Infant pitch perception: Missing fundamental melody discrimination

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Although recent results show that 3-month-olds can discriminate complex tones by their missing fundamental, it is arguable whether they are discriminating on the basis of a perceived pitch. A defining characteristic of pitch is that it carries melodic information. This study investigated whether 3-month-olds, 7-month-olds, and adults can detect a change in a melody composed of missing fundamental complexes. Participants heard a seven-note melody and learned to respond to a change that violated the melodic contour. To ensure that participants were responding on the basis of pitch, the notes in the melody had missing fundamentals and varied in spectral content on each presentation. In experiment I, all melodies had the same absolute pitch, while in experiment II, the melodies were randomly transposed into one of three different keys on each presentation. Almost all participants learned to ignore the spectral changes and respond to the changed note of the melody in both experiments, strengthening the argument that complex tones elicit a sense of musical pitch in infants. These results provide evidence that complex pitch perception is functional by 3 months of age. © *2017 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4973412]

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I. INTRODUCTION

Infants' ability to perceive pitch has important consequences for both speech and music perception. In speech, pitch conveys emotion (Ohala, 1983; Trainor *et al.*, 2000), is a cue for word segmentation (Kemler Nelson *et al.*, 1989), and can change word meaning in tonal languages. In music, pitch is an essential building block, with musical scales composed of notes with different pitch relationships and melodic contours composed of patterns of pitch changes. Early pitch-processing abilities are thought to enable infants' rapid acquisition of speech and enjoyment of music (Jusczyk and Bertoncini, 1988; Trehub, 2001).

The results of many studies suggest that the auditory system is already processing pitch in both speech and music at birth. Cortical responses in newborns have been recorded to changes in the pitch of harmonic complex tones, changes in the size of relative pitch intervals (Huotilainen *et al.*, 2003; Háden *et al.*, 2009; Stefanics *et al.*, 2009), and changes in speech prosody (Sambeth *et al.*, 2008). Behavioral studies also suggest that infants are sensitive to pitch from a young age. By 3 months, infants discriminate pitch contours in syllables of words (Karzon and Nicholas, 1989), prefer infant-directed speech characterized by exaggerated pitch contours (Cooper and Aslin, 1990; Pegg *et al.*, 1992), recognize familiar melodies (Plantinga and Trainor, 2009), and prefer high-pitched singing to low-pitched singing (Trainor and Zacharias, 1998).

A limitation of many of these studies is that the sounds used differed in both pitch and spectrum. Thus, infants' responses may have been either to changes in pitch or to the associated spectral properties. While pitch generally increases as the frequency of a pure tone increases, the pitch of a complex tone depends on the fundamental frequency and, within limits, is heard whether the complex contains low- or high-frequency harmonics. Moreover, the pitch of the complex is matched to the fundamental frequency, even when the fundamental frequency component is absent. A sound with a high-frequency spectrum can therefore have a low pitch. In order to be sure that listeners are responding to the pitch of a sound, spectral properties must be controlled.

Some of the more salient spectral cues that need to be considered include spectral edge cues (Kohlrausch *et al.*, 1992), which would allow listeners to respond based on the lowest or highest frequency component in the complex, as well as spectral centroid cues, which would allow listeners to respond based on where the spectral energy is concentrated (Moore and Moore, 2003; Micheyl and Oxenham, 2004; Micheyl *et al.*, 2012). To ensure that listeners are not responding on the basis of spectral information, one standard control in pitch experiments is the use of missing fundamental complexes. The ability to discriminate the pitch of a missing fundamental complex demonstrates that a listener is integrating information across the spectrum into a pitch percept as opposed to responding on the basis of the spectral components themselves.

While fewer studies have examined infant's pitch perception using the appropriate acoustic controls, their results are consistent with the idea that complex pitch perception develops very early in life. In several pioneering behavioral studies, Clarkson and colleagues showed that infants at 7 months of age can categorize complex tones by their missing fundamental frequency (Clarkson and Rogers, 1995; Montgomery and

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Clarkson, 1997). Although, one electrophysiological investigation conducted in younger infants found that 3-month-olds do not show a cortical response to missing fundamental pitch (He and Trainor, 2009), Lau and Werner (2012, 2014) found that both 3- and 7-month-olds behaviorally discriminated between harmonic complexes on the basis of the missing fundamental in the face of spectral changes resulting from varying harmonic composition. One limitation of these studies however, is that it is difficult to confirm that nonverbal infants actually perceived pitch. The present study was conducted to address this limitation.

