results show there were significant differences for both measures at both ages. Cohen's *d*s reveal that the magnitude of these differences were similar across the two age cohorts, indicating that the magnitude of the language differences across language groups remain the same from the 7- to 8-year-old to the 9- to 10-year-old cohorts.

Overall, these analyses support the main prediction of Hypothesis 3: There are greater differences in auditory functions between children with TYPL and RDSD at the younger age than at the older age, but differences in language measures are similar for both age cohorts. This finding is commensurate with that of Hautus et al. (2003).

Next, Pearson product–moment correlation coefficients were computed for each language measure and each auditory measure to test the proposal that these relationships would be stronger for younger than older children. These coefficients are displayed in Table 6. Again, children were not separated according to whether they had TYPL or RDSD in these computations, to provide the broadest range of scores possible. Significant coefficients are highlighted. These outcomes reveal that every correlation coefficient was significant for the 7- to 8-year-old cohort, but only one coefficient was significant for the 9- to 10-year-old cohort. Table 7 shows Fisher's *z* statistics for the comparison of correlation coefficients found for the 7- to 8-year-old versus the 9- to 10-year-old children. This table reveals there were no significant differences for the correlation coefficients involving spectral modulation detection at 0.5 cpo. Although the other comparisons involving phonological scores did not quite reach statistical significance, Fisher's *z* was generally large for all comparisons, suggesting that the younger children genuinely showed stronger relationships between the auditory measures and the language skills than did the older children. Thus, support is provided for Hypothesis 3. Furthermore, for both age cohorts, the strongest relationships were found between spectral modulation detection at 0.5 cpo and latent phonological scores. That finding further supports Hypotheses 1 and 2.

Discussion

General Findings

Children accomplish no greater feat during childhood than mastering human language. Juveniles of other

Table 6. Correlation coefficients between each latent language measure and each threshold for auditory tasks, separately for 7- to 8-year-old and 9- to 10-year-old children.

	SMD 0.5 cpo		SMD 2.0 cpo		TMD 16 Hz		TMD 64 Hz	
Language measure	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Latent lexicosyntactic score								
7- to 8-year-olds	**–.534**	**.001**	**.402**	**.020**	**–.494**	**.003**	**–.440**	**.010**
9- to 10-year-olds	–.340	.053	–.038	.834	–.007	.968	–.013	.943
Latent phonological score								
7- to 8-year-olds	**–.600**	**< .001**	**.488**	**.004**	**–.474**	**.005**	**–.582**	**< .001**
9- to 10-year-olds	**–.484**	**.004**	.193	.282	–.133	.460	–.287	.105

Note. Highlighted values represent coefficients with $p < .05$. When Bonferroni corrections are applied, only the 7- to 8-year-olds' coefficient for latent lexicosyntactic scores and SMD 2.0 ceases to be significant. SMD = spectral modulation detection; TMD = temporal modulation detection.

Table 7. Fisher's *z* statistic for comparison of correlation coefficients obtained from 7- to 8-year-old versus 9- to 10-year-old subjects.

	SMD 0.5 cpo		SMD 2.0 cpo		TMD 16 Hz		TMD 64 Hz	
Language measure	*z*	*p*	*z*	*p*	*z*	*p*	*z*	*p*
Latent lexicosyntactic	–0.94	.175	1.80	.036	2.07	.019	1.78	.038
Latent phonological	–0.64	.261	1.31	.095	1.48	.070	1.43	.076

species learn to walk, to vocalize, and to locate sounds in the environment, but only humans exploit motor control of the vocal mechanism and audition in service to this highly complex system of communication. Given its complexity, it is not surprising that roughly 8% of children encounter problems in learning language (Norbury et al., 2016). In the past, such language deficits did not impose serious limitations on an individual's quality of life, but as occupations have moved away from manual jobs and toward technical careers, the need for language proficiency has increased. Consequently, the search for the source of developmental language disorders has intensified, so that appropriate interventions can be designed.

Past efforts to examine the general hypothesis that auditory dysfunctions underlie language disorders have commonly focused on the processing of temporal structure; the language skill defining the experimental group or examined as a dependent variable was often general in nature. And although there have certainly been a considerable number of studies demonstrating relationships between temporal processing and language skill, however defined, outcomes have been less than consistent (Habib, 2021; Rosen, 2003; Studdert-Kennedy, 1995). This inconsistency has generated controversy among scientists and clinicians interested in childhood language disorders, including dyslexia, regarding whether auditory dysfunctions can legitimately be viewed as causal to language-learning delays. In the study reported here, we tested three related hypotheses in an effort to gain insight into the reasons for the disparate outcomes across studies.

