Infants can outperform adults in pitch and timbre discrimination

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Conflict of Interest

The authors declare no conflict of interests.

Abstract

Adults perceive pitch with fine precision, an ability ascribed to cortical functions that are also important for speech and music perception. Infants display neural immaturity in the auditory cortex, suggesting that pitch discrimination may improve throughout infancy. In three experiments, we tested the limits of pitch and timbre perception in 66 infants and 44 adults. Contrary to expectations, we found that infants surpassed adults in detecting subtle changes in pitch in the presence of random variations in timbre, and vice versa. The results indicate high fidelity of pitch and timbre coding in infants, implying that fully mature cortical processing is not necessary for accurate discrimination of these features. The surprising superiority of infants over adults may reflect a developmental trajectory for learning natural statistical covariations between pitch and timbre that improves coding efficiency in adults, but results in degraded perceptual acuity when expectations for such covariations are violated.

Keywords: cortical maturation, auditory development, pitch perception, timbre perception

INTRODUCTION

Pitch is a fundamental perceptual attribute of sound that can be arranged on a scale from high to low (ANSI, 2013) and is most closely related to the fundamental frequency (F0) or repetition rate of a stimulus. Adult listeners perceive pitch with extremely fine precision, particularly after training (e.g., Lau, Ruggles, Katyal, Engel, & Oxenham, 2017; Micheyl, Delhommeau, Perrot, & Oxenham, 2006). Studies investigating the neural correlates of pitch in humans and other primates have indicated the involvement of the auditory cortex (Bendor & Wang, 2005; Penagos, Melcher, & Oxenham, 2004; Zatorre, Evans, Meyer, & Gjedde, 1992).

Infant pitch perception is interesting in this regard because of the protracted development of the central auditory system, including the auditory cortex (Moore & Guan, 2001). Although infants begin responding to sound in the third trimester of gestation (Birnholtz & Benacerraf, 1983), it is hypothesized that brainstem processing supports early responses to sound because of cortical immaturity (Eggermont & Moore, 2012; Lau & Werner, 2012). Given the hypothesized cortical involvement in pitch, and its slow developmental trajectory, it may be that infant pitch perception is similarly slow to develop.

Many studies have shown that infants are sensitive to large pitch changes in both speech and music during the first few months of life. Infants can discriminate the pitch of pure tones (Olsho, 1984), complex tones (He & Trainor, 2009; Lau & Werner, 2012, 2014; Montgomery & Clarkson, 1997), musical melodies (Lau, Lalonde, Oster, & Werner, 2017; Plantinga & Trainor, 2009; Trehub, Thorpe, & Morrongiello, 1985), as well as lexical tones (Mattock, Molnar, Polka, & Burnham, 2008) and pitch contours of syllables and words (Karzon & Nicholas, 1989). Although infants perceive pitch, it is unclear whether they discriminate subtle changes with the acuity of an adult listener. For pure tones, infants discriminate changes in frequency as well as adults by 6 months in the high frequencies (Olsho, 1984) but in the low frequencies, discrimination thresholds do not seem to reach adult-like levels until 13-14 years of age (Maxon & Hochberg, 1982). Immature pure-tone frequency-discrimination thresholds have

also been reported in school-aged children at both high and low frequencies, likely influenced by non-sensory factors such as memory, sustained attention, and testing method (Buss, Taylor, & Leibold, 2014). Furthermore, with pure tones, it is difficult to determine whether participants are discriminating on the basis of pitch or a change in spectral content.

