

Pitch perception prior to cortical maturation

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**Abstract**

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Pitch perception plays an important role in many complex auditory tasks including speech perception, music perception, and sound source segregation. Because of the protracted and extensive development of the human auditory cortex, pitch perception might be expected to mature, at least over the first few months of life. This dissertation investigates complex pitch perception in 3-month-olds, 7-month-olds and adults – time points when the organization of the auditory pathway is distinctly different. Using an observer-based psychophysical procedure, a series of four studies were conducted to determine whether infants (1) discriminate the pitch of harmonic complex tones, (2) discriminate the pitch of unresolved harmonics, (3) discriminate the pitch of missing fundamental melodies, and (4) have comparable sensitivity to pitch and spectral changes as adult listeners. The stimuli used in these studies were harmonic complex tones, with energy missing at the fundamental frequency. Infants at both three and seven months of age discriminated the pitch of missing fundamental complexes composed of resolved and unresolved harmonics as well as missing fundamental melodies, demonstrating perception of complex pitch by three months of age. More surprisingly, infants in both age groups had lower pitch and spectral discrimination thresholds than adult listeners. Furthermore, no differences in performance on any of the tasks presented were observed between infants at three and seven months of age. These results suggest that subcortical processing is not only sufficient to support pitch perception prior to cortical maturation, but provides adult-like sensitivity to pitch by three months.

## TABLE OF CONTENTS

<b>1</b>	<b>PITCH PERCEPTION: AN INTRODUCTION</b>	<b>1</b>
<b>1.1</b>	<b>DEFINITION OF PITCH</b>	<b>2</b>
<b>1.2</b>	<b>PITCH-EVOKING STIMULI</b>	<b>3</b>
<b>1.3</b>	<b>PERIPHERAL CODES FOR PERIODICITY</b>	<b>5</b>
<b>2</b>	<b>PERCEPTION OF MISSING FUNDAMENTAL PITCH BY 3- AND 4-MONTH-OLD HUMAN INFANTS</b>	<b>8</b>
<b>2.1</b>	<b>EXPERIMENT I</b>	<b>10</b>
2.1.1	METHOD	10
2.1.1.1	Subjects	10
2.1.1.2	Stimuli	11
2.1.1.3	Procedure	12
2.1.2	RESULTS	15
2.1.3	DISCUSSION	17
<b>2.2</b>	<b>EXPERIMENT II</b>	<b>17</b>
2.2.1	METHOD	23
2.2.1.1	Subjects, Stimuli, and Procedure	23
2.2.2	RESULTS	25
2.2.3	DISCUSSION	27
<b>3</b>	<b>PERCEPTION OF THE PITCH OF UNRESOLVED HARMONICS BY 3- AND 7-MONTH-OLD HUMAN INFANTS</b>	<b>35</b>
<b>3.1</b>	<b>METHOD</b>	<b>38</b>
3.1.1	SUBJECTS	38
3.1.2	STIMULI	40
3.1.3	PROCEDURE	43
<b>3.2</b>	<b>RESULTS</b>	<b>47</b>
<b>3.3</b>	<b>DISCUSSION</b>	<b>51</b>
<b>4</b>	<b>PITCH PERCEPTION PRIOR TO CORTICAL MATURATION: IS IT REALLY PITCH?</b>	<b>59</b>
<b>4.1</b>	<b>METHOD</b>	<b>62</b>
4.1.1	SUBJECTS	62
4.1.2	STIMULI	63
4.1.3	PROCEDURE	64
<b>4.2</b>	<b>RESULTS</b>	<b>66</b>
<b>4.3</b>	<b>DISCUSSION</b>	<b>68</b>
<b>5</b>	<b>INFANT PITCH AND SPECTRAL ENVELOPE SENSITIVITY</b>	<b>73</b>
<b>5.1</b>	<b>EXPERIMENT I</b>	<b>75</b>
5.1.1	METHOD	75
5.1.1.1	Subjects	75
5.1.1.2	Stimuli	77
5.1.1.3	Procedure	79
5.1.2	RESULTS	82

5.1.3	DISCUSSION	86
<b>5.2</b>	<b>EXPERIMENT II</b>	<b>89</b>
5.2.1	METHOD	89
5.2.1.1	Subjects	89
5.2.1.2	Stimuli	90
5.2.1.3	Procedure	91
5.2.2	RESULTS	93
5.2.3	DISCUSSION	95
<b>5.3</b>	<b>GENERAL DISCUSSION</b>	<b>97</b>
<b>6</b>	<b>CONCLUDING REMARKS</b>	<b>103</b>

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## LIST OF FIGURES

Figure 1-1: Pure tone pitch.....	3
Figure 1-2: Complex pitch.....	4
Figure 1-3: Spectral pitch.....	5
Figure 2-1: Harmonic structures of stimuli in Experiment I and II. ....	11
Figure 2-2: Mean trials to criterion, Experiment I, no noise.....	16
Figure 2-3: Mean trials to criterion, Experiment II, with noise.....	20
Figure 2-4: Mean trials to criterion comparison, noise and no noise.....	21
Figure 2-5: Harmonic structures of stimuli in Experiment III.....	23
Figure 2-6: Mean trials to criterion, Experiment III.....	26
Figure 2-7: Mean trials to criterion comparison, Experiment II & III.....	27
Figure 3-1: Schematic diagram of unresolved stimuli.....	40
Figure 3-2: Harmonic structures of unresolved stimuli.....	41
Figure 3-3: Participant success.....	47
Figure 3-4: Mean trials to criterion, HIGH and LOW conditions.....	50
Figure 4-1: Schematic diagram of the melody.....	63
Figure 4-2: Participant success.....	67
Figure 4-3: Mean trials to criterion, MF melody discrimination.....	68
Figure 5-1: Schematic diagram of the pitch discrimination stimuli.....	77
Figure 5-2: Percent pitch change and background F0.....	78
Figure 5-3: Mean trials to criterion, resolved and unresolved.....	83
Figure 5-4: Pitch thresholds.....	84
Figure 5-5: Group sensitivity (d').....	86
Figure 5-6: Schematic diagram of the spectral discrimination stimuli.....	90
Figure 5-7: Percent timbre change and background CF.....	91
Figure 5-8: Mean trials to criterion, spectral discrimination.....	93
Figure 5-9: Timbre thresholds.....	94

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To my parents.

# 1 Pitch perception: An Introduction

With the careful pluck of a string, a harpist captivates her audience using the enchanting sound of a musical note. Whether it is for the enjoyment of music, to understand the words spoken around them, or perhaps to hear out the voice of the barista holding their espresso in a noisy coffee shop, humans rely on pitch to navigate their acoustic environment every day. In speech, pitch contributes to vowel identity (Fujisaki and Kawashima, 1968), is a cue for word segmentation (Kemler Nelson et al., 1989), conveys emotion (Ohala, 1983; Trainor et al., 2000), and can even change word meaning in tonal languages. In music, pitch is an essential building block, with musical scales composed of notes with different pitch relationships and melodic contours composed of patterns of pitch changes. Pitch also plays a role in the formation of auditory objects and the segregation of simultaneous sound sources. If pitch is critical to so many auditory tasks, can humans perceive pitch once hearing begins? What parts of the auditory system are required to perceive pitch? What do infants perceive when the string of a harp is plucked?

While infants begin responding to sound during the third trimester of gestation (Birnholtz and Benacerraf, 1983; Starr et al., 1977), the human auditory system develops over an extended period of time. At three months of age, the auditory cortex is markedly immature with activation of only the most superficial layer by the reticular articulating system pathway (Eggermont and Moore, 2012). Infants' responses to sound at this age are likely supported by brainstem processing (Moore, 2002). By seven months however, infants have access to mature thalamocortical connections despite significant immaturities in the auditory cortex that persist (Eggermont and Moore, 2012). The

primary question this dissertation addresses is whether subcortical processing is sufficient to support early pitch perception prior to cortical maturation. Each of the four following chapters is intended to be an independent article that investigates infants' ability to perceive complex pitch under different stimulus manipulations.

The participants in each study were 3-month-olds, 7-month-olds, and adults, ages when the organization of the auditory pathway is distinctly different. The same observer-based psychophysical procedure (Werner, 1995) is used throughout all four studies but the stimuli and test phases differ according to the questions proposed. Chapters two, three, and four, examine whether infants demonstrate the ability to perceive the pitch of resolved harmonics, unresolved harmonics, as well as missing fundamental melodies. Chapter five investigates infant sensitivity to pitch and spectral changes in the presence of variation in the other attribute (i.e., discrimination of pitch in the presence of spectral variation and vice versa). The remainder of this chapter will define pitch and the peripheral codes for periodicity as considered in the following chapters.

## **1.1 Definition of pitch**

The American National Standards Institute defines pitch as “that auditory attribute of sound according to which sounds can be ordered on a scale from low to high”, (ANSI, 1994). Many researchers have used the ability of a sound to produce a recognizable melody to determine whether or not that sound evokes a pitch (e.g., Burns and Viemeister, 1981). Chapter four employs the same rationale to investigate whether infants are indeed discriminating complex tones on the basis of perceived pitch. Another important point to note is that pitch is defined perceptually rather than by a physical property of the sound.

## 1.2 Pitch-evoking stimuli

Sound is typically described according to three physical properties: frequency, intensity, and time/phase. In the simplest case of a pure tone with a single frequency, frequency is the physical correlate of pitch. A description of this relationship for more complex pitch-evoking stimuli however, is not as straightforward. The primary physical property correlated to a pitch percept is periodicity, repetition over time. A signal  $x(t)$  is periodic if there exists a number  $\tau \neq 0$  such that  $x(t) = x(t-\tau)$  for all time  $t$ . Sounds that fit well with this description tend to have a salient pitch that depends on the period  $\tau$ . As stimuli differs from this description, becoming inharmonic, the salience of its pitch decreases. Despite the large number of stimulus conditions that evoke a percept of pitch, they fall into three main categories.

### 1.2.1. Pure tone pitch

The sound produced when you strike a tuning fork approximates a sinusoid or pure tone. The pitch of a pure tone corresponds to the period of the waveform in the time domain (Fig. 1-1A) and to the frequency of its single component in the spectral domain (Fig. 1-1B). Pure tones are rarely encountered in a natural listening environment but are a class of stimuli that are often used in studies of pitch perception.

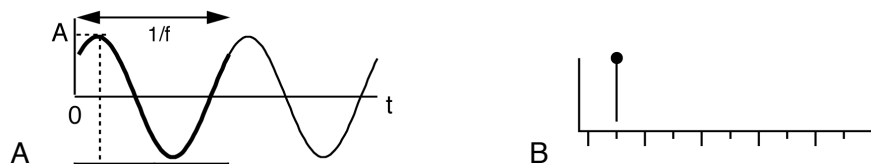


Figure 1-1: A. The time waveform of a sinusoid where the pitch corresponds to the period ( $1/f$ ). B. The spectrum of a sinusoid where the pitch corresponds to the single frequency component.

### 1.2.2. Complex pitch or Periodicity pitch

Harmonic complex sounds such as a musical note or a vowel in speech contain multiple frequency components that are all integer multiples of the fundamental frequency ( $F_0$ ). Its pitch is a unitary percept that corresponds to a pure tone at the  $F_0$ . In the time domain, this would be the period (Fig. 1-2A) and in the spectral domain, the  $F_0$  of the complex (Fig. 1-2B).

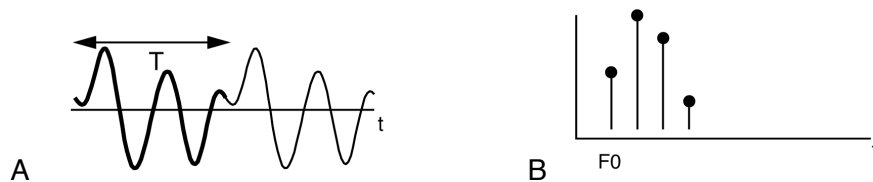


Figure 1-2: A. The time waveform of a complex tone where the pitch corresponds to the period ( $T$ ). B. The spectrum of a complex tone where the pitch corresponds to the  $F_0$ .

A classic phenomenon in pitch perception is that the pitch of a harmonic complex is the same regardless of whether energy at the fundamental is present. Missing fundamental complexes are used throughout the studies as a method of controlling for responses to pitch as opposed to frequency or other spectral changes.

Finally, complex pitch has at least two dimensions. Its perceptual structure has been described to be helical, with pitch chroma distributed circularly and pitch height distributed linearly. Pitch chroma is the dimension that accounts for the similarity between notes separated by an octave while pitch height is the dimension that they differ on. The focus of this dissertation is on the perception of pitch height. The term pitch and complex pitch are used interchangeably and will refer to periodicity pitch unless otherwise specified.

