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Research paper

Development of pitch processing: Infants' discrimination of iterated rippled noise stimuli with unresolved spectral content

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ABSTRACT

Sound frequency is extracted at the level of the cochlea, and is represented by two neural codes: a spectral (place) code that is maintained by tonotopic maps extending into primary auditory cortex, and a temporal code based on the periodicity of action potentials in auditory nerve fibers. To date, little work has examined infants' ability to perceive pitch when spectral content cannot be resolved by cochlear filters; the present experiments do so using high-pass filtered iterated rippled noise (IRN) stimuli. Using a conditioned head-turn paradigm, most 8-month-old infants showed above-chance discrimination of a change from 167 to 200 Hz in the fundamental frequency (F0) of such high-passed filtered IRN stimuli, but only when first exposed to a training target stimulus that emphasized pitch through the addition of a sine wave tone to the IRN stimulus at the F0. However, even after this period of pitch priming, performance was quite poor relative to that found in previous studies using stimuli with resolved spectral content. These results support the idea that 8-month-olds can perceive pitch when only unresolved spectral content is present in the stimulus, but that such processing is not yet robust.

1. Introduction

Sounds with pitch are complex in that they typically contain energy at a fundamental frequency and at harmonic frequencies that are at integer multiples of the fundamental frequency (F0). The formation of a single pitch percept from this frequency information is a complex process that depends on spectrotemporal processing of the sound stimulus. The accurate formation of a pitch percept is important for identifying sounds in the environment, and for acquiring language and music. Vocal F0 aids in speaker identification (e.g. van Dommelen, 1990), and provides a basis for the extraction of complex speech signals in the presence of background noise (e.g. Song et al., 2011). In addition, prosodic F0 contours signal lexical and syntactic information, as well as emotional expression (e.g. Frick, 1985; see Moore, 2012 for a review). Pitch is also central to music perception, as the way in which F0 varies over time describes musical melody (see Koelsch and Siebel, 2005; McDermott and Oxenham, 2008; Trainor and Corrigall, 2010 for reviews). Pitch processing is thus crucial for infants' acquisition of music and language. Pitch information also provides a primary cue for separating overlapping sounds and correctly attributing them to their sources (Bregman, 1990).

A number of studies examining how infant listeners perceive pitch-evoking stimuli have demonstrated that infants are capable of rather sophisticated pitch discriminations. For example, behavioral evidence indicates that 3- to 6-month-old infants show pure tone frequency difference limens as low as 2% at 1000 Hz (Olsho et al., 1982). Eight-month-old infants have been shown to discriminate complex stimuli that differ by 20% in F0 (e.g. 160 and 200 Hz; Clarkson and Clifton, 1985), although this value represents a commonly used interval and is likely well above the threshold of discrimination. Similar pitch changes have been used to demonstrate that infants, like adults, are sensitive to the pitch of the missing fundamental (a stimulus in which a pitch percept is formed from harmonics above F0, despite a lack of energy at F0; Clarkson and Clifton, 1985). Montgomery and Clarkson (1997) demonstrated further that the addition of a low-frequency noise masker does not impair the ability of 8-month-old infants to discriminate missing-fundamental stimuli. Thus, as in adults, infants' ability to perceive the pitch of the missing fundamental is not due to low-frequency combination tones resulting from non-linearities in the inner ear. Electrophysiological measures suggest that cortical representations of the pitch of the missing fundamental emerge between 3 and 4 months of age (He and Trainor, 2009). Furthermore, Clarkson and Clifton (1995) demonstrated that 7-month-old infants

Abbreviations: IRN, iterated rippled noise; 3AFC, 3-alternative, forced-choice

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can discriminate pitch changes in inharmonic complexes, and that, as in adults, performance is related to the degree of inharmonicity in a manner that is qualitatively similar to adult performance. Collectively, these results suggest that infants, like adults, use the harmonic structure of complex tones to determine their pitch.

Although infants appear to process pitch-evoking stimuli in a qualitatively adult-like manner by 4 months of age, little research has examined how infant listeners perceive stimuli containing limited spectral pitch cues. This question is a relevant one, as extracting pitch given limited spectral content is necessary for perceiving complex stimuli like speech in the presence of masking noises of various spectra found in the everyday environment. Complex tones containing harmonics of an F0 can be high-pass filtered such that spectral content is limited to the region beyond which individual harmonics can be resolved by the basilar membrane. While the spacing of harmonics in a complex tone is linear, the tonotopic organization of the basilar membrane is roughly logarithmic. Hence, the characteristic places along the membrane corresponding to the lower harmonics of a complex sound are sufficiently spaced that each harmonic falls within its own frequency channel. However, for higher harmonics, the bandwidth of frequency channels on the basilar membrane exceeds the spacing of harmonics such that multiple harmonics fall into the same frequency channel, activating the same cochlear nerve fibers. These harmonics are considered to be beyond the limit of cochlear resolvability (e.g. Moore, 2012). Within a complex tone, individual harmonics with numbers below 5 appear well-resolved, while resolvability decreases between 5 and 8, such that harmonics above 8 are at best poorly resolved (see Moore and Gockel, 2011 for review).

