Research Note

Pure-Tone Frequency Discrimination in Preschoolers, Young School-Age Children, and Adults

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Purpose: Published data indicate nearly adultlike frequency discrimination in infants but large child–adult differences for school-age children. This study evaluated the role that differences in measurement procedures and stimuli may have played in the apparent nonmonotonicity. Frequency discrimination was assessed in preschoolers, young school-age children, and adults using stimuli and procedures that have previously been used to test infants.

Method: Listeners were preschoolers (3–4 years), young school-age children (5–6 years), and adults (19–38 years). Performance was assessed using a single-interval, observer-based method and a continuous train of stimuli, similar to that previously used to evaluate infants. Testing was completed using 500- and 5000-Hz standard tones, fixed within a set of trials. Thresholds for frequency discrimination were obtained using an adaptive, two-down one-up procedure. Adults and most school-age children responded by raising their hands. An observer-based, conditioned-play response was used to test preschoolers and those school-age children for whom the hand-raise procedure was not effective for conditioning.

Results: Results suggest an effect of age and frequency on thresholds but no interaction between these 2 factors. A lower proportion of preschoolers completed training compared with young school-age children. For those children who completed training, however, thresholds did not improve significantly with age; both groups of children performed more poorly than adults. Performance was better for the 500-Hz standard frequency compared with the 5000-Hz standard frequency.

Conclusions: Thresholds for school-age children were broadly similar to those previously observed using a forced-choice procedure. Although there was a trend for improved performance with increasing age, no significant age effect was observed between preschoolers and school-age children. The practice of excluding participants based on failure to meet conditioning criteria in an observer-based task could contribute to the relatively good performance observed for preschoolers in this study and the adultlike performance previously observed in infants.

The ability to discriminate frequency differences plays an important role in speech understanding and has been associated with children's language and reading skills (e.g., Heath, Hogben, & Clark, 1999; Hill, Bailey, Griffiths, & Snowling, 1999; Mengler, Hogben, Michie, & Bishop, 2005). Frequency discrimination thresholds as low as 0.2% of the standard frequency have been reported for

trained adults (e.g., Buss, Taylor, & Leibold, 2014). Likewise, it has been shown that infants can perceive changes in pure-tone frequency as small as 1%–2% of the standard frequency (Olsho, Schoon, Sakai, Turpin, & Sperduto, 1982; Sinnott & Aslin, 1985). School-age children, however, often perform poorly on frequency discrimination tasks, with reported thresholds of 4%–10% of the standard frequency (e.g., Buss et al., 2014; Moore, Ferguson, Halliday, & Riley, 2008; Thompson, Cranford, & Hoyer, 1999). Although many aspects of development appear to progress in a monotonic pattern—increasing sensitivity with increasing child age—these published studies suggest that the development of frequency discrimination is nonmonotonic, worsening between infancy and early childhood and, then, improving until adultlike performance is reached. Similarly, Saffran and Griepentrog (2001) demonstrated a complex developmental trajectory with respect to frequency discrimination abilities.

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This study aimed to evaluate the effect of test methods and stimuli on frequency discrimination in young children. One possible explanation for the poorer performance in children than in infants is that children's performance was limited by their ability to perform the experimental task rather than their ability to discriminate sounds based on pitch. Whereas much of the frequency discrimination research with infants employed a single-interval, observer-based methodology and a continuous train of stimulus presentations (e.g., Olsho et al., 1982), studies involving the school-age population have generally utilized two-interval or three-interval forced-choice tasks and stimuli that were gated on and off only during observation intervals (Buss et al., 2014; Moore et al., 2008; Thompson et al., 1999). Thompson, Cranford, and Hoyer (1999) used a two-interval forced-choice (2IFC) task to study frequency discrimination in a group of 16 five-year-olds. Of this group, only five (31%) could complete the task; of those who failed, half could perform a 2IFC task with visual stimuli but not auditory stimuli, and half performed the auditory discrimination task well enough to pass the training phase but were unable to respond consistently during the test phase. This low rate of task completion was attributed to immature cognitive skills necessary to master a 2IFC pitch discrimination task (e.g., an understanding of "higher" vs. "lower" pitch, or memory for pitch). Likewise, Moore, Ferguson, Halliday, and Riley (2008) previously attributed a portion of the large child-adult difference for frequency discrimination abilities to immature ability to sustain attention to the pitch cue over time. We know that the child-adult difference is smaller for the detection of the dynamic frequency modulation than the frequency discrimination between gated pure tones (Buss et al., 2014). One explanation for this result is that memory for pitch is immature in school-age children. Using continuous trains of stimuli and a single-interval task could reduce the memory requirements compared with a two-alternative or three-alternative forced choice. One goal of this study was to test the hypothesis that the single-interval procedure using a continuous train of stimulus presentations would result in lower frequency discrimination thresholds for school-age children than previously observed using a forced-choice task.