To investigate the influence of cortical maturation on complex pitch perception, we compared pitch discrimination with different degrees of pitch change in 3-month-olds, 7-month-olds, and adults. To prevent participants from using the lowest spectral edge or the spectral centroid of the stimulus (e.g., Houtsma & Smurzynski, 1990), rather than the F0 (pitch), random variations in the spectral content were introduced, which resulted in changes in the sounds' perceived brightness, one dimension of timbre, or sound quality – the perceptual aspect of sound that allows us to distinguish between different instruments (e.g., a piano and a violin) or voices (e.g., male and female) when they produce the same note at the same loudness. Infants at 3 and 7 months were tested because the organization of the auditory pathways appears to be distinctly different at these two ages. At 3 months, the auditory cortex is markedly immature, with activation of only the most superficial layer of the cortex by the reticular activating system; by 7 months, infants have access to thalamocortical connections, although significant immaturities in the auditory cortex persist (Eggermont & Moore, 2012). To the extent that the thalamocortical pathways are required for precise pitch perception, we predicted a trajectory of improving pitch discrimination abilities from 3-month-olds to 7-month-olds to adults.

EXPERIMENT 1: PITCH DISCRIMINATION WITH BRIGHTNESS VARIATION

This experiment tested the limits of infants' and adults' ability to detect a change in the F0 (the physical correlate of pitch) within a sequence of complex tones, each containing a random selection of consecutive harmonics, leading to random changes in brightness from tone to tone. In some sequences, a change in the F0 was introduced ("change" trial; Fig. 1A); in others the F0 remained constant throughout the sequence ("no-change" trial; Fig. 1B). The same observer-

based psychophysical procedure (Werner, 1995) was used for both infants and adults, so that their discrimination abilities could be compared more directly.

Method

Participants

Participants were 26 infants, including 13 3-month-olds (7 female and 6 male) and 13 7-month-olds (8 female and 5 male), and 21 adults, including 10 (9 female and 1 male) with little or no musical training and 11 (6 female and 5 male) with two or more years of formal musical training, including school band or choir. A sample size of 10 per group was determined a priori based on estimates of variability obtained from our previous studies of infant pitch perception (Lau, Lalonde, et al., 2017; Lau & Werner, 2012, 2014), and was sufficient to detect a difference between groups when one group reliably reaches criterion performance on the task (80% or more meet criterion) and another group does not (20% or fewer meet criterion) with a power ($1-\beta$) of 0.8 and probability (α) of 0.05 (Rosner, 1995, p. 384).

All infants passed tympanometric screening and adults passed tympanometric and audiometric screening; see Supplemental Material for more details. All procedures were conducted according to protocols approved by the Institutional Review Board at the University of Washington.

Stimuli

The stimuli consisted of sequences of 650-ms harmonic complex tones, including 50-ms linear rise/fall times and separated by 500-ms gaps, each composed of 6 consecutive harmonics, combined with random starting phases and bandpass filtered using a Butterworth filter with 12 dB per octave slopes, spectrally centered on the complex tone.

The baseline F0 was around 200 Hz, similar to the average female voice. Seven $\Delta F0$ values were used, ranging from 0 to 5%. The tones at F0 had lowest harmonic numbers

ranging between 3 and 7, and the tones at $F0 \pm \Delta F0$ had lowest harmonic numbers from 2 to 6, thereby introducing random variations in brightness.

The 70-dB SPL tones were embedded in a 65-dB SPL pink noise (1 to 12000 Hz) to reduce the audibility of any distortion products and were presented via an Etymotic ER-2 insert earphone to the right ear.

Procedure

The task was to listen to the sequence of complex tones and respond when there was a pitch ($F0$) change. The observer-based procedure has a long history in both visual (Teller, 1979) and auditory (Werner, 1995) psychophysics and has been widely used in developmental studies (Benasich, Choudhury, Realpe-Bonilla, & Roesler, 2014; Lau & Werner, 2012). Only the participant hears the stimuli, and the experimenter (who is blind to the trial type) must judge whether the $F0$ changed during the trial, based solely on the observed behavior of the participant.

During testing, infants sat on a caregiver's lap inside a sound-attenuated booth. An assistant in the booth manipulated toys to keep the infants facing midline. There were two mechanical toys in a dark Plexiglas box and a monitor to the participant's right. Either the toys were activated or a video was presented to reinforce the infant's response to a pitch change. The experimenter sat outside the sound booth and observed through a window. The adults in the booth were unable to hear the sounds because the stimuli were presented to the infant via an insert earphone. However, as an extra precaution, the caregiver and assistant both wore circumaural headphones, with the caregiver listening to music and the assistant listening to the experiment's instructions. The experimenter outside the sound booth also wore headphones and a microphone to communicate with the assistant inside the booth.

