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Early otitis media puts children at risk for later auditory and language deficits☆

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ABSTRACT

Background: Otitis media is a common disorder of early childhood suspected of hindering auditory and language development, but evidence regarding these effects has been contradictory. To examine potential sources of these contradictory past results and explore in more detail the effects of early otitis media on auditory and language development, three specific hypotheses were tested: (1) Variability in children's general attention could influence results, especially for measures of auditory functioning, leading to spurious findings of group differences; (2) Different language skills may be differentially affected, evoking different effects across studies depending on skills assessed; and (3) Different mechanisms might account for the effects of otitis media on acquisition of different language skills, a finding that would affect treatment choices.

Method: Children 5–10 years old participated: 49 with and 68 without significant histories of otitis media. The auditory function examined was temporal modulation detection, using games designed to maintain children's attention; two additional measures assessed that attention. Measures of lexical knowledge and phonological sensitivity served as the language measures.

Results: Sustained attention was demonstrated equally across groups of children with and without histories of otitis media. Children with histories of otitis media performed more poorly than peers without those histories on the auditory measure and on both sets of language measures, but effects were stronger for phonological sensitivity than lexical knowledge. Deficits in temporal modulation detection accounted for variability in phonological sensitivity, but not in lexical knowledge.

Conclusion: When experimental factors are tightly controlled, evidence emerges showing effects of otitis media early in life on both auditory and language development. Mechanism of effects on language acquisition appear to involve both delayed auditory development and diminished access to the ambient language.

1. Introduction

1.1. Problem statement

The anatomy of the developing middle-ear system leaves it especially vulnerable to infection. Although effective treatments exist, the original diagnosis can be difficult, and treatment can be more invasive than many parents would prefer for a seemingly minor medical problem. These considerations make it important to determine exactly how much of a risk early otitis media presents to later auditory and language development, what skills are most likely to be affected, and what the mechanisms of effect are. Having sufficient information regarding these questions could help clinicians decide how closely to monitor middle-ear status and how aggressively to treat any infections incurred. Research has been ongoing for decades regarding these questions, but outcomes across studies have been equivocal [1–11]. The goal of the current study was to take a fresh look at these issues, specifically addressing two possible confounds in earlier research: (1) Some of the uncertainty regarding auditory functioning may be attributable to variable attention on the part of children during testing. (2) Some of the confusion regarding effects on language acquisition may be attributable to differences in the exact skill being assessed.

1.2. Background

The primary concern regarding otitis media is the temporary hearing

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loss often associated with it, which can result in deprivation of auditory input during critical periods of auditory and language development. These periods of auditory deprivation may hinder the development of the auditory system itself or may instead simply interfere with a child's opportunity to hear the ambient language. Where auditory development is concerned, various processes have been examined, with some revealing deficits years after the otitis media and any associated raised thresholds have resolved. For example, Gravel and Wallace [3] reported that children with positive histories of otitis media require better signal-to-noise ratios to recognize speech in adverse listening conditions than do their peers with negative histories of otitis media. This finding has been supported by others [12,13]. Khavarghazalani et al. [14] observed both poorer binaural processing (dichotic digit test) and poorer temporal processing (gaps in noise) for children with positive histories of otitis media than their peers with negative histories. Of relevance to the current study, McKenna Benoit and colleagues [9] reported raised thresholds for amplitude modulation detection for children with positive histories of otitis media, again compared to same-age peers without such histories. Physiological measures of auditory function have shown some changes associated with early episodes of otitis media [15], suggesting that the behavioral alterations reported here would be expected. Nonetheless, behavioral evidence of delayed or deficient auditory processing has not been observed in all studies. In particular, Hartley and Moore [5] found no evidence of effects on auditory temporal resolution when subjects across groups were carefully matched. Hall and Grose [11] found that the auditory function examined by them – comodulation masking release – returned to age-appropriate levels within months of auditory thresholds returning to normal. Thus, findings across studies remain inconclusive regarding the extent and nature of the impact of early, chronic otitis media on the development of central auditory pathways and associated functions.

Research performed with non-human animals has been similarly inconclusive. Caras and Sanes [16] found that gerbils who had ear plugs for a brief period early in life showed sustained deficits in detection of temporal modulation. On the other hand, Green and colleagues [17] reported that deficits in gap detection exhibited by gerbils after earplugging were resolved following brief exposure to relevant stimuli. In the current study, we evaluated detection of temporal modulation by children either with significant histories of early otitis media or with little-to-no history of otitis media. In particular, we asked whether some of the conflicting evidence could be attributable to differences across the tasks employed by different investigators in how well children maintained general attention, a pervasive concern of scientists interested more broadly in developmental auditory deficits [18]. We addressed this question by constructing a procedure that could demonstrably maintain attention equally well for children with histories of otitis media and for those without significant histories.

The other developmental phenomenon that has been examined for potential consequences of early otitis media is language acquisition. As with auditory functioning, there is conflicting evidence regarding this issue. In this case we find that some language skills show continued deficits years after episodes of otitis media have ended, while others demonstrate no effects. In particular, phonological awareness appears to be especially impacted by early otitis media, while morphological awareness remains intact [2]. We appealed to two well-established psycholinguistic models to construct two alternative hypotheses that might explain how early otitis media could affect language acquisition, taking an especially heavy toll on phonological awareness (i.e., sensitivity). The first model we considered is Duality of Patterning [19,20], which describes the structure of language as bi-level. One level consists of real words and how they can be sequenced to represent relationships among those words. The second level consists of meaningless, word-internal phonological elements and how they can be sequenced to create real words. According to this model, these levels operate mostly independently, and the acquisition of representations at each level can be similarly independent [21].

The psycholinguistic model known as Lexical Restructuring [22,23] is the second model we invoked to construct the hypotheses to be tested. According to this model, a child's earliest linguistic units consist of whole words, largely unanalyzed with respect to internal phonological elements; this level of structure is comprised of spectrally dynamic, broad acoustic patterns. Thus, the child gains access to that first level of language structure (whole words) during initial stages of acquisition. Only as children approach the end of the preschool years do they begin discovering word-internal phonological units, the second level of language structure. Acquiring sensitivity to phonological units requires keener sensitivity to the acoustic details of speech. Therefore, one hypothesis for how early otitis media might affect language acquisition proposes an indirect route: any early deficit in temporal processing – the primary auditory function examined by us – arising from early otitis media would impact language acquisition, taking a toll primarily on phonological sensitivity, rather than lexical knowledge, because phonological sensitivity requires keen access to acoustic structure. To the extent that early otitis media is associated with a risk to lexical (vocabulary) development, the mechanism of effect would likely be the diminished opportunity to hear the ambient language imposed by periods of raised auditory thresholds [7]. In the current study, phonological sensitivity and lexical knowledge were both studied to help identify the mechanism of effect that early otitis media has on language acquisition. If the effect is due to delays in auditory development, phonological sensitivity should primarily be impacted, with strong relationships to temporal processing observed. If the effect is primarily due to a lack of hearing the ambient language, lexical knowledge would be expected to be impacted, without strong relationships to temporal processing.

