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FACTORS AFFECTING SENSITIVITY TO FREQUENCY CHANGE IN SCHOOL-AGE CHILDREN AND ADULTS

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Abstract

Purpose—The factors affecting frequency discrimination in school-age children are poorly understood. The goal of the present study was to evaluate developmental effects related to memory for pitch and the utilization of temporal fine structure.

Method—Listeners were 5.1- to 13.6-years-olds and adults, all with normal hearing. A subgroup of children had musical training. The task was a three-alternative forced choice, where listeners identified the interval with the higher frequency tone or the frequency modulated (FM) tone. The standard was 500 or 5000 Hz, and the FM rate was either 2 or 20 Hz.

Results—Thresholds tended to be higher for younger children than for older children and adults for all conditions, although this age effect was smaller for FM detection than for pure-tone frequency discrimination. Neither standard frequency nor modulation rate affected the child/adult difference in FM thresholds. Children with musical training performed better than their peers on pure-tone frequency discrimination at 500 Hz.

Conclusions—Testing frequency discrimination using a low-rate FM detection task may minimize effects related to cognitive factors, like memory for pitch or training effects. Maturation of frequency discrimination does not appear to differ across conditions in which listeners are hypothesized to rely on temporal cues and place cues.

INTRODUCTION

Auditory frequency discrimination is a basic ability, thought to be important in the processing of many stimuli, including speech. For example, there is an association between frequency discrimination and oral language abilities in children, but no such association between intensity discrimination and oral language abilities (Mengler, Hogben, Michie, & Bishop, 2005). Despite its importance, existing data on the development of frequency discrimination are inconsistent. Behavioral data from 6- to 12-month-olds indicate frequency discrimination thresholds for a 1000-Hz standard of approximately 2% of the standard frequency, compared to 0.5% for adults (Olsho, 1984; Sinnott & Aslin, 1985). In contrast,

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frequency discrimination for a 1000-Hz standard is commonly reported to be on the order of 10% in 6- to 7-year-olds (Halliday, Taylor, Edmondson-Jones, & Moore, 2008; Maxon & Hochberg, 1982; Moore, Ferguson, Halliday, & Riley, 2008). Although adult-like frequency discrimination can be observed by 8 years of age under some conditions (Banai, 2008; Sutcliffe & Bishop, 2005), other data indicate that maturation extends up to or beyond 12 years of age (Fischer & Hartnegg, 2004; Halliday, et al., 2008; Maxon & Hochberg, 1982). Remarkably, several studies have reported that a substantial proportion of young school-age children are unable to reliably discriminate between 1000- and 1500-Hz tones (e.g., Halliday, et al., 2008; Thompson, Cranford, & Hoyer, 1999). It is likely that this psychoacoustic result underestimates ‘true’ frequency discrimination, since a true inability to discriminate 1000 and 1500 Hz would likely preclude speech perception. Given the association between frequency discrimination and language abilities (reviewed by: McArthur & Bishop, 2004), a better understanding of the factors that affect psychophysical frequency discrimination could be of both theoretical and practical significance. The experiments described here attempted to shed light on these factors by assessing sensitivity to changes in frequency using pure-tone frequency discrimination and frequency modulation (FM) detection at 500 and 5000 Hz, with the goal of evaluating effects related to memory for pitch and temporal fine-structure cues to pitch.

The remarkably poor frequency discrimination sometimes observed in school-age children has been attributed largely to the maturation of cognitive factors underlying performance of the psychoacoustic discrimination task, such as auditory attention or memory (e.g., Moore, et al., 2008). This possibility is consistent with the finding that the structure of the task used to assess frequency discrimination has an impact on the age at which children attain adult-like performance (Banai, 2008; Sutcliffe & Bishop, 2005). For example, Banai (2008) measured sensitivity to frequency changes with a 1000-Hz standard in two paradigms: whereas 8-year-olds were adult-like when tested in a three-alternative task with 500-ms stimuli, 14-year-olds were not as good as adults at identifying the higher-frequency tone in a two-alternative task with 50-ms stimuli.

Psychoacoustic experiments require sustained attention, and it has been suggested that one factor in the poor performance of school-age children could be greater probability of a lapse in attention (Leibold, 2012). Moore et al. (2008) evaluated the effects of sustained attention on frequency discrimination by comparing performance of 6- to 12-year-old children on this auditory task with performance on a visual task. The expectation was that if maturation of a general ability to sustain attention were responsible for children's poor performance in auditory frequency discrimination, then scores on the auditory and visual tasks should be correlated. No such correlation was observed, and it was proposed that the dominant limitations with respect to attention could be modality specific (see also: Banai, 2008). While this possibility cannot be ruled out, there is some indication that sustained *auditory* attention may likewise fail to account for individual differences in the sensitivity to changes in frequency. Banai et al. (2011) measured both FM and amplitude modulation (AM) detection thresholds in 8- to 12-year-olds. There was evidence of maturation in both FM and AM detection over this age range, but across listeners there was no correlation between thresholds in the two tasks after controlling for child age. This result could be interpreted as indicating that the auditory processes underlying FM and AM detection are at least somewhat independent and mature at different rates. This perspective is consistent with the argument that individual differences in auditory performance in adults reflect multiple distinct auditory abilities (Johnson, Watson, & Jensen, 1987).