### 1.2.3. Spectral pitch

Formant-like stimuli can evoke two pitches, one related to  $f_{\text{locus}}$ , the spectral location with the most energy, referred to as spectral pitch, and one related to  $F_0$  referred to as periodicity pitch. A vowel in speech is an example of a sound that would evoke a pitch related to the  $F_0$  and a pitch related to the  $f_{\text{locus}}$ . Both spectral and periodicity pitch are represented in the time domain as well as the spectral domain (Fig. 1-3). The pitch categorization task presented to listeners in the first four studies control for responses to spectral pitch by requiring participants to ignore random spectral variation and respond only to changes in fundamental frequency.

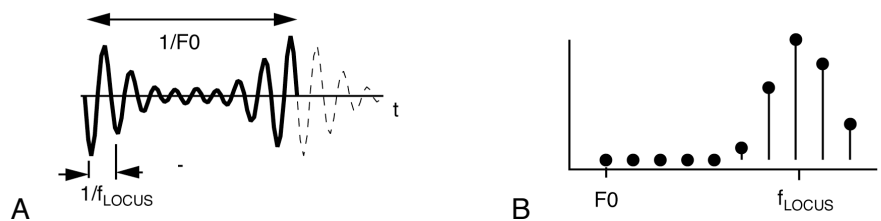


Figure 1-3: A. The time waveform of a formant-like stimulus with two pitches: one corresponding to the period ( $1/F_0$ ) and one corresponding to  $1/f_{\text{locus}}$ . B. The spectrum of a formant-like stimulus with a pitch corresponding to  $F_0$  and a pitch corresponding to  $f_{\text{locus}}$ .

### 1.3 Peripheral codes for periodicity

The studies in chapters three and five examine the two peripheral codes for pitch that coincide with the waveform and spectrum of a sound, both of which have been shown to contribute to pitch perception. The spectrum is represented in a rate-place code, which forms the basis of place models of pitch perception (Goldstein, 1973; Terhardt 1974; Wightman, 1973). When a sound enters the ear, the basilar membrane performs a spectral analysis; high-frequency components excite the basilar membrane towards the base and low-frequency components towards the apex. The place of excitation on the basilar membrane provides a code for frequency and the firing rate of

auditory nerve fibers at each place provides a code for intensity. Representation of the time waveform, referred to as the temporal code, is the basis of temporal models of pitch perception (Licklider, 1951). The temporal code is based on phase locking, the tendency for auditory nerve fibers to fire at the same time during each cycle of vibration of the time waveform. Synchronous firing to the time waveform provides a code for the fine structure of low-frequency components and modulation in firing rate provides a code for envelope fluctuations at all frequencies. There is evidence suggesting that temporal information matched to the correct tonotopic place is important for the generation of a pitch percept (Oxenham et al., 2004).

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## 2 Perception of missing fundamental pitch by 3- and 4-month-old human infants\*

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

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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 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.

## **2.1 EXPERIMENT I**

### **2.1.1 Method**

All procedures, including recruitment, consenting, and testing of human subjects followed the guidelines of the University of Washington Human Subjects Division and were reviewed and approved by the Institutional Review Board.

#### **2.1.1.1 Subjects**

The participants were 20 4-month-old infants, 21 3-month-old infants, and 20 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.

### 2.1.1.2 Stimuli

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 F0 + H5-H10 F0 + H7-H12	H3-H8 H5-H10 H7-H12
4	H3-H8 H5-H10 H7-H12	H2-H7 H4-H9 H6-H11

Figure 2-1: Harmonic structures of stimuli in Experiment I and II. F0 is the fundamental frequency; Hn refers to the other component frequencies by harmonic number.

Two sets of tonal complexes based on fundamental frequencies 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.

### 2.1.1.3 Procedure

Infants were tested in an average of 3.5 sessions (range=1-7). These sessions were completed in 60-minute 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 seconds 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 seconds 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-minute 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.

### **2.1.2 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 Figure 2-2 as a function of age group. Although it appears that the 4-month-olds required more trials to reach criterion than either adults or 3-month-olds, a one-way 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.

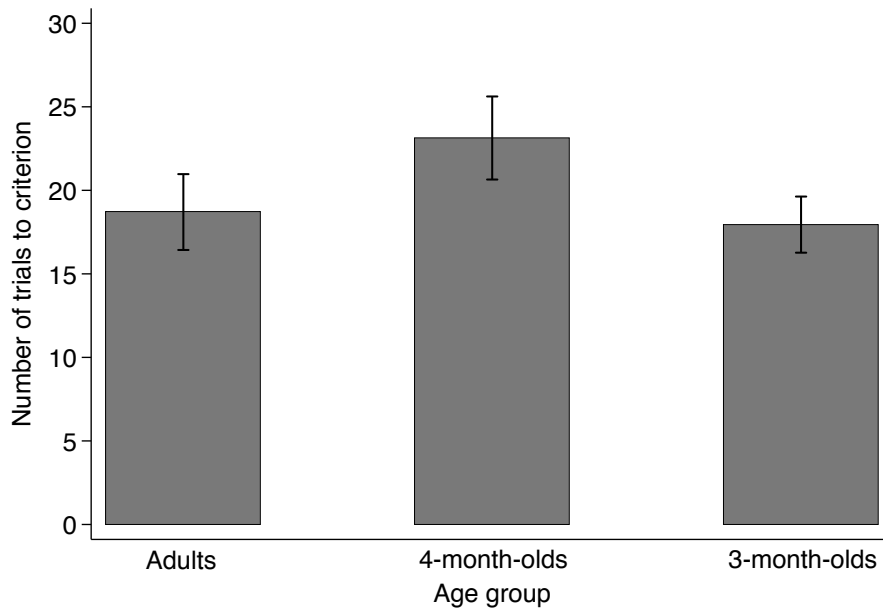


Figure 2-2: Mean ( $\pm 1$  SEM) number of trials to criterion for missing fundamental discrimination in Experiment I.

### **2.1.3 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.

## **2.2 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.

### **2.2.1 Method**

#### **2.1.1.1 Subjects**

The participants were 20 3-month-old infants and 20 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-second response window.

#### 2.1.1.2 Stimuli and Procedure

Experiment II consisted of 4 phases. Figure 2-1 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 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-minute 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-minute visit.

### 2.2.2 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 Figure 2-3. 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.

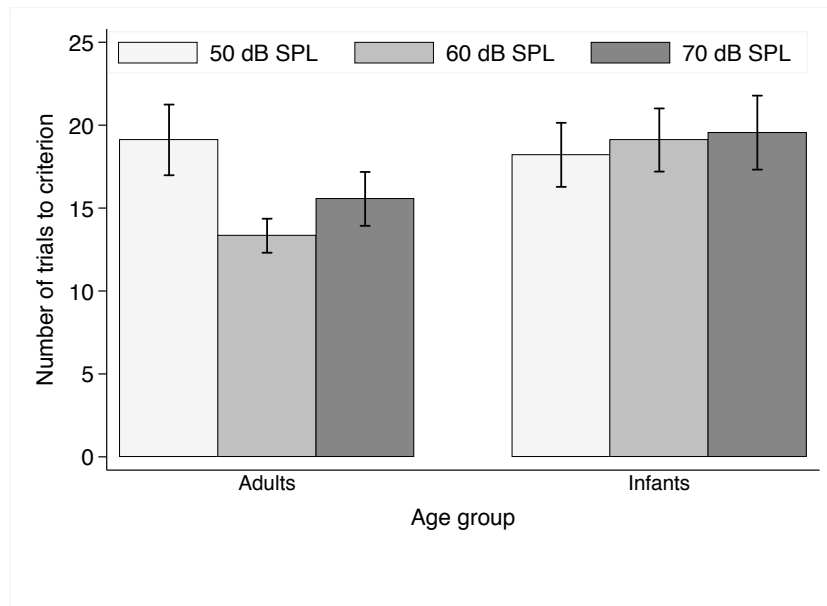


Figure 2-3: Mean ( $\pm 1$  SEM) number of trials to criterion for missing fundamental discrimination with noise in Experiment II.

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 (Figure 2-4). 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.

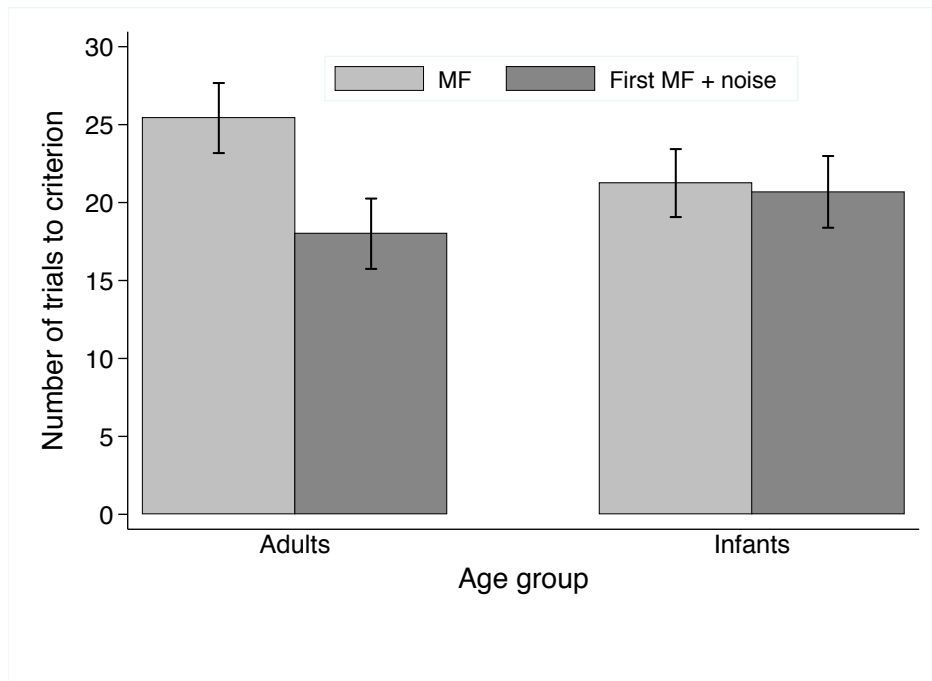


Figure 2-4: Mean ( $\pm 1$  SEM) number of trials to criterion for missing fundamental discrimination and the first missing fundamental discrimination completed with noise in Experiment II.

### 2.2.3 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 37 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 3 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.

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; Moore and Moore, 2003b; Dai, 2010; Kohlrausch et al., 1992). A third experiment evaluated the possible influence of spectral edge cues on infant pitch perception.

## 2.3 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; Moore and Moore, 2003b; 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.

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 H4-H9 H5-H10 H6-H11 H7-H12 H3,4,5,9,10,11 H3,4,6,8,10,11 H4,5,7,8,10,12 H5,6,7,9,10,11 H5,7,9,10,11,12	H2-H7 H3-H8 H4-H9 H2,3,4,7,8,9 H2,3,4,6,7,8 H2,4,5,6,7,9 H2,4,5,6,7,8 H3,4,5,7,8,9 H3,4,5,6,8,9 H3,5,6,7,8,9

Figure 2-5: Harmonic structures of stimuli in Experiment III. F0 is the fundamental frequency; Hn refers to the other component frequencies by harmonic

### 2.2.1 Method

#### 2.2.1.1 Subjects, Stimuli, and Procedure

The participants were 10 3-month-old infants and 11 adults and 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. Figure 2-5 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. 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-minute 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).

### 2.2.2 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-months-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 ( $p < 0.001$ ).