Another goal of this study was to compare frequency discrimination in preschoolers and young school-age children. If performance worsens between infancy and early school-age years, then there might be evidence of that non-monotonicity in the preschool years. Currently, there are limited data describing frequency discrimination abilities between infancy and the young school-age years, with notable sparsity in the preschool age range. Jensen and Neff (1993) evaluated intensity, frequency, and duration discrimination in a group of twenty-one 4-year-olds, ten 5-year-olds, and ten 6-year-olds. The task was a three-alternative forced choice. Although all the children tested could complete the task, the 4-year-old demonstrated greater variability in their performance compared with the older, 5- or 6-year-old participants. This variability was particularly evident for the frequency discrimination task. Moreover, while

there was a strong correlation between frequency discrimination threshold and age, two of the 4-year-olds performed and adult controls. Testing preschoolers and young school-age children thus provides an opportunity to obtain additional data to evaluate age-related changes in this basic auditory skill.

Method

Participants

Participants included 15 preschoolers ($M = 4.4$ years, range: 3.0–4.9 years) and 20 school-age children ($M = 6.4$ years, range: 5.2–7.7 years). All child participants passed a 226-Hz tympanometry middle ear screening with inclusion criteria of peak pressure greater than -200 daPa and admittance of greater than 0.2 mmhos in the test ear. For all children, parents reported no concerns for hearing loss or recent ear infections. All preschoolers passed their universal newborn hearing screenings. The decision not to screen preschoolers and school-age children for normal pure-tone thresholds was based on two considerations. First, threshold estimation would have increased test time, potentially reducing the quality of experimental data. Second, learning the conditioned-play responses required for threshold estimation could have interfered with learning the frequency discrimination task, particularly in preschoolers. A comparison group of 12 young adults ($M = 27.3$, range: 19.8–38.7 years) was also tested. All adults passed a normal hearing screen using a 20-dB HL criterion level at all major octave frequencies. Data from 13 additional preschoolers were excluded from the analysis: 10 preschoolers did not reach the training criteria, one preschooler did not tolerate the insert earphone, and two preschoolers completed testing but were excluded due to a high response rate on no-signal trials ($> 40\%$) and/or a low response rate on probe trials ($< 80\%$) for both 500- and 5000-Hz standard tones. Data from one additional school-age participant were excluded from the analysis because of a high response rate on no-signal trials ($> 40\%$) for one standard frequency and a low response rate on probe trials ($< 80\%$) for the other standard frequency.

Stimuli

Stimuli were continuous trains of tone bursts. The duration of each burst was 500 ms, including 20-ms raised-cosine onset/offset ramps. Tone bursts were repeated continuously throughout testing with 500-ms silent intervals between successive bursts. The standard frequency (f) was either 500 or 5000 Hz, fixed within a set of trials. The target was higher in frequency than the standard ($f + \Delta f$). On target trials, two target bursts were presented, sequentially interleaved with standard bursts (target–standard–target–standard). Stimuli were presented at 64 dB SPL. A custom MATLAB (Mathworks) program controlled the experiment and communicated with a real-time processor (RZ6, TDT) using ActiveX (RPvds, TDT). Monaural presentation of the stimuli was achieved by routing the output of the real-time

processor to an insert earphone (ER-1; Etymotic), such that neither the assistant nor the observer heard the stimuli. The stimuli were presented to the left ear for most participants. Two preschoolers were tested in the right ear due to cerumen accumulation, and one preschooler was tested in the right ear due to a negative pressure in the left ear.

