Perception of missing fundamental pitch by 3- and 4-month-old human infants

Bonnie K. Lau[a)] and Lynne A. Werner
Department of Speech and Hearing Sciences, University of Washington, 1417 NE 42nd Street, Seattle, Washington 98105

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A hallmark of complex pitch perception is that the pitch of a harmonic complex is the same whether or not the fundamental frequency is present. By 7 months, infants appear to discriminate on the basis of the pitch of the missing fundamental (MF). Although electrophysiological cortical responses to MF pitch changes have been recorded in infants younger than 7 months, no psychophysical studies have been published. This study investigated the ability of 3- and 4-month-olds to perceive the pitch of MF harmonic complexes based on fundamentals of 160 Hz and 200 Hz using an observer-based method. In experiment I, to demonstrate MF pitch discrimination, 3- and 4-month-olds were required to ignore spectral changes in complexes with the same fundamental and to respond only when the fundamental changed. In experiment II, a 60–260 Hz noise was presented with complexes to mask combination tones at the fundamental frequency. In experiment III, complexes were bandpass filtered with a −12 dB/octave slope to limit use of spectral edge cues and presented with a pink noise to mask all distortion products. Nearly all infants tested categorized complexes by MF pitch in these experiments, suggesting perception of the missing fundamental at 3 months.
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I. INTRODUCTION

Pitch perception plays a critical role in many complex auditory tasks including sound source segregation and the perception of speech and music. Although periodic sounds contain multiple harmonically related frequency components, a unitary pitch corresponding to the fundamental frequency is perceived. Many studies have suggested that complex pitch perception develops early in life. Infants are apparently sensitive to pitch in both speech and music from a young age. Infants younger than 3 months have demonstrated the ability to discriminate pitch contours in syllables and words (e.g., Karzon and Nicholas, 1989; Nazzi *et al.*, 1998). They also prefer infant directed speech characterized by exaggerated pitch contours to adult directed speech (e.g., Cooper and Aslin, 1990; Pegg *et al.*, 1992), consonant musical intervals to dissonant ones (Trainor *et al.*, 2002), and high-pitched singing to low-pitched singing (Trainor and Zacharias, 1998). However, the studies that have addressed this topic have generally not distinguished between sensitivity to frequency or spectral changes as opposed to sensitivity to pitch changes. Thus, very little is known about early pitch perception.

A classic phenomenon in pitch perception is that the pitch of a complex is the same whether or not the fundamental frequency is present (e.g., Schouten, 1938). The ability to perceive the pitch of the missing fundamental frequency of a complex demonstrates the perception of pitch as opposed to frequency or spectral components. In a series of studies, Clarkson and her colleagues demonstrated that 7-month-olds perceive the pitch of the missing fundamental (e.g., Clarkson and Clifton, 1985; Montgomery and Clarkson, 1997). When presented with missing fundamental complexes from two different pitch categories, 7-month-old infants responded to the complexes based on the missing fundamental frequency. More recently, cortical responses to missing fundamental pitch changes have been reported to emerge between 3 and 4 months of age by He and Trainor (2009). In this study, participants heard a series of complex tone pairs in which the pitch of the second complex was usually higher than that of the first. On some presentations, however, the second tone of the pair was a missing fundamental complex with higher harmonics, but a lower fundamental than the first tone. If the pitch rather than the spectral location of the complex were driving the cortical response, a novelty response would be expected to the latter tone pairs. Such responses were observed in 4-month-olds, but not 3-month olds. These findings differed from those of an earlier study in which cortical responses to a similar change were found at both 3- and 4-months to pairs of synthesized piano tones that contained the fundamental frequency (He *et al.*, 2007). The results of He and Trainor (2009), therefore, suggest the emergence of complex pitch representation between 3 and 4 months of age.

There is evidence from past research that missing fundamental pitch results from centrally mediated integration of information across the spectrum of a sound (e.g., Houtsma and Goldstein, 1972). Moreover, recent studies indicate that pitch is extracted in an area just outside primary auditory cortex in adult humans and other primates (e.g., Bendor and Wang, 2005; Hall *et al.*, 2005; Patterson *et al.*, 2002). Because the central auditory system undergoes extensive maturation postnatally, pitch perception might be expected to change, at least over the first few months of life. Until 4

[a)]Author to whom correspondence should be addressed. Electronic mail: blau@u.washington.edu

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months only the most superficial layer of the auditory cortex contains mature axons, and brainstem auditory pathways provide input to layer I via the reticular activating system (Moore, 2002). Thus, brainstem pathways apparently support infants' responses to sounds prior to 4 months of age while the auditory cortex is still developing. Electrophysiological cortical responses to missing fundamental pitch in 4-month-olds but not 3-month-olds (He and Trainor, 2009) appear consistent with these anatomical data. However, whether infants at these ages perceive the pitch of the missing fundamental is unknown.

The purpose of this study was to investigate whether 3- and 4-month-old infants are able to perceive the pitch of the missing fundamental. Infants' ability to discriminate changes in the missing fundamental of tonal complexes was tested. Based on the findings of He and Trainor (2009), it was predicted that 4-month-old infants would be able to discriminate on the basis of missing fundamental pitch, while 3-month-olds would not.

II. EXPERIMENT I

A. Method

1. Subjects

The participants were twenty 4-month-old infants, twenty-one 3-month-old infants, and twenty adults. Infant inclusion criteria were (1) full term birth, (2) no history of health or developmental concerns, (3) no history of otitis media within 3 weeks of testing and no more than 2 prior occurrences of otitis media, (4) no risk factors for hearing loss, and (5) passed newborn hearing screening. 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 at each test session. Infants in each age group completed testing within 10 days of the specified age. Adult participants were between 18 and 30 years of age, reported normal hearing bilaterally, had no history of noise exposure, less than 2 years of musical training and 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. Data from an additional two 4-month-olds and one 3-month-old were excluded because they did not complete all scheduled visits. Participants were recruited through the Communication Studies Participant Pool at the University of Washington.