Another factor that could affect children's performance on psychoacoustic tests of frequency discrimination is maturation of the ability to retain pitch information in memory. The work of Keller and Cowan (1994) showed that memory for pitch develops between 6 to 7 years of age and adulthood. In that study, the task was to report whether two tones were the same or different in frequency. The standard frequency was roved on a trial-by-trial basis between 85 and 725 Hz, with a mean of 405 Hz. After training, there were two stages of testing. In the first stage, the change in frequency (Δf) associated with 84% correct frequency discrimination was measured for an inter-tone interval (ITI) of 2 sec. As expected based on previous findings in the frequency discrimination literature (reviewed above), thresholds for 6- to 7-year-olds were higher than those for adults. In the second stage, the Δf was fixed at the threshold measured in the first stage of testing for each listener, and the ITI was adaptively varied to estimate thresholds associated with 84 and 71% correct performance. For conditions like these, frequency discrimination tends to worsen as the ITI is increased. The ITI threshold associated with 84% correct was similar across groups, indicating that the individualized values of Δf were successful at normalizing difficulty for the 2-sec ITI conditions, where memory demands were relatively modest. The ITI thresholds associated with 71% correct differed across groups, however. Adults' ITI thresholds were a factor of 1.5 longer than those of 6- to 7-year-olds. That is, when performance was matched across groups for a 2-sec ITI, adults were able to tolerate larger increments in the ITI than children. This result was interpreted as indicating more rapid decay of memory for pitch in the younger listeners.

In the present experiment, the role of memory for pitch in the maturation of frequency discrimination thresholds was evaluated by comparing pure-tone frequency discrimination to FM detection. Frequency discrimination for pure tones that are gated on and off requires that the listener remembers and compares pitch percepts in memory. Those comparisons can be restricted to stimuli in the intervals of a single trial, or they can include a template built up over a series of trials (Bull & Cuddy, 1972; Clement, Demany, & Semal, 1999). In contrast to frequency discrimination, FM detection can be performed based solely on dynamic pitch cues within a listening interval. The expectation was that developmental effects related to memory for pitch would lead to greater child/adult differences for pure-tone frequency discrimination than FM detection. Published data from children are broadly consistent with this expectation. Child/adult differences for 20-Hz FM detection are modest for 6- to 7-year-olds and may be absent for 8- to 10-year-olds (Bishop, Carlyon, Deeks, & Bishop, 1999; Sutcliffe & Bishop, 2005). These results suggest earlier maturation of FM detection that that reported in many studies using pure-tone frequency discrimination, although any comparison across existing datasets collected with different stimuli and methods is tenuous; both stimulus parameters (e.g., stimulus duration; Thompson, et al., 1999) and psychophysical procedures (Banai, 2008; Sutcliffe & Bishop, 2005) can have a large effect on the pattern of performance across age groups.

This general approach, of comparing performance for across-interval vs. dynamic within-interval stimulus changes as a way of assessing effects of stimulus memory, was used recently by Buss et al. (2013) to evaluate possible effects of memory for intensity discrimination in school-age children compared to adults. That study measured intensity discrimination for gated pure-tone stimuli and for the detection of amplitude modulation. Listeners of all ages were more sensitive to changes in stimulus intensity within than across intervals, and both children and adults benefitted from the provision of a dynamic cue to a comparable extent. This result was interpreted as indicating that maturation in the memory for intensity did not play an important role in the developmental effects observed for intensity discrimination. There are several reasons to believe that sensory memory could affect development differently for the discrimination of intensity and frequency, however. Intensity discrimination appears to mature earlier than frequency discrimination (Banai, et al., 2011; Jensen & Neff, 1993), and adult data also support the idea that these two tasks tap into different auditory abilities (Clement, et al., 1999). Given these dissociations between intensity and frequency discrimination, it is possible that auditory memory could play a role in the development of frequency discrimination despite the lack of an analogous effect in intensity discrimination.

Another question of interest in the present study was whether children's poor frequency discrimination in some conditions could be related to differences in maturation of the ability to make use of temporal and place cues to pitch. In adults, FM detection has been hypothesized to rely on different cues for different stimulus conditions. Moore and Sek (1996) argued that detection of low-rate FM of a low-frequency carrier is based on temporal fine-structure cues, whereas FM detection for relatively high modulation rates and high carrier frequencies is related to place of transduction in the cochlea (see also Ernst & Moore, 2012). There is some indication that low-rate FM detection may be slightly elevated in younger listeners relative to higher-rate FM detection. Dawes et al. (2008) measured FM detection for a 1000-Hz standard and found evidence of earlier maturation of FM detection for a 40-Hz than a 2-Hz rate; performance was adult-like for 40-Hz FM by 7 years of age, but it wasn't until 9 years of age that 2-Hz FM detection was as good as adults'. While these results are consistent with a more prolonged time-course of development for temporal than place cues to pitch, they are inconclusive because no data were collected at a higher carrier frequency where fine-structure cues are likely to be weak or absent. Other data indicate that children may rely on temporal fine-structure cues to a greater extent than adults (Allen & Bond, 1997; Allen, Jones, & Slaney, 1998). For example, Allen and Bond (1997) argued that 7-year-olds rely predominantly on temporal fine-structure when judging the similarity across a wide range of stimuli, whereas adults use both temporal and spectral features in judgments of similarity. The present study measured FM detection at two rates (2 and 20 Hz) and for two carrier frequencies (500 and 5000 Hz) to evaluate the relative importance of temporal fine structure and place of transduction in development of adult-like performance.

METHODS

Listeners

Listeners were adults and 5- to 13-year-old children. All listeners had normal hearing, defined as pure-tone thresholds of 20 dB HL or better at octave frequencies 250-8000 Hz (ANSI, 2010). Exclusion criteria included a history of hearing loss and known developmental delays.

There were two groups of adult listeners. The first group included 12 naïve listeners between 19 and 30 years of age (mean 23 years), none with more than two hours of previous psychoacoustic listening experience. The second group of adults included five listeners between 28 and 60 years of age (mean 41 years), each with 100 or more hours of prior psychoacoustic listening experience. The rationale for collecting data on experienced adult listeners was for comparison with published studies (e.g., Wier, Jesteadt, & Green, 1977), which typically provide listeners with extensive prior to data collection. No adult reported receiving more than 2 years of previous musical training.

