2pPPb1. Factors affecting frequency discrimination in school-aged children and adults

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Auditory frequency discrimination is a basic ability that may limit the maturation of speech and language skills in some listeners. Despite its importance, the factors affecting frequency discrimination in school-aged children are poorly understood. The goal of the present study was to evaluate effects related to memory for pitch, musical training, and the utilization of temporal fine-structure cues. Listeners were normal-hearing children, 5.1 to 13.6 years old, and adults. One subgroup of children had musical training (>150 hours) and the other did not. The standard stimulus was either a 500- or a 5000-Hz pure tone, and the target stimulus was either a tone of higher frequency or a frequency-modulated tone (2- or 20-Hz rate) centered on the standard frequency. As commonly observed, mean frequency discrimination thresholds tended to be elevated in younger listeners. This developmental effect was smaller for FM detection than for pure-tone frequency discrimination, consistent with an effect of memory for pitch. The child/adult difference tended to be smaller for musically trained than untrained children. Children were not particularly poor at 2-Hz FM detection for the 500-Hz standard, a condition thought to rely on temporal fine-structure cues. (Work supported by NIDCD R03DC008389.)

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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, and no such association between intensity discrimination and oral language (Mengler et al., 2005). Despite its importance, existing data on the development of frequency discrimination are surprisingly inconsistent. Behavioral data from 6- to 12-month-olds indicate relatively good frequency discrimination for a 1000-Hz standard; infants’ thresholds were approximately 2% of the standard frequency, compared to 0.5% for adults (Olsho, 1984; Sinnott and Aslin, 1985). In contrast, frequency discrimination for a 1000-Hz standard is commonly reported to be on the order of 10% in 6- to 7-year-olds (Maxon and Hochberg, 1982; Halliday et al., 2008; Moore et al., 2008).

Although adult-like frequency discrimination can be observed by 6-7 years of age under some conditions (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 and Hochberg, 1982). Remarkably, several studies have reported that a substantial proportion of young school-aged children are unable to reliably discriminate between 1000- and 1500-Hz tones (Thompson et al., 1999; Halliday et al., 2008). It is commonly assumed that this psychoacoustic result must underestimate ‘true’ frequency discrimination, since a generalized inability to discriminate 1000 and 1500 Hz would likely preclude speech perception.

The very poor frequency discrimination sometimes observed in school-aged children has been attributed largely to the maturation of cognitive factors underlying performance of the psychoacoustic discrimination task, such as attention or memory (e.g., Moore et al., 2008), rather than frequency discrimination as a basic auditory ability. This possibility is consistent with the finding that the structure of the task used to assess frequency discrimination has a larger impact on the thresholds obtained from younger listeners (Sutcliffe and Bishop, 2005). Given the association between frequency discrimination and language abilities (reviewed by: McArthur and 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 evaluating frequency discrimination in school-aged children and adults under a range of conditions designed to rely on different pitch cues or listening resources.

The work of Keller and Cowan (1994) showed that memory for pitch develops between 6-7 years of age and adulthood. In that study, memory for pitch was assessed by manipulating the duration of the temporal gap between the two tones to be compared. In the present experiment, the role of memory for pitch in the maturation of frequency discrimination thresholds was evaluated by comparing frequency discrimination for gated pure-tones with sensitivity to frequency modulation (FM). Gated frequency discrimination requires that the listener remember and compare pitch percepts over the course of a trial. In contrast, frequency modulation (FM) detection can be performed solely on dynamic pitch cues within a listening interval. The expectation was that developmental effects related to memory for pitch would preferentially elevate thresholds for the gated compared to the dynamic stimuli. Published data on FM detection in children are broadly consistent with this expectation. Age effects in 20-Hz FM detection are modest for 6- to 7-year-olds and may be absent by 8-10 years of age (Bishop et al., 1999; Sutcliffe and Bishop, 2005). These results are better than those reported in many studies using gated frequency discrimination, although any comparison across studies using slightly different methods is tenuous given the dramatic effect that psychophysical procedures can play in performance (Sutcliffe & Bishop, 2005).

