Perception of the pitch of unresolved harmonics by 3- and 7-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

(Received 6 November 2013; revised 22 June 2014; accepted 25 June 2014)

Three-month-olds discriminate resolved harmonic complexes on the basis of missing fundamental (MF) pitch. In view of reported difficulty in discriminating unresolved complexes at 7 months and striking changes in the organization of the auditory system during early infancy, infants' ability to discriminate unresolved complexes is of some interest. This study investigated the ability of 3-month-olds, 7-month-olds, and adults to discriminate the pitch of unresolved harmonic complexes using an observer-based method. Stimuli were MF complexes bandpass filtered with a -12 dB/octave slope, combined in random phase, presented at 70 dB sound pressure level (SPL) for 650 ms with a 50 ms rise/fall with a pink noise at 65 dB SPL. The conditions were (1) "LOW" unresolved harmonics (2500–4500 Hz) based on MFs of 160 and 200 Hz and (2) "HIGH" unresolved harmonics (4000–6000 Hz) based on MFs of 190 and 200 Hz. To demonstrate MF discrimination, participants had to ignore spectral changes in complexes with the same fundamental and respond only when the fundamental changed. Nearly all infants tested categorized complexes by MF pitch suggesting discrimination of pitch extracted from unresolved harmonics by 3 months. Adults also categorized the complexes by MF pitch, although musically trained adults were more successful than musically untrained adults. © 2014 Acoustical Society of America.

[<http://dx.doi.org/10.1121/1.4887464>]

PACS number(s): 43.66.Hg, 43.66.Ba [EB]

Pages: 760–767

I. INTRODUCTION

Complex sounds containing multiple harmonically related frequency components evoke a pitch corresponding to their fundamental frequency (F0). Although the study of pitch perception has generated a massive body of research, the specific mechanisms involved are still under debate (Oxenham, 2012; Walker *et al.*, 2011). Current results suggest that both spectral and temporal information play a role in pitch perception and that some central processing is required to extract pitch from that information (Micheyl *et al.*, 2013; Oxenham *et al.*, 2004; Srulovicz and Goldstein, 1983). Furthermore, the neural structures that extract pitch have not been identified. Although there is evidence that an area outside of primary auditory cortex is involved in the processing of pitch evoking stimuli (e.g., Bendor and Wang, 2005; Hall and Plack, 2009; Patterson *et al.*, 2002; Penagos *et al.*, 2004), it is possible that pitch extraction is carried out at subcortical levels and that cortical structures inherit the results of the subcortical analysis.

The early development of pitch perception is interesting in this regard, because while subcortical structures are functional during early infancy, the auditory cortex is markedly immature. At 3 months of age, only the most superficial cortical layer is activated by the reticular activating system rather than by thalamocortical inputs (Eggermont and Moore, 2012). Thalamocortical connections are immature prior to 4 months, and infant responses to sound rely

primarily on brainstem processing (Moore, 2002). By 7 months of age, however, infants have access to thalamocortical pathways, although there are still significant immaturities in the auditory cortex (Eggermont and Moore, 2012). What is perhaps most interesting about these findings is that 3-month-olds are sensitive to many sounds in their environment including speech (Cooper and Aslin, 1990; Karzon and Nicholas, 1989) and music (Plantinga and Trainor, 2009; Trainor and Zacharias, 1998) despite the fundamentally different organization of their sensory pathway.

A series of studies showed that by 7 months, infants discriminate between sounds on the basis of complex pitch. Like adults, 7-month-olds can discriminate between complexes on the basis of fundamental frequency when energy at the fundamental is missing from the complexes. Moreover, their perception depends on the spectral characteristics of harmonic complexes in a manner similar to adults (Montgomery and Clarkson, 1997; Clarkson *et al.*, 1996; Clarkson and Clifton, 1995). Infants at 7 months discriminate pitch in the presence of noise masking the missing fundamental (Montgomery and Clarkson, 1997), they perform better with more harmonics (Clarkson *et al.*, 1996), and their performance deteriorates with increasing inharmonicity (Clarkson and Clifton, 1995). Infants at 3 months have also demonstrated the ability to discriminate the missing fundamental pitch of harmonic complexes (Lau and Werner, 2012).

These results may not be surprising, as the neural representation of sound that is the basis of pitch perception is functional, if not completely adultlike, early in infancy. Frequency resolution is mature at 500 and 1000 Hz by 3

^{a)}Author to whom correspondence should be addressed. Electronic mail: bonniekwlau@gmail.com

months and at 4000 Hz by 6 months (Spetner and Olsho, 1990). Recordings of the frequency-following response and the envelope following-response to amplitude-modulated pure tones in 1-month-olds suggest that temporal coding is functional at the level of the brainstem (Levi *et al.*, 1995). Infants have also demonstrated the ability to perform discriminations that rely on temporal processing: When presented with processed speech syllables containing only envelope cues and degraded temporal fine structure, 6-month-olds discriminated a voicing contrast (Bertoncini *et al.*, 2011).