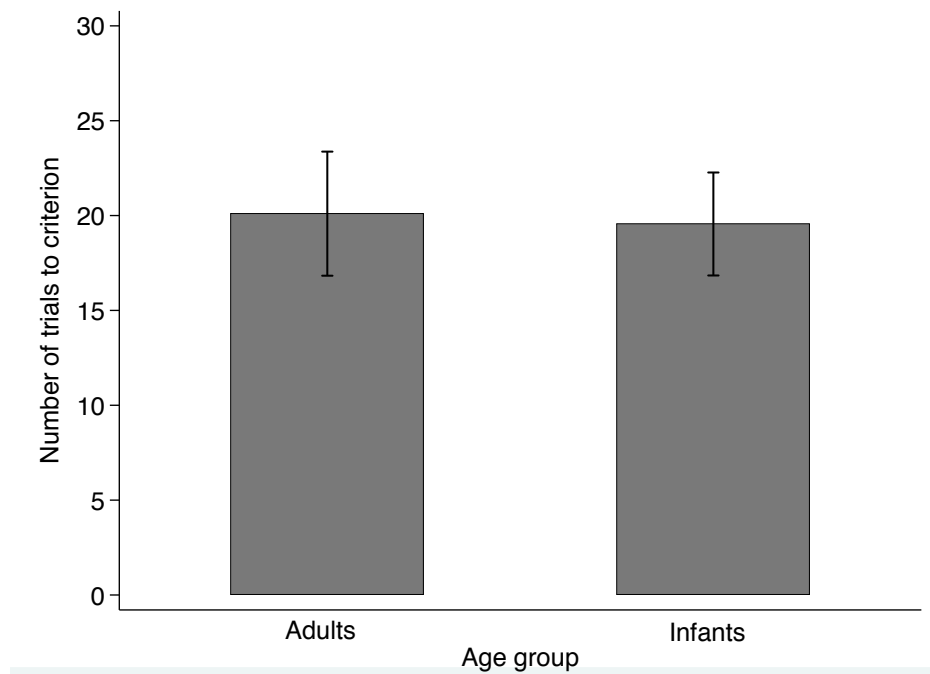


Figure 2-6: Mean ( $\pm 1$  SEM) number of trials to criterion for missing fundamental discrimination with spectrally shaped complexes and pink noise across frequencies in Experiment III.

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 Figure 2-6 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 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 Figure 2-7. 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.

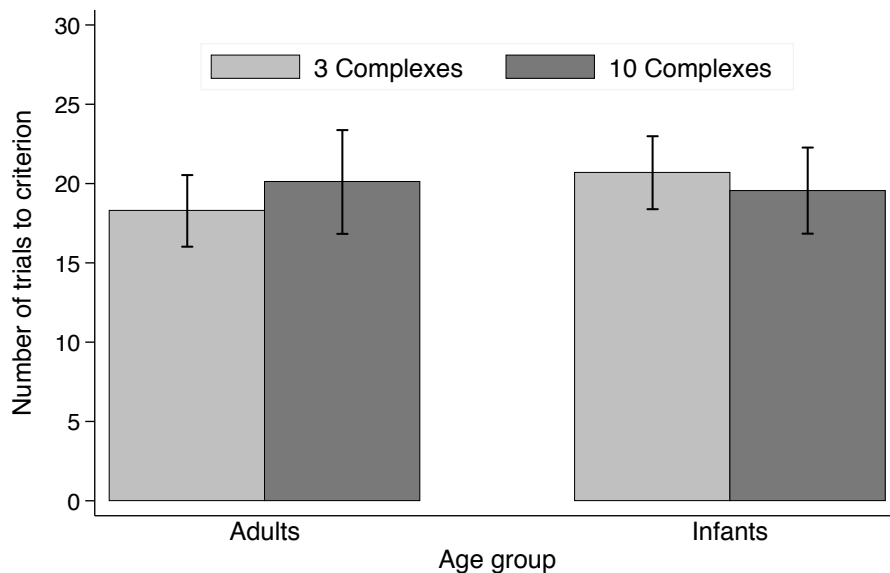


Figure 2-7: Mean ( $\pm 1$  SEM) number of trials to criterion for the first missing fundamental discrimination completed with noise in Experiment II with 3 complexes per pitch category and missing fundamental discrimination with noise in Experiment III with 10 complexes per pitch category.

### 2.2.3 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 the introduction, He et al. 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. 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. 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 stimuli 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; Clarkson and Clifton, 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.

## **ACKNOWLEDGEMENTS**

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### 3 Perception of the pitch of unresolved harmonics by 3- and 7-month-old human infants\*

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 only subcortical structures are functional during early infancy while cortical structures are not. At 3 months of age, the auditory cortex is markedly immature, and 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

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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. 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 adult-like, early in infancy. Frequency resolution is mature at 500 and 1000 Hz by 3 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 it is difficult to understand how 3-month-olds could demonstrate behavioral discrimination of missing fundamental changes without also generating a cortical response, 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 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.

### **3.1 METHOD**

#### **3.1.1 Subjects**

Infant participants in this study were 29 3-month-olds and 28 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 years 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 HL at octave frequencies between 250 and 8000 Hz. An initial group of 28 adults with less than 2 years 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.

### 3.1.2 Stimuli

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

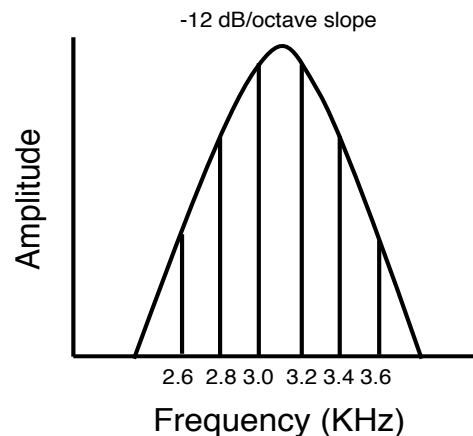


Figure 3-1: Schematic diagram showing the harmonic composition and the -12 dB/octave spectral slope of a complex in the test phase. The depicted complex has a missing fundamental of 200 Hz and is composed of 6 consecutive harmonics (harmonics 13 to 18, 2600 to 3600 Hz).

Tonal complexes were generated using MatLab (2010a, Mathworks, Natick, Massachusetts). A diagram of one complex is shown in Figure 3-1. The numbers and frequencies of harmonics in the complexes differed across phases of the experiment and are shown in Figure 3-2.

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)

Figure 3-2: 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.

In the conditioning phase and the training phase (described under Procedure), 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 under Procedure), the stimuli consisted of five complexes in each pitch category composed of six consecutive harmonics combined in random phase. In the LOW condition, the fundamental frequencies, 160 Hz 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 (explained further below). 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.

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. Harmonic numbers were also selected to ensure that participants could not rely on spectral edge cues to perform the task. With the harmonic numbers shown in Figure 3-1, a change in the frequency of the highest or lowest harmonics, 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 never lower than any of the harmonics in the higher pitch category, and the highest frequency component of the higher pitch category is never higher than any of the harmonics in the lower pitch category. 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.

### **3.1.3 Procedure**

Infants were tested in an average of 2.5 sessions (range=1-4). These sessions were completed in a single 60-minute 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 Hz or 190 Hz background complexes and 200 Hz target complexes, while the other half heard 200 Hz background complexes and 160 Hz or 190 Hz target complexes.

The experimenter initiated a trial when the participant was quiet and facing midline. On change trials 4 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 seconds 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 4 of the last 5 change trials and 1 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 4 of the last 5 change and 4 of the last 5 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 5 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 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.

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 5 correct responses on 6 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 4 of the last 5 change trials and at least 4 of the last 5 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-minute 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.

### 3.2 RESULTS

Figure 3-3 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 [ $Z=0.75$ ,  $p=.451$ ] nor the age group x condition interaction [ $Z=0.18$ ,  $p=.856$ ]. The analysis thus confirmed that more infants were successful than musically trained adults, but that success rate did not vary with condition.

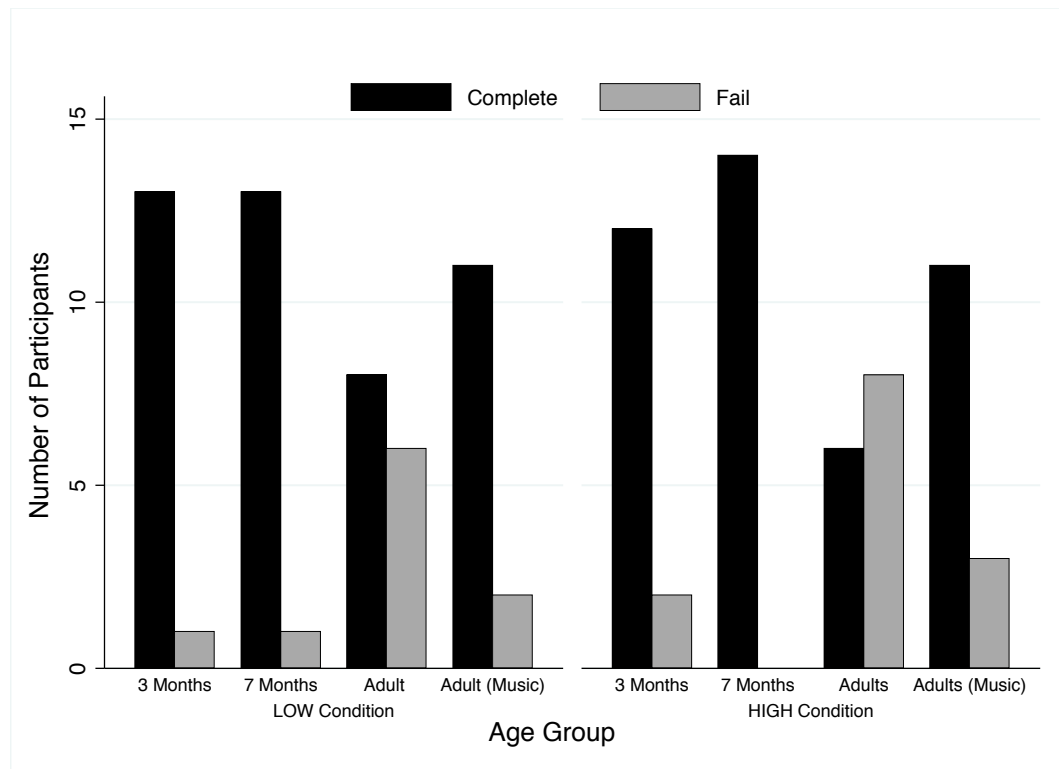


Figure 3-3: Number of participants in each age group to complete or fail the test phase by condition.

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 and Glasberg, 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 chi-square test confirmed that the number of participants reaching criterion did not differ among 3-month-olds, 7-month-olds, and musically trained adults [ $\chi^2(2) = 5.5051, p=.064$ ]. In contrast, a second Pearson chi-square test showed that the number of participants reaching criterion did differ between musically trained and untrained adults [ $\chi^2(1) = 6.0247, p=.014$ ]. 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 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.

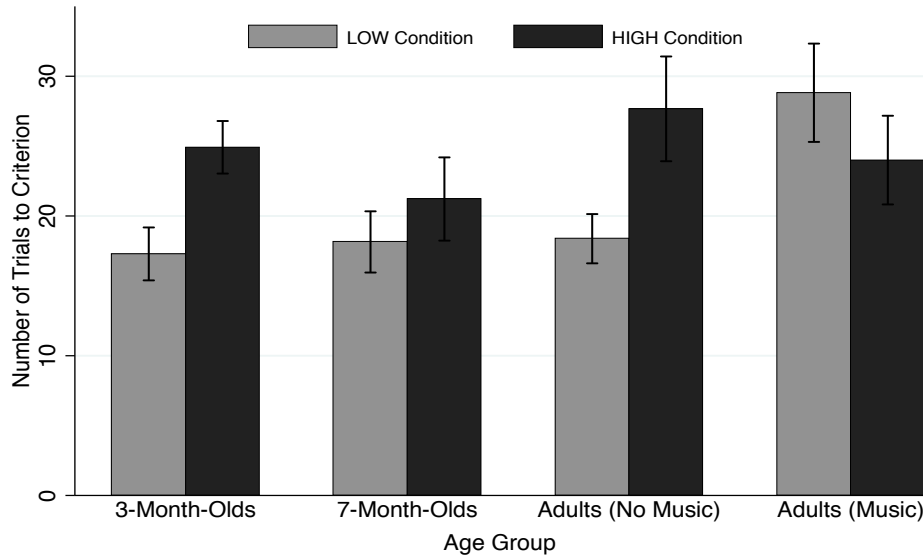


Figure 3-4: Mean ( $\pm$  1 SEM) number of trials to criterion as a function of age group in the HIGH and LOW Conditions.

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 Figure 3-4. 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 with a greater number of trials in the LOW condition than in the HIGH. A two-way 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 X condition interaction [ $F(3,82)=2.49, p=0.0663$ ]. The trend towards 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.

### **3.3 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 Hz to 200 Hz, 190 Hz 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 equally 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 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 and Glasberg, 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; 1996b) 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.

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## **4 Pitch perception prior to cortical maturation: is it really pitch?**

Whether infants can perceive pitch has important consequences for both speech and music perception. In speech, pitch contributes to vowel identity (Fujisaki and Kawashima, 1968), is a cue for word segmentation (Kemler Nelson et al., 1989), conveys emotion (Ohala, 1983; Trainor et al., 2000), and can even change word meaning in tonal languages. In music, pitch is an essential building block, with musical scales composed of notes with different pitch relationships and melodic contours composed of patterns of pitch changes. Early pitch-processing abilities are often interpreted as a predisposition for speech and music that enables infants to rapidly acquire the ability to understand speech and enjoy music (Jusczyk and Bertoncini, 1988; Trehub, 2006). Despite much recent attention on this topic, whether young infants with an immature auditory system have the ability to perceive pitch is still unclear. One critical issue that has been identified is if subcortical processing is sufficient to support early pitch perception prior to cortical maturation (Lau and Werner, 2012). This issue is further complicated by the fact that the role of the auditory cortex in the encoding and extraction of pitch information in the mature auditory system is still under investigation (Oxenham, 2012; Walker et al., 2011; Wang and Walker, 2012).