The child group included 34 listeners, distributed approximately uniformly between 5.1 and 13.6 years of age on a log scale. The goals of this study did not initially include an evaluation of the influence of musical training on frequency discrimination abilities. However, parental reports of musical training indicated two distinct groups. The musically trained group included children who had been enrolled in formal music lessons and had clocked more than 150 hours of structured practice (e.g., three hours a week for a year). The untrained group had little or no formal music education, with a maximum of 100 hours of formal music practice. The musically trained group included 13 children between 7.7 and 13.6 years of age, and the mean total practice time was 598 hrs. The group without musical training included 22 children between 5.1 and 13.2 years of age, and their mean total practice time was 25 hrs.

Three listeners who were initially enrolled were later excluded from study. One adult was unable to complete testing due to scheduling conflicts, and one child (5.7 years) was unable to master the forced-choice task. Data from one child (12.8 years) were collected but later omitted. This listener was clearly an outlier in her age group, performing at ceiling on the majority of threshold estimation tracks. However, the first threshold for each condition tended to be substantially better than subsequent thresholds. For example, the initial 500-Hz pure-tone discrimination threshold was 2% of the standard, whereas subsequent thresholds for this condition were ~8%. This inconsistency likely reflects flagging motivation rather than true hearing ability.

Stimuli

Stimuli were pure tones or FM tones presented at 70 dB SPL for 1 sec, as measured from the half-rise point of 50-ms raised-cosine onset and offset ramps. Standard tones had frequencies of either 500 or 5000 Hz, and FM tones were centered on the associated standard frequency. In the pure-tone frequency discrimination task, the target was higher in frequency than the standard. In the FM detection task, the target frequency began and ended at the standard frequency. Modulation depth rose from zero to its maximum value over the course of the stimulus onset and fell back down to zero over the course of the stimulus offset; this was achieved by gating the sinusoidal frequency modulator with the same 50-ms raised-cosine ramps used to shape stimulus onset and offset. For FM stimuli, the rate of modulation was either 2 or 20 Hz. The magnitude of the frequency difference (Δf) was defined as the difference between the minimum and the maximum frequency (i.e., peak-to-peak frequency difference in the case of FM)[1]. Stimuli were generated in software (RPvds; TDT), played out of a real-time processor (RP2; TDT), routed to a headphone buffer (HB7; TDT), and presented to the left channel of a pair of circumaural headphones (HD 25-1 II; Sennheiser).

Procedures

Thresholds were collected using a custom MATLAB (MathWorks) script. Each trial contained three 1000-ms intervals, separated by 500 ms. Two intervals contained the standard stimulus, and one randomly chosen interval contained the target. Intervals were indicated visually on a computer screen showing three animated frogs. Each frog opened and closed its mouth, synchronous with the onset and offset of the associated stimulus. The listener used a computer mouse to select the frog associated with the target. The instructions were to listen for the sound that was different from the other two. This task is easily understood by typically developing school-age children and adults. After each response, an animation of the target frog catching a fly appeared, providing immediate feedback.

Thresholds were estimated using a 2-down 1-up stepping rule, which converges on the Δf associated with 71% correct. Each track began above the expected threshold. The Δf was initially adjusted by a factor of 1.41. This was reduced to a factor of 1.19 after the second track reversal. Values of Δf were limited, such that the maximum frequency could not exceed 10% of the standard frequency. When the track algorithm called for a value of Δf above this limit, it was replaced with the maximum Δf. A track was terminated once eight reversals had been obtained. The threshold estimate associated with a track was the geometric mean of the Δf associated with the last six reversals, and the geometric means of all tracks completed are reported below. Listeners completed at least three threshold estimation tracks for each condition. An additional threshold was collected if the first three spanned a range greater than 5 Hz for the 500-Hz standard, or 10 Hz for the 5000-Hz standard.

Listeners were randomly assigned to start with either the 500-Hz or the 5000-Hz standard frequency. Within that frequency, listeners completed the three tasks in a random interleaved order. Those tasks were pure-tone frequency discrimination, 2-Hz FM detection, and 20-Hz FM detection. The subgroup of adults with psychoacoustic listening experience completed the experiment twice, and only the second set of data on these listeners is reported below. This was done to provide some task-specific training for the trained listener group.

[1]Detection of FM in the adult literature is often defined in terms of the full range of frequencies visited in a modulation period, or the peak-to-peak difference (e.g., Moore and Sek, 1996). The convention in the child literature is mixed, with many studies quantifying FM detection thresholds as the increment from the standard frequency, or the mean-to-peak difference (e.g., Bishop et al. 1999).

Thresholds are reported as a percent of the standard frequency ($100 \times \Delta f/f$), to facilitate a comparison across frequency, and all statistics were performed on log-transformed thresholds. Log units are thought to reflect perceptually equal changes in frequency and tend to equalize variance in psychoacoustic data (Micheyl, Delhommeau, Perrot, & Oxenham, 2006). Analyses including child age as a continuous variable likewise used the log of age. This choice of units was motivated by the observation that maturation tends to progress the most rapidly in the youngest listeners (Mayer & Dobson, 1982; Moller & Rollins, 2002). Bonferroni corrections were used for all simple effects testing, and Greenhouse-Geisser corrections were used as indicated. A significance level of α=0.05 was adopted.

The experiment was performed in a double-walled sound booth. Most children and naïve adults completed the experiment in two, one-hour visits; psychophysically experienced adults took between three and four hours to complete the experiment twice. All children and adults were given frequent breaks throughout testing. To maintain motivation, children were given small toys or prizes during these breaks.