1.3. *Current study*

In summary, the current investigation had three goals.

(1) To investigate whether deficits in temporal processing arising from early otitis media would be revealed when extreme care was exercised to ensure sustained attention.
(2) To investigate whether there is a stronger effect of early otitis media on the acquisition of phonological sensitivity or lexical knowledge.
(3) To examine whether temporal processing deficits arising from early otitis media are more strongly related to deficits in phonological sensitivity rather than lexical knowledge.

2. Preliminary study

A preliminary study was conducted to determine the most appropriate modulation rates to use in the main experiment; using too many modulation rates could interfere with sustained attention for young children. Tasks measuring temporal modulation detection are thought to rely on different auditory functions depending on modulation rate. At low rates, it is generally agreed that detection relies on recognition of patterns of amplitude change across time, a mostly central function. At higher modulation rates, it is thought that detection reflects the temporal resolution of the auditory system, so detection is more dependent on peripheral function. Although there is not an absolute point of separation, the point where the function involved in detection switches from mostly pattern recognition to mostly temporal resolution is generally thought to occur around 50 Hz modulation [24,25]. The major goal of this preliminary study was to see if the set of modulation rates required in the main experiment could be kept to a minimum, to maintain attention, while still tapping into both pattern recognition and temporal resolution.

2.1. Participants

Participants in the preliminary study were: 30 adults between 18 and 30 years of age; 13 children between 8 and 10 years of age, without significant histories of otitis media (defined as three or fewer episodes before three years of age, as reported by parents), 22 children between 5 and 7 years of age, without significant histories of otitis media (defined as above), and 16 children between 5 and 7 years of age, who had received myringotomy tubes before the age of 3 years, indicating they had a significant history of otitis media and had been diagnosed with middle-ear effusion. All participants were recruited through the distribution of flyers to the university community, local schools, and organizations. All participants were native speakers of American English; English was the only language these children heard in the home. All children were free of other diagnoses that would be expected to impact auditory or language development. Hearing screenings were conducted prior to testing, with pure tones of 0.5, 1.0, 2.0, 4.0, and 6.0 kHz presented at 20 dB sound pressure level to each ear separately. All participants passed these screenings.

2.2. Equipment

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 Soundblaster soundcard, a Samson C-Que 8 amplifier, and AKG-K141 headphones.

2.3. Stimuli and test procedures

All procedures in this preliminary study and in the main experiment were approved by the Institutional Review Board of the University of Florida. The same procedures were largely implemented in this preliminary study as in the main experiment.

For all stimuli, broadband noise (0.05–8.0 kHz) was used, sinusoidally amplitude modulated. In this preliminary study, modulation rates were 4, 16, 64, 128, and 512 Hz. Stimuli had 20-ms cosine-squared ramps at modulation onsets and offsets. Modulation depth (m) varied between 0 and 1, and is described in dB calculated as 20*log(m). All stimuli were 500 ms in duration, and a 400-ms interstimulus interval separated them upon presentation. Fig. 1 shows samples of these stimuli, with unmodulated (standard) stimuli on either side and a modulated (target) stimulus in the center.

One of two games could be used in testing, according to the participant's preference. In one – the 'robot' game – three cartoon robots were shown on the monitor, with the numerals 1 to 3 beneath them. Fig. 2 illustrates this configuration. These robots would pulse in sequence as each of the three stimuli was presented. The participant identified the robot that made a different sound by pointing to that robot and saying the numeral that identified it. That robot would then pulse. Different robots were used on each trial. The other game – the 'meow-meow-woof' game – consisted of three cartoon cat faces, with the numerals 1 to 3 beneath. Each would pulse in sequence as each stimulus was presented. The participant identified the cat that made a different sound, as described above. (Child participants were told that one of the cats was really a dog in disguise and they would know because it made a different sound.) When the participant identified the cat that made a different sound, that cat's face would change to a dog's face. In both games, the experimenter entered the participant's responses into the computer.

Pretest training introduced the procedure and consisted of standard stimuli with no modulation and target stimuli with 0-dB modulation depth (i.e., maximum). For the first few trials, the experimenter provided feedback, but participants needed to respond to nine out of ten consecutive stimuli without feedback to proceed to testing. Each participant was given a maximum of 30 trials in which to reach this criterion. If the participant did not, the participant would have been dismissed. No one failed to reach the criterion for any of the runs, so all proceeded to testing.

During testing, a two-down, one-up adaptive procedure [26] was implemented to obtain the 70.7 % threshold. Matlab scripts controlled a

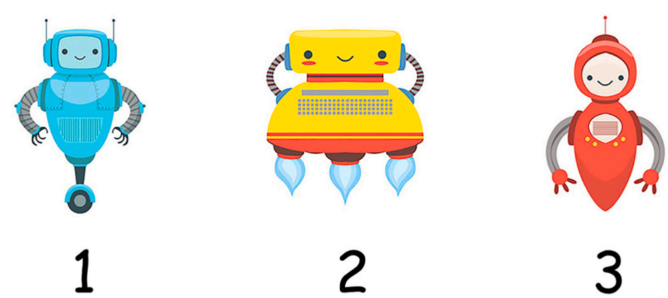

Fig. 2. Images used during testing to help children maintain attention and keep track of stimulus order.

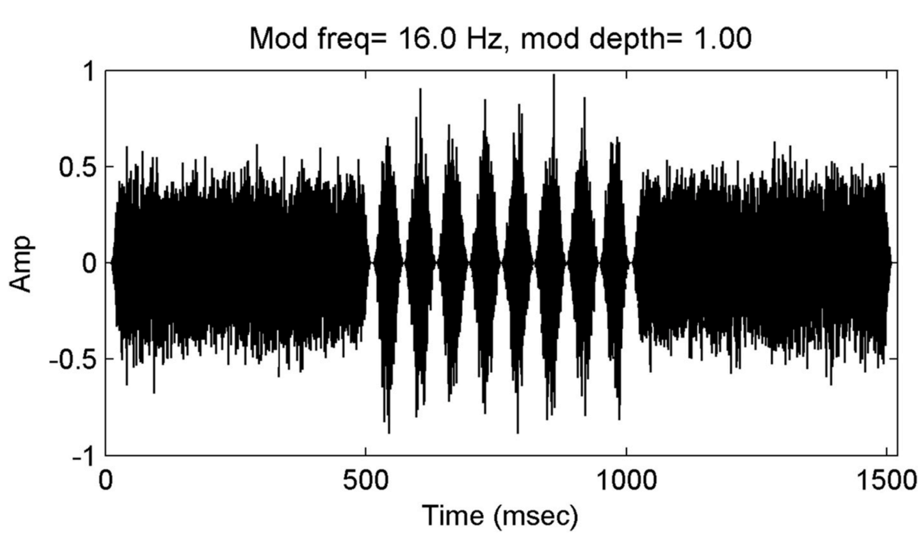

Fig. 1. Sample stimuli with unmodulated (standard) stimuli on either end and the modulated (target) stimulus in the center. In this example the modulated stimulus has a modulation rate of 16 Hz and a modulation depth (m) of 1.0 (0 dB). NOTE: Intervals between stimuli shown are less than the 400-ms interstimulus interval used in experiments.