At the start of a session, background tones ($F0$) were played repeatedly. The experimenter initiated a trial when the participant was quiet and facing midline. To control for

response bias, both change trials and no-change trials were presented to calculate a hit and false-alarm rate, respectively (Green & Swets, 1966). On change trials, four tones at $F0 \pm \Delta F0$ were played before the tones reverted to $F0$ (Fig. 1A); on no-change trials, $F0$ tones continued to repeat (Fig. 1B). The experimenter had 4 s from trial onset to decide which trial type had occurred. Typical behaviors used to make judgments included infants' eye-darts and head-turns towards reinforcers (mechanical toys or video), as well as facial expressions, like eye-widening. Computer feedback was provided to the experimenter after each trial. Adult participants sat alone in the booth and were instructed simply to raise their hand when they heard the sound change that activated the toys. In all other respects, the stimuli and procedure were the same for the adult and infant participants.

Conditioning and Training

Participants were taught to respond during a conditioning phase with the pairing of a large pitch change (5% $\Delta F0$) and the activation of mechanical animals or a video. The probability of a change trial was 80% and the reinforcer was activated after every change trial regardless of the experimenter's response. The experimenter had to respond correctly on 4 of 5 consecutive change trials and 1 no-change trial within a maximum of 15 trials to progress to the training phase.

In the training phase, the task and stimuli were the same but the probability of a change trial was 0.5 and the reinforcer was activated only when the experimenter correctly identified a change trial. Participants were required to achieve a hit rate of at least 80% and a false-alarm rate of at most 20% over the last 5 change and no-change trials, within 40 trials in order to pass the training phase. If the criterion was not met, the session was discontinued and participants were given a break. Participants had up to four attempts to reach criterion to progress to the test phases.

After passing the training phase, participants were tested on up to 6 additional phases that presented progressively smaller pitch changes, with the probability of a change trial remaining at 0.5. The values of $\Delta F0$ were 2.5, 1.5, 1, 0.5, 0.25, and 0% of the $F0$. In order to progress to the next $\Delta F0$ level, participants were required to reach the pass criterion of at least an 80% hit rate with a false-alarm rate of at most 20% on the last 5 change trials and the last 5 no-change trials, corresponding to a sensitivity (d') of about 1.68. To account for potential inattention, $\Delta F0$ reverted to the previous $\Delta F0$ level (larger pitch change) following four consecutive incorrect responses. If participants responded correctly on 5 of 6 consecutive trials in a maximum of 15 trials at the previous $\Delta F0$, demonstrating that they were again attending to the task, testing resumed at the lower $\Delta F0$ level (smaller pitch change). Otherwise, the session was discontinued. Participants had a maximum of four attempts at each $\Delta F0$ level, at which point testing was discontinued.

Results

To address our initial question of whether 7-month-old infants outperform 3-month-old infants in pitch acuity, we compared the proportion of each group that successfully performed the task at the smallest pitch difference (0.25%). As shown in Fig. 2A, no clear differences can be seen between the two infant groups, with 11 of 13 of both the 3-month-olds and 7-month-olds (~85% of each group; 95% binomial exact CI [0.55, 0.98]) achieving criterion performance. By contrast, none of the 10 adult participants without musical training (0; 95% binomial exact CI [0, 0.31]) achieved criterion performance at this pitch difference. Thus, the proportion of successful infants at the smallest pitch-change level was significantly greater than the proportion of adults, $\chi^2(1, N=23) = 16.22, p < 0.0001, \Phi_c = 0.84$ for each infant group. Of the adult group with musical training, 8 of 11 (0.73, 95% binomial exact CI [0.39, 0.94]) reached criterion. This proportion was significantly higher than that of the musically untrained adults, $\chi^2(1, N=21) = 11.75, p = 0.001, \Phi_c = 0.75$, but was not significantly different from the proportion of either the 3- or 7-

month-old infants, $\chi^2(1, N=24) = 0.51, p=0.48, \Phi_c = 0.15$ in both cases. As expected, no participant achieved criterion performance at the 0% pitch difference.