Nevertheless, recent neurophysiological studies suggest that the auditory system is already processing pitch in both speech and music at birth. Cortical responses in newborns have been recorded to changes in the pitch of complex tones (Huotilainen et al., 2003), the size of relative pitch intervals (Stefanics et al., 2009), prosodic information in speech (Sambeth et al., 2008), as well as pitch changes in the presence of timbre

variation (Háden et al., 2009). Many behavioral studies also demonstrate that infants are sensitive to pitch information from a young age. By 3 months, infants discriminate pitch contours in syllables of words (Karzon and Nicholas, 1989), prefer infant directed speech characterized by exaggerated pitch contours to adult directed speech (Cooper and Aslin, 1990; Pegg et al., 1992), recognize familiar melodies (Plantinga and Trainor, 2009) and prefer high-pitched singing to low-pitched singing (Trainor and Zacharias, 1998). However, it is important to note that when pitch in a sound changes, related acoustic cues such as frequency and other spectral changes can also be detected by listeners. Therefore, it is possible that infant responses in these previous studies were not elicited on the basis of pitch alone.

While complex sounds like musical notes and vowels in speech are composed of multiple frequency components, they produce a unitary pitch percept corresponding to their fundamental frequency, even when energy at the fundamental is missing. By presenting missing fundamental complexes to ensure that infants are responding to pitch as opposed to frequency or spectral changes, in addition to masking distortion products produced by cochlear nonlinearity, Clarkson and colleagues showed that infants at 7 months of age can categorize complex tones by their missing fundamental frequency (Clarkson and Rogers, 1995; Montgomery and Clarkson, 1997). More recently, Lau and Werner (2012, 2014) demonstrated that infants as young as 3 months of age are able to do so as well. However, one limitation of testing nonverbal listeners is that it is difficult to determine whether infants are discriminating on the basis of pitch *per se*. The question remains then, although very young infants can discriminate the fundamental frequency of a complex tone, are they discriminating on the basis of perceived pitch or is it a related percept such as roughness?

That 3-month-old infants discriminate the missing fundamental of complex tones provides evidence that subcortical processing is sufficient to support pitch perception (Moore, 2002). Furthermore, while Trainor and colleagues found a cortical response to spectral changes (i.e., changes in the pitch of piano tones) in 2-, 3-, and 4-month-olds, (He et al., 2007) a cortical responses to missing fundamental pitch changes was only found in 7-month-olds and 4-month-olds but not 3-month-olds (He and Trainor, 2009). Together these results suggest a change in the cortical representation of pitch between 3 and 4 months of age. To further investigate whether infants at 3 months of age are in fact discriminating on the basis of pitch, we refer to a widely accepted definition of pitch as an attribute of sound that can be used to produce musical melodies (Plack and Oxenham, 2005). With this rationale, a melody discrimination task in which missing fundamental complexes carried the melody was presented to 3-month-olds, 7-month-olds and adults using an observer-based psychophysical procedure (Werner, 1995).

Past studies of melody discrimination show that by 6 to 8 months, infants can detect changes in melodies under numerous conditions when the melodies are composed of either pure tones or two-component complexes. They can detect a change in a single note in any position of a six-note melody (Trehub et al., 1985) and the change can be within the same key as the original melody or from a different key (Trainor and Trehub, 1992). Infants can even detect changes in melodies belonging to scales from non-native cultures in addition to those from native Western scales (Lynch et al., 1990). However, the performance of infants younger than 6 months and whether performance is the same for complex pitch are unknown.

The melodies in this study were composed of missing fundamental complexes that were each composed of six harmonics. To ensure that participants were responding on the basis of the missing fundamental of each note, the stimuli consisted of five

variations of the background melody and five variations of the change melody. In each variation, the harmonic composition of each note differed, such that the upper and lower edge frequencies did not change in the same direction as the pitch contour of the melody. Participants were therefore required to ignore the spectral changes and respond only when they hear a change in the melody being presented, demonstrating that they perceive the missing fundamental pitch of each note. Based on the results of Lau and Werner (2012, 2014), it was predicted that infants at both 3 and 7 months of age would be able to discriminate melodies on the basis of missing fundamental pitch.

## **4.1 METHOD**

### **4.1.1 Subjects**

Participants in this study were 11 3-month-olds, 9 7-month-olds, and 10 adults. All infants were 1) born full term, 2) had no history of otitis media within 3 weeks of testing and no more than two prior occurrences, 3) had no risk factors for hearing loss, 4) had no history of health or developmental concerns, and 5) passed newborn hearing screening. At each test session, all infants were healthy and passed a tympanometric screen with a peak admittance of at least 0.2 mmhos and peak pressure between -200 and +50 daPa with a 226 Hz probe tone. 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 two 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 as well as an audiometric screen at 20 dB HL for pure tone frequencies of 250, 500, 1000, 2000, 4000, and 8000 Hz. Data from an additional two 3-month-olds were

excluded because they were too tired, hungry, or fussy to complete the task and two 7-month-olds because they did not pass the tympanometric screen. Data from one additional adult was excluded because they could not pass the training phase. Participants were recruited through the Communication Studies Participant Pool at the University of Washington.

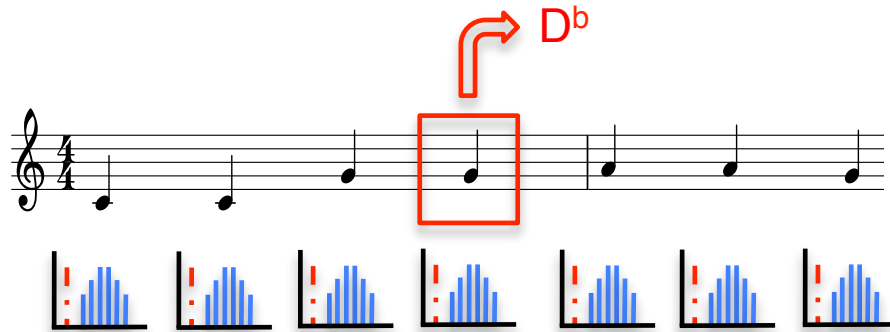


Figure 4-1: Schematic diagram of the melody. The background melody was the first seven notes of “Twinkle, Twinkle, Little Star”. Each note was a missing fundamental complex consisting of 6 consecutive harmonics. The change melody contained a wrong note: a  $D^b$  instead of a G in the fourth position of the melody.

#### 4.1.2 Stimuli

Two sets of melodies composed of missing fundamental tonal complexes were generated using MatLab (2010a, Mathworks, Natick, Massachusetts). The background melody was the first seven notes of “Twinkle, Twinkle, Little Star” (C C G G A A G) and the change melody contained a wrong note (C C G  $D^b$  A A G). Figure 4-1 shows a schematic diagram of the melody. Five variations of the background melody and five variations of the change melody were composed by varying the number and frequencies of harmonics of each note, which are shown in Figure 4-1. Although the spectral composition of each note differed, the pitch of each note and therefore the pitch contour of the melody remained the same. Each note was composed of six consecutive harmonics which were combined in random phase and bandpass filtered with a -12

dB/octave slope to limit participants' ability to use spectral centroid cues. Furthermore, harmonic numbers were selected for each note so that the upper and lower edge frequencies did not change in the same direction as the pitch contour of the melody.

Melodies were 7.55 s in duration with each note presented for 650 ms with a 50 ms rise/fall time and 500 ms between successive notes. 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. All sounds were presented monaurally through an Etymotic ER-2 insert earphone in the right ear. Sound pressure levels were calibrated in a Zwislocki coupler and checked in the subject's ear canal at the time of testing. All melodies 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.

#### **4.1.3 Procedure**

Infants were tested in an average of 1.45 sessions (range=1-2) completed in a single 60-minute visit. An observer-based psychophysical procedure was used (Werner, 1995). During testing, infants sat on a caregiver's lap in the booth and an assistant in the booth manipulated toys to keep infants facing midline. There were two mechanical toys with lights in a dark Plexiglas box and a monitor 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. A melody from the background category was randomly selected and played repeatedly to the participant

from the start of the test session, with a 500 ms silent interval between melodies. The goal of the task was to determine whether the participant detected a change in the melody (i.e., when the melody contained a wrong note).

The experimenter initiated a trial when the participant was quiet and facing midline. There were two trial types, which occurred with equal probability during testing. On change trials a melody from the change category was randomly selected and played, while on no-change trials a melody from the background category continued to play. To discriminate the change melody from the background melody, participants had to ignore the spectral changes and perceive each melody based on the missing fundamental pitch of each note. 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 (the "reinforcer") for 4 seconds only if the experimenter correctly identified a change trial.

The study consisted of one training phase and one test phase. The participants were required to reach criterion in training before advancing to the test phase. The purpose of the training phase was to demonstrate the association between the reinforcer and the target, the change melody, 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 phase.

In the test phase, the task and stimuli were the same as in the training phase but the probability of change and no-change trials was 0.5 and the reinforcer was activated only when the experimenter correctly identified a change trial. To demonstrate perception of the missing fundamental melodies, the experimenter was required to respond correctly on 4 of the last 5 change and 4 of the last 5 no-change trials to complete the test 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. Participants received up to 40 trials to meet criterion in the test phase. If criterion was not met, the session was discontinued and infants were given a break. A new session was started when the infant returned to the booth.

Adults were also tested in an average of 1.5 sessions (range=1-3) completed in a single 60-minute 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.

## **4.2 RESULTS**

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

Figure 4-2 shows the number of participants in each age group to complete and fail the missing fundamental melody discrimination task. All participants except one 3-month-old, one 7-month-old, and one adult reached criterion. 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 0.58 for infants and 0.49 for adults. A simulation of 5000 sessions in which responses occurred randomly at these rates in 2 test sessions each showed that criterion was met in only 16.6% of sessions with a response rate of 0.58 and 14.6% with a response rate of 0.49. Two exact binomial tests with an assumed probability of 0.17 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.

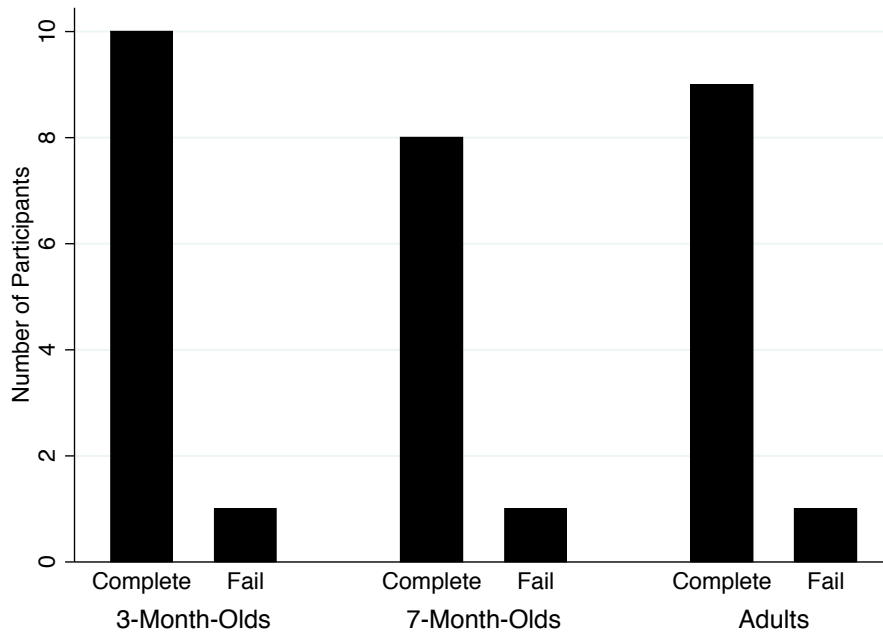


Figure 4-2: Number of participants in each age group to complete or fail missing fundamental melody discrimination task.

For successful participants, the number of trials required to reach criterion is plotted as a function of age group in Figure 4-3. The number of trials to reach criterion appeared to be slightly less for adults. However, a one-way ANOVA testing the effect of age on the number of trials to criterion revealed no significant effect of age [ $F(2,24)=0.68$ ,  $p=0.5176$ ]. There was therefore no indication that infants took more trials than adults to learn to discriminate the missing fundamental melodies.