RESULTS

Results were analyzed in two ways. The first approach was to compare performance between the naïve adults and three age groups of children: 5- to 6-year-olds, 7- to 8-year-olds, and 9- to 13-year-olds. The second approach was to evaluate age effects within the entire population of child listeners, with consideration of effects related to musical training. In both cases, the questions of interest were: 1) whether developmental effects were greater for pure-tone frequency discrimination than FM detection, a result that would be consistent with the hypothesis that memory for pitch contributes to age effects in pure-tone frequency discrimination; and 2) whether developmental effects differed for 2-Hz FM detection at 500 Hz compared to other FM conditions, a result that would implicate differential maturation of the ability to make use of temporal fine-structure cues and place cues for pitch.

A. Group differences

Mean thresholds are plotted in Figure 1 as the percent change in frequency, on a log scale, for each condition and listener group. Data are shown separately for 5- to 6-year-olds, 7- to 8-year-olds, 9- to 13-year-olds, naïve adults, and experienced adults. Thresholds for the later group of adults are included for reference but are not formally compared to those of children due to confounds between maturation and prior psychoacoustical experience. Children with and without musical training are grouped together in this figure. In general, younger children performed more poorly than naïve adults. This is particularly evident for pure-tone discrimination at 500-Hz. These observations were assessed using a repeated-measures analysis of variance (rmANOVA), with three levels of task (pure-tone discrimination, 2-Hz FM detection, and 20-Hz FM detection), two levels of frequency (500 and 5000 Hz), and four levels of listener age group (5- to 6-year-olds, 7- to 8-year-olds, 9- to 13-year-olds, and naïve adults). The results of this analysis appear in Table 1. There were main effects of listener age group ($p<0.001$) and task ($p<0.001$), as well as two-way interactions between group and task ($p=0.001$), and between task and frequency ($p<0.001$). The three-way interaction was not significant ($p=0.104$). A within-subjects Helmert contrast indicated that the effect of group was larger for the pure-tone stimuli than for the FM stimuli ($F[3,42]=6.37$, $p = 0.001$), but that the effect of age group was not different for the 2-Hz and 20-Hz FM rates ($F[3,42]=1.01$, $p = 0.396$). The interaction between task and frequency was due to relatively low thresholds for 20-Hz FM at 5000 Hz compared to 20-Hz FM thresholds at 500 Hz, and compared to thresholds in the other 5000-Hz conditions. Simple effects testing indicated that for all six conditions, the 5- to 6-year-olds and 7- to 8-year-olds performed more poorly than adults, but the 9- to 13-year-olds did not.

B. Effects of age and musical training within the child groups

The focus now turns to the effect of age within the entire population of child listeners. Figure 2 shows thresholds for individual child listeners, plotted as a function of listener age on a log scale, with adults' thresholds shown on the far right. Each panel shows results for a different stimulus condition, with filled circles indicating data for children who were musically trained and open circles indicating data for children with no such training. Recall that Δf was limited, such that the maximum target frequency could not exceed 10% of the standard frequency. All threshold estimation tracks were examined to evaluate the possible effects of this limit by identifying all cases in which the Δf limit was applied two or more times after the second track reversal. This occurred in approximately 2% of all tracks collected, all in child listeners. There were only three cases in which a child listener provided fewer than two tracks that were unaffected by limits to Δf: two cases for pure-tone discrimination at 500 Hz (5.1 and 5.5 yrs), and one case for pure-tone discrimination at 5000 Hz (8.5 yrs). The thresholds reported for these listeners in these conditions may therefore slightly underestimate true threshold.

The lines in each panel of Figure 2 indicate the correlation between child age and threshold, without consideration of musical training. These correlations were significant for all six stimulus conditions, as assessed by one-tailed tests with Bonferroni correction: correlations ranged from $r = -0.64$ (pure-tone discrimination at 500 Hz) to $r = -0.46$ (20-Hz FM detection at 500 Hz). A rmANOVA was performed on children's thresholds, with log of age as a covariate, to assess the effect of child age and history of musical training on frequency discrimination. There were three levels of task (pure-tone discrimination, 2-Hz FM detection, and 20-Hz FM detection), two levels of frequency (500 and 5000 Hz), and two levels of training (musically trained and untrained). The results appear in Table 2. The only significant effects were the main effect of age ($p = 0.001$) and the three-way interaction between task, frequency, and training ($p = 0.031$). Simple effects testing indicated that training had an effect on pure-tone discrimination at 500 Hz ($p = 0.043$), but not for any of the other conditions ($p >= 0.254$). Analysis of data just from the untrained children resulted in a similar pattern of results as that observed for the entire group of child listeners with respect to age, task, and frequency.

Whereas age is clearly associated with performance, there is considerable variance in the child data that is not explained by listener age. Correlations were examined to evaluate the extent to which this variability is due to consistent individual differences. Before controlling for listener age, the correlations between thresholds for the six conditions range from $r = 0.30$ to $r = 0.71$. Partial correlations, controlling for listener age, range from $r = 0.11$ to $r =$

0.63. After Bonferroni correction, only four of these partial correlations reached significance (α = 0.05, one-tailed): correlations among the three 5000-Hz conditions (r = 0.52 to r = 0.63), and the correlation between the 2- and 20-HzFM detection at 500 Hz (r = 0.60). None of the non-significant correlations approached significance (p>=0.345). This result is consistent with the idea that individual differences in the age-corrected thresholds are frequency specific, but that the 500-Hz pure-tone condition is special, in that variability in this condition is unrelated to, or weakly related to, variability in FM detection at 500 Hz. The suggestion that frequency discrimination at 500-Hz may be a special case with respect to individual differences is consistent with the finding that musical training was related to performance in this condition.