three-interval, forced choice task in which two stimuli were unmodulated (the standard stimuli) and one stimulus (the target) had the designated modulation rate and depth. Twelve reversals were obtained on each run. Initial depth of the target was 0 dB. Step size was 2 dB for the first 4 reversals, and 1 dB for the last 8 reversals. Thresholds were computed as the means of the last eight reversals. Fig. 3 shows a sample adaptive track. For most participants, thresholds for all modulation rates were obtained on each of two days, in an order that varied across listeners and varied across days for each listener. Attention to the task diminished across a single test session for a few children; in those cases, testing for the last modulation rate was not conducted at that session. However, at least one threshold for every modulation rate was obtained from every participant. More negative thresholds represent better temporal modulation detection.

2.4. General procedures

On the first day of testing, informed consent was obtained from adult participants, or from the parents of child participants. Written assent was obtained from children between 7 and 10 years of age; verbal assent was obtained from children between 5 and 6 years of age. Next the hearing screening was performed. Thresholds for modulation detection at the five rates of modulation were then obtained on the first day of testing. On the second day, threshold measurements for all five rates of temporal modulation were again collected. All stimuli were presented at 68 dB sound pressure level.

2.5. Results and conclusions

Fig. 4 shows temporal modulation transfer functions for adults and children. Because not all children were able to maintain attention to testing across all five modulation rates in a single session, these functions represent the 'best' (i.e., lowest) threshold of each listener to each modulation rate. Based largely on these outcomes, the decision was made to use the modulation rates of 16 and 64 Hz for the main experiment. One additional consideration was that stimuli at the 4-Hz modulation rate may not provide an adequate sample of amplitude prominences with stimuli as brief as 500 ms, an effect observed by others [27,28], and using longer stimuli prolongs testing to the extent that

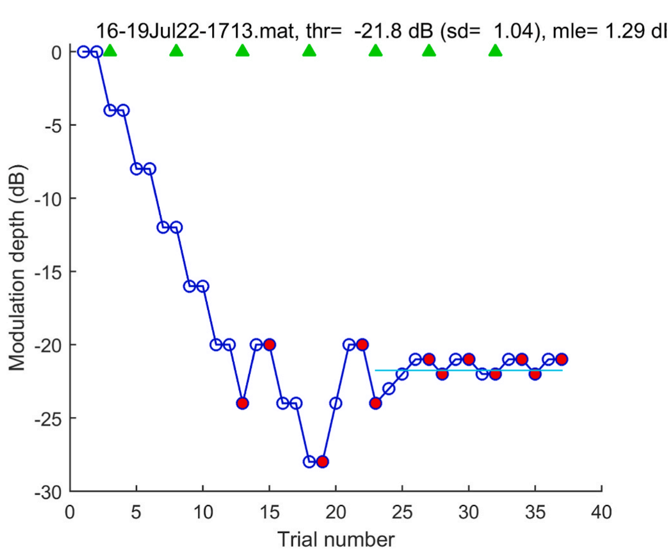

Fig. 3. Sample adaptive track showing reversals as red circles. Step size following the first four reversals was 2 dB; following the last eight reversals it was 1 dB. Green triangles show correct responses to the catch trials; incorrect responses would be represented by red triangles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

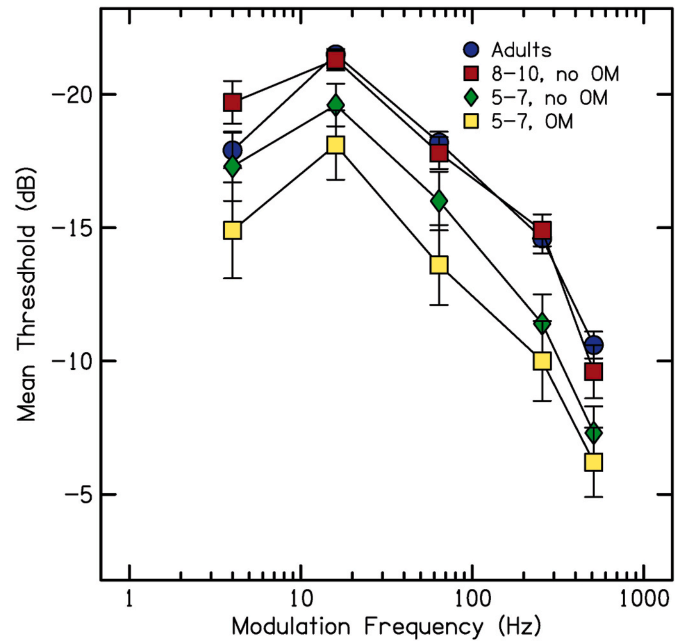

Fig. 4. Temporal modulation transfer functions from preliminary study for adults and three groups of children: 8–10 year olds with no histories of otitis media; 5–7 year olds with no histories of otitis media; 5–7 year olds with histories of otitis media.

participants' attention could be compromised. Another consideration was that children demonstrated the most difficulty responding at modulation rates higher than 64 Hz. For reasons similar to these, the modulation rates of 16 and 64 Hz have been used in past research with school-age children [28].