A common definition of pitch is that it is an attribute of sound that can be used to produce musical melodies (Plack and Oxenham, 2005). One approach to verifying whether certain sounds produce a pitch is to ask listeners to identify melodies constructed from those sounds. Melody discrimination requires access to global pitch information about the pattern of rising and falling pitch changes, or pitch contour, as opposed to the absolute frequencies of individual tones. Burns and Viemeister (1976, 1981) argued that sinusoidally amplitude-modulated (SAM) noise elicits a pitch percept because listeners can identify melodies composed of SAM noise. More recently, Oxenham *et al.* (2011) used a melody discrimination task to show that pure tones above 6 kHz that alone do not produce a sense of musical pitch do so when combined into a harmonic complex tone. The current study, therefore, addresses the question of whether infants perceive complex pitch using a melody discrimination task. Infants' ability to discriminate melodies composed of complex tones would add to the interpretation of previous results (Clarkson and Rogers, 1995; Montgomery and Clarkson, 1997; Lau and Werner, 2012, 2014) by confirming that infants can extract melodic pitch information from complex tones.

Although there have been no previous studies investigating infants' ability to perceive melodies composed of missing fundamental complexes, many studies conducted with pure tones have shown that infants can detect changes in melodies on the basis of contour, intervals, and rhythm (Trehub *et al.*, 1985; Trainor and Trehub, 1992; Hannon and Trehub, 2005). The question addressed in this study was whether they can detect changes in melodies composed of missing fundamental harmonic complexes. Listeners learned to respond when the melodic contour of a repeating standard melody changed and to ignore spectral variation that did not change the melodic contour. If infants are able to detect such a melodic violation, it strengthens the argument that these tones are eliciting a sense of musical pitch in infants. With that rationale, 3-month-olds, 7-month-olds, and adults were tested on a melody discrimination task in which missing fundamental complexes carried the melody.

To ensure that listeners were not responding on the basis of spectral changes, we introduced irrelevant spectral variation between notes. All notes were composed of six consecutive harmonics of the appropriate fundamental frequency but with different harmonic compositions. Furthermore, five variations of the background melody and five variations of the change melody were used. Thus, within a single variation, it would sound as if a different musical instrument played each note, and as if a different set of instruments played the notes in each variation. In experiment I, the absolute pitch (key) of the melody stayed the same on each presentation. The participants learned to discriminate a pitch change (wrong note) in one element of a sequence of varying pitches, with access to both absolute pitch and relative pitch cues. Participants could use the absolute pitch cues, or fundamental frequency, of each note independent of the other notes. They could also use the relative pitch cues, or the pitch relations between notes, to perform the discrimination. In experiment II, however, each presentation of the melody was randomly selected from one of three transpositions (different keys) to ensure that listeners were discriminating on the basis of the relative pitch cues of the melodic contour as opposed to the absolute pitch. As infants at both 3 and 7 months of age were able to discriminate the missing fundamental of complex tones in Lau and Werner (2012, 2014), it was predicted that this ability would generalize to the discrimination of pitch in a melody.

II. EXPERIMENT I

A. METHOD

1. Subjects

Participants in this study were 11 3-month-olds, 9 7-month-olds, and 11 adults. All infants were (1) born full term, (2) had no history of otitis media within 3 weeks of testing and no more than two prior occurrences, (3) had no risk factors for hearing loss, (4) had no history of health or developmental concerns, and (5) passed newborn hearing screening. At each test session, all infants were healthy and passed a tympanometric screen with a peak admittance of at least 0.2 mmhos and peak pressure between −200 and +50 daPa with a 226 Hz probe tone.[1] Infants in each age group completed testing within 10 days of the nominal age. All adults were (1) between 18 and 30 years of age, (2) reported normal hearing bilaterally, (3) had no history of noise exposure, (4) had less than two years of musical training, and (5) had no prior experience as participants in psychoacoustic experiments. All adults passed a tympanometric screen with a peak admittance of at least 0.9 mmhos and peak pressure between −200 and +50 daPa with a 226 Hz probe tone, as well as an audiometric screen at 20 dB hearing level (HL) at octave frequencies between 250 and 8000 Hz. Data from an additional two 3-month-olds were excluded because they were too tired, hungry, or fussy to complete the task; one 7-month-old did not pass the tympanometric screen. Data from one additional adult were excluded due to a failure to pass the demonstration phase. Participants were recruited through the Communication Studies Participant Pool at the University of Washington.