2. Stimuli

Two sets of tonal complexes based on fundamental frequencies (F0) of 160 and 200 Hz, respectively, were generated using MATLAB (2010a, Mathworks, Natick, Massachusetts). The harmonics for each complex were equal in amplitude and combined in random phase. All complexes were presented monaurally for 650 ms with a 50 ms rise/fall time and 500 ms between presentations through an Etymotic ER-2 insert earphone in the right ear. The foam tip of the insert earphone was trimmed to fit the ear canal as needed. Sound pressure levels were calibrated in a Zwislocki coupler and checked in the subject's ear canal at the time of testing. All flat-weighted stimulus levels were 70 dB SPL. Testing was conducted in a double-walled, sound attenuating booth.

The number and frequencies of harmonics in each complex differed across the four phases of the experiment.

3. Procedure

Infants were tested in an average of 3.5 sessions (range = 1–7). These sessions were completed in 60-min visits on 3 separate days within a 2-week period. Infants were tested using an observer-based psychophysical procedure (Werner, 1995). During testing, infants sat on a caregiver's lap with an assistant in the booth manipulating toys to keep infants facing midline. There were two mechanical toys with lights in a dark Plexiglas box and a monitor on 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. Harmonic complexes from one pitch category, the "background," were played repeatedly to the participant from the start of the test session. The goal was to determine whether the participant detected a change in the complex to the other pitch category, the "target." Half of the participants were randomly assigned to hear 160 Hz background complexes and 200 Hz target complexes, while the other half heard 200 Hz background complexes and 160 Hz target complexes.

The experimenter initiated a trial when the participant was quiet and facing midline. There were two trial types that occurred with equal probability during testing. On change trials the target complex with a pitch change was presented four times, while on no-change trials complexes from the background pitch category continued to play. On each trial, the experimenter, blind to trial type, decided within 4 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, increases and decreases in body movement, and facial expressions like widening of the eyes were common behaviors observed. Computer feedback was provided to the experimenter at the end of a trial. During the test phases, participants' responses were reinforced with the presentation of a mechanical toy or video for 4 s only if the experimenter correctly identified a change trial.

The study consisted of one training phase and 3 test phases. The phases were presented in a fixed sequence, and participants were required to reach criterion on one phase before advancing to the next. The first phase was a training phase. The purpose of the training phase was to demonstrate the association between the reinforcer and the target, the F0 change, to the participant. The probability of a change trial was 0.80, and the reinforcer was activated after every change trial regardless of the experimenter's response. The experimenter had to respond correctly on 4 of the last 5 change trials and 1 no-change trial to complete the training phase and progress to the test phases.

In the 3 subsequent test phases, the probability of change and no-change trials was 0.5, and the experimenter was required to respond correctly on 4 of the last 5 change and 4 of the last 5 no-change trials to move on to the next phase. This criterion corresponds to a hit rate of 80% and a false alarm rate of 20% on the last 5 consecutive change and no-change trials, respectively. In the second phase, the task and stimuli were the same as in the training phase but the reinforcer was activated only when the experimenter correctly identified a change trial. The purpose of the second phase was to teach the participant that an observable response to pitch change was required to activate the reinforcer.

The third phase was a pitch categorization task. The purpose of the third test phase was to teach the participant to respond to pitch changes, but not to other changes. While in phases 1 and 2, the same set of harmonics was associated with each F0 on every presentation, in phase 3, three different sets of harmonics with one F0 were randomly presented in the background and on no-change trials and three different sets of harmonics with the other F0 were randomly presented on change trials. In other words, three harmonic complexes, each with a different set of 6 harmonics and the same F0, represented each pitch category. One of these complexes was randomly chosen on each presentation. Participants were required to ignore the spectral changes and respond only when there was a pitch change.

In the final phase, participants were required to perform the same pitch categorization task with the F0 missing from all complexes. The procedure was the same as that in the previous phase. The purpose of the final phase was to demonstrate that participants perceived the pitch of the missing fundamental (MF).

To address confusion during the progression from one phase to the next, as well as failure to respond due to factors such as sleepiness or boredom, a reminder procedure similar to the one used by Clarkson and Clifton (1995) was implemented. If participants responded incorrectly on four consecutive trials, responding to no-change trials or not responding to change trials, stimuli were presented from the last test phase completed. For example, after four incorrect responses participants in the third phase would hear stimuli from the second phase. Participants received up to 12 trials of such "reminder" stimuli to meet a criterion of 5 correct responses on 6 consecutive trials. If this criterion was met, the participant returned to the next phase. If this criterion was not met, the session was discontinued and infants were given a break or returned on another day. A new session was started when the infant returned to the booth. In subsequent sessions, a few reminder training trials were presented, after which the last incomplete test phase was resumed. If participants were unable to meet criterion on a test phase after three separate presentations of reminder stimuli, testing was discontinued, and the participant was judged to be unable to complete that test phase. Note that when a participant was classified as having completed a test phase, it was always because the number of correct responses was at least 4 of the last 5 change trials correct and at least 4 of the last 5 no-change trials correct in that test phase.

Adults were tested in an average of 1.8 sessions (range = 1–4). These sessions were completed in a single 60 min visit. They sat alone in the booth and were instructed to raise their hand when they heard "the sound 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. The first analysis addressed whether the number of participants in each age group reaching criterion in the MF test phase was greater than expected by chance. The second analysis addressed the relative difficulty of the task for infants and adults by comparing the average number of trials to meet criterion in the MF test phase across age groups.