That both 3- and 7-month-olds can discriminate the pitch of harmonic complexes could indicate little cortical involvement in complex pitch perception given the differences in cortical organization across this age range. Interestingly, He *et al.* (2007) observed a cortical response to spectral pitch changes in 2-, 3-, and 4-month-olds, but a cortical response to missing fundamental pitch changes only in 4-month-olds (He and Trainor, 2009). While the lack of a cortical response in 3-month-olds' is inconsistent with their behavioral demonstration of missing fundamental pitch discrimination, He and Trainor's (2009) result is certainly consistent with a re-organization of pitch processing in early infancy.

It may be that the ongoing re-organization of the auditory pathway is reflected in 7-month-olds' poor performance on temporal pitch tasks. When spectral information for pitch is limited and a temporal representation is required, 7-month-olds demonstrate greater difficulty with pitch discrimination. Clarkson and Rogers (1995) presented infants with complexes composed of either resolved or unresolved harmonics and found that more infants were able to discriminate the resolved complexes: Of the 18 infants presented with resolved harmonics, 12 infants (67%) were successful at categorizing the complexes by missing fundamental pitch, while only 3 of 18 (17%) were successful with unresolved harmonics. More recently, Butler *et al.* (2013) tested 8-month-olds' discrimination of a change from 167 Hz to 200 Hz in the fundamental frequency of high-pass filtered iterated ripple noise (IRN). Performance varied widely across infants, leading the authors to conclude that while infants were able to discriminate the pitch of IRN, it was a difficult task for them. However, despite the variable behavioral performance, in a companion electrophysiological study, Butler and Trainor (2013) reported a mismatch negativity to IRN pitch changes in infants at both 4 and 7 months of age.

Adults' ability to perceive the pitch of IRN and of unresolved harmonics supports a contribution of the temporal code to pitch perception (Burns and Viemeister, 1981; Yost, 1996). Because it is likely that peripheral temporal coding is functional from an early age, 7-month-olds' difficulty perceiving the pitch of unresolved harmonics and IRN could be an indication of immature temporal pitch extraction. If so, one might predict that 3-month-olds would have even greater difficulty. There have been no studies to date testing temporal pitch perception in 3-month-olds. The purpose of this study was to investigate the ability of 3-month-olds, 7-month-olds, and adults to perceive the pitch of unresolved harmonic complexes using an observer-based method.

Missing fundamental complexes composed of unresolved harmonics from two pitch categories were presented to participants. To demonstrate missing fundamental pitch discrimination, participants had to ignore spectral changes in complexes with the same fundamental and respond only when the fundamental changed. Because temporal pitch discrimination is difficult even for 7-month-olds (Clarkson and Rogers, 1995; Butler *et al.*, 2013) and because 3-month-olds' auditory pathway organization is immature, it was predicted that 7-month-olds would be able to discriminate unresolved harmonic complexes on the basis of missing fundamental pitch but that 3-month-olds would not.

II. METHOD

A. Subjects

Infant participants in this study were twenty-nine 3-month-olds and twenty-eight 7-month-olds. All infants were (1) born full term, (2) had no history of otitis media within 3 weeks of testing and no more than 2 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. Infants in each age group completed testing within 10 days of the specified age. All adult participants were between 18 and 30 yr of age, reported normal hearing bilaterally, had no history of noise exposure, 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 as well as an audiometric screen at 20 dB hearing level (HL) at octave frequencies between 250 and 8000 Hz. An initial group of 28 adults with less than 2 yr of musical training was tested. Subsequently, a group of 27 musically trained adults was added for reasons that will be explained in the results section. Adults in the latter group were required to have two or more years of formal musical training. A very liberal definition of musical training was adopted, including experiences such as band or choir at school.

Data from an additional two 7-month-olds and four 3-month-olds were excluded because the infants were too tired, hungry, or fussy to complete the task, and data from three 7-month-olds were excluded because the infant did not pass the tympanometric screen. Data from two additional adults were excluded because the adults did not respond within a required 4-s window and data from two additional musically trained adults were excluded because the adults were unable to complete the testing session due to fatigue. Participants were recruited through the Communication Studies Participant Pool at the University of Washington.

B. Stimuli

Many aspects of auditory processing at 3 months of age are immature at high frequencies including absolute

TABLE I. Harmonic structures of stimuli in the two conditions: LOW unresolved and HIGH unresolved. F0 is the fundamental frequency; Hn refers to the other component frequencies by harmonic number. The frequency of the lowest and highest harmonic in each complex is in brackets.