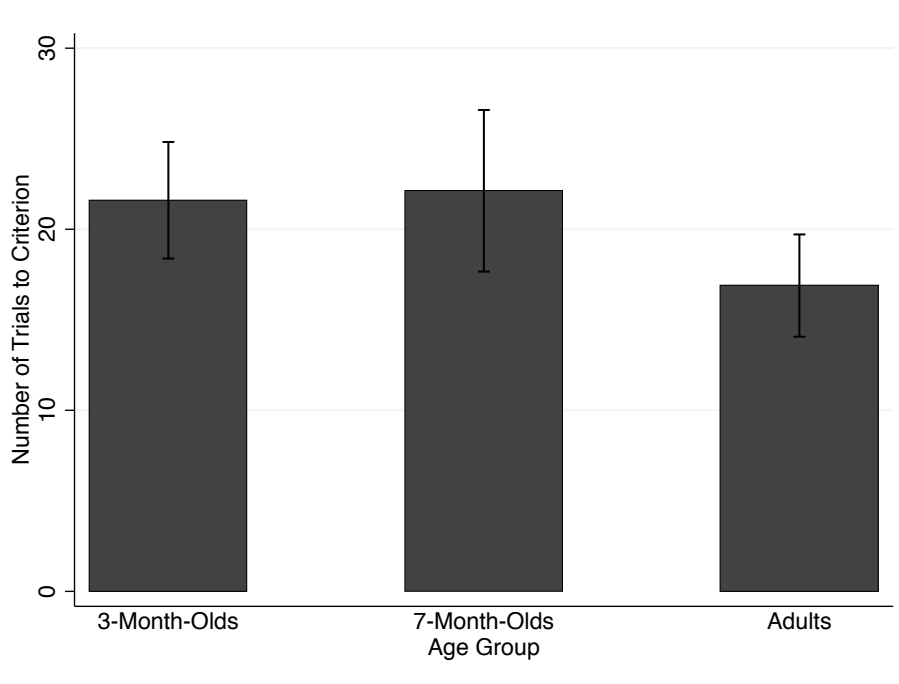


Figure 4-3: Mean ( $\pm 1$  SEM) number of trials to criterion as a function of age group on the missing fundamental melody discrimination test phase.

### 4.3 DISCUSSION

Results from this experiment demonstrate that adults and infants at both 3 and 7 months of age are able to discriminate missing fundamental melodies. Almost all infants at both ages successfully completed the melody discrimination task. Furthermore, infants appeared to have no greater difficulty than adults reaching criterion. This finding

suggests that because infants are able to perceive melodic information conveyed by a pitch sequence, they are indeed discriminating complex tones on the basis of pitch.

These results are consistent with neurophysiological and behavioral studies suggesting that very young infants are already sensitive to pitch in speech and music and the results of Lau and Werner (2012, 2014), which found that 3-month-olds could discriminate the fundamental frequency of missing fundamental complexes. The auditory cortex at 3 months is markedly immature and thalamocortical connections are not yet functional (Eggermont and Moore, 2012). Cortical activation at this age is provided through a projection from the brainstem reticular activating system to neurons in the superficial layer of the auditory cortex (Eggermont & Moore, 2012). This reticular-cortical pathway is presumed to act as a change detection system that supports infants' responses to sound (Eggermont & Moore, 2012). That 3-month-old infants can discriminate complex pitch suggests that pitch-related information is sufficiently encoded and extracted by brainstem pathways.

While infants demonstrated the ability to discriminate a melody composed of complex tones like they can with melodies composed of pure tones (Trainor and Trehub, 1992; Trehub et al., 1985), how complex pitch and pure tone pitch perception compares is unclear. This study only had one condition presenting a highly familiar melody with a change that was always the same note. Whether infants are able to detect a change in other conditions is also unknown.

Finally, like Lau and Werner (2012, 2014), no age-related changes in performance are observed in this melody discrimination task suggesting that 3-month-olds perceived the stimuli in this study in a similar manner to 7-month-olds and adults. These results provide evidence for a model of pitch perception in which subcortical processing is sufficient to encode and extract the pitch-related information in a sound

during early infancy. Although findings from studies of pitch representation in adults and other primates suggest that a region just outside of auditory cortex is involved in pitch processing (Bendor and Wang, 2005; Griffiths et al., 2001; Patterson et al., 2002), it is possible that the representation of complex pitch in the auditory system undergoes reorganization during development. A similar shift from subcortical to cortical mechanisms is thought to occur during the development of sound localization (Clifton, 1992). Additional studies investigating infant sensitivity to pitch changes and their ability to perceive complex pitch under different stimulus manipulations are required to further characterize how pitch perception changes with cortical maturation and how it may affect the development of speech and music perception.

#### **ACKNOWLEDGEMENTS**

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## 5 Infant pitch and spectral envelope sensitivity

Adult humans perceive very small changes in pitch, and with training, pitch perception can improve even further (Micheyl et al., 2006). This sensitivity to pitch is critical for enjoying music and understanding speech, especially in complex acoustic environments with numerous concurrent sounds. However, how the brain represents and extracts the information required to produce a pitch percept is still an area of ongoing research. Studies of pitch representation in humans and other primates indicate that an area outside of primary auditory cortex is involved in pitch processing (e.g., Bendor and Wang, 2005; Hall and Plack, 2009; Patterson et al., 2002). Improvements in infants' ability to perceive pitch might therefore be expected with cortical maturation.

Infant pitch perception is interesting in this regard because of the protracted development of the central auditory system. Although infants begin responding to sound in the third trimester of gestation (Birnholtz and Benacerraf, 1983; Starr et al., 1977), the development of the auditory system occurs over an extended period of time. The cochlea and the auditory nerve reach mature status at approximately three months postnatal age (Eggermont and Moore, 2012). Subsequently, the auditory brainstem reaches maturity at about 1.5 years while the thalamus, the auditory radiation and the cortex continue to mature until about twenty years of age (Eggermont and Moore, 2012; Kral and Eggermont, 2007). In early infancy, it is likely that responses to sound are supported by the auditory periphery and brainstem (Moore, 2002).

Nevertheless, many studies show that infants appear sensitive to pitch in both speech and music during the first few months of life (e.g., Cooper and Aslin, 1990; Háden et al., 2009; Huotilainen et al., 2003; Lau and Werner, 2012; Plantinga and Trainor, 2009). Recent results of Lau and Werner (2012, 2014) demonstrate that 3-

month-olds can discriminate the pitch of complex tones, suggesting that sufficient information to encode the pitch of complex sounds 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 at 3 months of age. However, the pitch change discriminated by infants in these studies was a large difference of twenty percent, and whether infants can discriminate smaller changes in pitch has not been investigated. If infants' pitch perception is immature, it would be predicted that they would require larger changes in pitch to discriminate between complexes than adults do.

The purpose of this study was to compare the limits of infants' and adults' ability to perceive changes in pitch. Pitch discrimination thresholds were measured in 3-month-olds, 7-month-olds and adults. Infants at three and seven months of age were tested because the organization of the auditory pathway appears to be distinctly different at these two ages. At three months of age, the auditory cortex is markedly immature with activation of only the most superficial layer of the cortex by the reticular articulating system (Moore, 2002). By seven months however, infants have access to mature thalamocortical connections although significant immaturities in the auditory cortex persist (Moore, 2002). To the extent that the thalamocortical pathway is required for mature pitch perception, 3-month-olds would have higher thresholds than 7-month-olds. To the extent that mature cortical processing is necessary for mature pitch perception, it was further predicted that adults would have lower discrimination thresholds than either infant group.

Finally, the effect of harmonic resolvability on pitch perception was examined in infants and adults. There are at least two possible neural codes for pitch: a place code and a temporal code (discussed by Oxenham(2012)). Because the width of auditory filters increases with center frequency (Glasberg and Moore, 1990), high frequency

harmonics are unresolved by the cochlea and perceiving the pitch of unresolved harmonics relies on the temporal code (Plack and Oxenham, 2005). Two conditions were included in this study, one in which the complexes were composed of resolved harmonics and one in which the complexes were composed of unresolved harmonics. Pitch information from both the place code and the temporal code are available for resolved harmonics, but only the temporal code is available for unresolved harmonics. Unresolved harmonics have a less salient pitch and adult pitch discrimination thresholds for unresolved harmonics are usually higher than for resolved (e.g., Shackleton and Carlyon, 1994). When two groups of 7-month-olds were presented with complexes composed of either resolved or unresolved harmonics, fewer infants discriminated the unresolved harmonics compared to the resolved harmonics (Clarkson and Rogers, 1995). It was predicted that infants' F0 discrimination thresholds for unresolved harmonic complexes would be higher than those of adults, possibly to a greater extent than observed for resolved harmonic complexes.

## **5.1 EXPERIMENT I**

### **5.1.1 Method**

#### **5.1.1.1 Subjects**

Infant participants were 23 3-month-olds (13 resolved and 10 unresolved) and 23 7-month-olds (13 resolved and 10 unresolved). 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 participant group completed testing within 10 days of the specified age.

Two groups of adult participants were tested: 24 adults with less than 2 years of musical training (14 resolved and 10 unresolved) and 21 adults with two or more years of formal musical training (11 resolved and 10 unresolved). A very liberal definition of musical training was adopted, including experiences such as band or choir at school. The adults with musical training were included as an additional comparison group, because in a previous study, some musically untrained adults had difficulty hearing F<sub>0</sub> changes in the face of spectral variation, even though infants apparently had no difficulty doing so (Lau and Werner, 2014). Adults with musical training can also discriminate smaller changes in pitch (Micheyl et al., 2006). The aim was to allow appropriate comparisons between infants and adults. All adult participants were between 18 and 30 years of age, reported normal hearing bilaterally, had no history of noise exposure, and no prior experience as participants in psychoacoustic experiments. Adults were also required to pass a tympanometric screen with a peak admittance of at least 0.4 mmhos and peak pressure between -200 and +50 daPa with a 226 Hz probe tone as well as an audiometric screen at 20 dB HL at octave frequencies between 250 and 8000 Hz. For ease of reference, adult without musical training will subsequently be referred to just as “untrained” adults and for those with musical training, as “trained” adults.

Data from 6 additional 7-month-olds were excluded, because they did not complete all test sessions (2), they did not pass the training phase (1), or they did not pass the tympanometric screen (3). Data from 2 3-month-olds were excluded, because they were too fussy to complete testing. Data from 6 additional untrained adults and 2 trained adults were excluded because they were unable to complete the training phase. One trained adult could not complete the session due to fatigue, and one trained adult

did not respond within the 4 s response window. Participants were recruited through the Communication Studies Participant Pool at the University of Washington.

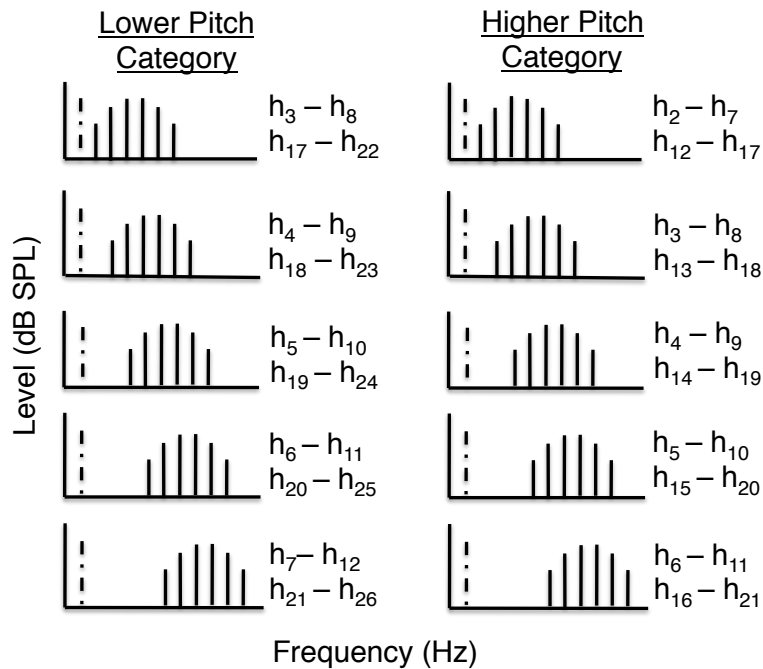


Figure 5-1: Schematic diagram of the stimuli. The missing fundamental frequency is depicted with a dotted line.  $h_n$  refers to the other component frequencies by harmonic number. The top row is for complexes in the resolved condition while the bottom row is for the unresolved condition. In each pitch category, there are five complexes with the same  $F_0$  but composed of a different set of six harmonics

#### 5.1.1.2 Stimuli

Tonal complexes were generated using Matlab (Mathworks, Natick, Massachusetts). All stimuli were missing fundamental complexes to ensure that participants were responding on the basis of pitch as opposed to frequency or spectral changes. Each complex was composed of 6 consecutive harmonics combined in random phase and were bandpass filtered with a -12 dB/octave slope to reduce spectral

edge and spectral centroid cues (Micheyl and Oxenham, 2004; Micheyl et al., 2012; Moore and Moore, 2003). A schematic diagram of the stimuli is shown in Figure 5-1.