All adults, 75% of 4-month-olds, and 90% of 3-month-olds reached criterion in the MF test phase. To determine the proportion of subjects expected to reach criterion by chance, the response rate on all trials in all sessions meeting criterion was calculated for infants and for adults. The overall response rate was 0.49 for adults. The overall response rate was 0.60 for both 3-month-olds and 4-month-olds. A simulation of 2000 sessions in which responses occurred randomly at these rates showed that criterion was met in all phases of the experiment in only 1.0% of sessions with a response rate of 0.60, and in only 1.1% of sessions with a response rate of 0.49. Three exact binomial tests with an assumed probability of 0.011 were conducted based on the number of participants who reached criterion in each age group. Not surprisingly, more participants were found to meet criterion than expected by chance ($p < 0.001$) for all three ages.

Initial analyses indicated that there was no effect of background/target assignment on trials to criterion, so that variable was ignored in subsequent analyses. The number of trials required to reach criterion in the MF phase is plotted in Fig. 1 as a function of age group. Although it appears that the 4-month-olds required more trials to reach criterion than

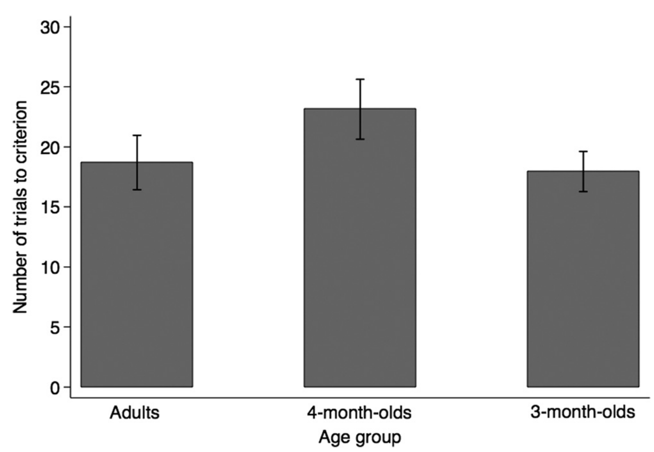

FIG. 1. Mean (±1 SEM) number of trials to criterion for missing fundamental discrimination in experiment I.

either adults or 3-month-olds, a one-way analysis of variance (ANOVA) testing the effect of age on the number of trials to criterion showed that this apparent difference was not statistically significant [$F(2,51) = 1.54$, $p = 0.224$]. Thus, there was no indication that infants took more trials than adults to learn to categorize MF complexes on the basis of pitch.

C. Discussion

These results demonstrate that adults and infants perceived the pitch of the missing fundamental of tonal complexes. All but a few infants met criterion in the MF categorization task. In fact, the overall proportion of infants meeting criterion, about 83%, is greater than the 78% success rate reported for 7-month-old infants by Clarkson and Clifton (1995). These results suggest that both 3- and 4-month-olds perceive the pitch of the missing fundamental, contrary to initial expectations. However, it is possible that participants' discrimination of the MF pitch was based on combination tones (e.g., Pressnitzer and Patterson, 2001). A second experiment evaluated the possible influence of combination tones on infant pitch perception.

III. EXPERIMENT II

Seven-month-old infants demonstrated the ability to categorize complexes on the basis of the pitch of the missing fundamental in the presence of low-frequency masking noise, suggesting that they did not rely on combination tones to judge the pitch of the complexes (Montgomery and Clarkson, 1997). In experiment II, to determine whether 3-month-old infants could be using combination tones to categorize complexes on the basis of the pitch of the missing fundamental, infants were tested on categorization of MF complexes by pitch with the addition of a band of masking noise in the region of the F0. To investigate the effect of masker level on performance, participants were required to complete the task with three different levels of masking noise.

A. Method

1. Subjects

The participants were twenty 3-month-old infants and twenty adults. Data from one additional infant were excluded, because he did not complete all scheduled visits. One adult participant was excluded because of equipment malfunction and a second because of failure to respond within the 4 s response window.

2. Stimuli and procedure

Experiment II consisted of 4 phases. Table I lists the harmonic structure of the complexes used during each phase. The stimuli and tasks for the initial training phase and second pitch discrimination phase were as described in experiment I. The third phase corresponded to the fourth phase in experiment I: three different MF harmonic complexes represented each pitch category.

For the fourth phase, three new harmonic complexes, each containing a different set of 6 consecutive harmonics were used to represent each of the two pitch categories and the fundamental component was removed. A bandpass noise with a low-frequency cutoff of 60 Hz and a high-frequency cutoff of 260 Hz was continuously presented with the complexes in phase 4, the MF + noise (MF + noise) phase. The range of harmonics differed for the complexes in MF and MF + noise to prevent participants from responding based on memorization of specific stimulus frequencies from the previous phase. The purpose of the noise was to mask any combination tones. Each participant completed the fourth phase 3 times, once at each of 3 noise levels. The order of noise level presentation was counterbalanced across participants. All complexes were presented at a flat-weighted level of 70 dB SPL. The bandpass noise was presented at 50, 60, or 70 dB SPL. Infants were tested in an average of 4.2 sessions (range = 1–7). These sessions were completed in 60 min visits on 3 separate days within a 2-week period. Adults were tested in an average of 2.6 sessions (range = 1–6). These sessions were completed in a single 60 min visit.

TABLE I. Harmonic structures of stimuli in experiment I and II. F0 is the fundamental frequency; H*n* refers to the other component frequencies by harmonic number.

Test Phase	Experiment I Stimuli	Experiment II Stimuli
1	F0 + H2-H9	F0 + H2-H9
2	F0 + H2-H9	F0 + H2-H9
3	F0 + H3-H8	H3-H8
	F0 + H5-H10	H5-H10
	F0 + H7-H12	H7-H12
4	H3-H8	H2-H7
	H5-H10	H4-H9
	H7-H12	H6-H11

B. Results

Several analyses were completed to assess the effect of the low-frequency masking noise on infant's discrimination of the pitch of the missing fundamental. First, the proportion of subjects reaching criterion at each noise level was compared to the proportion expected by chance. Second, the effects of masker level and age on trials to criterion were examined to determine whether infants had more difficulty reaching criterion than adults and whether the masker level had any effect on performance. Finally, the difference between the number of trials to criterion in the MF phase was compared to the number of trials to criterion in the first MF + noise phase completed to examine the general effect of the noise on performance.