Phase	LOW Unresolved Harmonics (2500 Hz to 4500 Hz)		HIGH Unresolved Harmonics (4000 Hz to 6000 Hz)	
	MF 160 Hz	MF 200 Hz	MF 190 Hz	MF 200 Hz
1. Conditioning	F0+H2-H9	F0+H2-H9	F0+H2-H9	F0+H2-H9
2. Training	F0+H2-H9	F0+H2-H9	F0+H2-H9	F0 H2-H9
3. Test Phase	H17-H22 (2720-3520 Hz)	H13-H18 (2600-3600 Hz)	H22-H27 (4180-5130 Hz)	H20-H25 (4000-5000 Hz)
	H18-H23 (2880-3680 Hz)	H14-H19 (2800-3800 Hz)	H23-H28 (4370-5320 Hz)	H21-H26 (4200-5200 Hz)
	H19-H24 (3040-3840 Hz)	H15-H20 (3000-4000 Hz)	H24-H29 (4560-5510 Hz)	H22-H27 (4400-5400 Hz)
	H20-H25 (3200-4000 Hz)	H16-H21 (3200-4200 Hz)	H25-H30 (4750-5700 Hz)	H23-H28 (4600-5600 Hz)
	H21-H26 (3360-4160 Hz)	H17-H22 (3400-4400 Hz)	H26-H31 (4940-5890 Hz)	H24-H29 (4800-5800 Hz)

sensitivity (Tharpe and Ashmead, 2001), frequency resolution (Spetner and Olsho, 1990), and frequency discrimination (Olsho *et al.*, 1987). For that reason, it might be expected that 3-month-olds' ability to hear temporal pitch would be influenced by the frequency range of the harmonics. To investigate the effect of spectral region on performance, two conditions were included. The conditions were (1) "LOW" unresolved harmonics (harmonic numbers 13 to 26, 2500–4500 Hz) based on missing fundamentals of 160 and 200 Hz and (2) "HIGH" unresolved harmonics (harmonic numbers 20 to 31, 4000–6000 Hz) based on missing fundamentals of 190 and 200 Hz. Past studies have shown that adults can extract pitch from unresolved harmonics in both of these spectral regions (Bernstein and Oxenham, 2003; Houtsma and Smurzynski, 1990; Shackleton and Carlyon, 1994). For an F0 of 200 Hz, Houtsma and Smurzynski (1990) measured a difference limen of about 2.5% for unresolved complexes with the lowest harmonic number above 13. The pitch changes presented, 20% in the LOW condition and 10% in the HIGH condition, are well above discrimination threshold for adults and should not affect their performance. The expectation was that any differences between 3-month-olds and older listeners would be greater in the HIGH condition than in the LOW condition.

Tonal complexes were generated using MATLAB Release 2010a (The Mathworks, Natick, MA). The numbers and frequencies of harmonics in the complexes differed across phases of the experiment and are shown in Table I. A diagram of one complex is shown in Fig. 1.

In the conditioning phase and the training phase (described in Sec. II C), the stimuli consisted of one complex containing the F0 and harmonics 2 to 9 for each pitch category. Complexes with resolved harmonics and energy at the fundamental were selected as the conditioning and training stimuli to direct the participant's attention to pitch as the relevant dimension, using stimuli with highly salient pitch. Previous work has shown that pitch changes to these complexes are readily discriminated by both infants and adults (Lau and Werner, 2012).

In the unresolved harmonics test phase (described in Sec. II C), the stimuli consisted of five complexes in each pitch category composed of six consecutive harmonics combined in random phase. Harmonics above the tenth are generally considered to be unresolved (Bernstein and Oxenham, 2003). Only harmonic 13 and higher were used here to ensure that all complexes were unresolved. In the LOW condition, the fundamental frequencies, 160 and 200 Hz, were selected to remain consistent with past studies of infant pitch perception (e.g., Clarkson and Rogers, 1995; Butler *et al.*, 2013; Lau and Werner, 2012). For the HIGH condition, the lower pitch category was changed to 190 Hz so that even with the high harmonic numbers, the harmonics in both pitch categories would fall within the same spectral region, ensuring that spectral edge cues could not be used to perform the task. Furthermore, with the harmonic numbers shown in Table I, a change in the frequency of the highest or lowest harmonic, would not be correlated with the change in pitch and so could not be used as a cue. The lowest frequency component of the lower pitch category is not the lowest frequency, and the highest frequency component of the higher pitch category is not the highest frequency.

FIG. 1. Schematic diagram showing the harmonic composition and the -12 dB/octave spectral slope and of a complex in the test phase. The depicted complex has a missing fundamental of 200 Hz and is composed of 6 consecutive harmonics (harmonics 13 to 18, 2600 to 3600 Hz).

Besides spectral edge cues, listeners may also rely on shifts in the spectral centroid to discriminate the complexes, so the stimuli were bandpass filtered with a -12 dB/octave slope (Micheyl and Oxenham, 2004; Micheyl *et al.*, 2012; Moore and Moore, 2003). 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. To mask distortion products, 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. Sound pressure levels were calibrated in a Zwislocki coupler and checked in the subject's ear canal at the time of testing. All complexes were presented at a flat-weighted level of 70 dB SPL and the pink noise was presented at 65 dB SPL. Testing was conducted in a double-walled, sound attenuating booth.

C. Procedure

Infants were tested in an average of 2.5 sessions (range = 1–4). These sessions were completed in a single 60-min visit for most infants. Six infants who were unable to complete all experimental phases within a single visit completed testing during a second visit.