2. Stimuli

Two sets of melodies composed of missing fundamental tonal complexes were generated using MATLAB (Mathworks, Natick, MA). The standard, "background," melody was the first seven notes of "Twinkle, Twinkle, Little Star" in the key of C major (C C G G A A G) and the change melody contained a wrong note (C C G $\mathbf{D^b}$ A A G). Thus, the two melodies consisted of identical notes, except for the 4th note.

Each note was composed of six consecutive harmonics, which were combined in random phase. The tonal complexes were bandpass filtered to limit participants' ability to use spectral edge cues with a Butterworth filter with a −12 dB/octave slope; edge frequencies were the third and forth component of each tone. To control for responses to spectral changes as opposed to pitch changes, random spectral variation was introduced between notes by varying the harmonic composition of consecutive notes, shown in Table I. These changes in spectral composition are perceived as changes in timbre, the quality of sound that differs between two sounds that have the same loudness, pitch, and duration, as for example, when different musical instruments play the same note. Although the timbre of each note changed, its pitch, and therefore the pitch contour of the melody remained the same on each presentation. Harmonic numbers were selected for each note so that the upper and lower edge frequencies did not change in the same direction as the pitch contour of the melody.

Besides the irrelevant spectral variation introduced within each melody, five variations of the background melody and five variations of the change melody were used. Each variation used a different set of harmonic compositions. A different background melody was selected for each repetition. Therefore, although repetitions of the background melody always had the same pitch contour ("Twinkle, Twinkle, Little Star"), timbre varied from one note to the next within a melody, as well as across the five variations of the melody.

The melodies were 7.55 s in duration. Each note was presented for 650 ms with a 50 ms rise/fall time and 500 ms between successive notes so that there were no rhythmic cues. A pink noise with a low-frequency cutoff of 1 Hz and a high-frequency cutoff of 20 000 Hz was presented continuously with the complexes to mask distortion products. All sounds were presented monaurally through an Etymotic (Elk Grove Village, IL) ER-2 insert earphone in the right ear. The foam eartip was trimmed to fit infants' ear canals as needed. All melodies were presented at a flat-weighted level of 70 dB sound pressure level (SPL) and the pink noise was presented at 65 dB SPL, calibrated in a Zwislocki coupler. At the time of testing, levels were checked in the subject's ear canal via an Etymotic ER-7C probe microphone system. Testing was conducted in a double-walled, sound attenuating booth.

3. Procedure

Infants were tested in a single 60-min visit using an observer-based psychophysical procedure (Werner, 1995). During testing, infants sat on a caregiver's lap in the booth and an assistant in the booth manipulated toys to keep infants facing midline. There were two mechanical toys with lights in a dark Plexiglas box and a monitor to the participant's right. The experimenter sat outside the booth and observed through a window. Both the assistant and caregiver wore circumaural headphones during testing. Because the infant listened to sounds through an insert earphone, it would be difficult for the adults in the booth to hear those sounds. As an extra precaution, the caregiver listened to music of their choice, and the assistant listened to the experimenter's instructions.

From the start of the session, the background melody (i.e., "Twinkle, Twinkle, Little Star") was played repeatedly with a 500-ms silent interval between melodies. For each presentation, the background melody was randomly selected from the set of five variations. While the melody remained the same, the timbre of each note changed from one note to the next. The goal of the task was to determine whether the participant could ignore the timbre changes and detect a pitch change that would violate the melodic sequence (i.e., when the melody contained a wrong note: C C G **D^b** A A G). If a participant responded to every pitch change, they would not be able to successfully complete the task since sequential tones change in pitch according to the melody.

The experimenter initiated a trial when the participant was quiet and facing midline. There were two trial types, which occurred with equal probability during the criterion phase. On change trials a melody from the change category was randomly selected and played, while on no-change trials another melody from the background category played.

TABLE I. Harmonic composition of melodies. Lower edge frequencies in Hz and harmonic number (H*n*) of notes in the background and change melodies. Each note is composed of the lower edge frequency shown in above, and the next five consecutive harmonics.