3. Main experiment

3.1. Participants

Children between 5 years, 0 months and 10 years, 11 months participated. All children were recruited through the distribution of flyers to local schools and organizations. Children with strong histories of otitis media were identified when parents noted on an intake sheet that their children had six or more ear infections before 3 years of age. Children with little-to-no history of otitis media were defined as those with three or fewer incidences recalled by parents. In total, 117 children participated: 68 children without significant histories of early otitis media (53 % male) and 49 children with significant histories of early otitis media (59 % male). All children came from homes where only English was spoken to them, and none had any other condition that could put them at risk for delayed auditory or language development, other than a significant history of otitis media in the case of children in that group. These children were further divided into two groups based on age, because slightly different tests of phonological sensitivity needed to be used for younger and older children. Table 1 provides demographic information for these children, with separate descriptions for children in the Young (5–7 years old) and Old (8–10 years old) Groups. Socioeconomic status (SES) was defined using a two-factor index in which both occupation and highest educational attainment are ranked from 1 to 8, lowest to highest [7]. These scores are multiplied together, and the product serves as the SES index. Neither mean age nor SES differed between groups of children with positive and negative histories of otitis media, but estimated number of ear infections before 3 years was significantly different: for the Young Group, $t(63) = 16.35, p < .001$; for the Old Group, $t(50) = 15.18, p < .001$; and for the overall group, $t(115) = 21.81, p < .001$.

Table 1
Mean demographic information for children with and without significant histories of otitis media, for the Young and Old Groups separately, as well as for the overall group.

	Age (months)		Socioeconomic Status		Estimated Ear Infections <3 Years	
	M	*SD*	M	*SD*	M	*SD*
Young Group						
Typical (35)	80.3	*9.9*	38.6	*15.0*	1.2	*1.1*
OME (30)	78.1	*11.1*	37.9	*13.4*	8.0	*2.1*
Old Group						
Typical (33)	113.4	*10.3*	44.6	*14.0*	1.4	*1.3*
OME (19)	110.2	*10.4*	37.5	*14.9*	9.2	*2.3*
Overall Group						
Typical (68)	96.4	*19.2*	41.5	*14.7*	1.3	*1.2*
OME (49)	91.0	*19.1*	37.7	*13.9*	8.5	*2.3*

NOTE: Socioeconomic status is on a 64-point scale.

Hearing screenings were conducted prior to testing, with pure tones of 0.5, 1.0, 2.0, 4.0, and 6.0 kHz presented at 20 dB sound pressure level to each ear separately. All children passed these screenings.

3.2. Equipment

The same equipment was used in this main experiment as that used in the preliminary study for the hearing screenings and auditory measures. Materials for the phonological task were recorded using an AKG C535 EB microphone, a Shure M268 amplifier, and a Creative Laboratories soundcard. Children's responses for the vocabulary and phonological tasks were video recorded using a SONY HDR-XR550V video recorder, and listeners wore Sony FM transmitters to ensure good sound quality.

3.3. Stimuli and test procedures

3.3.1. Temporal modulation detection

The stimuli and procedures for this main experiment were the same as for the preliminary study, but only stimuli with 16-Hz and 64-Hz modulation rates were used. A threshold for each modulation rate was obtained on each day of testing for all children. For this main experiment, children's attention to the task was carefully monitored. For the most part, it was assumed the game context would maintain children's attention, but that assumption was assessed. Catch trials were interleaved into testing at the rate of one in every five to seven actual trials. Catch trials always used the 0-dB target. If any child had gotten three or more catch trials incorrect, data for that run would have been excluded from analysis, but that never happened. On Fig. 2, the green triangles near the top of the adaptive track indicate correct responses to these catch trials. In addition to catch trials, variability of the last eight reversals was measured, based on the premise that less-attentive children would show greater variability in reversals, with longer excursions between those reversals. For this assessment, a metric termed *mean length of excursion* was developed, which was the mean difference between all adjacent pairs of the last eight reversals. No difference in this metric was observed across groups based on otitis media history. The mean length of excursion was 2.0 dB for children in the Young Group and 1.9 dB for children in the Old Group. Thus, both the catch trials and mean length of excursion indicate that children maintained attention throughout the temporal modulation detection task.

3.3.2. Vocabulary

The Expressive One-Word Picture Vocabulary Test [29] was used to assess vocabulary knowledge. In this task, children were shown a series of pictures and had to label each one in turn. The experimenter recorded responses as correct or incorrect, and testing stopped after six consecutive errors. Standard scores were used in analyses; these scores are normalized based on age.

Expressive vocabulary was selected for use in this study, rather than a receptive measure, because it provides a test of a deeper level of vocabulary knowledge. In a receptive task, the participant hears a word and need only select the picture (out of four) representing that word. This procedure allows a child to respond positively to words that have not yet reached the level of retention, according to the terminology of fast mapping [30]. In an expressive vocabulary task, children see a picture and must retrieve the correct lexical label, thus ensuring that the word has reached the level of retention.

3.3.3. Phonological sensitivity

Two sets of materials were utilized to measure phonological sensitivity because the acquisition of this sensitivity is a developmental process: children acquire sensitivity to word-initial structures before they acquire sensitivity to word-final structures. The two sets of stimuli shared many characteristics, but children in the Young Group were tested for sensitivity to structure at the beginning of words (the Initial Consonant Choice task, or ICC) and children in the Old Group were tested for sensitivity to structure at the ends of words (the Final Consonant Choice task, or FCC). All words used in these tasks were selected to be within the vocabularies of young children, and both tasks have been used extensively in the past (e.g., Ref. [31]). Stimuli for both tasks are listed in the Appendices. In both tasks, the child is presented with a target word via a video of an adult, male talker shown on the computer monitor. The child repeats this target and then the video-recorded talker presents three words. The child must select the word that begins (ICC) or ends (FCC) in the same sound as the target. There are 48 test items in this task, sequenced from simplest to hardest. Six items are presented first as practice. A Matlab program controls testing and keeps track of responses. Testing is discontinued by the software after six consecutive errors. Percent correct scores were used for analyses.

At the start of testing for this main experiment, only the FCC task was used, but the first eight children in the Young Group with no histories of otitis media performed at chance. Thus, it was decided that ICC needed to be used, as well, with all children. With the ICC stimuli, however, the first seven children in the Old Group with no histories of otitis media obtained scores of 100% correct, so testing with ICC was discontinued with that age group. In this report, results for FCC are presented for the Old Group and results of ICC are presented for the Young Group based on these developmental effects.

3.4. General procedures

On the first day of testing, informed consent was obtained from the children's parents, and assent was obtained from the children, either verbal or written, depending on age. Next the hearing screening was performed. Thresholds for temporal modulation detection at both modulation rates were obtained on the first day of testing, along with either the vocabulary measure or the measure of phonological sensitivity. On the second day, thresholds for temporal modulation detection at both modulation rates, along with either the vocabulary measure or the measure of phonological sensitivity (whichever had not been collected on the first day) were obtained. All stimuli were presented at 68 dB sound pressure level.

After testing, an independent laboratory staff member reviewed the video recordings of vocabulary and phonological sensitivity testing to ensure that all recorded answers were correct. Although rare, an item was corrected if it had been scored incorrectly. SPSS software was used for analyses.