An observer-based psychophysical procedure was used (Werner, 1995). During testing, infants sat on a caregiver's lap in the booth. 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 on the participant's right. The mechanical toys were activated or a video was presented on the monitor to reinforce the infants' response to a pitch change. The experimenter, or "observer," 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 heard complexes from the 2500–4000 Hz LOW condition; the other half heard complexes from the 4000–6000 Hz HIGH condition. Half of the participants within each condition were randomly assigned to hear 160 or 190 Hz background complexes and 200 Hz target complexes, while the other half heard 200 Hz background complexes and 160 or 190 Hz target complexes.

The experimenter initiated a trial when the participant was quiet and facing midline. On change trials, four complexes with the target F0 were played, 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. Except in the initial conditioning 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.

The study consisted of a conditioning phase, a training phase, and a test phase. The three phases were presented in a fixed sequence, and participants were required to reach criterion in one phase before advancing to the next. The purpose of the conditioning phase was to demonstrate the association between the reinforcer and the target, the F0 change. 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 four of the last five change trials and one no-change trial within a maximum of 15 trials to complete the conditioning phase.

In the subsequent training and test phases, the probability of change and no-change trials was 0.5, the reinforcer was only activated if the experimenter correctly identified a change trial, and the experimenter was required to respond correctly on four of the last five change and four of the last five no-change trials within a maximum of 40 trials to move on to the next phase. This criterion corresponds to a hit rate of at least 80% and a false alarm rate of no more than 20% on the last five consecutive change and no-change trials, respectively. In the training phase, the stimuli were the same as in the conditioning phase. The purpose of the training phase was to teach the participant that an observable response to a pitch change was required to activate the reinforcer and to demonstrate to the observer that participants were able to perform the basic task.

The test phase was a missing fundamental pitch categorization task with complexes composed of unresolved harmonics. The purpose of the test phase was to demonstrate that participants perceived the pitch of the missing fundamental. In the test phase, five different sets of harmonics with one F0 were randomly presented in the background and on no-change trials, while five different sets of harmonics with the other F0 were randomly presented on change trials. In other words, five harmonic complexes, each with a different set of six 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.

To address confusion during the progression from the training phase to the test phase, 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 in the test phase—stimuli were presented from the previously completed training phase. Participants received up to 12 trials of such "reminder" stimuli to meet a criterion of five correct responses on six consecutive trials. If this criterion was met,

the participant returned to the test 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 test phase was resumed. If participants were unable to meet criterion on the test phase after three separate presentations of reminder stimuli, testing was discontinued, and the participant was judged to be unable to complete the test phase. Note that when a participant was classified as having completed the test phase, it was always because at least four of the last five change trials and at least four of the last five no-change trials had been correct.

Musically untrained adults were also tested in an average of 2.5 sessions (range = 1–4) while musically trained adults were tested in an average of 2.1 sessions (range = 1–3). These sessions were completed in a single 60-min visit. Adults 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.

III. RESULTS

Figure 2 shows the number of participants in each age group to complete and fail the test phase by condition. More infants than musically untrained adults reached criterion in the test phase: 53 out of 57 infants (93%) reached criterion while 14 out of 28 musically untrained adults (50%) reached criterion. A logistic regression model was used to test the effect of age group and condition on the number of participants to reach criterion. This analysis revealed a significant effect of age group [$Z=2.01$, $p=0.044$], but effects of neither condition [$Z=0.75$, $p=0.451$] nor the age group $\times$ condition interaction [$Z=0.18$, $p=0.856$]. The analysis thus confirmed that more infants were successful than musically trained adults, but that success rate did not vary with condition.

That only half of the adults in the original group reached criterion in discriminating unresolved harmonic complexes is problematic. Adults have repeatedly been shown to

perceive the pitch of unresolved harmonic complexes (Bernstein and Oxenham, 2003; Houtsma and Smurzynski, 1990; Shackleton and Carlyon, 1994). If we cannot replicate that effect, it is hard to make a convincing case that infants are discriminating between these stimuli on the basis of pitch. Several studies have suggested, however, that listeners can be distracted from pitch by spectral variation (Borchert *et al.*, 2011; Micheyl and Oxenham, 2004; Moore, 1990). It stands to reason that such distraction would have more dramatic effects when the pitch is not salient, as in the case of unresolved harmonics. Moreover, because the complexes are repeated many times over the course of a session, the listener is exposed to a great deal more spectral variation than might be experienced in a two-alternative forced-choice procedure. Thus, it could be that all adults are capable of discriminating between the pitch categories with these stimuli, but that the repeated spectral variation in the stream of complex tones made it difficult for some of them to do so. Ignoring for the moment the fact that infants did not appear to be so distracted, we tested a group of adults expected to be less distracted by spectral variation, those with musical training. The goal of including this group was simply to demonstrate that adults could discriminate between the complexes used in this study on the basis of pitch.

