Amplitude modulation detection and temporal modulation cutoff frequency in normal hearing infants^{a)}

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The goal of this study was to determine if temporal modulation cutoff frequency was mature in three-month-old infants. Normal-hearing infants and young adults were tested in a single-interval forced-choice observer-based psychoacoustic procedure. Two parameters of the temporal modulation transfer function (TMTF) were estimated to separate temporal resolution from amplitude modulation sensitivity. The modulation detection threshold (MDT) of a broadband noise amplitude modulated at 10 Hz estimated the y-intercept of the TMTF. The cutoff frequency of the TMTF, measured at a modulation depth 4 dB greater than the MDT, provided an estimate of temporal resolution. MDT was obtained in 27 of 33 infants while both MDT and cutoff frequency was obtained in 15 infants and in 16 of 16 adults. Mean MDT was approximately 10 dB poorer in infants compared to adults. In contrast, mean temporal modulation cutoff frequency did not differ significantly between age groups. These results suggest that temporal resolution is mature, on average, by three months of age in normal hearing children despite immature sensitivity to amplitude modulation. The temporal modulation cutoff frequency approach used here may be a feasible way to examine development of temporal resolution in young listeners with markedly immature sensitivity to amplitude modulation. © 2019 Acoustical Society of America. <https://doi.org/10.1121/1.5111757>

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I. INTRODUCTION

The capacity to discriminate changes in a sound's intensity over time is crucial for understanding speech in normal hearing and hearing-impaired individuals.¹ Although fluctuations slower than 50 Hz, known as “envelope cues,” are sufficient to provide cochlear-implanted listeners with the ability to understand speech in quiet,² faster temporal characteristics including periodicity and fine structure cues are variably incomplete or absent for these patients. Thus, important acoustic cues for speech voicing, stress, and intonation may be lost¹ as well as cues relevant for music perception.³

Re-establishment of temporal cues through improved signal processing is an active field of cochlear implant research aimed at improving efficacy of these devices.^{4–6} Several studies have demonstrated that acoustic temporal perception measured by various tasks is predictive of speech processing in adult cochlear implant users.^{7–9} Furthermore, it has been suggested that temporal perception could be a potential marker of CI efficacy and benefit for CI users who are too young or otherwise unable to undergo speech perception testing. Development of such a behavioral test for use with young listeners was the primary motivation for the present study.

Given the immature auditory system of young listeners, it is not surprising to find gradual development of their

sensitivity to changes in sound intensity over time. Behavioral sensitivity to acoustic temporal changes matures over a long time period, for some tasks through adolescence.¹⁰ For instance, infants' gap detection and duration discrimination is an order of magnitude worse than adults'.¹¹ Gap detection remains immature until 6–12 years of age,^{11–13} whereas duration discrimination does not mature until at least 10 years of age.¹⁴ Interestingly, when gap detection was measured in infants and adults using the auditory brainstem response, electrophysiological thresholds were found to be adult-like down to 3 months of age suggesting that underlying neural representation of the gap is mature much earlier than the behavioral response would suggest. Evidence for earlier maturation has also been seen for temporal masking tasks. Susceptibility to forward masking becomes mature by 6 months of age^{15,16} whereas children remain more susceptible to backward masking through 5–10 years old, although the severity of the age effect is task dependent.^{15,17}

Immature psychoacoustic performance of children is not unique to temporal processing. Gradual improvement with age, observed across a range of tasks and methodologies, is fundamental to nearly all aspects of hearing development.^{10,18} One model to account for this prolonged development is the idea that listeners' performance on any psychoacoustic task depends on two independent factors: “processing efficiency” and “auditory resolution.”¹⁸ In other words, “temporal resolution” reflects the auditory system's ability to accurately encode changes in intensity over time and depends on maturation of basic neural mechanisms including phase locking and neural

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synchrony. In contrast, processing efficiency includes the effect of variables such as intensity resolution, physiological noise, and attention that affect performance on listening tasks, independent of the subjects' temporal resolution. In this model, processing efficiency affects task performance in general, whereas temporal resolution affects task performance at higher rates of acoustic change. Because attention and other non-sensory effects can be controlled with standard psychophysical test methods, intensity resolution is the primary contributor to processing efficiency in well-trained, adult listeners. However, non-sensory variables are likely to contribute to processing efficiency in young listeners.