Testing Procedure

Data were collected using an adaptive, single-interval, observer-based procedure to estimate thresholds associated with 71% correct frequency discrimination. This procedure relies on operant conditioning and is based on the observer-based infant procedure developed by Werner et al. (e.g., Olsho et al., 1982). One benefit of using this procedure is that it can incorporate a variety of participant responses. Participants were evaluated across one to two sessions, with each session lasting an hour or less. Testing was completed in a single-walled, sound-treated booth with a two-way window. Preschoolers sat at a small table inside the booth with an assistant. Parents occasionally sat in the booth behind their preschooler. The assistant taught the preschooler to perform a play-based motor response, such as placing a block in a bucket when he or she heard changes in the frequency of the repeating sequence of tones. The assistant could choose from a variety of toy/game options that were kept out of sight of the child during testing. School-age children and adults sat in a chair in the center of the booth and were asked to raise their hand when they heard a frequency change occurring in the tone sequence. The use of a hand-raise response for school-age children and adults, as opposed to a play-based response for preschoolers, ensured an age-appropriate experience for all participants. Some school-age children did not reliably raise their hand, and in these cases, a play-based response was used instead. For all participants, an observer sat outside of the booth and initiated trials when the participant was quiet, facing forward, and judged to be in a “ready” state. The observer and the test assistant wore circumaural headphones and could communicate with one another throughout testing.

There were two types of trials, each with a duration of 4 s. Change trials consisted of alternating standard and target tone bursts (target–standard–target–standard), whereas no-change trials consisted of only standard tone bursts that were indistinguishable from the train of the tone bursts presented between trials. Each participant completed a conditioning phase, a criterion phase, and a testing phase. The conditioning phase only included change trials. The frequency separation between the standard and target tones for the conditioning phase was selected to be easily discriminable, based on previous research on young school-age children (Buss et al., 2014) and pilot data from preschoolers. Specifically, the frequency of target tones was 596 and 5960 Hz for the 500- and 5000-Hz standard frequencies, respectively, hereby referred to as the *maximum frequencies*. For preschoolers, the objective of the conditioning phase was to teach the child to perform a play-based motor response when the target tones were presented; this was

accomplished through hand-over-hand operant conditioning by the assistant. Similar to the principles of conditioned play audiometry, the motor response itself was enjoyable for the preschooler and served as reinforcement (Northern & Downs, 2014). Preschoolers also received social praise reinforcement from the test assistant during all phases of testing. For school-age children and adults, the goal of the conditioning phase was to ensure the participant raised his or her hand in a time-locked manner to the change in frequency. School-age children and adults received social reinforcement for correct responses on change trials during the conditioning and criterion phases but did not receive reinforcement during the testing phase. This stage continued for a minimum of four trials or until the observer had confidence that the participant understood the task.

The goal of the criterion phase was to ensure that the observer could successfully identify the participant’s behavioral responses when change and no-change trials occur with equal probability in a randomized order. To successfully complete this phase, the observer was required to respond correctly based on the participant’s behavior on four of the last five change trials and four of the last five no-change trials. During the criterion phase, change trials contained target tones at the maximum frequency. The observer was required to decide the trial type based solely on the participant’s behavior within 5 s of the initial presentation of target tones. The observer received feedback after each trial.

The testing phase began upon completion of the conditioning and criterion phases. The target tones started at the respective maximum frequencies for each standard frequency. The difference between the standard frequency and the target frequency (Δf) subsequently dropped by a factor of two until the participant responded incorrectly (a miss); the adaptive track then began, and the step size changed to a factor of 1.41. After two reversals, the step size changed to a factor of 1.19 for all subsequent trials. During the testing phase, the observer and test assistant remained blinded to the trial type. Trials were presented in randomized blocks of 14, of which 10 trials were change trials, two trials were probe trials, and two trials were no-change trials. Probe trials were change trials at the maximum signal frequency. Probe trials were independent of the adaptive track and were intended to demonstrate whether the participant remained on task. Testing continued until eight track reversals occurred.