In the group of musically trained adults, 22 of 27 participants reached criterion in the test phase, which appeared comparable to infants. A Pearson χ^2 test confirmed that the number of participants reaching criterion did not differ among 3-month-olds, 7-month-olds, and musically trained adults [$\chi^2(2)=5.5051$, $p=0.064$]. In contrast, a second Pearson χ^2 test showed that the number of participants reaching criterion did differ between musically trained and untrained adults [$\chi^2(1)=6.0247$, $p=0.014$]. As expected, a high proportion of musically trained adults discriminated the unresolved harmonic complexes, demonstrating that adults could discriminate between these complexes on the basis of pitch.

Two further analyses were conducted to evaluate the participants’ performance. The first analysis addressed whether the number of participants reaching criterion in each age group was greater than expected by chance. Then, the relative difficulty of the task for infants and adults as well as the relative difficulty of the LOW and HIGH conditions was addressed by comparing the average number of trials required to meet criterion across age groups and conditions. Preliminary analyses indicated that there was no effect of pitch change direction, so that variable was not considered in subsequent analyses.

To determine the proportion of participants 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 0.56 for infants and 0.52 for adults in an average of 2.4 sessions. A simulation of 5000 participants in which responses occurred randomly at these rates in 3 test sessions each showed that criterion was met in all phases of the experiment in only 10.2% of participants with a response rate of 0.56 and 9.76% of participants with a response rate of 0.52. Four exact binomial tests with an assumed probability of 0.10 were conducted based on the number of participants who reached criterion in each

FIG. 2. Number of participants in each age group to complete or fail the test phase by condition.

participant group. More participants were found to meet criterion than expected by chance ($p < 0.001$) for 3-month-olds, 7-month-olds, and both musically trained and untrained adults.

For successful participants, the number of trials required to reach criterion in the test phase is plotted as a function of participant group for the two conditions in Fig. 3. The number of trials to reach criterion appeared to be about the same for infants and untrained adults, but greater for the HIGH condition than for the LOW condition. While musically trained adults required about the same number of trials to reach criterion, they appeared to need a greater number of trials in the LOW condition than in the HIGH. A two-way analysis of variance (ANOVA) testing the effect of age group and condition on the number of trials to criterion revealed a marginally significant effect of condition [$F(1,82) = 3.67$, $p = 0.0589$] but no significant effect of participant group [$F(3,82) = 2.49$, $p = 0.0660$] or the participant group $\times$ condition interaction [$F(3,82) = 2.49$, $p = 0.0663$]. The trend toward a greater number of trials to criterion for infants and musically untrained adults in the HIGH condition may be a result of decreasing pitch salience with the higher harmonics. The musicians, however, do not appear to be affected in the same way. Nevertheless, there is no indication that infants took more trials to learn the task than adults.

IV. DISCUSSION

The results of this experiment demonstrate that participants in all age groups tested—3-month-olds, 7-month-olds, and adults—perceive the pitch of unresolved harmonics. Almost all infants at both ages reached criterion in the unresolved harmonics categorization task. Furthermore, infants appeared to have no greater difficulty than adults reaching criterion.

Previous studies have shown that 7–8-month-old infants can discriminate the pitch of unresolved harmonics (Clarkson and Rogers, 1995) and of high-pass filtered IRN (Butler *et al.*, 2013; Butler and Trainor, 2013). However, the performance of infants in the current study is much better than that reported previously. The overall proportion of infants meeting criterion in this study, about 93%, is notably greater than the 17% success rate reported for 7-month-old

infants by Clarkson and Rogers (1995) and less variable than the performance reported for 8-month-olds by Butler *et al.* (2013). One possible explanation for this is that in the current study, the complexes were presented at 70 dB SPL compared to 55–60 dBA in Clarkson and Rogers and 58 dBA in Butler *et al.* The 67% success rate reported for discrimination of resolved harmonics in Clarkson and Rogers is also lower than the 90%–100% success rate found in previous studies on infants' discrimination of resolved harmonics by with similar stimuli presented at 70 dB SPL (Lau and Werner, 2012). Nozza (1987) reported that infant speech discrimination became significantly poorer when the level of the stimuli was reduced from 70 to 60 or 50 dB SPL, consistent with that explanation. Furthermore, in the Butler and Trainor (2013) study reporting a cortical response to changes in IRN pitch at both 4 and 7 months, the stimuli were also presented at 70 dBA.

Another possible factor is that the complexes in the present study were presented with a continuous pink noise to mask distortion products while the complexes in Clarkson and Rogers (1995) were presented in quiet. The presence of a background noise has been found to perceptually “fill in” the missing fundamental and other missing harmonics in a complex tone (Hall and Peters, 1981; Houtgast, 1976; McDermott and Oxenham, 2008). The pink noise used in this study to mask distortion products may have facilitated the perception of the missing fundamental. Because neither Clarkson and Rogers (1995) nor Butler *et al.* (2013) report results for adult listeners, comparison of infant-adult differences across the studies is not possible.