This efficiency/temporal resolution model can be applied to an amplitude modulation detection task where the modulation depth required to detect modulation is measured at various modulation rates to derive the temporal modulation transfer function (TMTF).¹⁹ The TMTF describes the relationship between modulation rate and the modulation depth required to detect amplitude modulation of a sound. Modulation depth is typically expressed in decibels:

$$\text{Depth(dB)} = 20 * \log_{10}(M),$$

where M is the modulation index, or the proportion of modulation relative to the carrier amplitude. The TMTF resembles the response of a low-pass filter with a cutoff frequency of 50–60 Hz and high-frequency slope of about 3-dB/octave. At low modulation rates, performance is limited primarily by processing efficiency. Thus, the overall height of the function reflects processing efficiency. In contrast, the temporal modulation cutoff frequency (TMCf) and high frequency slope of the TMTF reflect the additional limits imposed by temporal resolution at faster modulation rates. Hypothetical functions from listeners with mature and immature TMTFs are shown in Fig. 1.

Hall and Grose have shown that the general shape of the TMTF in children down to age 4 years is similar to that seen

FIG. 1. Temporal modulation transfer functions and two-point TMCf results for three hypothetical groups of listeners are shown in (b). Function #1 is derived from the y-intercept and TMCf parameters for adult normal hearing listeners reported by Park *et al.* (Ref. 21). Function 2 (immature MDT, mature temporal resolution), derived from 60% poorer MDT but mature TMCf compared to NH adults from Park *et al.*, is the hypothetical function for infants with mature temporal resolution. Function 3 (immature MDT and temporal resolution), derived from 60% poorer (larger depth) MDT and 36% poorer (slower rate) TMCf compared to NH adults from Park *et al.*, is the hypothetical function for infants with immature temporal resolution.

in adults.²⁰ They compared the TMTF of adults to that of children aged 4 to 10 years and determined TMCf and high frequency TMTF slopes. While modulation detection thresholds at low modulation rates were not mature until nine to ten years, the TMCf and slope did not differ significantly among age groups. These results suggest that while processing efficiency continues to develop until nine to ten years, temporal resolution is mature by 4 years old.

A similar approach was used by Park *et al.* to examine TMTFs in four groups of listeners: postlingually deaf adult CI users, normal hearing adults, prelingually deaf cochlear implanted children (7–16 years old) and normal-hearing children (8–14 years old).²¹ Although TMCf was lower for CI users relative to normal hearing listeners, no age differences in TMCf were seen within hearing method. A different pattern of results was observed for the overall height of the TMTF. While TMTF height was adult-like in normal hearing children, children with CIs showed lower TMTF height than CI adults suggesting that development of processing efficiency for acoustic modulation detection was atypical in these children relative to their normal hearing peers.²¹ This study illustrates the importance of examining temporal resolution and processing efficiency independently in young children with atypical auditory input during development.

To date, investigations of TMTF shape have not been reported in children younger than 4 years of age. An important practical limitation for measuring TMTFs in younger children is that it is very difficult to obtain sufficient data to describe the function in an individual child. Thus, it would be potentially beneficial to develop a method to estimate TMTF parameters without having to obtain many modulation detection thresholds at different modulation frequencies.^{19,20} Previously, Shen and Richards used a fast Bayesian procedure to measure TMTF parameters directly and showed excellent concordance between this method and parameters derived from the traditional approach.²² However, this method would be difficult to adapt to an inattentive listener who is tested across multiple sessions and test visits. For the present study, we developed a two-point method to derive the TMTF parameters from individual listeners. This method assumes that the infant TMTF has the same low-pass filter form as the TMTF of older children and adults. First, the listener's modulation detection threshold (MDT) was determined by varying modulation depth in dB at 10 Hz. This threshold gives an estimate of the y-intercept of the TMTF. The TMCf was then measured at a modulation depth 4 dB above the MDT by varying modulation rate. Hypothetical points are shown in Fig. 1 and a schematic of the two-point method is shown in Fig. 2.