The frequency discrimination threshold was calculated as the geometric mean of Δf on the last six reversals. Thresholds were then converted to represent the percent change from the standard frequency ($100 \times \Delta f/f$) to allow for comparisons across the two standard frequencies. Most of the participants were evaluated for both standard frequencies, with the order of the standard frequencies assigned in a pseudorandom manner. One school-age participant was tested only on the 500-Hz standard frequency due to time constraints. Data from one of the two standard frequencies were excluded from the analysis when a high response rate on no-change trials (> 40%) or a low response

rate on probe trials (< 80%) was observed: At 500 Hz, data from one adult participant were excluded; at 5000 Hz, data from two preschoolers, four school-age children, and one adult were excluded. Preschooler and adult data were always excluded due to a high response rate on no-change trials. School-age data were excluded due to high response rates on no-change trials and low response rates on probe trials equally.

Results

Figure 1 shows the distribution of valid threshold estimates for the three listener age groups. White boxes indicate data for the 500-Hz standard, and grey boxes indicate data for the 5000-Hz standard. The horizontal lines indicate the 50th percentiles, boxes span the 25th to the 75th percentiles, and vertical lines span the 10th to the 90th percentiles. Data for individual listeners are shown with open circles. This figure illustrates a child/adult difference at both frequencies but little or no evidence of an age effect within child listeners. These data were analyzed using a linear mixed model with fixed effects of frequency and age group and a random effect of the subject. Subject age and thresholds for frequency discrimination were log-transformed prior to analysis. There is a main effect of standard frequency, $t(35) = 2.31$, $p = .027$, reflecting better performance at 500 Hz than at 5000 Hz. In addition, the age group was a significant main effect. Thresholds for the adults were significantly lower than thresholds for both preschoolers, $t(44) = 4.38$, $p = .0001$, and school-age children, $t(44) = 3.78$, $p = .0005$. No significant difference in the threshold was observed between preschoolers and school-age children, $t(61) = 1.27$, $p = .2101$. No significant interaction between frequency and age group was identified.

In addition to this analysis by group, child data were also evaluated as a function of age. Figure 2 shows thresholds of child listeners plotted as a function of age. Cases where a child did not make it out of training are indicated

with filled symbols at 19.2%, the maximum frequency used in the conditioning and criterion phases. A linear mixed model was fitted to valid child thresholds, with age as a continuous variable. This analysis excluded children who failed to condition (filled symbols in Figure 2). There was no effect of frequency, $t(25) = 0.67$, $p = .508$, no effect of age, $t(25) = -0.78$, $p = .444$, and no interaction, $t(25) = -0.17$, $p = .866$. Although there is no indication of an age effect in threshold data, there is some indication in Figure 2 that older children were more likely than younger children to successfully pass through the conditioning and criterion phases and provide a valid threshold estimate. The significance of this observation was evaluated with logistic regression, where the dependent variable was binary: whether or not the child passed through training and provided a threshold estimate. Child age was a significant predictor for both the 500-Hz standard ($z = 1.98$, $p = .047$) and the 5000-Hz standard ($z = 2.67$, $p = .008$).

Discussion

For untrained adult participants, pure-tone frequency discrimination thresholds (1.0%–1.6%) were consistent with previously reported observations of approximately 1.0% (Olsho et al., 1982; Thompson et al., 1999). In some instances, adult thresholds for frequency discrimination previously reported in the literature reflect slightly better performance of 0.3%–0.5% (e.g., Sinnott & Aslin, 1985). Frequency discrimination thresholds for young school-age children in this study (mean of 2.4% at 500 Hz and 4.0% at 5000 Hz) were better than those reported in some previous studies (e.g., Moore et al., 2008; Thompson et al., 1999). While thresholds observed for school-age children in this study agreed with Buss, Taylor, and Leibold (2014) at 5000 Hz, better performance was observed at 500 Hz in this study for all age groups. Although it is unclear how to account for the discrepancy across studies, the observed decrement in sensitivity at 5000 Hz compared with 500 Hz may be related to human listeners' difficulty recognizing pure-tone melodies in a continuous train of stimuli at or above 5000 Hz (Oxenham, Micheyl, Keebler, Loper, & Santurette, 2011). In contrast to previously reported thresholds of approximately 11% in 4-year-old participants (Jensen & Neff, 1993), frequency discrimination thresholds for preschoolers in this study (3.0%–5.0%) were similar to those observed for young school-age children. Such a result would be consistent with reduced cognitive demands for detecting frequency changes in a continuous stream of tones, compared with a two-alternative forced-choice task. Note, however, that thresholds were not obtained for preschoolers who could not complete the training in this study, and there are a number of other methodological differences across studies that could contribute to differences in the results (e.g., the d' associated with threshold).