	C	C	G	G	A	A	G
F0	261.6	261.6	392.0	392.0	440.0	440.0	392.0
Background 1	1569.6 H6	1569.6 H6	1176.0 H3	1176.0 H3	880.0 H2	880.0 H2	1176.0 H3
Background 2	1308.0 H5	1831.2 H7	1568.0 H4	1960.0 H5	1320.0 H3	1760.0 H4	2352.0 H6
Background 3	1569.6 H6	1569.6 H6	1176.0 H3	2744.0 H7	2200.0 H5	2640.0 H6	2352.0 H6
Background 4	1308.0 H5	1831.2 H7	1960.0 H5	2744.0 H7	2640.0 H6	1760.0 H4	1960.0 H5
Background 5	1569.6 H6	1831.2 H7	1568.0 H4	1568.0 H4	2200.0 H5	2640.0 H6	2744.0 H7
	C	C	G	D^b	A	A	G
F0	261.6	261.6	392.0	277.2	440.0	440.0	392.0
Change 1	1569.6 H6	1569.6 H6	1176.0 H3	1386.0 H5	880.0 H2	880.0 H2	1176.0 H3
Change 2	1308.0 H5	1831.2 H7	1568.0 H4	2217.6 H8	1320.0 H3	1760.0 H4	2352.0 H6
Change 3	1569.6 H6	1569.6 H6	1176.0 H3	1940.4 H7	2200.0 H5	2640.0 H6	2352.0 H6
Change 4	1308.0 H5	1831.2 H7	1960.0 H5	2494.8 H9	2640.0 H6	1760.0 H4	1960.0 H5
Change 5	1569.6 H6	1831.2 H7	1568.0 H4	1663.2 H6	2200.0 H5	2640.0 H6	2744.0 H7

Figure 1 shows an example of a change trial. To discriminate the change melody from the background melody, participants had to ignore the spectral changes and respond to each melody based on the missing fundamental pitch of the notes. On each trial, the experimenter, blind to trial type, decided within 6 s of trial onset whether a change or no-change trial had occurred, based only on the infant's behavior. The behavior used by experimenters to make judgments varied from infant to infant. Eye movements, head turn toward reinforcers, and facial expressions such as widening of the eyes were common behaviors observed. Computer feedback was provided to the experimenter at the end of a trial. During the criterion phase, participants' responses were reinforced with the presentation of a mechanical toy or video (the "reinforcer") for 4 s only if the experimenter correctly identified a change trial.

All participants were tested in one 60-min visit to the laboratory. The study consisted of one demonstration phase and one criterion phase. During the demonstration phase, the probability of a change trial was 0.80. The reinforcer was activated after every change trial regardless of the experimenter's response because the purpose of the demonstration phase was to demonstrate the association between the reinforcer and the target, the change melody, to the participant. The experimenter had to respond correctly on 4 of the last 5 change trials and 1 no-change trial within a maximum of 15 trials to complete the demonstration phase and progress to the criterion phase. All infants tested reached criterion in the demonstration phase in the first session attempted. However, four adults required a second attempt to complete the demonstration phase. No more than two attempted sessions were permitted in the demonstration phase.

In the criterion phase, the task and stimuli were the same as in the demonstration phase but the probability of change and no-change trials was 0.5, with the constraint that an equal number of change and no-change trials occurred

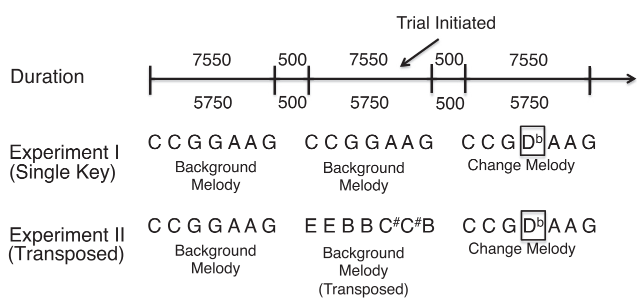

FIG. 1. Example of a change trial in experiments I and II. The background melody is played repeatedly until the experimenter initiates a trial (when the participant is quiet and facing midline). The remainder of the background melody is presented prior to the start of a target trial. The next melody presented is either another background melody (no-change trial) or a change melody as shown. In experiment I, the melodies are randomly selected from a stimulus set that contains five different background and five different change melodies. The timbre varies from one note to the next in all melodies. In experiment II, there are 15 background and 15 change melodies, consisting of the same melodies in experiment I and the melodies in two transpositions. The task is to respond when a change melody is presented. Because the inter-note-interval was shortened from 500 to 200 ms in the second experiment, experiment I duration is depicted on top of the trial schematic and experiment II duration is depicted below.

every ten trials. In addition, the reinforcer was activated only when the experimenter correctly identified a change trial. To complete the criterion phase, the experimenter was required to respond correctly on four of the last five change and four of the last five no-change trials. This criterion corresponds to a hit rate of 80% and a false alarm rate of 20% on the last five consecutive change and no-change trials, respectively. Participants received up to 40 trials to meet criterion. If criterion was not met, the session was discontinued and participants were given a break. If infants became fussy or inattentive during a test session, they were also given a break. A new session was started when the infant returned to the booth. If the participant did not complete the criterion phase in the second session attempted, the participant was judged to have failed the task.