Six values of  $\Delta F0$  were used, ranging from 0 to 5%. Each  $\Delta F0$  was tested in a separate block of trials. For each block, 5 different complexes were generated at  $F0$ , and 5 different complexes were generated at  $F0 + \Delta F0$ . Within each category, the complexes differed in the harmonic numbers included. Background  $F0$  was changed slightly between blocks to prevent subjects from “memorizing” a small set of background complexes. The  $F0$ s of the complexes as well as the percent pitch change for each test phase are shown in Figure 5-2.

Phase	Resolved		Unresolved	
	% $\Delta F0$	Background $F0$ (Hz)	% $\Delta F0$	Background $F0$ (Hz)
<b>Condition</b>	5	195	5	198
<b>Training</b>	5	195	5	198
<b>Test 1</b>	2.5	196	3	199
<b>Test 2</b>	1.5	197	2	200
<b>Test 3</b>	1	198	1	201
<b>Test 4</b>	0.5	199	0.5	202
<b>Test 5</b>	0.25	200	0.25	203
<b>Test 6</b>	0	200	0	203

Figure 5-2: The percent pitch change and the  $F0$  (Hz) of complexes in the background pitch category for conditioning, training, and each of the six test phases in both conditions

Complexes were presented monaurally for 650 ms with a 50 ms rise/fall time every 1150 ms 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 sound-attenuating booth.

#### 5.1.1.3 Procedure

Infants were tested in an average of 5.8 sessions (*range*=3-9) over an average of two one-hour visits on separate days (*range*=1-3). An observer-based psychophysical procedure (Werner, 1995) was used to present a single interval pitch categorization task to participants. 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 experimenter sat outside the booth and observed through a window. 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, both the assistant and caregiver wore circumaural headphones during testing: 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 participant learned to respond when a complex from the other category, the "target" was played. Half of the participants heard pitch increases and half heard pitch decreases, randomly determined.

The experimenter initiated a trial when the participant was quiet and facing midline. There were two trial types. On change trials four complexes with the target pitch 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. During the test phases, participants' saw a mechanical toy or video (the "reinforcer") for 4 s if the experimenter correctly identified a change trial.

The study consisted of a conditioning phase, a training phase, and 6 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. In each phase, 5 complexes composed of different harmonics but with the same F0 were randomly presented in the background and on no-change trials while 5 complexes with the other F0 were randomly presented on change trials. In other words, 5 harmonic complexes, each with a different set of 6 harmonics and the same F0, represented each pitch category. One complex from the appropriate category was randomly chosen on each presentation. Participants were required to ignore the spectral changes and respond only when F0 was changed.

The purpose of the conditioning 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 within no more than 15 trials to complete the conditioning phase.

In all subsequent 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 within a maximum of 40 trials to move on to the next phase. In the training phase, the task and stimuli were the same as in the conditioning phase, but the reinforcer was activated only when the experimenter correctly identified a change trial. The purpose of the training phase was to teach the participant that an observable response to pitch change was required to activate the reinforcer and to demonstrate that participants were able to perform the basic task.

Threshold was estimated in the test phases that followed using an adaptive method. Participants were classified as having completed a test phase when the number of correct responses was at least 4 of the last 5 change trials and at least 4 of the last 5 no-change trials in at most 40 trials in that test phase. When participants reached criterion on one test phase, testing continued in the next test phase and the  $\Delta F0$  decreased progressively across test phases. The following procedure was used to ensure that failure in a test phase was not the result of boredom or fatigue: if participants responded incorrectly on four consecutive trials, responding to no-change trials or not responding to change trials, they returned to the last previously completed, larger  $\Delta F0$ , test phase. They then received up to 12 trials to meet a criterion of 5 correct responses on 6 consecutive trials in the previously completed phase. If the 5 out of 6 criterion was met, participants returned to the incomplete, smaller  $\Delta F0$ , test phase. If the 5 out of 6 criterion was not met, the session was discontinued and participants were given a break or returned on another day. A new session was started when participants returned to the booth. In subsequent sessions testing began in the last incomplete test

phase. If participants were unable to meet criterion on a test phase after three separate successful reversals to a previously completed test phase, testing ended, and the participant was judged to be unable to complete the last test phase. Participants were given a maximum of three attempts at each test phase. Threshold was defined as  $\Delta F0$  in the last successfully completed test phase. If participants did not meet criterion on three separate successful reversals to the previously completed test phase, the data were excluded.

Adults were tested in an average of 3.6 sessions (*range*=1-7). These sessions were completed in a single 60-minute visit. Adults sat alone in the booth and were instructed to raise their hand when they heard “the sound change that makes the toy come on”. The experimenter recorded adults’ responses. In all other respects, the stimuli and procedure were the same for adults and infants.

### **5.1.2 Results**

Three analyses were conducted to evaluate participants’ performance on the adaptive threshold measure. The first analysis addressed relative difficulty of the task for infants and adults by comparing the number of trials to reach criterion in the training phase across participant groups in each condition. The second analysis assessed infant and adult sensitivity to pitch by comparing thresholds across participant groups and conditions. Finally whether group sensitivity at the threshold test phase is comparable across participant groups was addressed. Preliminary analyses indicated that there was no effect of pitch change direction, so that variable was not considered in subsequent analyses.

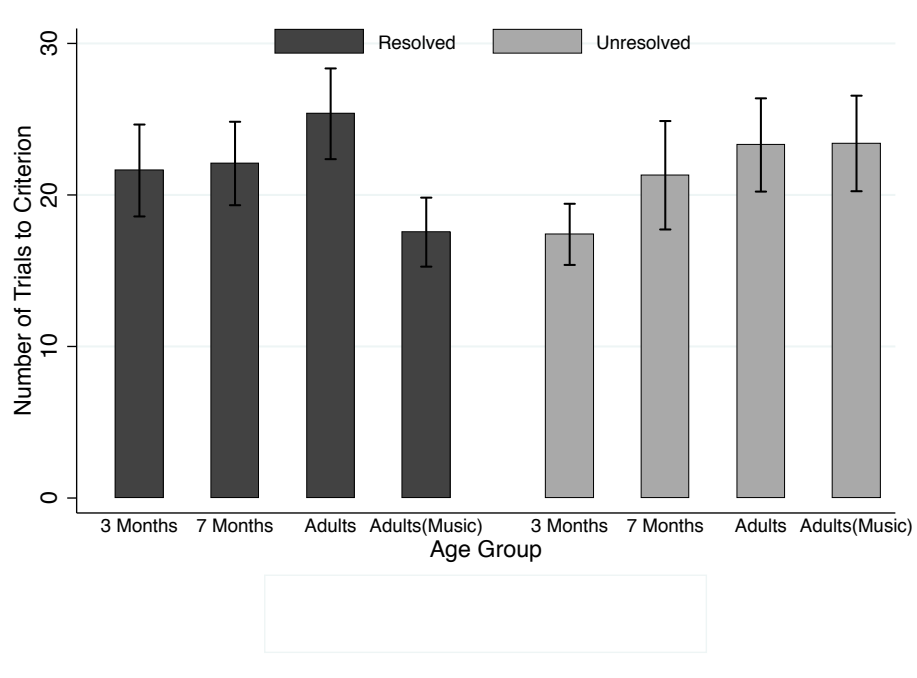


Figure 5-3: Mean ( $\pm 1$  SEM) number of trials to criterion as a function of participant group in the resolved and unresolved conditions.

Figure 5-3 shows the mean number of trials for participants to reach criterion in the training phase as a function of participant group (3-month-olds, 7-month-olds, trained adults, and untrained adults) for each condition. The number of trials to reach criterion did not appear to differ across groups in either condition. A Group X Condition ANOVA revealed no significant effect of Group [ $F(3,83)=1.02$ ,  $p < 0.3854$ ], Condition [ $F(1,83)= 0.02$ ,  $p=0.8866$ ], or the Group X Condition interaction [ $F(3,83)= 1.04$ ,  $p=0.3792$ ]. There is therefore no indication that infants took more trials than adults to learn to categorize these MF complexes on the basis of pitch.

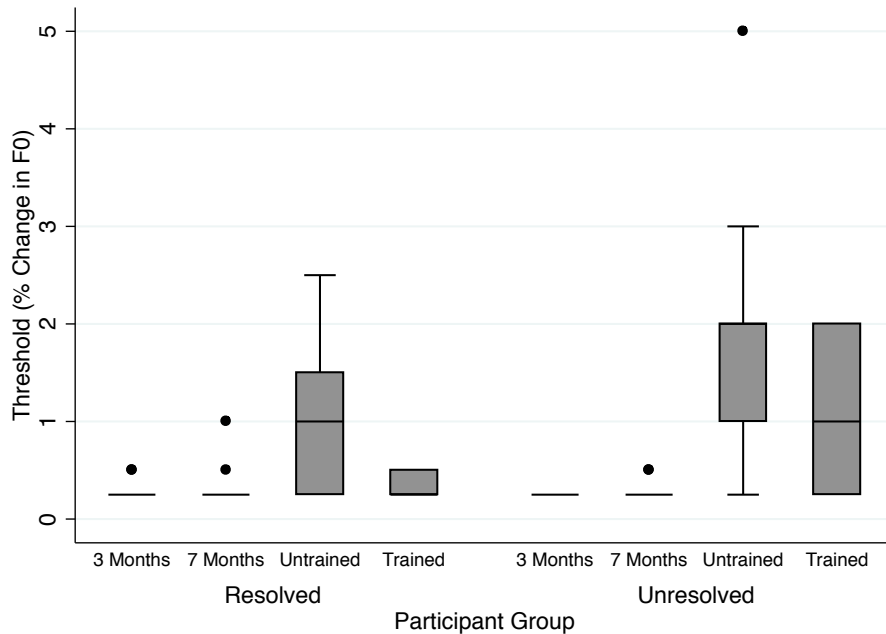


Figure 5-4: Box plot of thresholds as a function of participant group by condition.

Figure 5-4 shows a box plot of participant thresholds as a function of participant group by condition. Almost all infants tested discriminated a  $0.25\% \Delta F_0$  in both the resolved and unresolved conditions, which is comparable to the performance of trained adults. However, untrained adult thresholds were much more variable. In the resolved condition, infants and adults with musical training had a mean threshold of  $0.31\% \Delta F_0$  while adults had a higher threshold of  $1\% \Delta F_0$ . In the unresolved condition the infants had the lowest mean threshold of  $0.28\% \Delta F_0$  followed by trained adults with a mean threshold of  $1.1\% \Delta F_0$ , then untrained adults with the highest threshold of  $2\% \Delta F_0$ .

To follow up on the significant interaction a one-way ANOVA testing the effect of participant group on threshold was conducted revealing a significant effect of group for the resolved condition [ $F(3,47)=8.76, p = 0.001$ ] as well as the unresolved condition [ $F(3,36)=11.75, p < 0.001$ ]. In the resolved condition, post-hoc testing with Tukey-Kramer

pairwise comparisons showed significant differences between untrained adults and all other groups - 3-month-olds, 7-month-olds, as well as trained adults. In the unresolved condition, post-hoc testing with Tukey-Kramer pairwise comparisons showed significant differences between both 3- and 7-month-olds and untrained adults but no significant differences between infants and trained adults, or between the two adult groups.

To examine the effect of resolvability at each age, a one-way ANOVA testing the effect of condition on threshold for each participant group was conducted. This analysis revealed no significant effect of condition for 3-month-olds [ $F(1,21)=1.66, p = 0.2116$ ] or 7-month-olds [ $F(1,21)=0.13, p = 0.719$ ] but a significant effect of condition for untrained [ $F(1,22)=5.57, p=0.0275$ ] and trained adults [ $F(1,19)=9.68, p =0.0058$ ]. Apparently, while both trained and untrained adults had thresholds that are higher in the unresolved condition as expected, there is no significant difference between the two conditions for infants.

To investigate whether group sensitivity is comparable across participant groups at threshold, group  $d'$  was calculated from the last five change and last five no-change trials at each participant's threshold and are shown in Figure 5-5. Although all participants reached the same 80% hit rate and 20% false alarm rate in the last-completed test phase, adults sensitivity was somewhat better than infants' in that test phase. The implication is that differences in threshold may be somewhat greater than they would have been had sensitivity been the same in all groups. The greatest difference was between infants and untrained adults in the unresolved condition with an infant  $d'$  of 1.68 and an adult  $d'$  of 2.32.