Ninety percent of adults reached criterion at all three noise levels; 100% of infants reached criterion at 70 dB SPL; one infant failed to reach criterion at 50 dB SPL and one infant at 60 dB SPL, yielding a 95% success rate at those levels. Overall experimenter response rates of 0.53 for adult sessions and 0.59 for infant sessions were comparable to experiment I, so a 0.011 probability for reaching criterion on all three MF + noise phases by chance was assumed. Two exact binomial tests with an assumed probability of 0.011 were conducted based on the number of participants who reached criterion in each age group.

More adults and 3-month-olds met criterion than expected by chance ($p < 0.001$).

Initial analyses indicated that adults who heard the 200 Hz background and 160 Hz target took more trials to reach criterion than adults who heard the 160 Hz background and 200 Hz target for the MF + noise phases only. We have no explanation for this finding. Because the background/target assignment did not interact with any other variables, it was not included in subsequent analyses. The effect of noise level test order on number of trials to criterion in the three masker levels was not significant in initial analyses, so this variable was not included in subsequent analyses.

The average number of trials it took to reach criterion for the MF + noise phases is plotted as a function of age for the three masker levels in Fig. 2. It appears that adults took fewer trials to reach criterion at 60 dB and 70 dB noise levels than at 50 dB, but this difference was not statistically significant. Infants took about the same number of trials to reach criterion at each noise level, and the number of trials to criterion is about the same for adults and infants. An age X level repeated measures analysis of variance of the number of trials to criterion revealed no significant effect of age [$F(1,36) = 3.02$, $p = 0.091$], level [$F(2,70) = 0.77$, $p = 0.466$], or the age X level interaction [$F(2,70) = 1.99$, $p = 0.145$]. Thus, infants seemed to have no greater difficulty learning to discriminate on the basis of missing fundamental frequency than adults did, even with the masker. Further, increasing the masker level did not increase trials to criterion in either age group.

Finally, the number of trials to criterion in the MF phase was compared to the number of trials to criterion in the first MF + noise phase completed (Fig. 3). The number of trials to criterion in these two conditions was about the same for the infants. A paired t test of the number of trials to criterion indicated that the difference in infants' performance on the two phases was not statistically significant [$t(18) = 0.35$, $p = 0.733$]. Adults appeared to take more trials to reach criterion in the MF phase than in the MF + noise phase. A paired t test indicated that this difference was statistically significant [$t(17) = 2.85$, $p = 0.011$], but the effect is in the opposite direction from what might be expected. Apparently adults took awhile to learn the missing fundamental discrimination, but once they had learned it, had no difficulty generalizing to the noise condition. Infants did not have more difficulty learning the missing fundamental discrimination with a masker than without.

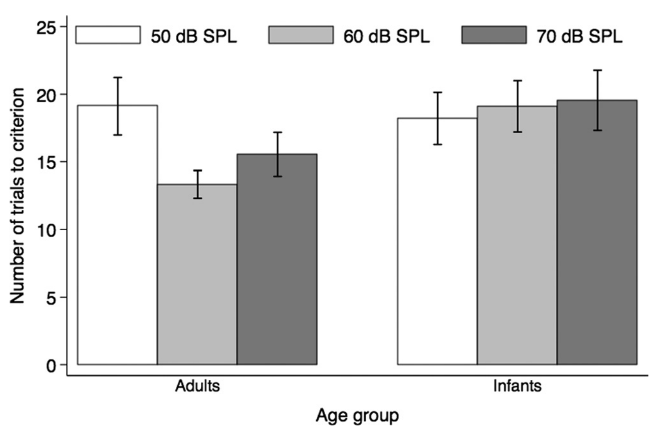

FIG. 2. Mean (±1 SEM) number of trials to criterion for missing fundamental discrimination with noise in experiment II.

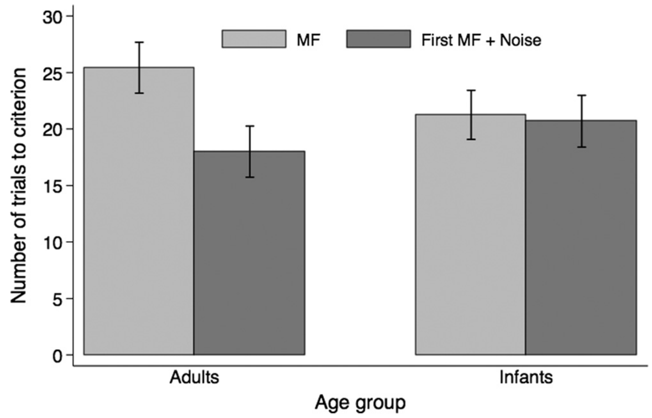

FIG. 3. Mean (±1 SEM) number of trials to criterion for missing fundamental discrimination and the first missing fundamental discrimination completed with noise in experiment II.

C. Discussion

Results of this study show that adults and 3-month-olds were able to categorize MF complexes by pitch even with a masker noise around the missing fundamental frequency. All of the infants tested categorized the complexes by MF pitch in the presence of a low-frequency noise. Thus, 3-month-olds, like the 7-month-olds tested by Montgomery and Clarkson (1997), do not rely on combination tones to categorize complexes on the basis of the pitch of the missing fundamental. Further evidence that combination tones were not involved is that increasing masker level had no effect on performance. Moreover, participants took no longer to reach criterion in the first noise condition they heard, than they had in the previous no-noise condition. Finally, 3-month-olds appeared to have no greater difficulty than adults in reaching criterion in this task.