In adults, FM detection is thought to rely on different cues for different stimulus conditions. Moore and Sek (1996) argued that detection of low-rate FM on a low-frequency carrier is based on temporal fine-structure cues, whereas FM detection for relatively high modulation rates and carriers is related to place of transduction in the cochlea. 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 40-Hz than 2-Hz FM detection; performance was adult-like for 40-Hz FM by age 7, but it wasn’t until age 9 that 2-Hz FM detection was as good as adults’. It is unclear what role, if any, the use of temporal fine-structure cues played in this result, in part because no data were collected at a higher carrier frequency where fine-structure cues are weak or absent. The present study measured FM detection at two rates (2 and 20 Hz) and for two carrier frequencies (500 and 5000 Hz). Based on the results of Moore and Sek (1996), the prediction was that young children might perform particularly poorly for 2-Hz FM detection at 500 Hz, the condition thought to rely most heavily on temporal fine-structure cues in adults.

Another factor that could impact the development of frequency discrimination in children is the effect of practice. Learning in a psychoacoustic task takes different forms, from task learning to learning related the specific test stimulus. Psychoacoustic frequency discrimination has been shown to improve with practice for both children...
and adults (e.g., Halliday et al., 2008). Another way that children might learn about pitch perception is through musical training. Psychoacoustic and musical training have also 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: listeners with extensive classical music training and those with no training. At baseline, musicians outperformed untrained listeners by a factor of six. Subsequent practice on the frequency discrimination task 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 practice to hone in on these cues. In the present study, frequency discrimination was compared for children with and without formal musical training. The rationale was that musically trained children might be less susceptible to psychoacoustic practice effects than untrained children. While children with and without musical training could differ in important ways (e.g., genetic predisposition for good musical ability), it seems likely that these effects are related to the provision of training (for discussion, see: Trainor et al., 2003).

**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, 2004). Exclusion criteria included a history of hearing loss and known developmental delays. One adult (29.3 years) was unable to complete testing due to scheduling conflicts, and one child (5.7 years) was unable to master the forced-choice task. Parents of children in the musically trained group reported that their children were currently 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 non-musically trained group included 16 children between 5.1 and 13.2 years of age, and their mean total practice time was 30 hrs. Adults were relatively untrained in psychoacoustics, having participated in no more than 2 hours of previous listening; no adult reported receiving more than 2 years of previous musical training. This adult group included 12 adult listeners between 19.1 and 29.9 years of age (mean 22.6 years).

**Stimuli**

Stimuli were tones or FM tones presented for 1 sec, measured from the half-rise point of 50-ms raised-cosine onset and offset ramps. Standard tones were either 500 or 5000 Hz, and FM tones were centered on the associated standard frequency. Presentations of the FM tones 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 FM with the same 50-ms raised-cosine ramps used to shape stimulus onset and offset. The rate of modulation was either 2 or 20 Hz. Stimuli were generated in software (RPvds; TDT), played out of a real-time processor (RP2; TDT), routed to an impedance-matching headphone buffer (HB7; TDT), and presented to the left channel of a pair of circumaural headphones (HD 25-1 II; Sennheiser).

**Procedures**

The task was couched in the form of a computer game. Each trial consisted of a three-alternative forced choice; two intervals contained the standard stimulus, and one randomly chosen interval contained the target. Intervals were indicated visually on a computer screen. This display included three animated frogs. Each frog opened and closed its mouth, synchronous with the onset and offset of the associated stimulus. The listener was then required to use a computer mouse to select the frog associated with the target. It was also acknowledged that the subject was listening for the one that sounded different, or made a wobbly sound. This task was easily understood by typically developing school-aged children and adults. When the listener responded correctly, an animation of the target-signal frog catching a fly appeared, providing immediate feedback.
Thresholds were estimated using a 2-down 1-up stepping rule, which converges on the $\Delta f$ associated with 71% correct. Each track began above the expected threshold. The $\Delta f$ was initially adjusted by a factor of 1.41. This was reduced to a factor of 1.19 after the second track reversal. A track was terminated once eight reversals had been obtained. Listeners were randomly assigned to start with either the 500- or the 5000-Hz standard frequency. Listeners completed three blocks each of the gated and modulated (2 Hz and 20Hz) conditions for that standard frequency. These blocks were completed in quasi-random order. Listeners whose threshold estimates were not within 5 dB of each other in the 500 Hz condition and 10 dB of each other in the 5000 Hz condition were repeated. The threshold estimate associated with a track was the geometric mean of the $\Delta f$ associated with the last six reversals, and all statistics were performed on log-transformed values. Bonferroni corrections were used for all simple effects testing, and Greenhouse-Geisser corrections were used as indicated. A significance level of $\alpha=0.05$ was selected.