Our first aim was to determine feasibility of measuring the TMCf in individual infants using the two-point method with an observer-based psychoacoustic method. The second aim was to determine whether the TMCf was mature in three-month-old infants. Based on previous literature,²³ it was hypothesized that infant temporal resolution, as measured by the TMCf, would be mature at 3 months of age. However, it was expected that infants would show markedly poorer amplitude modulation detection thresholds than adults.

FIG. 2. Steps to measure 10 Hz MDT and then to measure TCMF at 4 dB greater than MDT are illustrated. In step 1, modulation rate is fixed at 10 Hz and modulation depth is varied to find the smallest depth at which the listener can detect modulation (MDT). In step 2, modulation depth is fixed at 4 dB greater than the MDT and modulation rate is varied to find the fastest modulation rate at which the listener can detect modulation (TCMF).

II. METHODS

Institutional review board approval at the University of Washington was obtained prior to initiation of the study.

A. Subjects

Sixteen adult listeners and 33 3-month-old infants were recruited for this study. Infants were recruited from the Communication Studies Participant Pool at the University of Washington. Infants met the following inclusion criteria: full-term birth (at least 38 weeks gestation), passed newborn hearing screening bilaterally, no diagnosed hearing loss or developmental delay, no family history of hearing loss, no history of otitis media within three weeks of testing, no more than two previous episodes of otitis media, and no risk factors for hearing loss.²⁴ Infants were tested at 12 ± 1 week with the exception of one infant who was tested at 15 weeks due to scheduling issues. The adult subjects reported no hearing loss, no significant noise exposure, and no prior psychoacoustic testing. The average age of adult subjects ranged from 18 to 25 years ($M = 20.1$ years). All participants were screened using either tympanometry with a 226 Hz probe (pass criteria were peak admittance ≥ 0.2 mmhos and pressure between -200 and $+50$ daPa) or distortion product otoacoustic emission screen (Otodynamics, Alabama, USA). The lab adapted the latter screening method during the course of the study. Compensation for each participant was \$15 per hour.

B. Stimuli

Unmodulated and modulated stimuli were created. Unmodulated stimuli were ten 2-s random samples of Gaussian noise with sampling frequency 44.1 kHz. Modulated noises were created based on the equation

$$y(t) = [f(t)] \times [1 + m_i \sin(2\pi f_m t)],$$

where $f(t)$ = noise carrier, m_i = modulation index, f_m = modulation frequency (or rate), and t = time. The final modulated

stimulus consisted of 1 s of unmodulated noise concatenated with 1 s of modulated noise. This transition was not audible at the lowest modulation depths based on careful informal listening checks by the coauthors.

Modulation depth varied from 100% to 3.162% modulation to in 2-dB steps. The root-mean-square (RMS) amplitudes of the modulated and unmodulated parts of the stimuli were matched. At each modulation depth, ten stimuli were created for AM rates of 10, 25, 50, 75, 100, 125, 150, and 200 Hz. Modulation rate increased in a roughly linear rather than logarithmic scale so that step size would naturally decrease as the listener progressed to higher AM rates. All unmodulated and modulated stimuli were ramped with 10-ms linear onset and offset ramps. Example stimulus time waveforms are illustrated in Fig. 3.

The stimuli were presented in soundfield in a sound attenuating booth. A loudspeaker (Fostex 6301D with 80–13 k Hz frequency response) was placed directly in front of the listener at a distance of 1.6 m. The level of presentation, measured at the location of the listener's head, was 65 dB sound pressure level.

C. Procedure

For each subject, the MDT was determined first by measuring the smallest modulation depth at which the modulation could be detected at a modulation rate of 10 Hz. The TCMF was then determined by measuring the highest modulation rate at which the modulation could be detected at a modulation depth 4 dB greater than the MDT.

A single-interval, forced-choice observer-based psychoacoustic procedure was used to measure MDT and TCMF for each listener.^{25,26} The listener was seated in a chair or on the caregiver's lap. For infant listeners, an assistant sat to the right manipulating toys to direct the infant's attention toward midline. Two mechanical animal toys with lights sat in a dark plexiglass box to the listener's left. On top of the plexiglass box was a 15-in monitor connected to a DVD player. One of three trained observers sat outside the test booth and watched the listener's behavior through a glass window. The caregiver, assistant, and observer all wore circumaural headphones that played masking stimuli, preventing all but the listener from hearing the stimuli. For each subject, a single observer collected data for all test sessions.