C. Effects of psychophysical practice in adults

Within the adults' data, the group with psychoacoustic listening experience had lower thresholds than the psychoacoustically naïve group. This is particularly evident for pure-tone frequency discrimination at 500 Hz. A rmANOVA was performed on the data of adult listeners, with three levels of task (pure-tone discrimination, 2-Hz FM detection, and 20-Hz FM detection), two levels of frequency (500 and 5000 Hz), and two levels of group (naïve and experienced). Results appear in Table 3. There was a main effect of listener group (p=0.005). The only other significant effect was an interaction between frequency and task (p<0.001). Contrasts indicated that pure-tone discrimination thresholds were lower at 500 than 5000 Hz (p=0.015). In contrast, 20-Hz FM detection thresholds were higher at 500 than 5000 Hz (p=0.004). There was no effect of frequency for the 2-Hz FM task (p=0.056). The absence of a three-way interaction indicates that the effect of prior psychoacoustic listening experience did not differ significantly across the six conditions.

DISCUSSION

Results for both naïve and experienced adults were broadly consistent with those in the literature. Pure-tone frequency discrimination thresholds for naïve adults were 0.8 and 0.9% for the 500- and 5000-Hz standard frequencies, respectively. Thresholds for these conditions were lower for adults with psychoacoustical listening experience: 0.3 and 0.6%, respectively. In trained adults, frequency discrimination thresholds are expected to be on the order of 0.2 and 0.3% at 500 and 5000 Hz, respectively (Micheyl, Xiao, & Oxenham, 2012; Wier, et al., 1977). The higher thresholds than observed previously could be due to the provision of relatively limited task-specific practice in frequency discrimination in the present study. Thresholds for FM detection were between 0.6 and 0.8% in the group data of psychoacoustically experienced adults, and between 0.6 and 1.1% in the group data of naïve adults. These values are similar to those observed previously in adult listeners by Moore and Sek (1996). In that study, thresholds at 500 Hz were ~0.9% (2-Hz FM) and ~1.3% (20-Hz FM), and those at 4000 Hz were ~ 0.7% (2-Hz FM) and ~0.6% (20-Hz FM). Larger effects of listening experience for frequency discrimination than FM detection is consistent with the results of Moore (1976), showing greater individual differences and larger changes with practice in the pure-tone frequency discrimination task.

Pure-tone frequency discrimination thresholds in 6- to 7-year-olds have been reported to be 10% or more for a 1000-Hz standard and a 200-ms duration (Halliday, et al., 2008; Moore, et al., 2008). In the present experiment thresholds of the 5- to 6-year-olds were ~4%. One reason for the better performance in the present study could be the use of longer stimuli (1 sec vs 200 ms). Whereas adults' performance is relatively insensitive to increased stimulus duration above 200 ms (Freyman & Nelson, 1986), this might not be the case for children.

Children's FM detection thresholds are comparable to those reported by Bishop et al. (1999). In that study thresholds for 2- and 20-Hz FM were measured for a 1000-Hz standard frequency and 400-ms stimulus duration. Representing threshold as the peak-to-peak frequency difference, mean thresholds in a group of typically developing 8.7- to 11.0-year-olds were ~ 1.2% at both rates. In the current data set, FM thresholds for the eleven children in this age range were between 1.0 and 1.4% across standard frequencies and FM rates. Sutcliffe and Bishop (2005) reported 20-Hz FM thresholds of 1.7% in 6- to 7-year-olds and 0.6% in 8- to 9-year-olds, a larger improvement with age than observed in the current dataset at either carrier frequency.

A. Pure-tone frequency discrimination and FM detection

The relationship between pure-tone frequency discrimination and the detection of FM has been the topic of investigation in adults for some time. One approach to understanding the detection of FM is the sampling theory, which holds that the listener samples the stimulus frequency over the course of a listening interval and bases the detection decision on the difference between those samples or on the match between sample frequencies and a template of the target FM. A competing view is that there are change detectors in the auditory system dedicated specifically to the detection of FM (e.g., Sek & Moore, 1999). By either view, memory for pitch would be more severely taxed in pure-tone discrimination than FM detection, in that for the pure-tone stimulus the listener must remember and compare pitch across intervals, whereas for FM detection the listener could identify the target based just on cues present within the target interval.

In the present study, the effect of listener age was less pronounced for FM detection than for pure-tone frequency discrimination. This result is consistent with the hypothesis that memory for pitch limited performance for young children to a greater extent than for older children and adults. Because the present paradigm used a fixed standard frequency (without rove), the memory component could be related to the pitch of the three stimuli within a trial and/or to a template of the pitch of the standard frequency, built up over a series of trials. Determining the relative importance of these two factors is the topic of ongoing study. In either case, the finding of a smaller child/adult difference for FM detection than pure-tone frequency discrimination stands in contrast to previous data on intensity (Buss, et al., 2013), showing that the difference between amplitude modulation detection and pure-tone intensity discrimination is similar for children and adults. These differences are broadly consistent with the hypothesis that frequency and intensity discrimination tasks tap into different auditory abilities in adults (Clement, et al., 1999).