To keep the test procedure as similar as possible, only vague directions were given to adult participants since verbal directions were not provided for infants. Adults sat alone in the booth and were instructed to raise their hand when they heard "the sound change that makes the toy come on." The experimenter recorded adults' responses. In all other respects, the stimuli and procedure were the same for adults and infants.

B. Results

Two analyses were conducted to evaluate participants' performance on the melody discrimination task. The first analysis addressed whether the number of participants in each age group reaching the criterion phase criterion was greater than expected by chance. The second analysis addressed the relative difficulty of the task for infants and adults by comparing the number of trials to meet criterion in the criterion phase across age groups.

All participants except one 3-month-old (91% of infants tested), one 7-month-old (89% of infants tested), and one adult (90% of adults tested) reached the pass criterion of at least a 80% hit rate with no more than a 20% false alarm rate on five consecutive change and five consecutive no-change trials in the criterion phase. The participants who reached this criterion are considered to have successfully completed the discrimination task. To determine the proportion of participants expected to reach criterion by chance, a simulation of 10 000 participants was conducted. The simulation estimates the proportion of participants that would be expected to reach criterion if the experimenter had been guessing on each trial. The input parameter of the simulation was the response rate calculated from all trials of all sessions run, including sessions in which criterion was not met. The response rate refers to the percentage of trials on which the experimenter judged that a change trial had occurred, with both change and no-change trials included in the calculation. Response rates were calculated separately for the demonstration and criterion phases because the difference between the phases in the probability of a change would be expected to influence the probability of a response. Two attempted sessions were permitted for each test phase. For adult participants, the overall response rate was 0.48 in the demonstration phase and 0.43 in the criterion phase. For infant participants, the overall response rate was 0.66 in the demonstration phase and 0.58 in the criterion phase. The output of the simulation showed that both the demonstration phase and criterion phase criteria would be expected to be met by chance in 45.29% of adults and 41.32% of infants.

Two exact binomial tests with an assumed probability of 0.45 and 0.41 were conducted based on the number of participants who reached criterion in each age group. More participants were found to meet criterion than expected by chance for both infants ($p < 0.001$) and adults ($p = 0.005$).

For successful participants, the number of trials required to reach criterion is shown in a box plot as a function of age group in Fig. 2. All trials, including those from unsuccessful sessions, are shown to capture each subject's overall stimulus exposure in the criterion phase. The number of trials to reach criterion appeared to be slightly lower for adults. However, a one-way analysis of variance (ANOVA) testing the effect of age on the number of trials to criterion revealed no significant effect of age [$F_{2,24} = 1.872$, $p = 0.176$]. There was, therefore, no indication that it was more difficult for infants to discriminate the missing fundamental melodies than adults.

C. Discussion

Results from this experiment demonstrate that adults and infants at both 3 and 7 months of age are able to discriminate between tonal sequences composed of missing fundamental complexes when the sequences differ in a single note. Almost all infants at both ages successfully completed the melody discrimination task, and they had no greater difficulty than adults reaching criterion. That infants can detect a specific pitch change in a sequence of pitch changes suggests that missing fundamental complex tones are indeed eliciting a sense of pitch in infants. However, because the absolute pitches of the tones in the sequence did not vary, it is possible that listeners did not discriminate on the basis of the melodic contour. Experiment II addressed that possibility.