4. Results

4.1. Group differences

The first analyses were performed to assess potential differences in performance between children with and without histories of otitis media. Fig. 5 shows outcomes for temporal modulation detection and Fig. 6 shows outcomes for the two language measures. These outcomes are shown separately for the Young and the Old groups: Because separate analyses needed to be done for the measures of phonological sensitivity, it seemed reasonable to do separate analyses for all measures. Welch's *t* tests were used to compare means, as is appropriate when there are unequal numbers of participants across groups. These outcomes are shown on Table 2, with results across age groups and results for age groups separately shown for the temporal modulation and vocabulary measures. One-sided *p* values are reported, because the prediction was clearly that the children with positive otitis media histories would perform more poorly. Across all measures, children with histories of otitis media generally performed more poorly than children without those histories, for both age groups, with moderate effect sizes observed. The one exception to this trend involved temporal modulation detection thresholds at the 16-Hz modulation rate, for children in the Young group. Nonetheless, Fig. 5 indicates that the distribution of scores for the children in the Young group with otitis media histories extends to poorer thresholds. Where language measures are concerned, the deleterious effects of early, chronic otitis media were larger for phonological sensitivity than for vocabulary scores for both age groups.

4.2. Correlational analyses

The second set of analyses performed were Pearson product-moment correlations. These analyses were performed to investigate the magnitude of relationship between temporal modulation detection thresholds at each modulate rate and each language measure: vocabulary knowledge and phonological sensitivity. The correlation coefficients were computed for each of the four groups (age x otitis media history) separately, and results are shown on Table 3. Children in the Old Group with no histories of otitis media showed no significant relationships among these measures. For the other three groups, vocabulary scores did not correlate with temporal modulation detection thresholds at either modulation rate. Phonological sensitivity, however, showed significant correlations with temporal modulation detection thresholds. Furthermore, for children in the Young Group without histories of otitis media, significantly stronger correlations were found for phonological sensitivity with thresholds at 16 Hz than for thresholds at 64 Hz, test statistic $z = -1.809$, $p = .035$. Although that pattern is seen in correlation coefficients for the other two groups, neither *z* statistic was significant.

Although it was not statistically significant, the correlation coefficient between temporal modulation detection thresholds and vocabulary scores for children in the Old group with positive otitis media histories was moderately high at −.442. Because the correlation coefficient was also moderately high between temporal modulation detection thresholds and phonological sensitivity for this group, the question could be asked of whether one language skill mediated the relationship involving the other language skill. To address that question, partial correlation coefficients were computed between temporal modulation detection thresholds and each language skill, controlling for the effects of the other language skill. Where phonological sensitivity is concerned, controlling for vocabulary scores had little effect, partial $r(16) = -0.503$, $p = .033$. On the other hand, when phonological sensitivity was controlled, the relationship between temporal modulation detection thresholds and vocabulary scores was eliminated, partial $r(16) = -0.291$, $p > .10$. Thus, for these older children with positive otitis media histories, the relationship between temporal modulation detection and phonological sensitivity completely accounted for the relationship

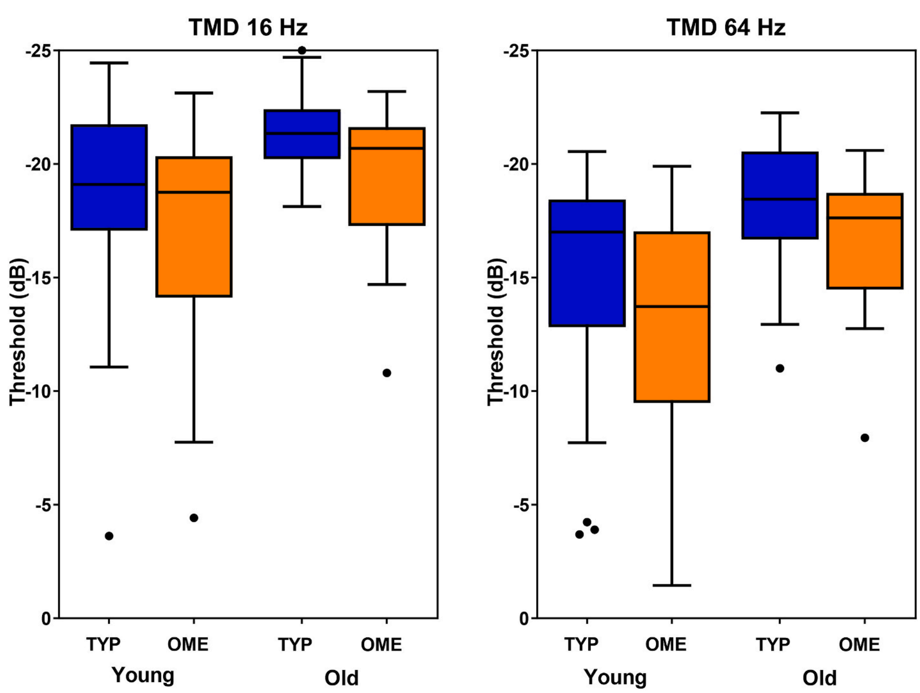

Fig. 5. Tukey box and whisker plots for temporal modulation detection thresholds for modulation rates of 16 Hz and 64 Hz for children with no histories of otitis media and children with histories of otitis media. Results for the Young Group and the Old Group shown separately.

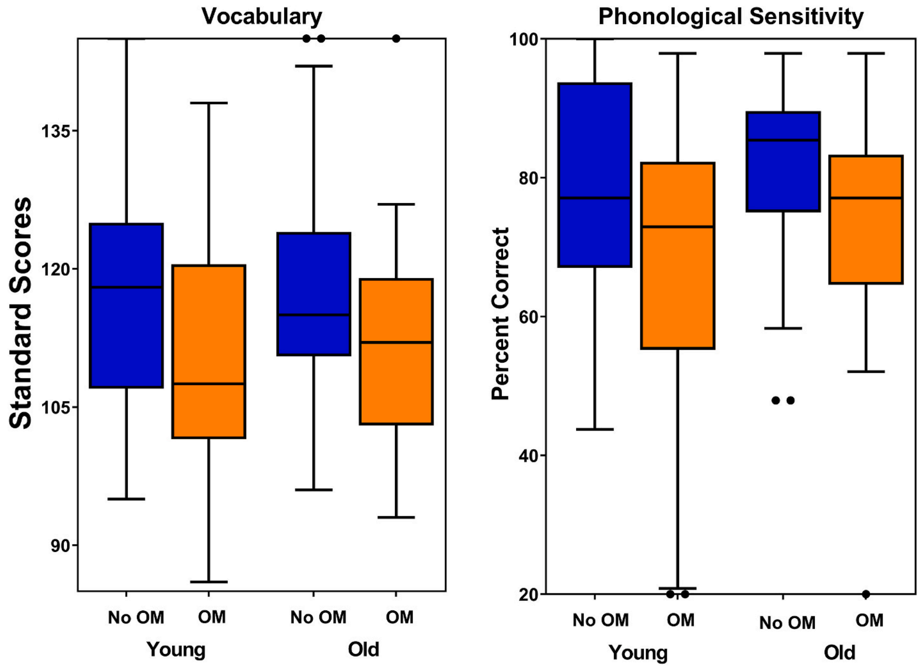

Fig. 6. Tukey box and whisker plots for both language measures for children with no histories of otitis media and children with histories of otitis media. Results for the Young Group and the Old Group shown separately.