Thresholds for FM detection in younger listeners were a factor of 1.7 to 2.7 lower than those for pure-tone frequency discrimination. In contrast, thresholds of experienced adults for FM detection at 500 Hz were a factor of 2.2 to 2.5 *higher* than those for the pure-tone discrimination. This finding with experienced listeners is consistent with previous reports that adults' thresholds for detecting low-rate FM on a low-frequency carrier are a factor of ~1.8 worse than those in the pure-tone stimulus paradigm (Hartmann & Klein, 1980). This is relevant to the present experiment in that it shows that memory for pitch is not the only factor that affects the pattern of thresholds across stimulus conditions. For example, temporal features of the stimulus (e.g., time spent at the frequency extremes) are also likely to play a role in performance. Despite these factors, maturation of memory for pitch is a likely explanation for the greater child/adult difference in pure-tone discrimination than FM detection. This finding adds to a growing body of evidence that different test procedures give very different results regarding the child/adult differences in sensitivity to changes in frequency (Banai, 2008).

B. Temporal fine structure

One factor that could contribute to the maturation of frequency discrimination is the ability to make use of temporal fine-structure cues. At low frequencies, pitch information is thought to be conveyed by temporal properties of neural firing, following the periodicity of the stimulus. As frequency increases, however, this temporal code becomes degraded due to limitations in phase locking, and place cues play an increasingly important role in pitch perception. In the context of low-rate FM detection, Moore and Sek (1996) argued that adults' thresholds were dominated by temporal cues for carrier frequencies below about 4000 Hz, and by place cues above 4000 Hz.

In the present study, the developmental effect in FM detection was fairly uniform across both FM rate and standard frequency. That is, younger children's thresholds for 2-Hz FM detection at 500 Hz did not appear more or less adult-like than FM detection thresholds for other conditions. If 2-Hz FM detection at 500 Hz reflects fine temporal coding, the present results are consistent with an interpretation that maturation of frequency discrimination follows parallel courses for temporal and place cues to pitch. This interpretation is tempered somewhat by two recent studies: one arguing that low-rate FM detection at both 500 and 5000 Hz could rely on temporal fine-structure cues (Ernst & Moore, 2012), and another arguing that peripheral phase locking is not the limiting factor in pitch discrimination (Micheyl, Schrater, & Oxenham, 2013). In light of these considerations, a conservative conclusion is that the present results provide no support for the idea that young children are particularly poor at making use of temporal fine-structure cues.

Some published studies indicate that the ability to use temporal fine structure may be slow to develop (e.g., Thompson, et al., 1999), while others suggest that children may rely on temporal fine-structure cues to a greater extent than adults (Allen & Bond, 1997), even in cases where place cues might support better performance (Allen, et al., 1998). The finding of parallel maturation for conditions thought to rely on temporal and place cues is qualitatively consistent with the results of Bertoncini et al. (2009). That study examined the ability to discriminate consonants in an /aCa/ context when stimuli had been processed in one of two ways: 1) noise vocoding, to degrade temporal fine-structure cues, or 2) dividing bands of speech by the associated envelope, to degrade envelope cues. Adults and 5- to 7-

year-olds performed similarly in the face of these two stimulus manipulations, supporting the conclusion that the ability to make use of cues based on temporal fine structure may develop in parallel with other auditory abilities. One caveat to this conclusion is that this experimental approach to quantifying the use of fine-structure cues in speech perception has recently been brought into question (Shamma & Lorenzi, 2013).

C. Effects of listening experience and musical training

While the experimental design did not initially include consideration of musical training, the sample of children recruited for the study fell into two distinct groups: those with and those without musical training. Musical training may provide an opportunity to learn about pitch, which could in turn support better performance on psychophysical frequency discrimination. That possibility is considered here.

Learning in a psychoacoustic task takes different forms, from task learning to learning related to the specific test stimulus. Frequency discrimination has been shown to improve with practice for both children and adults (Delhommeau, Micheyl, & Jouvent, 2005; Halliday, et al., 2008; Jeffrey, 1958). For example, Halliday et al. (2008) measured the ability to detect an increment in frequency of a 1000-Hz standard tone over the course of 600-trial practice session, and they compared performance of adults to that of 6- to 7-year-olds, 8- to 9-year-olds, and 10- to 11-year-olds. Thresholds for all four groups improved with practice, with the largest effects observed in the first 225 trials, although changes in performance within groups were small relative to the mean differences in thresholds across groups. At the completion of practice, mean thresholds for 6- to 7-year-olds were still nearly a factor of 10 higher than those of adults. This might be interpreted as indicating that the child/adult difference cannot be attributed to children requiring more practice than adults to optimize their listening strategy. It is possible, however, that practice on a psychoacoustic task is not the best way for children to learn about pitch given the repetitive nature of the procedures and the relatively restricted time period of exposure.

Another way that children might learn how to discriminate pitch is through musical training. Psychoacoustic and musical training have been argued to improve behavioral frequency discrimination in similar ways in adults. Micheyl et al. (2006) measured frequency discrimination thresholds with a 330-Hz standard in two groups: adults with extensive classical music training and those with no training. At baseline, musicians outperformed untrained listeners by a factor of six. Subsequent practice on frequency discrimination had a modest effect on the musicians' performance, whereas the untrained listeners' thresholds improved substantially. There was no difference between groups after 4-8 hours of practice. One way to think about this result is that intensive prior training on pitch perception in the context of music allowed musicians to selectively attend to the most efficient cues and/or develop strategies for remembering the pitch of the stimuli with minimal psychoacoustic practice, whereas untrained listeners required more psychoacoustic practice to refine these strategies.

In addition to short-term practice effects demonstrated in human psychophysics, long-term training on frequency discrimination has been shown to expand the tonotopic region tuned to the trained frequency in the cortex of non-human primates (Recanzone, Schreiner, &

Merzenich, 1993). Some evidence for neural plasticity in response to training is also available in humans, for both psychoacoustic frequency discrimination (Bosnyak, Eaton, & Roberts, 2004; Menning, Roberts, & Pantev, 2000) and musical training (Pantev et al., 1998; Shahin, Bosnyak, Trainor, & Roberts, 2003). For example, Bosnyak et al (2004) measured evoked potentials (EPs) in adults undergoing frequency discrimination training with a 2000-Hz standard tone that was amplitude-modulated at 40 Hz. Both psychoacoustic sensitivity and the amplitude of the EPs increased with training. Similar changes have been demonstrated in children with extensive musical training (Shahin, Roberts, & Trainor, 2004), supporting the conclusion that musical and psychoacoustic training have similar physiological effects.