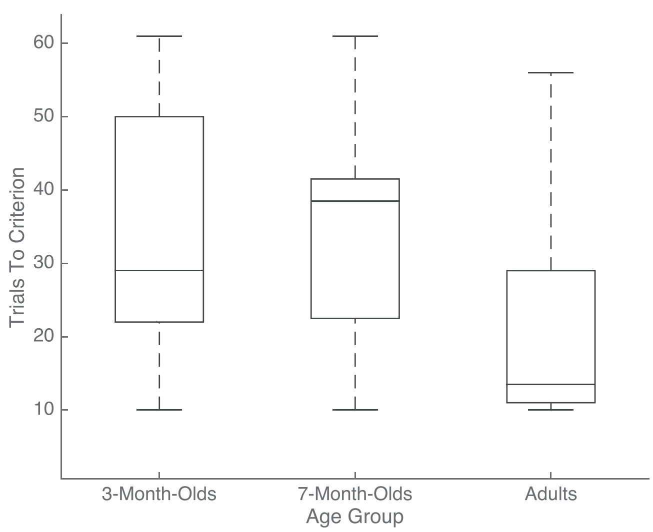

FIG. 2. Median number of trials to criterion as a function of age group on the missing fundamental melody discrimination criterion phase in experiment I. Box = 25th and 75th percentiles; bars = minimum and maximum values.

III. EXPERIMENT II

Melody discrimination requires extraction of the global pitch contour as opposed to the absolute pitch of successive notes in a sequence. In experiment II, the melodies from experiment I were transposed into two additional keys, so that all ten background and change melodies could be presented in each of three different keys. Each transposition would have the same global pitch contour and, thus, all would be melodically equivalent.

A. Method

1. Subjects

Participants were 14 3-month-olds, 11 7-month-olds, and 8 adults. All subject inclusion criteria were the same as in experiment I. Data from five additional 3-month-olds and three additional 7-month-olds were excluded because they were too fussy, tired, or hungry to participate; one 7-month-old failed the tympanometric screen; and one 3-month-old was excluded because of experimenter error. Data from five additional adults were excluded due to a failure to pass the demonstration phase. Although these subjects were excluded from the study, this surprising finding will be considered in Sec. IV.

2. Stimuli and procedure

Ten melodies in the key of C major were presented in experiment I with five spectral variations of the background melody and five spectral variations of the change melody. The same melodies were used in experiment II with two additional changes. First, each of the 10 melodies was transposed by 2 and by 3 semitones, resulting in 5 spectral variations in 3 keys (C, D, E^b) for a total of 15 background melodies and 15 change melodies. The second change was that the interval between two successive tones in each melody was shortened from 500 ms to 200 ms based on feedback that the long inter-note-interval made the task difficult for adult listeners from experiment I. All other aspects of the stimuli, including all spectral controls, were the same.

The test procedure, as well as the demonstration and criterion phases, were the same as in experiment I. The primary difference in the second experiment was that there were 15 melodies belonging to 3 keys in each of the background and change stimulus sets as opposed to 5 of each in a single key. For each presentation, the computer randomly selected 1 of the 15 background or change melodies. As in experiment I, each note within a single sequence was still composed of a different set of harmonics, so it would sound as if a different musical instrument played each note. The key from one melody to the next, however, could change depending on which melody was selected. If participants perceived the melodic contour, the three transpositions would be equivalent and the task would therefore be the same as in experiment I, to discriminate when a violation of the melody occurred. Listeners responding on the basis of absolute pitch would not reach criterion in the task.

All infants and adults were tested within a single 60-min visit to the laboratory. Two infants required a second attempted session to reach criterion in the demonstration phase. For the criterion phase, 12 infants required 2 attempted sessions to reach criterion. Because several adult participants had difficulty completing the demonstration phase, up to three attempted sessions were permitted. In addition, three adult participants required the additional instruction to "raise their hand when they heard the wrong note in the melody" (see Sec. IV for further comments). All adults who passed the demonstration phase completed the criterion phase in a single attempted session.

B. Results

Two analyses were conducted to evaluate participants' performance in experiment II. The first analysis addressed whether the number of participants in each age group reaching criterion was greater than expected by chance. The number of trials to meet criterion across age groups was then compared to address the relative difficulty of the task for infants and adults.

All participants except two 3-month-olds (86% of infants tested), one 7-month-old (91% of infants tested), and one adult (87.5% of adults tested) reached the pass criterion in the criterion phase. To determine the proportion of participants expected to reach criterion by chance, a simulation that generated random responses for 10 000 participants was conducted as in experiment I. Two attempted sessions were permitted for each test phase except the adult demonstration phase, which was increased to three attempts. For adult participants, the overall response rate was 0.53 in the demonstration phase and 0.49 in the criterion phase. For infant participants, the overall response rate was 0.63 in the demonstration phase and 0.59 in the criterion phase. The output of the simulation showed that both the demonstration phase and criterion phase criteria would be expected to be met by chance in 49.25% of adults and 41.39% of infants.