During the test session, the listener was presented with repeating stimuli with 2-s of silence between stimuli. In between trials, randomly selected unmodulated stimuli were presented. When the listener was facing forward in a calm, quiet state, the observer initiated a trial by pressing a keyboard button. The type of trial, "unmodulated" or "modulated" was determined pseudorandomly so that there were 20 of each trial type over 40 trials. The observer was blind to trial type. A response window began 1 s after the trial stimulus onset and lasted 4 s. During this window, the observer decided whether a modulated or unmodulated trial had occurred based on the listeners' behavior, pressing a button on a computer keyboard. Behavioral cues for infants varied from a head turn toward the reinforcer to eye movements, facial expressions or sudden changes in overall motor activity. Adult listeners were

FIG. 3. Time waveforms of example stimuli. Modulated stimuli were composed of individually concatenated, RMS balanced samples of broadband noise with the second sample modulated in amplitude. Shown are two modulation depths with modulation index (M) of 0.4 and 0.16. Modulation depth can be expressed as dB relative to a modulation depth of 1 using $20 \cdot \log_{10}(M)$. Modulation detection is easier at smaller depth and slower modulation rate.

instructed to raise their hand when they heard the sound that was associated with activation of the reinforcer. Feedback was provided to the observer at the end of each trial by dialogue box on a monitor in the observation room. Listener feedback was provided by a 4-s video clip or activation of a mechanical toy after each correct identification of a modulated trial. It is important to note that unmodulated test trials were indistinguishable from background stimuli to the listener.

Prior to testing, listeners completed a training phase where 75% of trials were modulated and the reinforcer was activated following each modulated trial regardless of listeners' response. For training, modulated stimuli with 0 dB modulation depth and 10 Hz modulation rate were used. The training period ended when the listener-observer pair reached $\geq 80\%$ hit rate and $\leq 80\%$ false alarm rate over the last five modulated trials and the last five unmodulated trials, respectively. If training was not complete after 20 trials, a second training phase was run.

After training, a criterion phase was administered to confirm that the listener-observer pair could detect the modulated stimulus at maximal modulation depth. Stimuli were the same as those used for training. In this phase, 50% of the trials were modulated with trial type ordered pseudorandomly in blocks of 20. Unlike training, the reinforcer was activated only after correct responses to modulated stimuli. The criterion phase ended when the listener-observer pair reached $\geq 80\%$ hit rate and $\leq 20\%$ false alarm rate over the last five modulated and unmodulated trials (80% correct "pass rule"). If the criterion phase was not passed within 40 trials, the phase was repeated once. When the criterion phase was not passed on the second try, no further testing was done and no threshold was obtained.

For each subsequent test phase, the task was made more difficult by decreasing the modulation depth in 4-dB steps. The same "pass" rule and maximum number of trials described above for the criterion phase was used for the test phases. The 4-dB step size was chosen based on pilot testing of adults and infants to balance step precision against the number of trials an infant could be expected to complete. A "hardest level passed" approach to derive threshold was employed as previously described by Horn *et al.*²⁵ The smallest modulation depth at which the listener-observer pair achieved the "pass" rule, corresponding to a proportion correct [$p(C)$] of 0.8, was taken as the listeners' modulation detection threshold (MDT).

After the MDT was determined for an individual listener, the next test phase was run with modulated stimuli set to a modulation depth of 4 dB higher than the MDT at a modulation rate of 25 Hz. For each subsequent test phase, modulation rate was increased in 25–50 Hz steps. The same "pass" rule was applied to advance to subsequent test phases and the "hardest level passed" approach was used to determine threshold. The highest modulation rate at which the listener-observer pair achieved the "pass" rule was taken as the listeners' temporal modulation cutoff frequency (TMCf).