The studies considered above are consistent with the idea that musical training in children could be associated with better frequency discrimination, with the reasoning that musically trained children might benefit less from psychoacoustic practice than untrained children due to relatively good performance at baseline. In the present study, children with and without musical training tended to perform similarly. The one exception was pure-tone frequency discrimination at 500 Hz, for which there was a benefit of musical training. This condition also stood out in the pattern of individual differences among child listeners: after controlling for age, children's thresholds were correlated within conditions at a particular frequency, with the exception of 500-Hz frequency discrimination. In the mean data of adults, there was also a trend for psychoacoustic experience to have a larger beneficial effect at 500 than 5000 Hz, although this trend did not reach significance. Olsho, Koch, and Carter (1988) argued that providing adults with practice on pure-tone frequency discrimination has a greater beneficial effect on thresholds for a 500-Hz standard than for a 4000-Hz standard, although this result is not always observed (Delhommeau, et al., 2005). Some aspects of the present data are consistent with the hypothesis that both musical training (in children) and psychoacoustic listening (in adults) have greater beneficial effects on pure-tone discrimination at low than high frequencies. While it might be tempting to interpret the effect of musical training in terms of listening experience, an effect of innate ability cannot be ruled out. The exact nature of the relationship between musical training and frequency discrimination remains elusive; it could be due to a selection bias, with good pitch discrimination contributing to the decision to pursue training, or it could be due to beneficial effects of the training itself.

D. Do the present results resolve any inconsistencies?

The original motivation for the present study was to better understand apparent inconsistencies in the literature on the development of frequency discrimination. Data on school-age children indicate that frequency discrimination thresholds can be a factor of 10 or more above those of adults (Halliday, et al., 2008; Maxon & Hochberg, 1982; Moore, et al., 2008). In contrast, the adult/infant differences reported in the literature range from a factor of five (Sinnott & Aslin, 1985) to a factor of two or less (Aslin, 1989; Olsho, 1984). Olsho (1984) argued that infants' performance was adult-like at 4000-8000 Hz, with developmental effects restricted to lower frequencies (e.g., 500 Hz). Whereas these discrepancies are hard to reconcile, we know that both stimulus parameters (e.g., stimulus duration; Thompson, et al., 1999) and psychophysical procedures (Banai, 2008; Sutcliffe &

Bishop, 2005) can have a pronounced effect on the pattern of performance across age groups.

The present study tested the idea that one contributor to the poor performance of school-age children could be relatively poor memory for pitch. In the present study, thresholds of 5- to 6-year-olds in pure-tone discrimination were a factor of 4-5 higher than those of naïve adults. Comparing this group of children to adults with psychoacoustical listening experience increased the apparent age effect to a factor of 14 at 500 Hz. These results broadly replicate the very poor performance reported for this age group. For FM detection, 5- to 6-year-olds' thresholds were a factor of 2-3 greater than those of naïve adults, with no indication of a frequency effect in the child/adult difference. This result is also generally consistent with that of Olsho (1984), the absence of a frequency effect notwithstanding.

The question then becomes why children require a dynamic stimulus to perform as well as infants do with pure tones. The answer to this question may have to do with the paradigm used to test infants. In the study of Olsho (1984), for example, the stimulus was a continuous train of 500-ms tones, with 500 ms between sequential tones. Listening intervals were not explicitly marked, and the listener's task was to respond whenever a difference in frequency was detected. This presentation scheme gives the listener many opportunities to become familiar with the standard frequency, and does not require the listener to identify *which* of the tones differed in frequency. Future study is needed to determine whether these procedural details fully explain the relatively good frequency discrimination of infants compared to young children.

CONCLUSIONS

As observed in previous studies, sensitivity to frequency change was poor in younger children relative to adults. Detection of FM was more adult-like in children than pure-tone frequency discrimination, as would be expected if memory for pitch were an important factor in performance with the pure-tone stimuli. These results add to a growing body of evidence that the methods used to assess the maturation of frequency discrimination have a large impact on the results (Banai, 2008; Sutcliffe & Bishop, 2005). There was no evidence of a difference in the developmental effect for 2-Hz FM detection at 500-Hz than for other FM conditions, however, as might be expected if maturation of the ability to make use of temporal fine-structure cues differed from maturation of the ability to use place cues. Musical training was associated with better performance, particularly for pure-tone frequency discrimination at 500 Hz. Children's low-rate FM detection thresholds might more accurately reflect sensitivity to changes in frequency than pure-tone frequency discrimination, which appears to be more influenced by cognitive factors, like memory for pitch or training effects. Evaluating FM detection as a precursor to speech and language development may also have more ecological validity than pure-tone frequency discrimination, as the majority of pitch cues contributing to speech perception are dynamic in nature. This association is supported by the finding that evoked potentials elicited with FM stimuli are highly predictive of receptive language deficits (Duffy et al., 2013).