The proportion of 3-month-olds successfully completing this task in a 70 dB SPL noise (100%) is actually greater than that reported by Montgomery and Clarkson (1997) for 7-month-old infants. Of the thirty-seven 7-month-olds tested in that study, 12 discriminated the pitch of harmonic complexes. Of those 12 infants, 6 categorized MF complexes by pitch. All three 7-month-olds tested on categorization of MF complexes in the presence of a low-frequency noise were successful. The higher percentage of infants completing all test phases in this study may be due to the fact that the harmonic complexes were presented at 70 dB SPL here, compared to 50 dB SPL by Montgomery and Clarkson (1997).

Although results of this study suggest that MF pitch was not perceived on the basis of combination tones, it is possible that spectral edge cues contributed to participants' discrimination of MF pitch (e.g., Micheyl *et al.*, 2012; Moore and Moore, 2003a,b; Dai, 2010; Kohlrausch *et al.*, 1992). A third experiment evaluated the possible influence of spectral edge cues on infant pitch perception.

IV. EXPERIMENT III

Since harmonic complexes were composed of equal amplitude components, it is possible that participants relied on shifts in the frequency of the lowest and highest harmonics of the complexes in experiment I and II (e.g., Micheyl *et al.*, 2012; Moore and Moore, 2003a,b; Dai, 2010). Bandpass-filtered complexes with shallow slopes have been used in past studies to reduce spectral edge cues (e.g., Micheyl *et al.*, 2012; Carlyon and Shackleton, 1994; Moore and Moore, 2003a; Micheyl and Oxenham, 2004). In experiment III, to determine whether 3-month-old infants could be using spectral edge cues, infants were tested on categorization of spectrally shaped MF complexes in a masking noise.

A. Method

1. Subjects

The participants were ten 3-month-old infants and eleven adults.

2. Stimuli and procedure

Experiment III consisted of 3 phases. The tasks for the initial training phase and second pitch discrimination phase were as described in experiment I. The third phase corresponded to the MF pitch categorization task with noise in the fourth phase of experiment II. Table II lists the harmonic structure of the complexes used during each phase.

Four primary changes to the stimuli were made in this experiment. First, all complexes were passed through a bandpass filter with a −12 dB/octave slope. The purpose of the filter was to limit participants' ability to use spectral edge cues to perform the task. Second, only harmonics 3 to 12 were used in the 160 Hz pitch category and only harmonics 2 to 9 were used in the 200 Hz pitch category. The purpose of limiting the harmonics used was to prevent subjects from responding to a change in the frequency of the highest or lowest harmonics that happened to correspond to the change in complex pitch. These were trials on which the lowest harmonic of the last randomly selected 160 Hz background complex was lower than any of the harmonics of the 200 Hz target complex or on which the highest harmonic of the last randomly selected 200 Hz background complex was higher than any of the harmonics of the 160 Hz target complex. Such trials would have occurred about a third of the time in experiments I and II. By restricting the harmonic numbers used as stated, such trials would not occur. Third, to mask distortion products at any frequency, a pink noise with a low-frequency cutoff of 1 Hz and a high-frequency cutoff of 12 000 Hz was continuously presented with the complexes in phase 3. Finally, to reduce the possibility that participants responded based on memorized background and target categories rather than responding based on the pitch of category, the number of complexes in each pitch category was increased from 3 to 10. All complexes were presented at a flat-weighted level of 70 dB SPL. The pink noise was presented at 65 dB SPL.

These sessions were completed for both adults and infants in a single 60 min visit. Infants were tested in an average of 2.3 sessions (range = 1–3) and adults were tested in an average of 1.56 sessions (range = 1–3).

TABLE II. Harmonic structures of stimuli in experiment III. F0 is the fundamental frequency; H*n* refers to the other component frequencies by harmonic number.

Test Phase	160 Hz F0 Complexes	200 Hz F0 Complexes
1	F0 + H2-H9	F0 + H2-H9
2	F0 + H2-H9	F0 + H2-H9
3	H3-H8	H2-H7
	H4-H9	H3-H8
	H5-H10	H4-H9
	H6-H11	H2,3,4,7,8,9
	H7-H12	H2,3,4,6,7,8
	H3,4,5,9,10,11	H2,4,5,6,7,9
	H3,4,6,8,10,11	H2,4,5,6,7,8
	H4,5,7,8,10,12	H3,4,5,7,8,9
	H5,6,7,9,10,11	H3,4,5,6,8,9
	H5,7,9,10,11,12	H3,5,6,7,8,9

B. Results

Three analyses were conducted to evaluate participants' performance. The first analysis addressed whether the number of participants in each age group reaching criterion in the MF + noise test phase was greater than expected by chance. The second analysis addressed the relative difficulty of the task for infants and adults by comparing the average number of trials to meet criterion in the MF + noise test phase across age groups. The third analysis addressed the relative difficulty of the task with 10 complexes in each pitch category and 3 complexes in each pitch category by comparing the average number of trials to meet criterion in the first MF + noise test phase in experiment II and the MF + noise phase in experiment III.

The proportion of participants reaching criterion in the MF + noise test phase was 91% for adults and 90% for 3-month-olds. To determine the proportion of subjects expected to reach criterion by chance, the response rate on all trials in all sessions meeting criterion was calculated for infants and for adults. Overall response rates of 0.49 for adult sessions and 0.54 for infant sessions were comparable to experiment I, so a 0.011 probability for reaching criterion on the third MF + noise phase by chance was assumed. Two exact binomial tests with an assumed probability of 0.011 were conducted based on the number of participants who reached criterion in each age group. More adults and 3-month-olds met criterion than expected by chance ($p < 0.001$).