Hypothesis 1 was that spectral processing difficulties would be more responsible for language-learning deficits than temporal processing difficulties. To support this hypothesis fully, it was necessary to show both (a) larger differences between children with typical language and children with language deficits for spectral than temporal processing and (b) that spectral processing is more strongly related to language skills than is temporal processing. The hypothesis was supported, but only for signals with a low rate of spectral modulation. Across the full age range, the largest group difference involving auditory functions was found for spectral modulation detection thresholds at 0.5 cpo. When 7- to 8-year-old and 9- to 10-year-old children were considered separately, however, outcomes were more nuanced. Where 7- to 8-year-old children are concerned, all auditory measures except for spectral modulation detection at 2.0 cpo showed significant between-group effects. Where the 9- to 10-year-old children are concerned, the only group difference found to be significant was detection of spectral modulation at that 0.5-cpo modulation rate. The difference in findings for spectral modulation detection depending on modulation rate, with the low modulation rate showing a significant language-group difference regardless of age, but the higher rate of modulation failing to do so, may be related to the idea that spectral resolution develops to mature status sooner than cross-frequency intensity sensitivity: Even when development is delayed, spectral resolution appears to reach mature status by 9–10 years.

The second component of Hypothesis 1 was also supported, but with caveats: The strongest correlations between auditory and language measures were found for spectral modulation detection thresholds, but again, only for the low modulation rate. And when correlation coefficients were computed for the 7- to 8-year-old and the 9- to 10-year-old cohorts separately, the spectral modulation threshold at 0.5-cpo was the only auditory measure to show any significant relationship to language measures for the 9- to 10-year-old children. For the 7- to 8-year-old children, however, every auditory measure showed a moderately strong relationship to every language measure.

Hypothesis 2 was that phonologically based language skills would be more strongly affected by auditory dysfunctions than would lexicosyntactic skills; this was based on the premise that recovering phonological structure from the speech signal requires keen access to acoustic details. Support is found in the outcomes for Hypothesis 2, primarily when children are combined across the entire age range. When 7- to 8-year-old and 9- to 10-year-old cohorts are viewed separately, we find that the 9- to 10-year-old children showed significant correlations between just one auditory measure (spectral modulation detection at 0.5 cpo) and the latent phonological score, but not the latent lexicosyntactic score. Again, however, for 7- to 8-year-old children, significant correlations were observed for every auditory measure matched with both the latent phonological and lexicosyntactic scores.

Finally, Hypothesis 3 was that the largest group differences (TYPL vs. RDSD) in auditory measures would be observed for 7- to 8-year-old, rather than 9- to 10-year-old children and the strongest effects of those auditory measures on language skills would be found for the 7- to 8-year-old children. It was predicted that the diminishment in effects at older ages would be traceable to older children with language deficits having modulation detection scores resembling those of their peers with typical language. These predictions were clearly met, with the exception of spectral modulation detection at 0.5 cpo, where the 9- to 10-year-old children with RDSD continued to show poorer detection thresholds than their peers with TYPL. This developmental trend is undoubtedly the most intriguing finding to come out of these analyses. It suggests that even though development of suprathreshold auditory functions may be delayed, children can catch up by the end of the first decade of life, with the notable exception of cross-frequency sensitivity to amplitude patterns. It appears, however, that the toll imposed on language abilities at young ages remains, in undiminished form. Thus, auditory dysfunctions appear to create a distal threat to language learning, one that may be readily measured at young ages, but that is lost to observation as children get older.

Overall, the outcomes of this investigation suggest that appropriate access to acoustic structure in the speech signal is necessary for language development. Without it, language acquisition is hindered. Although auditory functions in affected children may catch up, those early delays leave these children with long-term challenges.

Possible Limitations

The results of this study should help to design future investigations, and those investigations will need to address at least one shortcoming in the current study. This study was cross-sectional in design, rather than longitudinal. The conclusion that children with language-learning challenges have larger auditory deficits at younger ages presumes that the 7- to 8-year-old and the 9- to 10-year-old children in this study are comparable. However, the finding of larger differences between the TYPL and RDSD groups at younger, rather than older, ages for the auditory measures could be idiosyncratic to these groups of children. A longitudinal study in which children are tested repeatedly as they mature across the age span examined here—effectively bridging the period of essential literacy acquisition—will help support or refute the findings obtained with these children.

Concern might exist that the criterion for being assigned to the RDSD group did not define a specific language disorder, but rather only identified children who would be suspected of having poor phonological sensitivity by including children with diagnoses of reading or speech disorder, however identified by their speech pathologists. That decision was a deliberate effort to establish a continuum of skill in recognizing phonological structure. Including younger children with diagnosed SDs enhanced our ability to recruit young children with phonological deficits, before diagnoses of dyslexia may be made. Future studies might try to identify auditory dysfunctions in groups of children who are diagnosed with other language disorders using explicit inclusionary criteria.