The same pattern of performance is observed when comparing mean d' , a measure of sensitivity that takes potential differences in response bias into account (Fig. 2B; see Supplemental Material Fig. S1 for d' values across all $\Delta F0$ levels). Of the participants that made it to the 0.25% $\Delta F0$ level, average d' values for the 3-month-old, 7-month-old, and musician adult groups on the last five change and no-change trials were greater than 1 (3 Months: $N=11$, mean $d' = 1.84$, $SEM = 0.11$; 7 Months: $N=11$, mean $d' = 1.85$, $SEM = 0.12$; Musicians: $N = 8$, mean $d' = 1.91$, $SEM = 0.23$), whereas the average d' value for the musically untrained participants who made it to the smallest $\Delta F0$ level was -0.37 ($N = 6$, $SEM = 0.29$), which was not significantly different from zero; one-sample t-test, $t(5) = -1.30, p = 0.25$, 95% CI $[-1.11, 0.36]$, Cohen's $d = -0.53$, consistent with chance-level performance. The four musically untrained adults who did not make it to the smallest $\Delta F0$ level failed either at $\Delta F0 = 2.5\%$ ($N=2$) or at $\Delta F0 = 0.5\%$ ($N=2$). This outcome demonstrates that the difference between the groups reflects a true difference in sensitivity rather than simply a difference in response bias.

To assess the stability of the results, the proportions of infants and adults reaching criterion at the 0.25% $\Delta F0$ level were resampled using bootstrapping with replacement to generate 1000 replications. The 95% confidence intervals using the percentile method were then computed based on the bootstrap sampling distribution. The bootstrapped confidence interval for adults (95% percentile bootstrap CI $[0, 0]$) did not overlap with the 3-month-olds' (95% percentile bootstrap CI $[0.62, 1.0]$) or the 7-month-olds' (95% percentile bootstrap CI $[0.62, 1.0]$), confirming the significant difference in performance between the adults without musical training and both groups of infants.

EXPERIMENT 2: BRIGHTNESS DISCRIMINATION WITH PITCH VARIATION

The results from Experiment 1 did not support our initial hypothesis that 7-month-olds would outperform 3-month-olds in a pitch-discrimination task. In fact, the two groups of infants performed similarly and both groups outperformed musically untrained adults. One possible explanation for this surprising outcome is that the variations in brightness (due to the randomly selected harmonics in each trial) interfered with adults', but not infants', ability to discriminate pitch. That might occur because the infants perceived the brightness variations, but the variations did not interfere with their pitch discrimination, or because the infants simply did not perceive the brightness variations. Experiment 2 was designed to distinguish between these two possibilities by testing the limits of infants' and adults' ability to perceive changes in the brightness of harmonic complex tones. The task was the same as in Experiment 1 except that the parameters were reversed: Listeners were required to detect a change in brightness (induced by varying the spectral centroid of the stimulus) while ignoring random and uninformative variations in pitch (induced by varying F0).

Method

Participants

The new participants were 20 3-month-olds (12 female, 8 male), 20 7-month-olds (7 female, 13 male), and 10 musically untrained adults (5 female, 5 male). As in Experiment 1, a minimum sample size of 10 per group was determined, based on an ability to detect a difference between two groups in which proportions of 0.8 and 0.2 achieve the performance criterion. All recruitment and participant inclusion criteria were the same as in Experiment 1.

Stimuli

All tones were 500-ms harmonic complexes, including 20-ms raised-cosine rise/fall ramps, separated by silent gaps of 500 ms. All harmonics were generated up to 10 000 Hz, combined

in sine phase, and bandpass filtered using a Butterworth filter with 24 dB per octave slopes around the appropriate center frequency (CF).