	<b>Resolved</b>	<b>Unresolved</b>
<b>Infants</b>	d' = 1.79	d' = 1.68
<b>Untrained</b>	d' = 2.07	d' = 2.32
<b>Trained</b>	d' = 2.22	d' = 1.84

Figure 5-5: Group sensitivity calculated from the last five change and last five no-change trials at each participant's threshold test phase.

### 5.1.3 Discussion

These results demonstrate that infants at both 3 and 7 months of age are able to discriminate smaller changes in pitch in the presence of spectral variation than untrained adults in both the resolved and unresolved conditions. Furthermore, no difference in performance was observed between infants in the two age groups. Overall, infant thresholds were more comparable to the thresholds of adults with musical training than the thresholds of those without.

That 3-month-old infants had thresholds comparable to musically trained adults suggests that sensitivity to pitch is mature by 3 months of age. This finding provides further evidence that sufficient information to encode the pitch of complex sounds is available in the auditory nerve, and that very accurate extraction of the F0 can be accomplished at subcortical levels of the auditory system. Neither development of the thalamocortical pathway during infancy and childhood nor development of cortical pitch extraction mechanisms seems to improve pitch sensitivity.

While infant sensitivity to pitch was found to be mature, two additional observations from this study suggest that adult-infant differences in pitch perception do exist, just contrary to predictions. First, the thresholds of both musically trained and untrained adults were higher in the unresolved condition as expected but there was no

difference between resolved and unresolved thresholds for infants. Further investigations with stimuli of varying resolvability and pitch salience are required to fully characterize how infant pitch perception is affected by harmonic resolvability.

The most surprising finding of this study may be that infants were discriminating smaller changes in pitch than the untrained adults. It is possible that the higher adult thresholds are because of a difference in sensitivity at threshold, with adult thresholds obtained from a higher point on the psychometric function than infant thresholds. This difference likely arises from adults' tendency to have a conservative bias in this procedure. However, looking at the group  $d'$ 's at threshold, the largest difference is between the infant  $d'$  of 1.68 and the adult  $d'$  of 2.32 in the unresolved condition. These would correspond to a  $p(c)_{\max}$  of 80% versus 88% which is likely insufficient to account for the entire difference in infant and adult thresholds observed. Additional data on the psychometric function for F0 discrimination would be required to more precisely determine the impact of this effect.

Adult performance may also have been worse because of some other aspect of the procedure designed to test infants. However, two additional musically trained adults were tested using the same stimuli in a 3-alternative-forced-choice procedure and no change in threshold was seen. Furthermore, the adult thresholds obtained in this study, 1% $\Delta F0$  for resolved harmonics and 2% $\Delta F0$  for unresolved harmonics is within the range of adult thresholds obtained in past studies of pitch perception using standard procedures (e.g., Houtsma and Smurzynski, 1990; Bernstein and Oxenham, 2003).

Finally, it may be that adult thresholds are actually comparable to infant thresholds, but that the spectral variation in the task interfered with their ability to discriminate pitch. There have been many reports that responding on the basis of the fundamental frequency becomes more difficult for adult listeners when sequentially

presented complex tones contain spectral variation like those used in this study (e.g., Allen and Oxenham, 2014; Borchert et al., 2011; Micheyl and Oxenham, 2004; Moore and Glasberg, 1990). Adults with musical training on the other hand, are more likely to respond to complex tones on the basis of pitch as opposed to spectral changes (Seither-Preisler et al., 2007).

To further investigate, we tested 12 untrained adult listeners with single exemplars from each pitch category. In the resolved condition, half of the participants discriminated complexes composed of harmonics 3 to 8 and half of the participants discriminated complexes composed of harmonics 4 to 9. In the unresolved condition, all participants discriminated complexes composed of harmonics 17 to 22. They were the same complexes used in Experiment I with a -12 dB slope, harmonics combined in random phase and presented with a pink noise to mask distortion products. With the elimination of spectral variation from the task, untrained adults were able to discriminate the complexes as well as infants and musically trained adults, suggesting that the spectral variation was indeed interfering with their pitch discrimination.

The question remains then, why infants are not affected by this spectral variation. One possibility is that pitch is prioritized during early infancy due to its importance in other auditory tasks such as sound source segregation as well as speech and music perception. Perhaps rather than improvements in pitch perception, cortical maturation results in a loss of pitch priority, unless it is maintained, as in the case of musically trained adults.

Another possibility is that infants do not perceive the spectral variation and are therefore unaffected by it in the pitch discrimination task. Past studies show that infants can discriminate gross changes in the spectral envelope of a sound such as an upward sloping spectra versus a downward sloping spectra (Clarkson, 1996), an envelope with

formant peaks corresponding to an [a] versus an [i] (Trehub et al., 1990), or the spectral envelopes of two tones with different harmonic composition (Clarkson et al., 1988). Although there are no studies that have investigated the limits of infant spectral envelope discrimination, Allen and Wightman (1992) show that even children 4 to 9 years of age require larger envelope depths than adults did to discriminate variations in spectral envelope frequency. While the stimuli presented in their task, tonal complexes with sinusoidally rippled amplitude spectra, are different than the spectral changes introduced in this study, it is plausible that infant spectral discrimination may be immature. For this reason, Infant's ability to discriminate shifts in the spectral centroid of harmonic complex tones were tested in the next experiment to determine whether it may have contributed to their better pitch discrimination thresholds.

## **5.2 EXPERIMENT II**

The purpose of this experiment is twofold, (1) to determine infant sensitivity to spectral variation and (2) to investigate infant pitch "priority" by testing whether variations in pitch disrupt spectral discrimination. Spectral envelope discrimination thresholds were measured in 3-month-olds, 7-month-olds and adults. Participants were presented with a spectral discrimination task that required them to ignore changes in the pitch of complex tones and respond when the spectral centroid shifted in center frequency (CF). Based on the results of Allen and Wightman (1992), it was predicted that infants at both 3 and 7 months of age would have higher thresholds than adults.

### **5.2.1 Method**

#### **5.2.1.1 Subjects**

The participants were 20 3-month-olds, 20 7-month-olds, and 10 adults. Data from two additional 3-month-olds and one 7-month-old were excluded because they

were too fussy to complete testing. Data from one additional adult who was unable to complete the training phase and one adult who did not pass the tympanometric screen were also excluded.

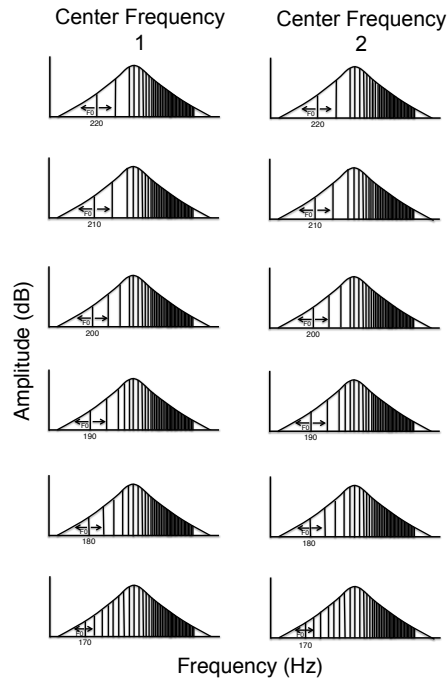


Figure 5-6: Schematic diagram of the stimuli. In each CF category, there are six complex tones with the same CF but different F0s. Participants are required to ignore the pitch variation of complexes from the same category and respond only when complexes from the other pitch category are played.

### 5.2.1.2 Stimuli

Two sets of 500-ms harmonic complex tones with harmonics combined in sine phase and 20-ms raised cosine onset/offset ramps were generated with Matlab for each of the test phases (Mathworks, Natick, MA). All harmonics were generated up to 10 000 Hz then bandpass filtered with a -24 dB/octave slope around the center frequency (CF). Each set consisted of six complex tones with spectral centroids at that same CF but different fundamental frequencies (170, 180, 190, 200, 210, and 220 Hz). The two sets

used in each phase differed in CF by 0 to 15%. The CFs of the two sets differed across test phases to prevent participants from “memorizing” the exemplars in one set. A schematic diagram of the stimuli is shown in Figure 5-6. The CF of one set of complexes, and the % $\Delta$ CF for each test phase are shown in Figure 5-7. All flat-weighted stimulus levels were presented at 70 dB SPL.

<b>Test Phase</b>	<b>%<math>\Delta</math>CF</b>	<b>Background CF</b>
<b>Conditioning</b>	15	1100
<b>Training</b>	15	1100
<b>Test 1</b>	10	1250
<b>Test 2</b>	5	1200
<b>Test 3</b>	2	1150
<b>Test 4</b>	0.5	1050
<b>Test 5</b>	0	1000

Figure 5-7: The percent CF change and the F0 (Hz) of complexes in the background pitch category for conditioning, training, and each of the five test phases.

### 5.2.1.3 Procedure

Infants were tested in an average of 2.5 sessions (*range*=1-4) in a single one-hour visit. The same procedure from Experiment I was used; however, this study consisted of a conditioning phase, a training phase, and only two test phases. The task in this study was the reverse of Experiment I; participants were required to ignore the variations in pitch, perceive each complex on the basis of the CF and respond only when there was a CF change. These shifts in the spectral centroid of the complex tone are perceived as a change in timbre, which is the perceptual attribute that distinguishes two different sounds with the same pitch and loudness. When two instruments such as a cello and a flute play the same note at the same duration and loudness, the characteristics that nonetheless make them distinct is referred to as timbre.

In each phase there were two CF sets and in each set, there were six harmonic complex tones. The tones in each CF category had a spectral centroid at the same CF, but each tone had a different F0, and therefore different pitches. At the start of a session, complexes with different F0s but the same CF were randomly presented in the background and on no-change trials while four complexes with the other CF were randomly presented on change trials. Half of the participants heard CF increases, half CF decreases, randomly determined.

The purpose, the probability of change and no-change trials, and the pass criteria for both the condition and training phase were the same as in Experiment I. A CF discrimination threshold was estimated in the test phases that followed again using the same adaptive method. However, in this study, infants were randomized into two groups; half of the 3-month-olds and half of the 7-month-olds were tested in each group. Both groups of infants were conditioned and trained to categorize two sets of complexes that differed by a 15% shift in the center frequency of their spectral centroids. The test phases for group one presented a 10% $\Delta$ CF and 5% $\Delta$ CF and the test phases for group two presented a 2% $\Delta$ CF and 0.5% $\Delta$ CF. The  $\Delta$ CFs of 15%, 10%, and 5% were initially selected based on adult results reported by Allen and Oxenham (2014). However, because infants were successful at discriminating these changes during pilot testing, test phases with  $\Delta$ CFs of 2% and 5% were added.

All other criteria for determining threshold in the test phases was the same as in Experiment I, and likewise, threshold was defined as the last test phase a participant reached a criterion of correct responses on 4 out of 5 consecutive change trials and 4 out of 5 consecutive no-change trials.

Adults were tested in an average of 4.7 sessions (*range*=3-8) in a single 60-minute visit. The adults were conditioned and trained on a 15% $\Delta$ CF like infants but were

presented with all four test phases instead of only two. Adults sat alone in the booth and were instructed to raise their hand when they heard “the sound change that makes the toy come on”. The experimenter recorded adults’ responses. In all other respects, the stimuli and procedure were the same for adults and infants.

### 5.2.2 Results

Three analyses were conducted to evaluate participants’ performance on the adaptive threshold measure. The first analysis addressed relative difficulty of the task for infants and adults by comparing the number of trials to reach criterion in the training phase across participant groups in each condition. The second analysis assessed infant and adult sensitivity to shifts in the spectral envelope by comparing thresholds across participant groups. Finally, whether group sensitivity at the threshold test phase is comparable across participant groups was assessed. Preliminary analyses indicated that there was no effect of CF change direction (increase or decrease in CF), so that variable was not considered in subsequent analyses.