To ensure that non-sensory factors related to attention and arousal were not responsible for a failure to reach criterion, a "reminder" procedure was used.^{27,28} If the listener-observer pair was incorrect on four consecutive trials, or failed to reach criterion after 40 trials, then up to 12 reminder trials at 0 dB modulation depth and 10-Hz modulation rate were administered. If the listener-observer pair could achieve 5/6 correct consecutive trials, then testing either resumed (for listeners who had not yet reached 40 trials at the hardest depth

or rate tested) or was considered complete (for listeners who had reached 40 trials at the hardest depth or rate tested). Up to two reminder procedures were allowed at each modulation depth or rate. If the reminder trial criterion was not met, the session ended. Thus, a threshold was only judged to have been reached if the listener-observer pair reached criterion at one depth or rate, failed to reach criterion at the next more difficult depth or rate, and reached criterion on the reminder trials. If testing was ended prior to obtaining a threshold, the visit either ended or, if time and infant state permitted, an additional test session was run. Subsequent test sessions began with the lowest modulation depth (or fastest modulation rate) at which the infant had previously been tested.

Adults were tested using the same observer-based procedure as the infants. Prior to beginning the first session, adults were told they would be hearing repeating sounds and instructed to raise their hand when they heard the sound that activated the reinforcer. The rest of the procedure was carried out as described above. For infants, testing was completed over three to four 1-h visits spread out over 7 to 14 days whereas adults were tested over a single 1–2-h visit. The vast majority of infants completed 1–2 sessions per day and no infants completed more than three sessions in a given day.

III. RESULTS

Of the 33 infants tested, three were excluded due to inability to pass the criterion phase at 10 Hz, and an additional seven infants did not provide an MDT threshold due to failure to pass the reminder trials. Of the remaining 23 infants, 15 provided both an MDT and TMCF threshold. The eight infants who provided only an MDT threshold were either unable to pass the criterion phase at 25 Hz ($n = 4$) or did not pass the

reminder trials at higher modulation rates ($n = 4$). The average MDT was not significantly different for infants who provided both thresholds (avg = -10.4 ; $sd = 4.5$) compared to those who only provided an MDT (avg = -9.5 ; $sd = 5.2$) by two-tailed independent samples t -test [$t(21) = -0.434$; $p = 0.669$]. Only data from infants who provided both thresholds were used in the analyses below. All adults tested provided both an MDT and a TMCF threshold.

Figures 4(a) and 4(b) plot the MDT and TMCF for individual infants and adults, respectively. Infant MDT varied from -4 to -16 dB modulation depth while adult MDT varied from -16 to -24 dB. In other words, the best infant MDT threshold (in 4 of 15 infants) was the same as the worst adult threshold. The range of TMCF thresholds for both adults and infants was 25 to 175 Hz. Age group differences are summarized in box-whisker plots shown in Figs. 4(a) and 4(b). Mean MDT was -10.4 dB ($sd = 4.5$) and -20.2 dB ($sd = 2.9$) for infants and adults respectively. Thus, infants required 10 dB greater modulation depth, on average, to detect 10 Hz modulation than adults. The difference between infants and adults in MDT was statistically significant via two-tailed independent samples t -test [$t(29) = 7.107$, $p < 0.0001$]. Mean TMCF was 81.7 Hz ($sd = 45.8$) and 87.5 Hz ($sd = 58.5$) for infants and adults, respectively. Mean infant TMCF was lower than adult TMCF; however, this difference did not reach statistical significance via two-tailed independent samples t -test [$t(29) = -0.308$, $p = 0.759$]. Thus, infants were less sensitive than adults at detecting amplitude modulation, but their TMCF, on average, did not significantly differ from adults'.

Previous studies have examined whether poor infant thresholds could be explained using a “lapse” model where a

FIG. 4. Box-whisker plots summarizing age-group effects for MDT in dB (a) and TMCF in Hz (b). Upper and lower boxes show the 1st and 3rd quartile ranges separated by a horizontal line representing the group median (infant MDT median was 8 dB and therefore not visible in the plot). Error bars show the maximal and minimal observed values. The “X” represents the mean MDT or TMCF for each age group. Individual infant (open triangles) and adult (open circles) who provided both thresholds are shown. Individual infants who provided just an MDT threshold are shown as small filled circles (but these data were not used to calculate the plots).

listener, an inattentive infant, has no information about the stimulus and guesses on a certain proportion of trials.^{29–32} In order to examine whether the difference in infant and adult MDT could be explained by guessing alone, a lapse rate of 30% was modelled, based on previously reported data for infant tone and broadband noise detection.^{29,32} The mean MDT at each modulation rate across all adult listeners is shown in Fig. 5. The raw mean data were then “rescaled” assuming that the 30% lapse rate and both functions were fit using logistic equations and least-squares method. The effect of rescaling was approximately 2–4.5 dB depending on the P(C) used to determine threshold. Thus, inattention as modeled here could contribute to the difference between infants and adults in MDT but cannot account for the entire age difference in MDT.