Initial analyses indicated that there was no effect of background/target assignment on trials to criterion, so that variable was ignored in subsequent analyses. The number of trials required to reach criterion in the MF phase is plotted in Fig. 4 as a function of age group. The number of trials required by infants and adults appears to be the same; a one-way ANOVA testing the effect of age on the number of

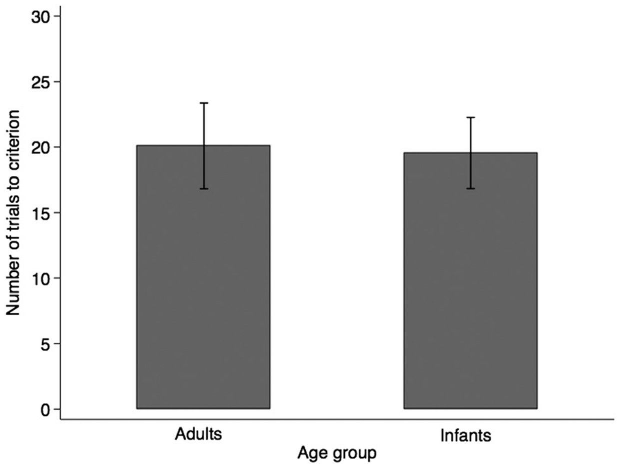

FIG. 4. Mean (±1 SEM) number of trials to criterion for missing fundamental discrimination with spectrally shaped complexes and pink noise across frequencies in experiment III.

trials to criterion showed no statistically significant effect [$F(1,17) = 0.02$, $p = 0.9009$]. Thus, there was no indication that infants took more trials than adults learn to categorize these MF complexes on the basis of pitch.

Finally, the number of trials to criterion in the MF+ noise phase in experiment III, with 10 complexes in each pitch category, was compared to the number of trials to criterion in the first MF + noise phase in experiment II, with 3 complexes in each pitch category. The number of trials participants took to reach criterion in these two conditions is plotted in Fig. 5. The number of trials to criterion appears to be the same in the two experiments, for both infants and adults. An age X number of exemplars analysis of variance of the number of trials to criterion revealed no significant effect of age [$F(2,51) = 0.01$, $p = 0.9867$], number of exemplars [$F(1,51) = 0.10$, $p = 0.7544$], or the age X number of exemplars interaction [$F(1,51) = 1.99$, $p = 0.4165$]. Thus, neither infants nor adults seemed to have greater difficulty learning to discriminate on the basis of pitch with 10 complexes in each pitch category than with 3.

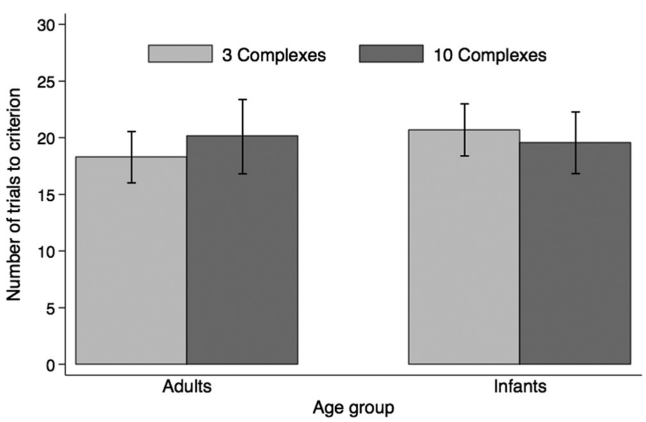

FIG. 5. Mean (±1 SEM) number of trials to criterion for the first missing fundamental discrimination completed with noise in experiment II with 3 complexes per pitch category and missing fundamental discrimination with noise in experiment III with 10 complexes per pitch category.

C. Discussion

These results demonstrate that adults and young infants perceive the pitch of the missing fundamental of tonal complexes without the use of spectral edge cues or distortion products. Nearly all 3-month-olds met criterion in the missing fundamental categorization tasks, with and without noise, and when spectral edge cues were removed. Infants appeared to have no greater difficulty than adults reaching criterion on this task. That learning to categorize by missing fundamental pitch did not take longer for infants or adults when the number of complexes in each category was increased from three to ten suggests that participants were not simply memorizing the specific exemplars of each pitch category without reference to the pitch.

He *et al.* (2007) reported mismatch evoked responses to a change in the fundamental frequency of a repeated piano tone in 2-, 3-, and 4-month-old infants, and He *et al.* (2009) found that mismatch responses were elicited in both 2- and 4-month-olds when two elements in an alternating low-high tone sequence were presented in reverse order (i.e., high-low). However, He and Trainor (2009), reported that mismatch responses to a similar change in the direction of a pitch shift signaled by a missing fundamental complex could not be elicited from infants younger than 4 months of age.

In adult humans and other primates, responses to missing fundamental pitch changes are first observed in cortical areas just beyond primary auditory cortex (e.g., Barker *et al.*, 2012; Bendor and Wang, 2005; Hall *et al.*, 2005; Patterson *et al.*, 2002). Auditory cortex is markedly immature in the early months of infancy (Moore and Linthicum, 2007). In fact, Eggermont and Moore (2012) have suggested that the thalamocortical pathway is not functional at this early age and that cortical responses recorded in young infants are generated through a reticular activating system projection to neurons in cortical layer I. This reticular-cortical pathway is held to act as a change detection system, leading infants to respond to changes in speech or other sounds, based on the representation of those sounds provided by the auditory brainstem. If, in fact, the representation of complex pitch only emerges in cortex, this model would not predict cortical responses to missing fundamental pitch changes in infants younger than about 4 months of age.

If 3-month-olds lack the cortical structures necessary for the representation of missing fundamental pitch, how can they respond to changes in missing fundamental pitch behaviorally? One possibility is that 3-month-olds do represent missing fundamental pitch cortically, but that the cortical neural response to complex pitch changes is not evident at the scalp. As He *et al.* (2007) point out, the evoked response recorded at the scalp may reflect the sum of activity resulting from different neural processes. This fact may explain why different studies of the mismatch response in early infancy report such different waveform morphologies in infants of the same age (reviewed by He *et al.*, 2007). He *et al.* also note that mismatch response morphology differs with the type of change used to elicit it (e.g., duration, pitch, or loudness). He and Trainor (2009) examined the responses of 3-month-olds under different filtering conditions to assess the possibility that the apparent lack of a mismatch response resulted from the superposition of two different responses. However, the fact remains that the generators of the mismatch response in infants have not been fully characterized.