Table 2
Results of Welch's *t* tests computed on dependent measures.

	Welch's t	df	p	Hedges' g
16-Hz TM Thresholds				
Across age groups	−2.57	92.834	.006	−0.49
5–7 year olds	−1.10	59.107	.138	-0.27
8–10 year olds	−2.88	24.901	.004	−0.94
64-Hz TM Thresholds				
Across age groups	−3.05	91.339	.001	−0.59
5–7 year olds	−2.052	57.970	.022	−0.51
8–10 year olds	−2.309	33.135	.014	−0.68
Vocabulary				
Across age groups	2.61	98.323	.005	0.49
5–7 year olds	2.19	59.606	.016	0.54
8–10 year olds	1.31	35.815	.099	0.39
Phonological Sensitivity				
5–7 year olds	2.66	48.986	.005	0.68
8–10 year olds	1.75	26.990	.046	0.55

Table 3
Pearson product-moment correlation coefficients between temporal modulation detection thresholds and each language measure.

	Vocabulary			Phonol. Sensitivity		
	df	r	*p*	df	r	*p*
Young Group, No OM History						
16-Hz thresholds	35	−.014	> *.10*	27	−.676	< *.001*
64-Hz thresholds	35	−.012	> *.10*	27	−.417	*.030*
Young Group, OM History						
16-Hz thresholds	30	−.293	> *.10*	30	−.413	*.023*
64-Hz thresholds	30	−.321	*.084*	30	−.370	*.044*
Old Group, No OM History						
16-Hz thresholds	33	−.056	> *.10*	33	−.087	> *.10*
64-Hz thresholds	33	−.278	> *.10*	33	−.306	*.083*
Old Group, OM History						
16-Hz thresholds	19	−.442	*.058*	19	−.586	*.008*
64-Hz thresholds	19	−.135	> *.10*	19	−.291	> *.10*

observed with vocabulary, most likely due to vocabulary abilities at this older age being somewhat dependent on sensitivity to phonological structure.

5. Discussion

Otitis media in infants and children is a common problem, but uncertainty has prevailed regarding potential long-term consequences. The study reported here had three goals. First, we strove to ensure that all children participating in the experiment would demonstrate sustained attention to the task, so that measures of temporal modulation detection would be as sensitive and reliable as possible. In pursuit of that goal, we developed procedures that were sufficiently interesting to children in the age range tested, and assessed their attention both by interspersing trials at maximum modulation depth and by assessing variability of responding around the computed threshold. Both measures revealed that children in both groups maintained attention. Using these methods, significant group differences were found for detection of temporal modulation, with moderate effect sizes for the most part. Although some children with positive otitis media histories showed similar temporal modulation detection thresholds as the average child without those histories, there is clearly evidence of risk imposed by early, chronic otitis media.

The second goal of this study was to evaluate children's knowledge and skill regarding two levels of language structure: whole words (vocabulary) and word-internal phonological structure. The purpose was to assess whether previous, conflicting results about potential effects of otitis media on language acquisition might be related to the language structure being assessed. Specifically, we examined whether it is possible that studies examining knowledge and skills affiliated with lexical structure, including how lexical items are sequenced (i.e., syntax), might be less likely to show effects than studies examining skills related to phonological structure. Here we observed that the magnitude of effect of early otitis media on phonological sensitivity was greater than the magnitude of effect on lexical knowledge, a claim supported by the fact that effects were larger for phonological than for vocabulary scores. Thus, the hypothesis tested as the second goal of this study was supported: otitis media had a stronger effect on phonological sensitivity than on lexical knowledge.

The third goal in this work was to examine whether the mechanisms of effect of otitis media on skills with those two levels of language structure might differ. It was hypothesized that any effect of otitis media on lexical knowledge would arise from not having ample access to the ambient language; any effect of otitis media on phonological sensitivity was hypothesized to arise from deficits in the auditory functions providing access to details of the speech signal. Outcomes of the correlational analyses revealed significant relationships between the temporal modulation detection thresholds and phonological sensitivity, but not between those thresholds and vocabulary scores. Thus, support is provided for the proposal that there are different mechanisms accounting for how otitis media affects language acquisition for these two levels of language structure. As a group, children with positive histories of otitis media showed poorer vocabulary knowledge than the children with negative histories of otitis media, but that effect was not related to auditory measures, suggesting that the deficits in vocabulary acquisition observed for children with otitis media histories arise due to diminished opportunities to hear the ambient language. Phonological sensitivity was poorer for children with positive otitis-media histories, as well, but these measures were related to the auditory measures. Thus, the suggestion is supported that these deficits are based on those weaker auditory abilities.

5.1. Limitations and future directions

The goals of this study were met, but there are a couple limitations worth noting. First, group membership as a child with or without a history of otitis media was dependent only on parental report. Consequently, information on the duration and extent of raised auditory thresholds among the children with otitis media histories was not available and could not be used to define group membership more exactly. There was surely variability in duration and extent of raised thresholds and that variability would likely influence outcomes. Similarly, the children who were categorized as not having significant histories of otitis media may have had more episodes than their parents knew about, or recalled, given how difficult accurate diagnoses can be. Thus, the groups in this study may not have been as well distinguished based on otitis media and hearing loss history as would be desired. Nonetheless, precisely because significant differences between the groups were observed, in spite of this limitation, it may be concluded that early otitis media is at least a serious risk factor for developmental delay and deficit in the kinds of auditory and language functions studied here. The clinical implication is that infants and young children should be monitored for otitis media, and medical, surgical, and behavioral interventions implemented as quickly and completely as possible if frequent episodes occur. Future research on the effects of otitis media on auditory and language development need to be designed with the findings here in mind.