If infants' pitch perception is at least qualitatively like adults' they would be expected to have more difficulty learning to categorize complexes with unresolved harmonics than with resolved harmonics. The overall proportion of infants meeting criterion on the unresolved harmonics categorization task (93%) is comparable to that of infants tested in our laboratory on the same task with resolved harmonics (90%–100%). However, the pitch changes presented in both Lau and Werner (2012) and the present study (e.g., 160 to 200 Hz, 190 to 200 Hz) are well above adult discrimination threshold (Bernstein and Oxenham, 2003; Houtsma and Smurzynski, 1990), so this measure may not be sensitive to differences in the difficulty of the task. That there was a trend for both infants and musically untrained adults to require more trials to learn to categorize complexes with higher number harmonics suggests that infants' and adults' pitch discrimination is similarly affected by a reduction in pitch salience. Nonetheless, whether harmonic resolvability and pitch salience affect infants' and adults' pitch discrimination in the same way would require further investigation with smaller pitch changes.

Musically trained adults were tested here to ensure that the results of previous studies of adult pitch perception could be replicated using the procedure and stimuli used to test infants. The question of why fewer musically untrained adults than either musically trained adults or infants were successful in learning to discriminate between unresolved harmonic complexes on the basis of pitch remains to be considered. Because the study was not intended to assess the

FIG. 3. Mean (± 1 SEM) number of trials to criterion as a function of age group in the HIGH and LOW Conditions.

effect of musical training on unresolved harmonic pitch discrimination, we can only speculate on possible answers to that question. One possible explanation is that conditioning and training with resolved harmonics and then testing with unresolved harmonics led musically untrained adults to adopt a suboptimal strategy. However, in an ongoing study we have found that some musically untrained adults continue to demonstrate difficulty with the task when unresolved harmonics are used in both training and testing. Another explanation for the result for musically untrained adults is consistent with previous reports that responding on the basis of pitch becomes more difficult in the presence of timbre variation (Borchert *et al.*, 2011; Micheyl and Oxenham, 2004; Moore, 1990). The spectral changes used in this study as a method of ensuring that responses were based on pitch may have caused “timbre confusion” in the adult participants. It is not surprising that musically trained adults’ pitch perception would be less influenced by spectral variation. For example, Seither-Preisler *et al.* (2007) showed that compared to nonmusicians, musicians are more likely to perceive harmonic complexes on the basis of pitch as opposed to timbre.

It may be of some interest that infants’ pitch perception seemed to be less influenced by spectral variation than was that of musically untrained adults. Lau and Werner (2014) have shown that infants are able to discriminate between harmonic complexes like those used in this study on the basis of the spectral centroid while ignoring fundamental frequency variation. Thus, it is not the case that infants do not hear the spectral variation. A potential scenario is that infants place greater weight on pitch variation than they do on spectral variation in their analysis of sound, and that during development the relative importance of those dimensions shifts, at least for some individuals. Of course, additional information on the relative discriminability of pitch and spectral changes would be needed to establish the plausibility of that scenario.

Perhaps the most surprising result of this study is that 3-month-olds’ performance was not different from that of 7-month-olds or of adults. We hypothesized that 3-month-olds would be poorer than older listeners in pitch discrimination of unresolved harmonics on the basis of two observations: First, that 7-month-old infants had more difficulty discriminating temporal pitch in previous studies (Clarkson and Rogers, 1995; Butler *et al.*, 2013); and second, that the organization of the auditory pathway is distinctly different at 3 and 7 months of age (Eggermont and Moore, 2012). Contrary to expectation, as many 3-month-olds reached criterion in the discrimination of unresolved harmonics as 7-month-olds and adults did, and there was no difference between the age groups in the number of trials to reach criterion. We further expected that 3-month-olds would perform worse in the HIGH condition due to immaturities observed in other aspects of sound processing in this frequency range. However, 3-month-olds were equally successful in both spectral regions. One interpretation of this result is that the reorganization of the auditory pathway in early infancy is more or less irrelevant to the discrimination of harmonic complexes on the basis of fundamental frequency. This idea is consistent with the view of Cariani and

Delgutte (1996a,b) that a temporal representation of pitch is available in the auditory nerve, a representation that appears to be functional in humans at 3 months (Gorga *et al.*, 1989; Levi *et al.*, 1995). It is also consistent with results showing that animals that lack a fully developed cortex like goldfish (Fay, 1982; Fay and Passow, 1982; Fay *et al.*, 1983) and budgerigar (Amagai *et al.*, 1999; Dooling and Searcy, 1981) can discriminate the pitch of IRN and sinusoidally amplitude-modulated noise.

To summarize, the current results show that both 3- and 7-month-old infants are able to discriminate between unresolved harmonic complexes on the basis of pitch. These results suggest that sufficient information to encode the pitch of such complexes is available in the auditory nerve and that the extraction of pitch from that information can be accomplished at subcortical levels of the auditory system. Further studies testing the limits of infants’ pitch discrimination would be needed to establish whether pitch perception is fully adult-like in early infancy. The relative importance of pitch and spectral characteristics in infants’ and adults’ auditory processing may be another question deserving additional attention.