IV. DISCUSSION

The first aim of the present study was to determine feasibility of a two-point method to define TMTF parameters in 3-month-old infants. For each TMTF parameter, there was approximately a 30% attrition rate such that approximately half of the infants provided both parameters. This attrition rate is not unusual for infant studies of intensity-based discrimination.³³ The fact that the same attrition rate was observed for the second data point suggests that infants who provide a first threshold are not necessarily “easier to test” than the rest of the sample. Furthermore, the mean MDT was similar between infants who did and infants who did not provide the TMTF threshold suggesting that infants who provided TMTF thresholds were not better listeners than the rest of the sample. Thus, the infants who provided data in this study appear to be representative of 3-month-olds. However, based on the fact that TMTF data were only obtained from 50% of the participants, it is clear that procedural changes will be necessary to make the two-point method clinically useful. For instance, preliminarily data

suggest that threshold yield can be improved by using a larger initial step size and decreasing once the listener fails to reach “pass criterion.” Furthermore, use of more frequent reminder trials can minimize trials when the infant become inattentive.

The second aim was to determine if the TMTF was mature at three months of age in normal hearing infants. In this study, TMTF parameters were measured at a far earlier age than the youngest age tested by Hall and Grose.²⁰ As hypothesized, sensitivity to amplitude modulation was markedly immature in 3-month-old infants with a 10-dB poorer MDT at 10 Hz than adults. This difference in modulation sensitivity between infants and adults is larger than the approximately 5 dB difference in modulation sensitivity between 4-yr-olds and adults tested by Hall and Grose and similar to the large differences between infant and adult listeners reported for sound detection in noise and intensity discrimination.^{29,32,34–36} These data suggest that that amplitude modulation sensitivity is markedly immature at birth and gradually reaches adult levels during adolescence.

In contrast to MDT, the temporal modulation cutoff frequency of 3-month-old infants was adult-like. The latter finding suggests that behavioral temporal resolution is, on average, mature at least by 3 months of age in normal hearing children. Although it is possible that our sample size was underpowered to detect a small difference in TMTF between infants and adults, such a small difference is unlikely to have functional consequences. In other words, these results are consistent with the hypothesis that temporal resolution matures far earlier than sensitivity to amplitude modulation detection alone would suggest. Importantly, these data demonstrate that modulation sensitivity is not a good indicator of temporal resolution in very young listeners.

An important question to address is whether the TMTF measured by varying the modulation rate at fixed depth measures cutoff frequency of the TMTF accurately. If it does, we would expect the TMTFs measured in the present study to be similar to those previously described. In order to compare the TMTFs obtained from the present study with those of Eddins³⁷ and Hall and Grose,²⁰ we assumed the form of the TMTF given by Eq. (2) from Eddins *et al.*³⁷

$$10 * \log \{1/[1 + (aF)^2]\},$$

where F is the modulation frequency and a determines TMTF shape. From this equation, the linear relationship between the 3 and 4 dB down points is

$$Fc_{3dB} = 0.81 * Fc_{4dB},$$

where Fc_{3dB} and Fc_{4dB} are the 3 and 4 dB down points, respectively. The 3-dB down point was derived for each listener who provided a TMTF in the present study. Mean derived 3-dB down points for infants and children are shown in Table I. As expected, mean derived 3-dB down point was lower in frequency, by approximately 15 Hz, than mean TMTF. For comparison purposes, the mean 3-dB down points for adults from Eddins³⁷ and for adults and 4–5-year-old children from Hall and Grose²⁰ are provided in Table I.