Two exact binomial tests with an assumed probability of 0.49 and 0.41 were conducted based on the number of participants who reached criterion in each age group. More participants were found to meet criterion than expected by chance for infants ($p < 0.001$) and adults ($p = 0.031$).

Figure 3 shows a box plot of the number of trials required to reach criterion for successful participants as a function of age group. All trials, including unsuccessful sessions, are shown to capture overall stimulus exposure in the criterion phase. A one-way ANOVA testing the effect of age on the number of trials to criterion revealed no significant effect of age [$F_{2,28} = 1.173$, $p = 0.199$]. Thus, infants and adults reached criterion in the same amount of trials, suggesting that the task was of comparable difficulty for both groups of infants and adults.

IV. GENERAL DISCUSSION

Results from these two experiments demonstrate that infants at both 3 and 7 months of age, like adults, can detect a change in a melody composed of missing fundamental complexes. In experiment I, about 90% of infants and about 90% of adults tested successfully completed the discrimination task. Because the absolute pitch of the notes remained

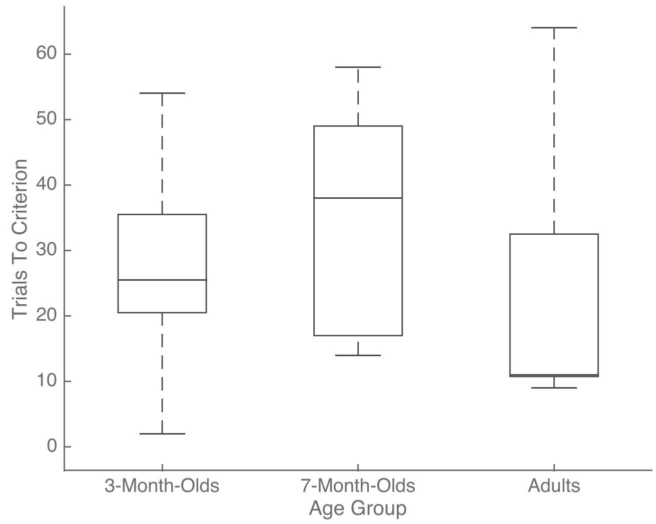

FIG. 3. Median number of trials to criterion as a function of age group on the missing fundamental melody discrimination criterion phase in experiment II. Box = 25th and 75th percentiles; bars = minimum and maximum values.

the same despite the presence of spectral variation, transpositions of the melody were introduced in a second experiment to assess whether participants were able to discriminate on the basis of the melodic contour. In experiment II, about 90% of infants tested also successfully detected changes in the melodic contour, demonstrating that they perceived the transpositions of the melodies as equivalent. Infants showed no greater difficulty than adults learning to discriminate the melodies in either experiment. Furthermore, the similar success rates of infants in the two experiments suggest that the melodic transpositions did not make the task more difficult. These results therefore provide evidence that the missing fundamental complexes elicit a sense of musical pitch in infants as young as 3 months of age. An additional interesting finding in experiment II is that there were five adult participants who were unable to pass the demonstration phase, even with additional verbal instructions.

A number of previous studies have demonstrated missing fundamental pitch perception in infants between 3 and 7 months of age in the context of a constant pitch background (Clarkson and Rogers, 1995; Montgomery and Clarkson, 1997; Lau and Werner, 2012, 2014). In Lau and Werner (2012, 2014), 3-month-old infants were presented with spectrally varying complex tones and were required to respond whenever they heard a change in pitch against a background of repeated presentations of one standard pitch. The current study extends those findings to the situation in which the pitch change occurs in the context of both spectral and pitch variations.

Because both absolute and relative pitch information was available in experiment I, it is possible that infants relied on absolute pitch cues to perform the task. In experiment II however, the use of relative pitch cues was required to perceive the transpositions of the melody as equivalent. Saffran and colleagues have shown that whether infants discriminate on the basis of absolute versus relative pitch cues can be influenced by the structure of the task (Saffran and Griepentrog, 2001; Saffran, 2003; Saffran *et al.*, 2005). When infants and adults were presented with a pitch sequence containing both types of cues, adults used the relative pitch cues while infants used absolute pitch cues (Saffran and Griepentrog, 2001; Saffran, 2003). However, in a subsequent task with the absolute pitch cues removed, infants also discriminated the pitch sequence using relative pitch cues like adults (Saffran *et al.*, 2005). The results of the current study are, therefore, consistent with Saffran's work.