The CF of each complex determined its brightness. Six values of ΔCF , from 0 to 15% of the CF, were used to test brightness discrimination. For each ΔCF and $CF \pm \Delta CF$ value, tones were generated with F0s of 170, 180, 190, 200, 210, and 220 Hz.

Procedure

Stimulus presentation, calibration, and procedures were the same as in Experiment 1. Only three ΔCF levels were tested for each infant, to reduce the testing time per infant. All adults and all but one infant completed testing in a single visit of approximately one hour. Both infants and adults were conditioned and trained to categorize two sets of complexes that differed by a 15% shift in their CF. Infants were then randomly assigned to one of two groups, with Group 1 tested on 10%, 5% and 0% ΔCF s and Group 2 tested on 2%, 0.5%, and 0% ΔCF s. Adults were tested with all ΔCF values.

Results

Infants at both ages were able to discriminate smaller changes in brightness than the adults (Fig. 3A). By the smallest ΔCF level, only 1 of 10 adult listeners (0.1, binomial exact 95% CI [0.003, 0.45]) reached the pass criteria, compared with 9 of 10 3-month-olds (0.90, 95% CI [0.56, 1.0]) and all 10 7-month-olds (1.0, 95% CI [0.69, 1.0]). The proportion of successful adults was significantly different from the proportion of successful 3-month-olds, $\chi^2(1, N=20) = 12.80$, $p < 0.0001$, $\Phi_c = 0.80$, and successful 7-month-olds, $\chi^2(1, N=20) = 16.36$, $p < 0.0001$, $\Phi_c = 0.91$. Resampling the infants and adults passing and failing the criterion at the 0.5% ΔCF level using bootstrapping with 1000 replications again showed that the confidence interval for adults (95% percentile bootstrap CI [0, 0.33]) did not overlap with the 3-month-olds' (95% percentile

bootstrap CI [0.67, 1.0]) or the 7-month-olds' (95% percentile bootstrap CI [1.0, 1.0]). As expected, none of the participants achieved criterion when the ΔCF was 0.

To ensure that the difference was not due to response bias differences, we assessed mean d' values at the smallest brightness change level (Fig. 3B; see Supplemental Materials Fig. S2 for d' values across all ΔCF levels). Of the participants that made it to the 0.5% ΔCF level, average 3-month-old and 7-month-old d' values for the last 5 change and no-change trials were greater than 1 (3 Months: $N = 9$, mean $d' = 1.77$, $SEM = 0.09$; 7 Months: $N = 10$, mean $d' = 1.86$, $SEM = 0.16$), whereas the average adult d' value was less than 1 ($N = 4$, mean $d' = 0.55$, $SEM = 0.91$) and was not significantly greater than zero (one-sample t -test: $t(3) = 0.60$, $p = 0.59$, 95% CI [-2.36, 3.46], Cohen's $d = 0.50$), consistent with chance-level performance. Note that the data from the one adult participant who reached the pass criteria at the 0.5% ΔCF level with a d' of 2.49 was included in this average.

These results rule out the possibility that infants' superior pitch discrimination found in Experiment 1 was due to an inability to perceive brightness changes. Indeed, as with pitch, infants' ability discriminate small changes in brightness appears to exceed that of musically untrained adults.

EXPERIMENT 3: ELIMINATION OF RANDOM VARIATIONS

If the adults' relatively poor performance was due to interference from variations in the irrelevant dimension, then eliminating the irrelevant variation would be expected to improve their performance. With new adults without musical training, we repeated the pitch discrimination task in Experiment 1, using tones with a constant brightness, and the brightness discrimination task in Experiment 2, using tones with a constant pitch. Complex tones from the Experiment 1 and 2 stimulus sets were used and all other aspects of the procedures remained the same.

Method

Pitch and brightness discrimination was measured without variation in the other irrelevant dimension were obtained in 13 new adults (8 female, 5 male) without musical training. A single exemplar of each F0 and CF was selected from the stimuli in Experiments 1 and 2. Otherwise, the stimuli and procedure were the same.