Another possibility is that 3-month-olds do not produce mismatch responses to changes in the direction of a pitch shift, such as those used by both He *et al*. (2009) and He and Trainor (2009) even when the fundamental frequency is present. As noted in Sec. I, He *et al*. (2009) presented infants with two alternating piano tones. The "deviant" stimulus was a reversal in the order of these two tones. Thus, in each standard pair of tones the pitch decreased, while in the deviant pair, the pitch increased. A mismatch response to the deviant was observed in 2-month-old infants. Similarly, He and Trainor (2009) presented infants with repeating pairs of complex tones; both the fundamental and harmonic frequencies of the second of the standard tone pair were higher than those of the first. In the deviant tone pair, the harmonic frequencies of the second tone increased, but the missing fundamental frequency of the second tone was lower than the fundamental (present) of the first tone. No mismatch response to the deviant was observed in 3-month-old infants. However, in the He and Trainor (2009) study, the fundamental frequency of the standard tones was varied randomly, while in the He *et al*. (2009) study, the two tones in each pair were always the same. Thus, it is possible that in the face of the general variability in pitch, 3-month-olds did not process the deviant tone pair as being particularly deviant. Furthermore, it is possible that infants in the He *et al*. (2009) study were not responding to the change in the direction of the pitch shift: Because the time interval between tones in a pair was the same as that between the second tone in one pair and the first tone in the next, infants could have been responding to the novel repetition of the same tone rather than to the change in the direction of pitch shift. In contrast, the time interval between the two tones in a pair was shorter than the time interval between pairs of tones in the He and Trainor study and with the fundamental frequencies randomized, infants would not hear a novel repetition. That He *et al*. (2007) observed mismatch responses to fundamental frequency changes in a single repeated tone in infants as young as 2 months of age certainly suggests that young infants are sensitive to spectral changes in complex tones. However, it is not clear that they would be sensitive to those changes if the complexes had been presented in the same configuration as that used by He and Trainor (2009).

A third possibility is that attention is required for infants to process the pitch of the missing fundamental. While infants were not required to attend to the stimuli in He and Trainor's (2009) study, in the present study, 3-month-olds were required to attend to the simuli to complete the task. Thus, attention may play a role in more complex pitch perception tasks, but not in simple spectral discriminations.

The results of the present study may still be thought inconsistent with the adult studies that show that the first representation of complex pitch is in a cortical area beyond primary auditory cortex. However, it appears that cortical representation is not necessary for perception of the pitch of a missing fundamental. The results of studies of missing fundamental perception in animals that lack a fully developed cortex suggest that subcortical processing can be sufficient for discriminating missing fundamental pitch. For example, Fay (2005) demonstrated missing fundamental perception in goldfish with a stimulus generalization paradigm. Goldfish were conditioned to respond to 100 Hz complex tones and then tested for generalization to other complex sounds that differed on one or more stimulus dimensions. These goldfish demonstrated similar generalization gradients to complex tones with different fundamental frequencies regardless of whether fundamental frequencies were present or absent in conditioning and testing. Cynx and Shapiro (1986) also reported perception of the missing fundamental in songbirds. In this study, starlings were trained to peck in response to 652 Hz complexes and to stop pecking in response to 400 Hz complexes. Harmonic composition was varied between tones requiring missing fundamental perception to perform the task. During testing, starlings transferred discrimination to sinusoidal fundamental frequencies of 652 Hz and 400 Hz demonstrating perception of missing fundamental complexes. Thus, it may not be surprising that 3-month-old human infants, with quite underdeveloped cortex, can also discriminate between sounds based on complex pitch. It is possible that during development the representation of complex pitch in the human auditory system undergoes a re-organization. Perhaps the mechanisms that control pitch perception shift from subcortical to cortical structures as thalamocortical and intracortical circuitry is established. A similar re-organization is believed to occur in the development of sound localization (Clifton, 1992).

A limitation of all of the studies of nonverbal listeners is that it is not always clear that listeners are discriminating between complexes on the basis of pitch *per se*. Certainly they distinguish complexes with different periodicities, but it is possible that they do so on the basis of roughness or some other percept related to periodicity. If stimulus manipulations influence infants' and adults' psychoacoustic performance similarly, one can be more confident that the underlying percept is qualitatively similar. Although 3-month-old infants demonstrated the ability to discriminate complexes with different missing fundamentals in the present study, their sensitivity to differences in fundamental frequency and perception under different stimulus conditions is unexplored. Clarkson and colleagues found that, relative to adults, 7-month-olds demonstrated increased difficulty discriminating changes in the pitch of inharmonic complexes, complexes with a small number of harmonics, and complexes composed of high-frequency harmonics, suggesting some level of immaturity at 7 months (Clarkson and Clifton, 1985, 1995; Clarkson and Rogers, 1995; Montgomery and Clarkson, 1997). If 3-month-olds do rely on subcortical processing to discriminate missing fundamental pitch, additional differences might be expected in their pitch perception abilities.

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Barker, D., Plack, C. J., and Hall, D. A. (**2012**). "Re-examining the evidence for a pitch-sensitive region: A human fMRI study using iterated ripple noise," Cereb. Cortex **22**, 745–753.

Bendor, D., and Wang, X. Q. (**2005**). "The neuronal representation of pitch in primate auditory cortex," Nature **436**, 1161–1165.

Carlyon, R. P., and Shackleton, T. M. (**1994**). "Comparing the fundamental frequencies of resolved and unresolved harmonics: Evidence for 2 pitch mechanisms," J. Acoust. Soc. Am. **95**, 3541–3554.

Clarkson, M. G., and Clifton, R. K. (**1985**). "Infant pitch perception: Evidence for responding to pitch categories and the missing fundamental," J. Acoust. Soc. Am. **77**, 1521–1528.