ACKNOWLEDGMENTS

This work was supported by NIH grants R01 DC00396 and P30 DC04661. We thank Andrew Oxenham for his advice, Ashley Flad for subject recruitment and Brandon Warren for software assistance.

- Amagai, S., Dooling, R. J., Shamma, S., Kidd, T. L., and Lohr, B. (1999). “Detection of modulation in spectral envelopes and linear-rippled noises by budgerigars (*Melopsittacus undulatus*),” *J. Acoust. Soc. Am.* **105**, 2029–2035.
- Bendor, D., and Wang, X. (2005). “The neuronal representation of pitch in primate auditory cortex,” *Nature* **436**, 1161–1165.
- Bernstein, J. G., and Oxenham, A. J. (2003). “Pitch discrimination of diotic and dichotic tone complexes: harmonic resolvability or harmonic number?,” *J. Acoust. Soc. Am.* **113**, 3323–3334.
- Bertoncini, J., Nazzi, T., Cabrera, L., and Lorenzi, C. (2011). “Six-month-old infants discriminate voicing on the basis of temporal envelope cues (L),” *J. Acoust. Soc. Am.* **129**, 2761–2764.
- Borchert, E. M. O., Micheyl, C., and Oxenham, A. J. (2011). “Perceptual grouping affects pitch judgments across time and frequency,” *J. Exp. Psychol. Human* **37**, 257–269.
- Burns, E. M., and Viemeister, N. F. (1981). “Played-again SAM: Further observations on the pitch of amplitude-modulated noise,” *J. Acoust. Soc. Am.* **70**, 1655–1660.
- Butler, B. E., Folland, N. A., and Trainor, L. J. (2013). “Development of pitch processing: Infants’ discrimination of iterated rippled noise stimuli with unresolved spectral content,” *Hear. Res.* **304**, 1–6.
- Butler, B. E., and Trainor, L. J. (2013). “Brief pitch-priming facilitates infants’ discrimination of pitch-evoking noise: Evidence from event-related potentials,” *Brain Cognit.* **83**, 271–278.
- Cariani, P. A., and Delgutte, B. (1996a). “Neural correlates of the pitch of complex tones I. Pitch and pitch salience,” *J. Neurophysiol.* **76**, 1698–1716.
- Cariani, P. A., and Delgutte, B. (1996b). “Neural correlates of the pitch of complex tones II. Pitch shift, pitch ambiguity, phase invariance, pitch circularity, rate pitch, and the dominance region for pitch,” *J. Neurophysiol.* **76**, 1717–1734.
- Clarkson, M. G., and Clifton, R. K. (1995). “Infants’ pitch perception: Inharmonic tonal complexes,” *J. Acoust. Soc. Am.* **98**, 1372–1379.
- Clarkson, M. G., Martin, R. L., and Miciek, S. G. (1996). “Infants’ perception of pitch: Number of harmonics,” *Infant Behav. Dev.* **19**, 191–197.