Another limitation involved in the current study was that auditory thresholds were not obtained above 6 kHz. Frequent infection within the middle-ear cavity can cross into the cochlea, leading to hearing loss in the high frequencies [32]. Future studies investigating potential effects of early, chronic otitis media on auditory development should measure auditory thresholds in frequencies higher than 6 kHz, as raised thresholds in those frequencies could affect both auditory and language functions. Nonetheless, animal models of temporary conductive hearing loss have shown deficits in auditory temporal processes similar to those observed in the current study [16]. Because the methods implemented in that work would not have put the animals at risk of sensorineural hearing loss it is doubtful that high-frequency hearing loss alone could have accounted for the findings reported here.

Temporal modulation depth detection thresholds were measured for two modulation rates, because it was hypothesized that sensitivity to low and high modulation rates may develop on different time tables, and may be differentially affected by early, chronic otitis media. However, little difference in effects was observed for the 16-Hz and 64-Hz modulation rates. The only potential difference is that there appears to be a stronger relationship between temporal modulation detection thresholds and phonological sensitivity when modulation detection is measured at the lower, 16-Hz, modulation rate. That finding may reflect the fact that lower modulation rates correspond more closely to the temporal envelope of the speech signal than do higher modulation rates, which correspond to temporal fine structure. To test that proposal, future studies will need to test children at modulation rates that are even more different from one another than those used here; that is, thresholds at lower and higher modulation rates will need to be collected, in spite of the challenges in doing so.

Finally, concern might exist that the significant correlation coefficients between temporal modulation depth detection thresholds and phonological sensitivity may reflect the fact that similar procedures were used for these two measures. For both, three-alternative, forced-choice procedures were used: in the first, the child needed to identify the interval with the different stimulus; in the second, the child needed to identify the interval with the stimulus that matched a target. These procedures differed from those used to assess vocabulary knowledge, which largely showed no relationship to temporal modulation detection. Future work will need to examine whether the strong relationship between temporal modulation detections thresholds and phonological sensitivity holds when different methods are used. Nonetheless, it may be suggested that this similarity in procedures likely does not account for the strong correlations observed between temporal modulation depth detection and phonological sensitivity, because some variability was observed in the magnitude of this relationship across subject age and modulation rate.

5.2. Summary

Otitis media is a common medical condition of childhood, affecting children during the most critical periods of auditory and language development. Sensory input through the auditory modality is essential at young ages to ensure proper development of central auditory pathways, suprathreshold auditory functions, and language abilities. It would seem apparent in prima facie manner that disruptions in auditory input and language experience at these ages would disrupt typical development. Nonetheless, the question of whether such disruption leads to long-lasting deficits has been strongly debated in the literature. This current study addressed three specific hypotheses for why outcomes across studies may be so variable: (1) General attention to the tasks, especially the auditory tasks, may differ across children in such a way as to hinder children with positive histories of otitis media more strongly than children without those histories; (2) Early, chronic otitis media, and any accompanying delays in auditory development, may hinder the acquisition of phonological sensitivity more than vocabulary development; and (3) Different aspects of the barriers imposed by early, chronic otitis media may affect different aspects of language development; specifically, delays in the development of suprathreshold auditory skills may affect the acquisition of phonological sensitivity, whereas reduced opportunity to hear the ambient language may affect vocabulary development. Although future research efforts will be required to replicate the findings reported here, evidence was gathered to support each of these hypotheses.

Declaration of competing interest

Neither author has any conflict of interest regarding this work.

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Appendix A. Initial Consonant Choice

Practice Examples

1. pet	fire	pack	night	4. ball	book	seed	mouth
2. blue	bag	fox	egg	5. face	pig	fur	top
3. cake	sheep	note	kite	6. seal	can	dog	sun

Test Trials

1. milk	date	moon	bag	25. clean	spoon	free	cry
2. pear	pen	tile	mask	26. lamb	lick	juice	cage
3. stick	slide	drum	flag	27. dog	dart	fall	girl
4. bone	meat	lace	bud	28. rake	pig	root	bike
5. soap	king	dime	salt	29. meat	mice	new	doll
6. claw	prize	crib	stair	30. boot	cat	bus	push
7. leg	pin	lock	boat	31. nail	lay	nut	bye
8. duck	door	soup	light	32. stop	skirt	train	crawl
9. plum	tree	star	price	33. top	two	gum	big
10. key	fist	cap	sap	34. hen	save	down	have
11. zip	zoo	web	man	35. keep	rock	bark	kiss
12. gate	sun	bin	gum	36. clap	crab	tree	slip
13. rug	can	rag	pit	37. queen	wheel	gift	quit
14. sky	sleep	crumb	drip	38. hot	hill	fence	base
15. fun	dark	pet	fan	39. jog	jar	dig	cow
16. peel	wash	pat	vine	40. zap	game	zoom	bed
17. grape	class	glue	swing	41. dot	pink	fish	dime
18. leap	lip	note	wheel	42. bat	song	barn	fun
19. house	rain	heel	kid	43. fly	truck	fruit	skip
20. toes	bit	girl	tip	44. need	nose	hop	draw
21. win	well	foot	pan	45. wall	deer	leaf	web
22. met	map	day	box	46. van	vase	part	like
23. sled	frog	brush	stick	47. town	dip	tick	king
24. jeep	lock	pail	jug	48. glow	fry	drop	grass

**Discontinue after 6 consecutive errors.

Appendix B. Final Consonant Choice

Practice Examples

1. rib	mob	phone	heat	4. lamp	rock	juice	tip
2. stove	hose	stamp	cave	5. fist	hat	knob	stem
3. hoof	shed	tough	cop	6. head	hem	rod	fork

****Discontinue after 6 consecutive errors.**

Test Trials

1. truck	wave	bike	trust	25. desk	path	lock	tube
2. duck	bath	song	rake	26. home	drum	prince	mouth
3. mud	crowd	mug	dot	27. leaf	suit	roof	leak
4. sand	sash	kid	flute	28. thumb	cream	tub	jug
5. flag	cook	step	rug	29. barn	tag	night	pin
6. car	foot	stair	can	30. doll	pig	beef	wheel
7. comb	cob	drip	room	31. train	grade	van	cape
8. boat	skate	frog	bone	32. bear	shore	clown	rat
9. house	mall	dream	kiss	33. pan	skin	grass	beach
10. cup	lip	trash	plate	34. hand	hail	lid	run
11. meat	date	sock	camp	35. pole	land	poke	mail
12. worm	price	team	soup	36. ball	clip	steak	pool
13. hook	mop	weed	neck	37. park	bed	lake	crown
14. rain	thief	yawn	sled	38. gum	shoe	gust	lamb
15. horse	lunch	bag	ice	39. vest	cat	star	mess
16. chair	slide	chain	deer	40. cough	knife	log	dough
17. kite	bat	mouse	grape	41. wrist	risk	throat	store
18. crib	job	hair	wish	42. bug	bus	leg	rope
19. fish	shop	gym	brush	43. door	pear	dorm	food
20. hill	moon	bowl	hip	44. nose	goose	maze	zoo
21. hive	glove	light	hike	45. nail	voice	chef	bill
22. milk	block	mitt	tail	46. dress	tape	noise	rice
23. ant	school	gate	fan	47. box	face	mask	book
24. dime	note	broom	cube	48. spoon	cheese	back	fin