FIG. 5. Mean raw and re-scaled adult proportion correct responses are shown (chance is 0.5) as a function of modulation depth. Error bars represent 95% binomial confidence intervals. Adult raw data were rescaled based on a “lapse rate” on 30% of trials (where proportion correct was 0.5). Both datasets were fit to a logistic function (shown as dashed lines).

TABLE I. Mean temporal modulation cutoff frequency of infants, children, and adults. Note that mean TMCFs for infants and adults from present study with mean of the 3-dB down point ($F_{c,3dB}$) derived using Eq. (2) from Eddins (Ref. 37). For comparison, mean 3-dB down points are shown for adults from Eddins (Ref. 37) and Hall and Grose (Ref. 20) and 4-5 year old children from Hall and Grose (Ref. 20).

	TMCF	$F_{c,3dB}$	Eddins (Ref. 37)	Hall and Grose (Ref. 20)
Infants	81.7 Hz	66.15 Hz		
Adults	87.5 Hz	70.88 Hz	74.4 Hz	50.8 Hz
Children				59.7 Hz

After accounting for the fact that TMCF was measured at a lower point on the TMTF than previous studies, the observed TMCFs are somewhat higher than those reported by Eddins³⁷ and Hall and Grose.²⁰ The better mean TMTFs relative to Hall and Grose can be explained by the wider bandwidth of the stimuli in the present study. Eddins³⁷ has shown that TMCF is positively correlated with carrier bandwidth with TMCF more than doubling per octave bandwidth to approximately 75 Hz at 2 kHz bandwidth. Indeed, TMCFs reported by Hall and Grose were 15–30 Hz slower than those reported by Eddins *et al.* for all bandwidths above 800 Hz. Thus, the TMCFs observed in the present study are consistent with previous results when these stimulus and methodological differences are accounted for.

Electrophysiological evidence from animals and humans suggests that the auditory system’s ability to accurately encode acoustic temporal patterns is immature at birth. For instance, phase-locking at the levels of the auditory nerve and cochlear nucleus is immature at birth in cats³⁸ and in humans.³⁹ Development of neural synchrony to acoustic stimulus onset also develops after birth in human infants.^{40,41} Mechanisms such as axonal myelination and synaptic maturation have been proposed to explain the development of these aspects of the neural response.^{42–44} Although myelination and synaptic maturation continue well beyond three months of age, the present study suggests that early immaturity does not constrain temporal resolution. It should be noted that the present findings do not rule out immature temporal resolution prior to three months of age, however.

The poor MDT of three-month old infants, despite adult-like TMCF, is consistent with the hypothesis that temporal resolution is not responsible for infants’ poor sensitivity to temporal acoustic changes. Rather, the “processing efficiency” model would suggest that other factors such as inattention, physiological noise, or poor intensity resolution are responsible for poor modulation sensitivity.³² Importantly, any behavioral task which depends on sensitivity to modulation of amplitude would be expected to be affected by these factors including gap detection and duration discrimination.^{11–14}

Although the exploration of these factors was not the aim of the present study, the potential effect of inattention was explored by modelling the effect of lapses. Based on the adult data from the current study, assuming a lapse rate of 30%, we found that inattention alone is insufficient to explain the degree of immaturity in 3-month old infants’ sensitivity to 10 Hz modulation. This is consistent with studies of infant tone and noise detection showing that inattention

alone would not account for the difference between infant and adult thresholds.^{29,32}

The psychophysical method employed here is a potential way to control for modulation sensitivity when attempting to measure temporal resolution using a modulation detection task. The basic method, to estimate the height of the modulation transfer function by varying modulation depth then measure the cutoff frequency by varying modulation rate, could be used for spectral modulation tasks as well. Further work is needed to determine the reliability and validity of this two-point method compared to traditional methods which fit the TMTF to modulation detection thresholds at several modulation rates.

V. CONCLUSION

Temporal resolution is important for auditory processing in normal hearing individuals and cochlear implant recipients alike. In this study, we find that behavioral temporal resolution, as measured by the TMCF, is mature by 3 months of age in normal hearing listeners. Nonetheless, sensitivity to amplitude modulation is markedly immature at this age consistent with previous studies. The two-point method to derive the shape of the TMTF appears to be feasible, producing results consistent with previous studies. This method could be employed for investigating development of temporal resolution in clinical populations such as in children who use a cochlear implant.

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