Results

With the elimination of brightness variation from the pitch discrimination task (purple line, Fig. 2A) all 13 adults (1.0, 95% binomial exact CI [0.75, 1.0]) were able to reach criterion on the 0.25% $\Delta F0$ test phase. This proportion was significantly greater than the proportion of musically untrained adults who reached criterion in Experiment 1, $\chi^2(1, N=23) = 23.00, p < 0.0001, \Phi_c = 1.0$, suggesting that the timbre variation interfered with adult pitch discrimination.

Similarly, once pitch variation was eliminated, adult brightness discrimination improved and more adults reached criterion for both the 2% ΔCF (0.85, 95% CI [0.55, 0.98]) and the 0.5% ΔCF (0.39, 95% CI [0.14, 0.68]) test phases (purple line, Fig. 3A). At the 2% ΔCF level, performance here was significantly better than performance of the adults in Experiment 2, $\chi^2(1, N=23) = 4.96, p = 0.03, \Phi_c = 0.46$, suggesting that the pitch variation interfered with adult brightness discrimination. However, the proportion of adults successful with and without random pitch variation was not statistically significant at the 0.5% ΔCF level $\chi^2(1, N=23) = 2.38, p = 0.12, \Phi_c = 0.32$. Overall, the results confirm that adult performance in Experiments 1 and 2 was disrupted by variation in the irrelevant dimension.

DISCUSSION

A total of 66 infants were tested on pitch and brightness discrimination in the presence of random variation in the other dimension. In Experiment 1, 85% of the infants tested were able to

reach the performance criterion at the smallest F0 difference (0.25%) in the test phase, whereas none of the adult participants without musical training reached this criterion. In Experiment 2, 95% of the infants were able to reach the performance criterion at the smallest CF difference (0.5%), compared to only 10% of the adult participants. These differences were highly significant in both experiments, with $p < 0.0001$ and an effect size, $\Phi_c > 0.8$ for each of the comparisons.

In terms of our primary research question to investigate the early development of complex pitch perception, these results showed that infants at both 3 and 7 months performed as well as adults with musical training. This finding is in line with previous studies showing that infants can discriminate pitch and timbre in the first few months in life (He & Trainor, 2009; Lau & Werner, 2012; Plantinga & Trainor, 2009). The surprising aspect of this finding is that no age-related improvements in discrimination were observed, as might be expected given the long developmental trajectory of auditory cortex. The fact that 3-month-olds performed as well as 7-month-olds and musically trained adults suggests that pitch and brightness discrimination is not dependent on a mature thalamocortical pathway or cortex.

The most unexpected finding – one that motivated Experiments 2 and 3 – is that infants outperformed adults without musical training on pitch discrimination in the presence of random variations in timbre and on timbre discrimination in the presence of random pitch variations. Adults often have difficulty distinguishing between pitch and the aspect of timbre known as brightness, describing increases in both as being “higher.” In studies of discrimination, interference between the two dimensions is common (Allen & Oxenham, 2014; Borchert, Micheyl, & Oxenham, 2011; Lau & Werner, 2014), and in functional imaging studies, substantial overlap between representations of pitch and brightness has been reported (Allen, Burton, Mesik, Olman, & Oxenham, 2019). Musical training typically leads to be better pitch discrimination prior to explicit training (Madsen, Marschall, Dau, & Oxenham, 2019; Micheyl et al., 2006), but does not eliminate such interference (Allen & Oxenham, 2014). Perceptual

interference between pitch and brightness may be an optimal coding strategy, as the two dimensions often covary in natural sounds (Kitahara, Goto, & Okuno, 2005; Whalen & Levitt, 1995). Indeed recent studies have demonstrated that relatively brief exposure to covariations in sound features can lead to very rapid perceptual learning in adults (Stilp, Rogers, & Kluender, 2010). These experiments have shown that adult listeners readily exploit statistical regularity in stimulus attributes to improve task performance. One interpretation of our unexpected results is that infants' inability to exploit the expected statistical covariations between stimulus attributes actually enhances their perceptual performance, relative to adults, in situations where expectations of covariation are violated.