References

[1] S. Friel-Patti, Otitis media with effusion and the development of language: a review of the evidence, Top. Lang. Disord. 11 (1990) 11–22.
[2] J.M. Carroll, H.L. Breadmore, Not all phonological awareness deficits are created equal: evidence from a comparison between children with Otitis Media and poor readers, Dev. Sci. 21 (2018), e12588.
[3] J.S. Gravel, I.F. Wallace, Listening and language at 4 years of age: effects of early otitis media, J. Speech Hear. Res. 35 (1992) 588–595.
[4] J.L. Paradise, Otitis media during early life: how hazardous to development? A critical review of the evidence, Pediatrics 68 (1981) 869–873.
[5] D.E. Hartley, D.R. Moore, Effects of otitis media with effusion on auditory temporal resolution, Int. J. Pediatr. Otorhinolaryngol. 69 (2005) 757–769.
[6] M. Mody, R.G. Schwartz, J.S. Gravel, R.J. Ruben, Speech perception and verbal memory in children with and without histories of otitis media, J. Speech Lang. Hear. Res. 42 (1999) 1069–1079.
[7] S. Nittrouer, L.T. Burton, 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, J. Commun. Disord. 38 (2005) 29–63.
[8] S. Rvachew, E.B. Slawinski, M. Williams, C.L. Green, The impact of early onset otitis media on babbling and early language development, J. Acoust. Soc. Am. 105 (1999) 467–475.
[9] M. McKenna Benoit, M. Orlando, K. Henry, P. Allen, Amplitude modulation detection in children with a history of temporary conductive hearing loss remains impaired for years after restoration of normal hearing, J. Assoc. Res. Otolaryngol. 20 (2019) 89–98.
[10] R.J. Eapen, E. Buss, J.H. Grose, A.F. Drake, M. Dev, J.W. Hall, The development of frequency weighting for speech in children with a history of otitis media with effusion, Ear Hear. 29 (2008) 718–724.
[11] J.W. Hall, J.H. Grose, Effect of otitis media with effusion on comodulation masking release in children, J. Speech Hear. Res. 37 (1994) 1441–1449.
[12] H.N. Shetty, V. Koonoor, Sensory deprivation due to otitis media episodes in early childhood and its effect at later age: a psychoacoustic and speech perception measure, Int. J. Pediatr. Otorhinolaryngol. 90 (2016) 181–187.
[13] A. Zumach, E. Gerrits, M.N. Chenault, L.J. Anteunis, Otitis media and speech-in-noise recognition in school-aged children, Audiol. Neurootol. 14 (2009) 121–129.
[14] B. Khavarghazalani, F. Farahani, M. Emadi, D.Z. Hosseni, Auditory processing abilities in children with chronic otitis media with effusion, Acta Otolaryngol. 136 (2016) 456–459.
[15] L.R. Borges, M.D. Sanfins, C. Donadon, D. Tomlin, M.F. Colella-Santos, Long-term effect of middle ear disease on temporal processing and P300 in two different populations of children, PLoS One 15 (2020), e0232839.
[16] M.L. Caras, D.H. Sanes, Sustained perceptual deficits from transient sensory deprivation, J. Neurosci. 35 (2015) 10831–10842.
[17] D.B. Green, M.M. Mattingly, Y. Ye, J.D. Gay, M.J. Rosen, Brief stimulus exposure fully remediates temporal processing deficits induced by early hearing loss, J. Neurosci. 37 (2017) 7759–7771.
[18] D.R. Moore, Editorial: auditory processing disorder, Ear Hear. 39 (2018) 617–620.
[19] C.F. Hockett, The origin of speech, Sci. Am. 203 (1960) 89–96.
[20] D.R. Ladd, What is duality of patterning, anyway? Lang. Cognit. 4 (2012) 261.
[21] S. Nittrouer, J. Antonelli, J.H. Lowenstein, The emergence of bifurcated structure in children's language, J. Exp. Psychol. Gen. 151 (2022) 3045–3059.
[22] S. Ainsworth, S. Welbourne, A. Hesketh, Lexical restructuring in preliterate children: evidence from novel measures of phonological representation, Appl. Psycholinguist. 37 (2016) 997–1023.
[23] M.M. Vihman, Learning words and learning sounds: advances in language development, Br. J. Psychol. 108 (2017) 1–27.
[24] J.W. Hall III, J.H. Grose, Development of temporal resolution in children as measured by the temporal modulation transfer function, J. Acoust. Soc. Am. 96 (1994) 150–154.
[25] B.A. Walker, C.M. Gerhards, L.A. Werner, D.L. Horn, Amplitude modulation detection and temporal modulation cutoff frequency in normal hearing infants, J. Acoust. Soc. Am. 145 (2019) 3667.
[26] H. Levitt, Transformed up-down methods in psychoacoustics, J. Acoust. Soc. Am. 49 (1971) 467–477.
[27] N.F. Viemeister, Temporal modulation transfer functions based upon modulation thresholds, J. Acoust. Soc. Am. 66 (1979) 1364–1380.
[28] E. Buss, C. Lorenzi, L. Cabrera, L.J. Leibold, J.H. Grose, Amplitude modulation detection and modulation masking in school-age children and adults, J. Acoust. Soc. Am. 145 (2019) 2565.
[29] N. Martin, R. Brownell, Expressive One-word Picture Vocabulary Test (EOWPVT-4), Academic Therapy Publications, Inc., Novato, CA, 2011.
[30] E.A. Walker, K.K. McGregor, Word learning processes in children with cochlear implants, J. Speech Lang. Hear. Res. 56 (2013) 375–387.
[31] S. Nittrouer, A. Caldwell-Tarr, E. Sansom, J. Twersky, J.H. Lowenstein, Nonword repetition in children with cochlear implants: a potential clinical marker of poor language acquisition, Am. J. Speech Lang. Pathol 23 (2014) 679–695.
[32] J. Zhang, S. Chen, Z. Hou, J. Cai, M. Dong, X. Shi, Lipopolysaccharide-induced middle ear inflammation disrupts the cochlear intra-strial fluid-blood barrier through down-regulation of tight junction proteins, PLoS One 10 (2015), e0122572.