Finally, a frequent criticism of work in this area is that unrelated comorbidities may exist for children involving delays in both the acquisition of auditory functions and language skills, and this is the source of any apparent connections between the two developmental phenomena uncovered (e.g., Rosen & Manganari, 2001). In this case, however, we made a prediction about a specific relationship between one auditory measure, spectral processing, and one language measure, phonological skills. Although observed relationships between auditory functions and language skills in the 7- to 8-year-old children were broad, the only relationship found for the 9- to 10-year-old children was the specific one predicted at the outset of this study. A deficit in auditory functioning was observed to persist for this 9- to 10-year-old cohort only for spectral modulation detection at a low rate of modulation, and this deficit was found to correlate only with the latent phonological measure. This relationship was predicted on a reasonable conceptual basis: Amplitude modulation across the spectrum at that low rate corresponds to the patterns of vocal-tract formants that define speech signals. Thus, the bar was met for proposing that the observed relationship was not spurious.

Clinical Implications

An implication of this study that has high clinical significance is that there appears to be a need for a shift in the field's perspective regarding reading disabilities. Dyslexia is commonly defined as a deficit in reading skill, in spite of there has been adequate educational opportunity to learn to read (Lyon et al., 2003). Although the source of that deficit is identified as a lack of sensitivity to phonological structure (Ramus et al., 2003; Snowling, 2000; Vellutino et al., 2004), the definition largely suggests that problems are found only with written language. The outcomes of this study suggest that perspective may be too narrow. Rather, a more appropriate view might be that there are some children with early deficits involving central perceptual mechanisms. One consequence of these deficits involves challenges in discovering word-internal phonological units, as required for learning to read alphabetic orthographies. However, given the nature of the underlying perceptual deficit, other speech and language problems would be expected, as well. Evidence for this adjusted view comes from the finding that children diagnosed with RDs may also exhibit enhanced difficulty recognizing speech under adverse listening conditions (Dole et al., 2012; Nittrouer, Krieg, & Lowenstein, 2018; Ziegler et al., 2009). To be sure, this finding has faced some of the same challenges as those described in the introduction regarding temporal processing deficits and reading (Calcus et al., 2017), and that may be for similar reasons, such as an asynchrony in development. Nonetheless, the confluence of deficits exhibited by children with reading problems provides reason for suspecting a broad perceptual deficit.

The relationship hypothesized to exist between problems in recognizing spectral or temporal modulation in the speech signal and difficulties acquiring sensitivity to word-internal phonological structure is that phonological structure depends heavily on being able to recognize that modulated structure. Patterns of amplitude peaks and valleys in the spectral structure (i.e., formants) define phonemic units, and patterns of peaks and valleys in the speech signal across time help with syllabic structure, intonation, and phonemic structure, as well. Although due to different mechanisms, spectral and temporal modulation in signals that compete with target speech signals (i.e., maskers) is hypothesized to facilitate recognition of speech under difficult listening conditions (e.g., Fogerty et al., 2018; Gibbs & Fogerty, 2018; Healy & Warren, 2003; Howard-Jones & Rosen, 1993; Miller et al., 2018). Better speech recognition in background signals has been observed for listeners with keener sensitivity to spectral or temporal modulation, based on the principle that they can "glimpse" bits of the target signal in the dips formed by that modulation (Alcántara et al., 2004; J. G. Bernstein & Grant, 2009; Nagels et al., 2021; Rosen et al., 2013; Won et al., 2011). Accordingly, the same deficit in spectral and temporal modulation detection that interferes with phonological acquisition by children with RDSD can also hinder their recognition of speech signals in noise. This means that clinicians working with these children must intervene to accommodate both deficits. The auditory tasks implemented in this study were sufficiently entertaining to maintain the attention of these children for the time required to collect modulation thresholds. In the future, such tasks could be used to screen young children at risk of the kind of perceptual deficit described here. Such a test would be especially helpful when operating in multilingual cultures where all children might not speak the dominant language. Early auditory training procedures could potentially ameliorate the early perceptual deficit that appears to constrain phonological acquisition. For school-age children, clinicians need to provide both phonological training and optimal classroom listening conditions.

Summary

Fifty years of research has suggested there is something awry in the auditory functioning of children with language disorders, yet there has been no general agreement regarding the nature of those auditory problems or how they are related to language development. This study tested three novel hypotheses regarding potential relationships between auditory and language functions: (a) that spectral processing difficulties would be found to be more responsible for language-learning deficits than temporal processing difficulties, (b) that phonological processes would be more impacted by deficits in auditory functions than would lexicosyntactic abilities, and (c) that auditory deficits would be larger for children with language disorders at younger than older ages. Results from 66 children between the ages of 7 and 10 years largely supported these hypotheses. Future studies will need to replicate and extend these findings.

Data Availability Statement

All reasonable requests for data sharing will be accommodated. Please contact the first author to make a request.

Acknowledgments

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