- 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.
- Cooper, R. P., and Aslin, R. N. (1990). "Preference for infant-directed speech in the first month after birth," *Child Dev.* **61**, 1584–1595.
- Dooling, R. J., and Searcy, M. H. (1981). "Amplitude modulation thresholds for the parakeet (*Melospittacus undulatus*)," *J. Comp. Physiol* **143**, 383–388.
- Eggermont, J. J., and Moore, J. K. (2012). "Morphological and functional development of the auditory nervous system," in *Springer Handbook of Auditory Research, Springer Handbook of Auditory Research*, edited by L. A. Werner, A. N. Popper, and R. R. Fay (Springer, New York), Vol. 42, pp. 61–105.
- Fay, R. R. (1982). "Neural mechanisms of an auditory temporal discrimination by the goldfish," *J. Comp. Physiol.* **147**, 201–216.
- Fay, R. R., and Passow, B. (1982). "Temporal discrimination in the goldfish," *J. Acoust. Soc. Am.* **72**, 753–760.
- Fay, R. R., Yost, W. A., and Coombs, S. (1983). "Psychophysics and neurophysiology of repetition noise processing in a vertebrate auditory system," *Hear. Res.* **12**, 31–55.
- Gorga, M. P., Kaminski, J. R., Beauchaine, K. L., Jesteadt, W., and Neely, S. T. (1989). "Auditory brainstem responses from children three months to three years of age: normal patterns of response II," *J. Speech Hear. Res.* **32**, 281–288.
- Hall, D. A., and Plack, C. J. (2009). "Pitch processing sites in the human auditory brain," *Cereb. Cortex* **19**, 576–585.
- Hall, J. W., and Peters, R. W. (1981). "Pitch for nonsimultaneous successive harmonics in quiet and noise," *J. Acoust. Soc. Am.* **69**, 509–513.
- He, C., Hotson, L., and Trainor, L. J. (2007). "Mismatch responses to pitch changes in early infancy," *J. Cogn. Neurosci.* **19**, 878–892.
- He, C., and Trainor, L. J. (2009). "Finding the pitch of the missing fundamental in infants," *J. Neurosci.* **29**, 7718–7822.
- Houtgast, T. (1976). "Subharmonic pitches of a pure tone at low S/N ratio," *J. Acoust. Soc. Am.* **60**, 405–409.
- Houtsma, A. J. M., and Smurzynski, J. (1990). "Pitch identification and discrimination for complex tones with many harmonics," *J. Acoust. Soc. Am.* **87**, 304–310.
- Karzon, R. G., and Nicholas, J. G. (1989). "Syllabic pitch perception in 2- to 3-month-old infants," *Percept. Psychophys.* **45**, 10–14.
- Lau, B. K., and Werner, L. A. (2012). "Perception of missing fundamental pitch by 3- and 4-month-old human infants," *J. Acoust. Soc. Am.* **132**, 3874–3882.
- Lau, B. K., and Werner, L. A. (2014). "Infants ability to perceive changes in timbre," *J. Acoust. Soc. Am.* **135**, 2163–2163.
- Levi, E. C., Folsom, R. C., and Dobie, R. A. (1995). "Coherence analysis of envelope-following responses (EFRs) and frequency-following responses (FFRs) in infants and adults," *Hear. Res.* **89**, 21–27.
- McDermott, J. H., and Oxenham, A. J. (2008). "Spectral completion of partially masked sounds," *Proc. Natl. Acad. Sci.* **105**, 5939–5944.
- Michéyl, 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.
- Michéyl, 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.
- Michéyl, C., Schrater, P. R., and Oxenham, A. J. (2013). "Auditory frequency and intensity discrimination explained using a cortical population rate code," *PLoS Comput. Biol.* **9**, e1003336.
- Montgomery, C., and Clarkson, M. G. (1997). "Infant's pitch perception: Masking by low-and high-frequency noises," *J. Acoust. Soc. Am.* **102**, 1372–1379.
- Moore, B. C. J. (1990). "Frequency discrimination of complex tones with overlapping and non-overlapping harmonics," *J. Acoust. Soc. Am.* **87**, 2163–2177.
- Moore, G. A., and Moore, B. C. J. (2003). "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. Suppl.* **189**, 7–10.
- Nozza, R. J. (1987). "Infant speech-sound discrimination testing: Effects of stimulus intensity and procedural model on measures of performance," *J. Acoust. Soc. Am.* **81**, 1928–1939.
- Olsho, L. W., Koch, E. G., and Halpin, C. F. (1987). "Level and age effects in infant frequency discrimination," *J. Acoust. Soc. Am.* **82**, 454–464.
- Oxenham, A. J. (2012). "Pitch perception," *J. Neurosci.* **32**, 13335–13338.
- Oxenham, A. J., Bernstein, J. G. W., and Penagos, H. (2004). "Correct tonotopic representation is necessary for complex pitch perception," *Proc. Natl. Acad. Sci.* **101**, 1421–1425.
- 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.
- Penagos, H., Melcher, J. R., and Oxenham, A. J. (2004). "A neural representation of pitch salience in nonprimary human auditory cortex revealed with functional magnetic resonance imaging," *J. Neurosci.* **24**, 6810–6815.
- Plantinga, J., and Trainor, L. J. (2009). "Melody recognition by two-month-old infants," *J. Acoust. Soc. Am.* **125**, EL58–EL62.
- Seither-Preisler, A., Johnson, L., Krumbholz, K., Nobbe, A., Patterson, R., Seither, S., and Lütkenhöner, B. (2007). "Tone sequences with conflicting fundamental pitch and timbre changes are heard differently by musicians and nonmusicians," *J. Exp. Psychol. Human* **33**, 743–751.
- Shackleton, T. M., and Carlyon, R. P. (1994). "The role of resolved and unresolved harmonics in pitch perception and frequency modulation discrimination," *J. Acoust. Soc. Am.* **95**, 3529–3540.
- Spetner, N. B., and Olsho, L. W. (1990). "Auditory frequency resolution in human infancy," *Child Dev.* **61**, 632–652.
- Srulovicz, P., and Goldstein, J. L. (1983). "A central spectrum model: A synthesis of auditory-nerve timing and place cues in monaural communication of frequency spectrum," *J. Acoust. Soc. Am.* **73**, 1266–1276.
- Tharpe, A. M., and Ashmead, D. H. (2001). "A longitudinal investigation of infant auditory sensitivity," *Am. J. Audiol.* **10**, 104–112.
- Trainor, L. J., and Zacharias, C. A. (1998). "Infants prefer higher-pitched singing," *Infant Behav. Dev.* **21**, 799–805.
- Walker, K. M. M., Bizley, J. K., King, A. J., and Schnupp, J. W. H. (2011). "Cortical encoding of pitch: Recent results and open questions," *Hear. Res.* **271**, 74–87.
- 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.
- Yost, W. A. (1996). "Pitch of iterated rippled noise," *J. Acoust. Soc. Am.* **100**, 511–518.