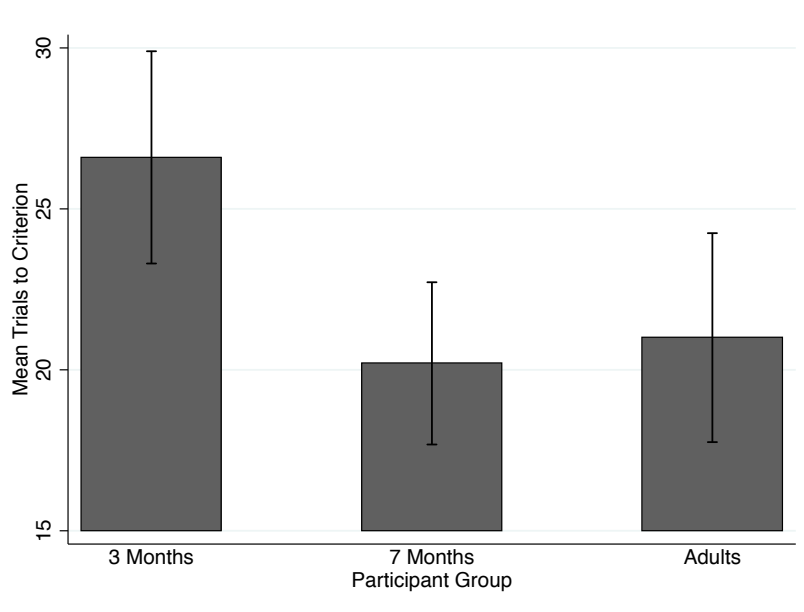


Figure 5-8: Mean ( $\pm 1$  SEM) number of trials to criterion as a function of participant group.

Figure 5-8 shows the mean number of trials for participants to reach criterion in the training phase as a function of participant group. The number of trials to reach criterion did not appear to differ for infants and adults. A one-way ANOVA testing the effect of participant group on the mean number of trials to criterion revealed no significant effect of age [ $F(2,47)=0.79, p=0.4606$ ]. There is therefore no indication that infants took more trials than adults to learn to categorize these complexes on the basis of CF.

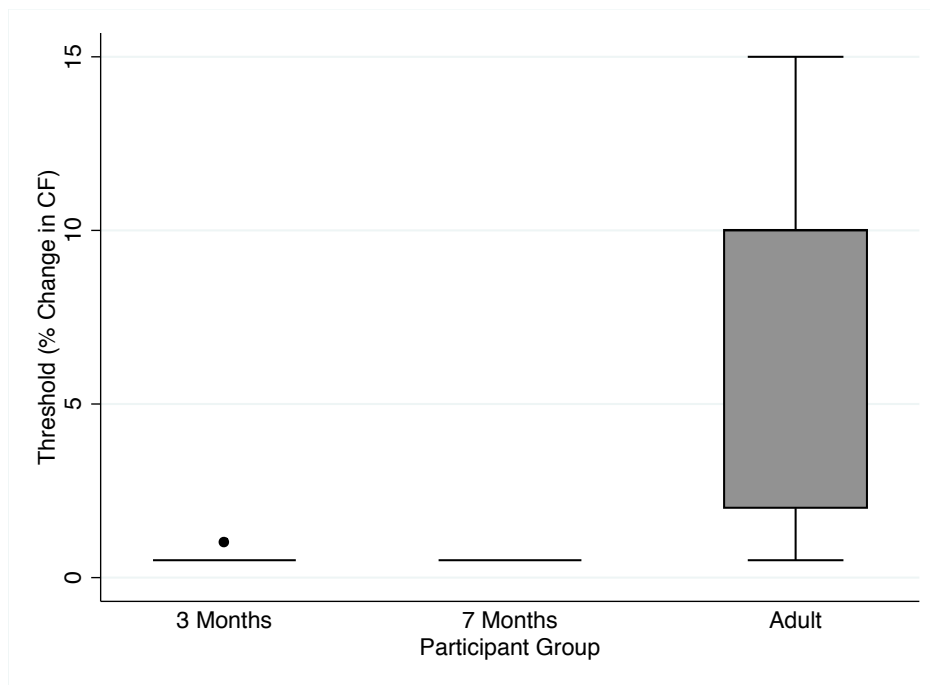


Figure 5-9: Box plot of threshold as a function of participant group.

All 20 infants in the first group reached criterion on the three  $\Delta$ CFs (15, 10, 5%) presented to them, demonstrating that infants discriminated these changes. Further threshold analysis were only conducted with the data from the second infant group who were presented with 15, 2, and 0.5% $\Delta$ CFs. The last test phase in which a participant reached criterion was considered their threshold. Figure 3 shows a boxplot of thresholds

as a function of participant group. Surprisingly, all infants except one 3-month-old had a threshold of 0.5% $\Delta$ CF while adult performance was much more variable. Infants had much lower thresholds than adults on this spectral discrimination task: 3-month-olds had a mean threshold of 0.55% $\Delta$ CF, 7-month-olds had a mean threshold of 0.5 % $\Delta$ CF and adults had a significantly higher threshold of 7.15 % $\Delta$ CF.

Whether spectral discrimination threshold differed across participant groups was assessed with a one-way ANOVA testing the effect of participant group and condition on threshold, revealing a significant effect of participant group [ $F(2,27)=17.46$ ,  $p < 0.001$ ]. Post-hoc testing with Tukey-Kramer pairwise comparisons showed significant differences between adults and 3-month-olds and well as adults and 7-month-olds but no significant difference between the two infant groups.

To investigate whether group sensitivity is comparable across participant groups at threshold, group  $d'$  was calculated from the last five change and last five no-change trials at each participant's threshold. Infant group  $d'$  at threshold was 1.56 and adult group  $d'$  was 2.17. As in the pitch discrimination task in Experiment I, there appears to be a difference in bias so that adult thresholds are actually at a higher point in the psychometric function than infant thresholds. However, this difference probably does not account for the large difference between infant thresholds (0.5% $\Delta$ CF) and adult thresholds (7.15 % $\Delta$ CF) observed.

### **5.2.3 Discussion**

These results demonstrate that infants at both 3 and 7 months of age are able to discriminate shifts in the spectral centroid of harmonic complex tones. Furthermore, they took no longer to learn the task and even discriminated smaller changes in CF than adults.

That infants demonstrate better sensitivity to these spectral changes than adults shows that the reason they had lower pitch thresholds in Experiment I was not because they could not perceive the spectral variation. The mean infant threshold of  $0.5\%\Delta CF$  corresponds to a 5.75 Hz shift in CF at 1050 Hz. The standard deviation of the spectral centroid shifts in Experiment I was 306 Hz for the resolved condition and 441 Hz for the unresolved condition, well above what infants discriminated in this current experiment.

As in Experiment I, 12 adult listeners were tested with single exemplars from each CF category to investigate whether the pitch variation was interfering with their ability to discriminate the spectral shifts. The same complexes from Experiment II were used and half of the participants discriminated complexes with a 180 Hz F0 and half of the participants discriminated complexes with a 200 Hz F0. After the elimination of pitch variation from the task, adult's ability to discriminate shifts in the CF of the complex tones also improved. Almost half of the adults discriminated a  $0.5\%\Delta CF$ , the mean infant threshold from Experiment II. This suggests that the pitch variation was indeed impairing adult performance.

Finally, that infants were able to ignore variations in pitch and respond to spectral changes in complex tones also provides evidence against the idea that pitch is prioritized during infancy. Not only are infants sensitive to spectral changes as they are to pitch, they took no longer to learn to discriminate the spectral changes than they took to discriminate changes in pitch. A one-way ANOVA testing the effect of task (pitch versus spectral shift) on the number of trials to criterion in the training phase revealed no significant difference between the two tasks [ $F(1,84)=0.80$ ,  $p =0.3734$ ].

### 5.3 GENERAL DISCUSSION

The results from these experiments demonstrate that infants at both 3 and 7 months of age are able to discriminate changes in the F0 or a shift in the spectral centroid of complex tones while ignoring variation in the other dimension. The most unexpected finding from these two experiments is the fact that infant sensitivity to both pitch and spectral changes is better than that of adult listeners.

These results suggest that subcortical processing is sufficient to support both pitch and spectral envelope discrimination in complex tones and that neither development of the thalamocortical pathway nor cortical maturation improves sensitivity to these changes. Although the discrimination of pitch and spectral envelope certainly rely on different underlying mechanisms, there are striking parallels between the results observed in the two experiments. One common aspect of the two studies is that participants were required to ignore variations in either pitch or spectral envelope while responding on the basis of the other. The shifts in the spectral envelope are perceived as changes in timbre and for adult listeners, pitch and timbre are interfering attributes; when either pitch or timbre is varied, perception of the other is impaired (Allen and Oxenham, 2014; Silbert et al., 2009). In both experiments, once variation on the other dimension was removed, adult performance improved.

While sensitivity to pitch and timbre changes is mature in infants, the infant-adult differences observed in these two experiments suggest that differences in infant auditory perceptual skills do exist. One possibility is that infants' and adults' processing strategies differ even when they are faced with the same task. Saffran and colleagues have shown that when infants were presented with both absolute and relative pitch cues in a tone sequence, they were more likely to respond on the basis of absolute pitch cues.

However, adult listeners, when presented with the same task, responded on the basis of relative pitch (Saffran, 2003; Saffran and Griepentrog, 2001). Nevertheless, when absolute pitch cues were removed from the tone sequence, infants and adults were both able to respond on the basis of relative pitch cues (Saffran et al., 2005).

Werner and Leibold (2004) suggest that one of the reasons is that infants and children are less flexible listeners than adults. This age difference in auditory processing has been demonstrated most clearly in children's phoneme identification. Although children and adults perform equivalently in identifying a consonant when both the spectral and temporal cues that distinguish consonants are available, children perform more poorly than adults when only the one of the cues was available (Hazan and Barrett, 2000). This suggests that children have difficulty changing their cue weights with the change in the sound. In the current context, that could mean that infants "latch on" to one cue that distinguishes the tonal complexes, and then do not process other cues that distinguish the individual exemplars. Future investigations on contextual effects and infant cue weighting will add to what we know about infant auditory perceptual skills.

Finally, although it is surprising that infants discriminate smaller changes in pitch and timbre than adults, there have been many reports of auditory tasks where infants outperform adults. Prior to about ten months of age, for example, infants can discriminate subtle acoustic changes in speech sounds and musical melodies, even from non-native languages and musical scales that adults cannot discriminate (e.g., Lynch et al., 1990; Trainor and Trehub, 1992; Werker and Tees, 1984). Thus, there are other examples in which perception becomes less precise with age during early development.

## **ACKNOWLEDGEMENTS**

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## 6 Concluding Remarks

One of the fundamental questions in human auditory development is how even very young infants demonstrate sophisticated sound processing abilities despite the protracted and extensive developmental period of the auditory cortex. The studies in chapters 2-5 have examined the development of pitch perception during early infancy, when auditory abilities likely rely on subcortical processing prior to cortical maturation. The results of these investigations are consistent with many past studies presenting both electrophysiological and behavioral evidence that infants are sensitive to pitch information in speech and music from a young age. Chapters 2-4 demonstrate that infants discriminate the pitch of resolved and unresolved harmonics as well as melodies composed of missing fundamental complexes. Chapter 5 goes on to show that infant pitch discrimination thresholds are comparable to the thresholds of the best performing adults.

Although there are differences in the organization of the auditory pathway at 3 and 7 months, no difference in performance was observed between infants in these age groups. The results of these experiments demonstrate that subcortical processing is sufficient to support complex pitch perception by 3 months of age. Furthermore, neither development of the thalamocortical pathway during infancy and childhood nor cortical maturation improves sensitivity to pitch. Nevertheless, while even 3-month-old infants demonstrated the ability to discriminate missing fundamental pitch and with sensitivity comparable to adult listeners, additional findings from these studies suggest that adult-infant differences in pitch perception do exist.

First, infants' ability to discriminate pitch in the presence of timbre variation was not affected in the same way as adults. Second, no difference was observed between

infants' ability to discriminate resolved and unresolved harmonics. The experiments in Chapter 5 suggest that these differences are the result of more general differences in infant and adult's use of auditory processing strategies.

However, there are several limitations to these studies that must be considered. While efforts have been made to keep the testing procedure as similar as possible between infants and adults, adult listeners were provided with vague instructions to "raise your hand when you hear the sound change that turns the toys on". The difference between an explicit versus implicit task for adults and infants may have affected the results obtained. A second limitation is that the measures used may not have captured differences between 3- and 7-month-olds in the processing of spectral variation as well as the less salient pitch of unresolved harmonics. Finally, the studies did not include age groups between 7 months and adulthood to fully capture the developmental progression.

The results of these studies highlight the many aspects of infant pitch perception that remain unknown. Future investigations should at least have three aims: (1) to fully characterize infant-adult differences in pitch perception including differences in timbre interference as well as harmonic resolvability and pitch salience, (2) to establish the relationship between infant's ability to perceive pitch and their ability to use pitch in the context of more complex auditory tasks such as sound source segregation, speech perception and music perception, and (3) to apply what is known about the development of pitch perception in normal hearing infants to the investigation of the development of impaired pitch perception such as in infants who use cochlear implants.