Another related possible explanation is that adults were more susceptible to a confusion effect induced from the interfering irrelevant dimension. Allen and Oxenham (2014) showed that adult discrimination thresholds were better when the irrelevant variations in pitch or timbre were congruent with the change in the target dimension as opposed to when they were incongruent. Our hypothesis would predict that if infants do not take into account the natural statistics of covariation, then they should not show the benefits of congruent variations in pitch and brightness found in adults, and should also not be adversely affected by incongruent variations in the two dimensions. This prediction remains to be tested.

An important point to note is that while all aspects of the stimuli, task, and protocol remained the same between infants and adults, adults were explicitly instructed to raise their hand when they heard the sound change while infants were implicitly conditioned to respond. It is possible that this difference between implicit versus explicit task performance may be in part responsible for the difference in behavioral performance between the infants and the musically untrained adults. Nevertheless, musically trained adults (who were instructed in the same way as the musically untrained adults) did perform at levels similar to the infants. Finally, because we designed the study to detect whether participants in a given age group can or cannot discriminate a pitch or timbre level, it is possible that there are more subtle differences in how

well 3- and 7-month-olds can discriminate pitch; however, our study was not sufficiently powered to detect such subtle differences.

In studies of speech perception, differential sensitivity to native and non-native phonetic contrasts has been shown in adults but not young infants (Werker & Tees, 1984). Although there are non-native phonemes that infants discriminate but adults cannot, adults generally outperform infants on native language speech discrimination (Kuhl et al., 2006). In other music-related studies that tested both infant and adults on comparable tasks such as musical perception, absolute performance is also generally poorer in infants (Hannon & Trehub, 2005; Trainor & Trehub, 1992). Remarkably, our results suggest the reverse developmental trajectory – that pitch perception in the presence of timbre variation, and vice versa, become poorer with age, although musical training may mitigate this effect. This conclusion does not necessarily imply a continuous degradation in pitch discrimination from infancy. Instead, it may be that statistical covariations between pitch and timbre are learned by 12 months (as are speech and musical regularities; see Hannon & Trehub, 2005; Saffran, Aslin, & Newport, 1996). As such, perceptual interference between pitch and timbre may emerge at a relatively early age, degrading performance in older infants (12+ months) on tasks, such as ours, that violate these learned expectations. This prediction remains to be tested. Nevertheless, it is clear from our study that accurate pitch and timbre discrimination can be achieved by 3- and 7-month infants, suggesting that accurate discrimination of these important auditory dimensions is not dependent on complete auditory cortical maturation, suggesting a possible subcortical substrate for both pitch and brightness coding.

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FIGURES

Fig. 1. Schematic diagram of a change (A) and a no-change trial (B) in Experiment 1. **A.** At the start of a session background tones are played repeatedly. Random variation in which harmonics are included in the tone is used to produce changes in brightness but not a change in pitch (blue tones). On change trials, a pitch change is presented when the change tones are played four times (red tones; $F_0 + \Delta F_0$). **B.** On no-change trials, background tones continue to play throughout the trial.

Fig. 2. A. Proportion of participants to reach the pass criterion as a function of pitch change level. Orange, red, green, and light blue lines show proportion of successful participants across pitch change levels by group from Exp. 1. Purple line shows proportion of successful adults from Exp. 3 with random brightness variation eliminated. **B.** Mean d' values (± 1 SEM) at the 0.25% $\Delta F0$ level for the different groups, as indicated by the symbol colors. The number of participants in each group is shown in brackets.

Fig. 3. A. Proportion of participants to reach the pass criterion as a function of timbre change level. Dark blue, red, and green lines show proportion of successful participants across timbre change levels by group from Exp. 2. Purple line shows proportion of successful adults from Exp. 3 with random pitch variation eliminated. **B.** Mean d' (± 1 SEM) values at the 0.50% Δ CF level. Number of participants in each group is shown in brackets.