The experiment was performed in a double-walled sound-proof booth. Most children and adults completed the experiment in two, one-hour visits. All children and adults were given frequent breaks throughout testing. Reinforcement (e.g., a small toy) was provided for children during these breaks. Data collection is ongoing; preliminary data are reported below.

**RESULTS**

Thresholds are plotted in Figure 1 in $\Delta f/f$ on a log scale. Data are shown separately for children younger than 7.0 years of age and children older than 7.0 years of age. One motivation for this division was the tendency for the youngest children to be in the untrained, as opposed to the musically trained, group. The youngest untrained child was 5.1 years, whereas the youngest musically trained child was 7.7 years. Analyzing just the children over 7.0 years of age resulted in approximate equal mean ages in the untrained and musically trained groups (9.6 vs 10.1 yrs, respectively; $t_{23}=0.67, p=0.51$). Due to the small number of children in the 5-6 year old group ($n=4$) it is omitted from analysis. However, most of the trends described below in 7-13 year-olds’ data are also evident in this younger group.

**FIGURE 1.** The geometric mean thresholds are plotted separately for four listener groups: young children (5-6 years, $n=4$), older musically trained children (7-13 yrs, $n=13$), older untrained children (7-13 yrs, $n=12$), and unpracticed adults ($n=12$). Listener group is indicated by symbols shape, 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 deviation, computed on log-transformed thresholds.

**Gated vs. FM**

To assess the difference between gated frequency discrimination and FM detection in untrained children and adults, thresholds for the 2- and 20-Hz FM rates were averaged in log units. A repeated-measures analysis of variance (rmANOVA) was then performed, with two listener groups (adults and 7-13 year-olds), two center
frequencies (500 and 5000 Hz) and two stimulus conditions (gated and FM). There was a main effect of listener group (F_{1,22}=25.86, p<0.001) and of condition (F_{1,22}=70.53, p<0.001). There was a significant interaction between condition and center frequency (F_{1,22}=4.86, p=0.038), reflecting a greater effect of condition at 5000 than 500 Hz. There was also an interaction between condition and group (F_{1,22}=6.89, p=0.015), reflecting the larger effect of condition for children than adults. Simple effects testing showed that children performed more poorly than adults in both gated frequency discrimination (p=0.001) and FM detection (p=0.006).

Effects of Musical Training

A second analysis carried out to assess the effects of training in 7-13 year-olds. A rmANOVA was performed, with two listener groups (7-13 year-olds with and without musical training), two center frequencies (500 and 5000 Hz) and two stimulus conditions (gated and FM). There was a main effect of condition (F_{1,23}=96.24, p<0.001) and an interaction between condition and frequency (F_{1,23}=13.41, p=0.001), reflecting the fact that the effect of condition was larger at 5000 than 500 Hz. There was also a three-way interaction (F_{1,23}=8.80, p=0.007). Simple effects tests indicate an advantage associated with musical training for gated frequency discrimination at 500 Hz (p=0.007) and FM detection at 5000 Hz (p=0.032), but not for the other two conditions (p>=0.237). Thresholds for the musically trained children were well within the confidence interval of those for adults in the two conditions associated with a training effect.

Effect of FM rate

A third analysis was performed to determine whether FM rate affected FM detection thresholds for untrained children and adults differently. A rmANOVA was performed, with two listener groups (adults and 7-13 year-olds), two center frequencies (500 and 5000 Hz) and two stimulus conditions (2- and 20-Hz). There was a main effect of listener group (F_{1,22}=9.30, p=0.006) and an interaction between frequency and rate (F_{1,22}=20.08, p<0.001), reflecting a larger effect of FM rate at 5000 than 500 Hz. None of the other effects reached significance. Of particular note, there were no differences across age groups in the effect of FM rate and no three-way interaction.

CONCLUSIONS

As observed in previous studies, frequency discrimination was elevated in 7-13 year olds compared to adults, although this age effect was reduced in children with musical training. The exact nature of the relationship between musical training and frequency discrimination remains a topic of future; 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. Detection of FM was more adult-like in children than gated frequency discrimination, as would be expected if memory for pitch were an important factor in performance with the gated stimuli. There was no evidence of a greater developmental effect for 2-Hz FM at the 500-Hz frequency, however, as might be expected if maturation of the ability to make use of temporal fine-structure cues were an important factor in performance.

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REFERENCES


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i. The rationale for applying a log transform prior to performing statistics appears in Micheyl et al (footnote #1; 2003). Briefly, log units are thought to reflect perceptually equal changes, and a log transformation tends to equalize variance in psychoacoustic data.