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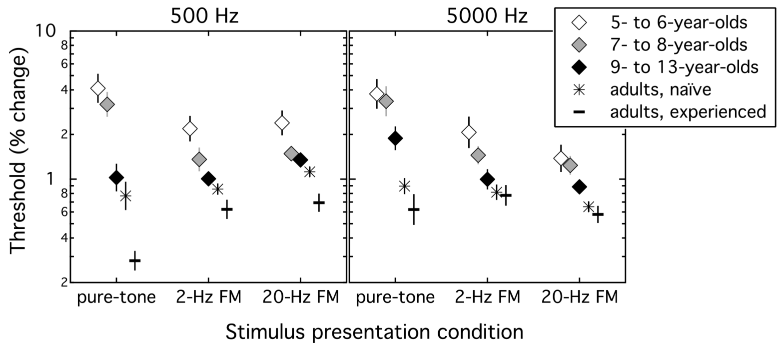

Figure 1.

The geometric mean thresholds are plotted separately for four listener groups: 5- to 6-year-olds (n=10), 7- to 8-year-olds (n=10), 9- to 13-year-olds (n=14), naïve adults without prior psychoacoustic listening experience (n=12), and adults with extensive prior psychoacoustic listening experience (n=5). Listener group is indicated by symbol shape and shading, as defined in the legend. Threshold condition is indicated on the abscissa, with data for the 500-Hz standard frequency in the left panel and those for the 5000-Hz standard frequency in the right panel. Error bars represent plus and minus one standard error of the mean, computed on log-transformed thresholds.

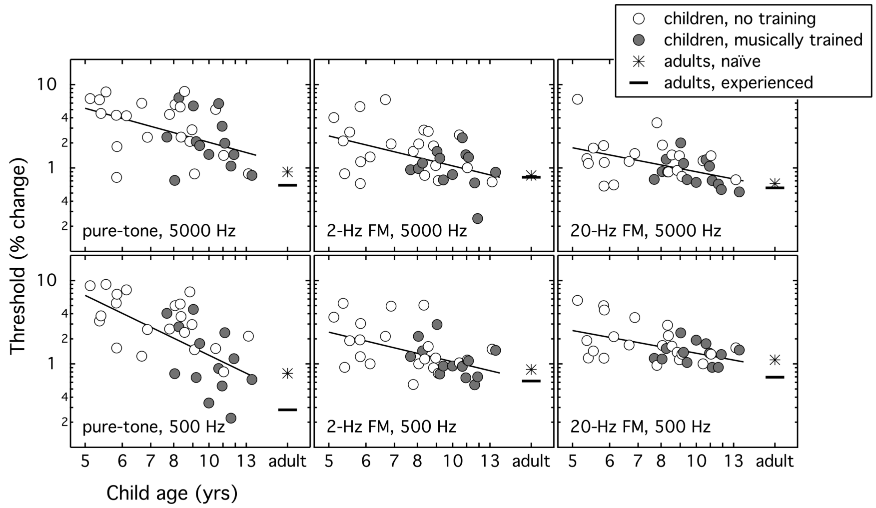

Figure 2.

Thresholds for individual child listeners are plotted with circles as function of age on a log scale. Symbol shading indicates whether or not a listener had received musical training. Lines indicate the linear association between age and threshold, both on a log scale. Thresholds for adults are shown at the far right of each panel. Results are shown separately for the two standard frequencies (rows) and three listener tasks (columns).

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Table 1

Results of an rmANOVA assessing effects of signal frequency (freq: 500, 5000 Hz) and listener task (task: pure-tone discrimination, 2-Hz FM detection, 20-Hz FM detection) on sensitivity to change in frequency. There were four levels of listener group: 5- to 6-year-olds, 7- to 8-year-olds, 9- to 13-year-olds, and naive adults. Effects marked with an asterisk were further examined with contrasts or simple main effects testing.

source	F	df	sig
group	19.88	3, 42	**$p < 0.001$**
freq	1.23	1, 42	$p = 0.274$
freq x group	0.77	3, 42	$p = 0.519$
task	25.69	1.6, 66.6	**$p < 0.001$**
group x task	5.04	4.8, 66.6	**$p = 0.001$** *
task x freq	18.21	1.9, 78.4	**$p < 0.001$** *
group x task x freq	1.86	5.6, 78.4	$p = 0.104$

Table 2

Results of an rmANOVA assessing effects of signal frequency (freq: 500, 5000 Hz), listener task (task: pure-tone discrimination, 2-Hz FM detection, 20-Hz FM detection), and musical training (training: trained, untrained) on the detection of frequency change. Listener age, in log of years, was a continuous variable.

source	F	df	sig
age	13.07	1, 31	**p = 0.001**
training	2.09	1, 31	p = 0.159
freq	0.33	1,31	p = 0.571
freq x age	0.29	1, 31	p = 0.593
freq x training	0.13	1, 31	p = 0.718
task	3.20	1.6, 52.4	p = 0.057
task x age	1.66	1.6, 52.4	p = 0.203
task x training	0.48	1.6, 52.4	p = 0.591
task x freq	0.01	1.9, 58.5	p = 0.990
task x freq x age	0.24	1.9, 58.5	p = 0.772
task x freq x training	3.77	1.9, 58.5	**p = 0.031** *

Table 3

Results of an rmANOVA on adult data, assessing effects of signal frequency (freq: 500, 5000 Hz), listener task (task: pure-tone discrimination, 2-Hz FM detection, 20-Hz FM detection), and prior psychoacoustical listening experience (group: naive, experienced). The effect marked with an asterisk was further examined with contrasts or simple main effects testing.

source	F	df	sig
group	10.77	1, 15	**p = 0.005**
freq	0.27	1, 15	p = 0.612
freq x group	2.83	1, 15	p = 0.113
task	2.98	1.3, 19.1	p = 0.093
group x task	2.68	1.3, 19.1	p = 0.112
task x freq	24.61	1.9, 28.0	**p < 0.001** *
group x task x freq	1.35	1.9, 28.0	p = 0.275