The trend for improving thresholds with increasing age from approximately 4 years of age to adulthood observed in this study is consistent with other investigations of basic frequency discrimination abilities in children (Jensen

Figure 1. Frequency discrimination thresholds plotted as a function of age group. Results for the 500-Hz standard are shown with white boxes, and those for the 5000-Hz standard are shown with grey boxes. Thresholds for individual listeners in each age group and condition are shown with circles.

Figure 2. Frequency discrimination thresholds as a function of age for child listeners. Results are plotted separately for the 500-Hz standard (left panel) and the 5000-Hz standard (right panel). Filled symbols indicate failure to successfully complete conditioning trials at 19.2% signal strength.

& Neff, 1993; Moore et al., 2008; Sinnott & Aslin, 1985; Thompson et al., 1999). While the trend for improving performance with increasing age was observed, the difference in performance between preschoolers and young school-age children was not statistically significant. The likelihood that a participant was successfully able to condition to the single-interval task was 56% for preschoolers and 95% for young school-age children. The mean age of preschoolers who passed the training phase of the experiment was 4.4 years, which implies a bias toward older preschoolers in the data set. Several of the excluded preschoolers were young 3-year-olds (mean age = 3.8 years). Tester observations of young preschoolers suggested that they had a basic understanding of the task but lacked the confidence to make definitive decisions about the similarity of a target tone to the standard tones. The inherent bias in the data due to the inclusion of only preschoolers who were able to condition to the play-based task with continuous stimuli may be a contributing factor to the failure to observe a significant difference in frequency discrimination thresholds between these age groups. Clearly, more work is needed to develop reliable test methods that are appropriate for the preschool population. The results of this study provide no evidence of nonmonotonicity in the development of frequency discrimination skills from preschoolers to adults when similar methods and stimuli are used for all groups, although thresholds for both groups of children were higher than previously observed for infants (Olsho et al., 1982). Olsho et al. (1982) evaluated 27 infants (aged 4–8 months), with usable data collected from only 14 of these participants. It is noteworthy, however, that the infants in the previous study were trained with target tones that differed by 9.6%, 4.8%, and 3.2% from standard frequencies of 1000, 2000, or 3000 Hz, respectively. A 3%–9% difference between the training tone frequency and the standard frequency could be at or below a participant's threshold for frequency discrimination; excluding infants who did not meet the criteria for conditioning trials could have biased the sample

toward an overrepresentation of better performing infants. In contrast, participants in this study completed training with target tones that differed by 19.2% from the standard frequency. In addition, whereas data associated with high false alarm rates (response rates > 40% on no-change trials) were excluded from this study, there were no criteria with respect to false alarms for retention of adaptive tracking data in Olsho et al. (1982). This could play some role in the higher thresholds observed in the present dataset.

Results of this study are consistent with the idea that frequency discrimination abilities improve with increasing age between the preschool years and adulthood; however, more research into the development of this basic auditory skill is needed to shed light on the development between infancy and preschool years. The selection of methods for assessment of frequency discrimination abilities in infants and young children remains a challenge. One future direction is to replicate measures of frequency discrimination in infants and preschoolers on a single-interval task using the same stimulus parameters and proportions of change and no-change trials as used in this study, as it is difficult to predict how the mix of trials of different types would affect results in the present paradigm compared with a forced-choice task, given the different task demands. Two-alternative and three-alternative forced-choice data are typically assumed to be free of interval bias, although that might not be strictly true. Another future direction is to investigate the effects of varying training criteria on thresholds for frequency discrimination.

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