Infants' success on these experiments is also consistent with past melody discrimination studies conducted with pure tones. In a task similar to the one used in the current study, Trehub *et al.* (1985) showed that 6- to 8-month-olds were able to detect a change in a six-note melody, no matter the position at which the change occurred. Similarly, Trehub *et al.* (1984) presented 8- to 10-month-old infants melodies in transposition and found that the transposition did not disrupt their ability to discriminate the melodies, as in experiment II here. While these comparable results suggest that infant pure tone melody discrimination abilities may generalize to complex tones, future investigations with different stimulus manipulations and different tasks are required to further explore the relationship between pure tone pitch and complex pitch in infants.

An additional infant-adult difference was observed in the demonstration phase of these two experiments. Infants readily learned the association between the reinforcers and the change melody. In experiment I, all infants passed the demonstration phase within 15 trials and in experiment II, only 2 infants required a second attempt. Adult listeners, showed considerably more difficulty learning this association. In experiment I, 3 of the 11 adult participants required 1 repetition of the demonstration phase to reach the pass criterion. In experiment II, 11 of 13 adult participants required more than 1 repetition of the demonstration phase. Furthermore, three of these participants required additional verbal instruction to listen for a wrong note in the melody to understand the task and four adults (one in experiment I, three in experiment II) were unable to pass the demonstration phase altogether. In the presence of constant spectral change, it appears that adult participants had difficulty isolating the specific pitch change (wrong note) and associating it with the reinforcers to learn the task. In experiment II, when the melodic transpositions were added, adult performance degraded further. This performance difference suggests that the salience of pitch in the context of constant spectral variation may be higher for infants than adults. This finding is consistent with previous studies showing that adult listeners have difficulty responding on the basis of pitch in the presence of timbre variation (Moore and Glasberg, 1990; Micheyl and Oxenham, 2004; Borchert *et al.*, 2011), which was also observed in Lau and Werner (2014). Further investigations are required, however, to determine why this "timbre confusion" does not affect infants.

The broad goal of this series of infant pitch discrimination studies (Lau and Werner, 2012, 2014) was to determine whether the immature auditory system is capable of encoding pitch-related information in complex sounds and generating a pitch percept. The results of Lau and Werner (2012, 2014) provide evidence that a functional representation of the pitch information in a sound is available in the infant auditory system. The question that remained was whether a pitch percept is generated, as it is difficult to confirm what a nonverbal listener hears. That no age-related differences in performance were observed in this melody discrimination task adds to the previous evidence that 3-month-olds perceived the stimuli in a similar manner to 7-month-olds and adults. This may be the strongest evidence that even 3-month-old infants perceive the pitch of complex tones like the older infants and adults. Despite significant cortical immaturity, infants demonstrate complex pitch discrimination behaviorally by 3 months of age. Additional studies investigating infant sensitivity to pitch changes and their ability to perceive complex pitch under different stimulus conditions would help characterize how pitch perception changes with cortical maturation.

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[1]Tympanometry using a 226-Hz probe tone is admittedly not the ideal screen for middle ear dysfunction in young infants (Baldwin, 2006). Two points support the argument that the use of the 226-Hz probe tone did not have a substantial effect on the outcome of these studies. First, about one-third of the 3-month-olds were also tested with a 1000-Hz probe and all passed the screen. Second, although no 3-month-olds failed the tympanometric screen, 90% of 3-month-olds tested successfully completed the experiment. Importantly, of the four 3-month-olds that did not complete the criterion phase, two of them did pass a tympanometric screen with a 1000-Hz probe. The inclusion of 3-month-olds with middle ear dysfunction might increase the variability in the data, but it would not affect any of the conclusions drawn based on those data. Similarly, if the two 3-month-old infants who did not successfully complete the experiment should have been excluded on the basis of tympanometry, the conclusions drawn would be no different. The 7-month-old infant in experiment I, who was excluded based on tympanometry, actually completed the criterion phase in 16 trials. The inclusion of this data point would increase the infant success rate slightly (90% success with 19 of 21 infants having completed the criterion phase). The 7-month-old infant in experiment II, who was excluded based on tympanometry, did not complete the criterion phase. The inclusion of this data point would yield an infant success rate of 85% with 22 of 26 infants having completed the criterion phase). In both experiments these success rates remain above chance ($p < 0.001$).

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