Clarkson, M. G., and Clifton, R. K. (**1995**). "Infant pitch perception: Inharmonic tonal complexes," J. Acoust. Soc. Am. **98**, 1372–1379.

Clarkson, M. G., and Rogers, E. C. (**1995**). "Infants require low-frequency energy to hear the pitch of the missing fundamental," J. Acoust. Soc. Am. **98**, 148–154.

Clifton, R. K. (**1992**). "The development of spatial hearing in human infants," in *Developmental Psychoacoustics*, edited by L. A. Werner and E. W. Rubel (American Psychological Association, Washington, DC), pp. 135–157.

Cooper, R. P., and Aslin, R. N. (**1990**). "Preference for infant-directed speech in the 1st month after birth," Child Dev. **61**, 1584–1595.

Cynx, J., and Shapiro, M. (**1986**). "Perception of missing fundamental by a species of songbird (Sturnus-Vulgaris)," J. Comp. Psychol. **100**, 356–360.

Dai, H. P. (**2010**). "Harmonic pitch: Dependence on resolved partials, spectral edges, and combination tones," Hear. Res. **270**, 143–150.

Eggermont, J. J., and Moore, J. K. (**2012**). "Morphological and functional development of the auditory nervous system," in *Springer Handbook of Auditory Research*, edited by L. A. Werner, R. R. Fay, and A. N. Popper (Springer, New York), pp. 61–106.

Fay, R. R. (**2005**). "Perception of pitch by goldfish," Hear. Res. **205**, 7–20.

Hall, D. A., Barrett, D. J. K., Akeroyd, M. A., and Summerfield, A. Q. (**2005**). "Cortical representations of temporal structure in sound," J. Neurophys. **94**, 3181–3191.

He, C., Hotson, L., and Trainor, L. J. (**2007**). "Development of infant mismatch responses to auditory pattern changes between 2 and 4 months old," Eur. J. Neurol., **29**, 861–867.

He, C., Hotson, L., and Trainor, L. J. (**2009**). "Mismatch responses to pitch changes in early infancy," J. Cognit. Neurosci. **19**, 878–892.

He, C., and Trainor, L. J. (**2009**). "Finding the pitch of the missing fundamental in infants," J. Neurosci. **29**, 7718–7722.

Houtsma, A. J. M., and Goldstein, J. L. (**1972**). "Central origin of pitch of complex tones-evidence from musical interval recognition," J. Acoust. Soc. Am. **51**, 520–529.

Karzon, R. G., and Nicholas, J. G. (**1989**). "Syllabic pitch perception in 2-month to 3-month-old infants," Percept. Psychophys. **45**, 10–14.

Kohlrausch, A., Houtsma, A. J. M., and Evans, E. F. (**1992**). "Pitch related to spectral edges of broad-band signals," Philos. Trans. R. Soc. London Ser. B **336**, 375–382.

Micheyl, C., and Oxenham, A. J. (**2004**). "Sequential F0 comparisons between resolved and unresolved harmonics: No evidence for translation noise between two pitch mechanisms," J. Acoust. Soc. Am. **116**, 3038–3050.

Micheyl, C., Ryan, C. M., and Oxenham, A. J. (**2012**). "Further evidence that fundamental-frequency difference limens measure pitch discrimination," J. Acoust. Soc. Am. **131**, 3989–4001.

Montgomery, C. R., and Clarkson, M. G. (**1997**). "Infants' pitch perception: Masking by low- and high-frequency noises," J. Acoust. Soc. Am. **102**, 3665–3672.

Moore, B. C. J., and Moore, G. A. (**2003a**). "Discrimination of the fundamental frequency of complex tones with fixed and shifting spectral envelopes by normally hearing and hearing-impaired subjects," Hear. Res. **182**, 153–163.

Moore, G. A., and Moore, B. C. J. (**2003b**). "Perception of the low pitch of frequency-shifted complexes," J. Acoust. Soc. Am. **113**, 977–985.

Moore, J. K. (**2002**). "Maturation of human auditory cortex: Implications for speech perception," Ann. Otol. Rhinol. Laryngol. **111**, 7–10.

Moore, J. K., and Linthicum, F. H. (**2007**). "The human auditory system: A timeline of development," Int. J. Audiol. **46**, 460–478.

Nazzi, T., Floccia, C., and Bertoncini, J. (**1998**). "Discrimination of pitch contours by neonates," Infant Behav. Dev. **21**, 779–784.

Patterson, R. D., Uppenkamp, S., Johnsrude, I. S., and Griffiths, T. D. (**2002**). "The processing of temporal pitch and melody information in auditory cortex," Neuron **36**, 767–776.

Pegg, J. E., Werker, J. F., and McLeod, P. J. (**1992**). "Preference for infant-directed over adult-directed speech-Evidence from 7-week-old infants," Infant Behav. Dev. **15**, 325–345.

Pressnitzer, D., and Patterson, R. D. (**2001**). "Distortion products and the pitch of harmonic complex tones," in *Physiological and Psychophysical Bases of Auditory Function*, edited by D. J. Breebaart, A. J. M. Houtsma, A. Kohlrausch, V. F. Prijs, and R. Schoonhoven (Shaker, Maastrict, The Netherlands), pp. 84–91.

Schouten, J. F. (**1938**). "The perception of subjective tones," Proc. K. Ned. Akad. Wet. **41**, 1086–1093.

Trainor, L. J., Tsang, C. D., and Cheung, V. H. W. (**2002**). "Preference for sensory consonance in 2-and 4-month-old infants," Music Percept. **20**, 187–194.

Trainor, L. J., and Zacharias, C. A. (**1998**). "Infants prefer higher-pitched singing," Infant Behav. Dev. **21**, 799–805.

Werner, L. A. (**1995**). "Observer-based approaches to human infant psychoacoustics," in *Methods in Comparative Psychoacoustics*, edited by G. M. Klump, R. J. Dooling, R. R. Fay, and W. C. Stebbins (Birkhauser, Boston, MA), pp. 135–146.