In adults, pitch salience is greater for harmonic stimuli that contain spectrally resolved components than for those that contain only high, unresolved components (Ritsma, 1962). Moreover, for stimuli that contain both resolved and unresolved components, the resolved components (in particular harmonics three through five) make the greatest contribution to the pitch percept (Plomp, 1967; Ritsma, 1967). The dominance of resolved harmonics is evident in performance on pitch-related tasks. For example, the performance of adult listeners on pitch interval-identification tasks degrades (Houtsma and Goldstein, 1972; Houtsma and Smurzynski, 1990) and difference limens for F0 increase (Houtsma and Smurzynski, 1990) as the lowest component present in a complex harmonic stimulus is increased. However, although low-frequency, resolved components may dominate pitch perception, high-frequency, unresolved components are sufficient to elicit a pitch percept in adult listeners. For example, performance on a pitch interval-identification task remains well above chance, even for harmonic stimuli that contain no resolvable components (Houtsma and Smurzynski, 1990).

Based on a number of studies reporting qualitatively adult-like pitch perception in infants by 8 months of age (Clarkson and Clifton, 1985, 1995; Montgomery and Clarkson, 1997), it is of interest to determine whether infants perceive a pitch percept for stimuli containing only unresolvable spectral cues. One previous study found that although 7- to 8-month-old infants were able to successfully categorize complex stimuli containing resolvable harmonics according to pitch, there was no evidence that they could do so when only unresolvable harmonics were present (Clarkson and Rogers, 1995). In the present study we examined infants' ability to detect pitch changes in the absence of information from resolvable harmonics using iterated rippled noise (IRN) stimuli. IRN stimuli are created by generating a sample of frozen white noise, and adding it to itself following a delay equal to the inverse of the frequency of the desired pitch percept. Although the resultant stimuli contain spectral ripples, high-pass filtering can remove spectral cues in the region of resolvable harmonics while preserving the sensation of pitch for adults. The strength of this pitch sensation, and resultant pitch discrimination thresholds, are dependent upon a number of stimulus parameters, including: the length of delay used to create the IRN, the number of iterations of the delay-and-add process, and the filter settings employed. For example, using a 3-alternative, forced-choice method designed to target 70.7% accuracy, Barker et al. (2011) demonstrated that adults can discriminate between IRN stimuli with F0 = 100 and 160 Hz, band-pass filtered between 1 and 2 kHz. Butler and Trainor (2012) presented electrophysiological evidence that adults can discriminate between IRN stimuli with F0 = 167 and 200 Hz, high-pass filtered at 2.6 kHz. The current study used a visually-reinforced, conditioned head-turn procedure to determine whether 8-month-old infants could discriminate behaviorally between these same stimuli.

2. Experiment 1

2.1. Method

2.1.1. Participants

Five healthy 8-month-old infants (3 males; age = 251 ± 3 days [mean ± SD]) participated. An additional four infants failed to complete the training phase of the experiment, and one infant completed the training phase, but was unable to complete the experimental phase due to fussiness. Eight-month-olds were chosen for three reasons: electrophysiological evidence has shown evidence that a cortical representation of pitch emerges well before this age (He and Trainor, 2009); the conditioned head-turn procedure provides a measure of functional discrimination in children of this age; and testing 8-month-olds allows for direct comparison with previous behavioral studies of infant pitch perception that have focussed on this age group. All infants were born within 2 weeks of full term, were healthy at the time of testing, and no parent reported a history of chronic ear infection or hearing impairment. All research protocols were approved by the McMaster Research Ethics Board.

2.1.2. Stimuli

IRN stimuli identical to those of Butler and Trainor (2012) were created. The delay-and-add process was repeated 16 times, as further iterations do not increase pitch salience for adults (Patterson et al., 1996). The delay time was set to 6 or 5 ms, in order to create signals with pitches corresponding to 167 Hz and 200 Hz, respectively. To ensure equal power across the length of the stimuli, the first and last 100 ms (which contain a gradual increase and decrease in power, respectively, resulting from the iterative delay-and-add process) were removed, resulting in stimuli with a total duration of 450 ms. The IRN stimuli were high-pass filtered at 2600 Hz (5th order Butterworth filter, slope = 30 dB/octave), representing the 13th harmonic of the 200 Hz stimulus, to remove spectral content in the range of the resolvable harmonics. The waveforms and spectrogram for the target stimulus used in experiment 1 are shown in panels A and B of Fig. 1. The background IRN stimulus had an F0 of 167 Hz, and was played repeatedly throughout both the training and experimental phases with a stimulus onset asynchrony of 2 s and a level of 58 dB(A) over a background environmental noise with a level of 26 dB(A) (as measured with an integrating sound level meter [Brüel & Kjær 2239 A]).

The stimuli were pilot tested on 6 adults using the infant procedure described below (the only difference being that adults raised their hand rather than turned their head to indicate the

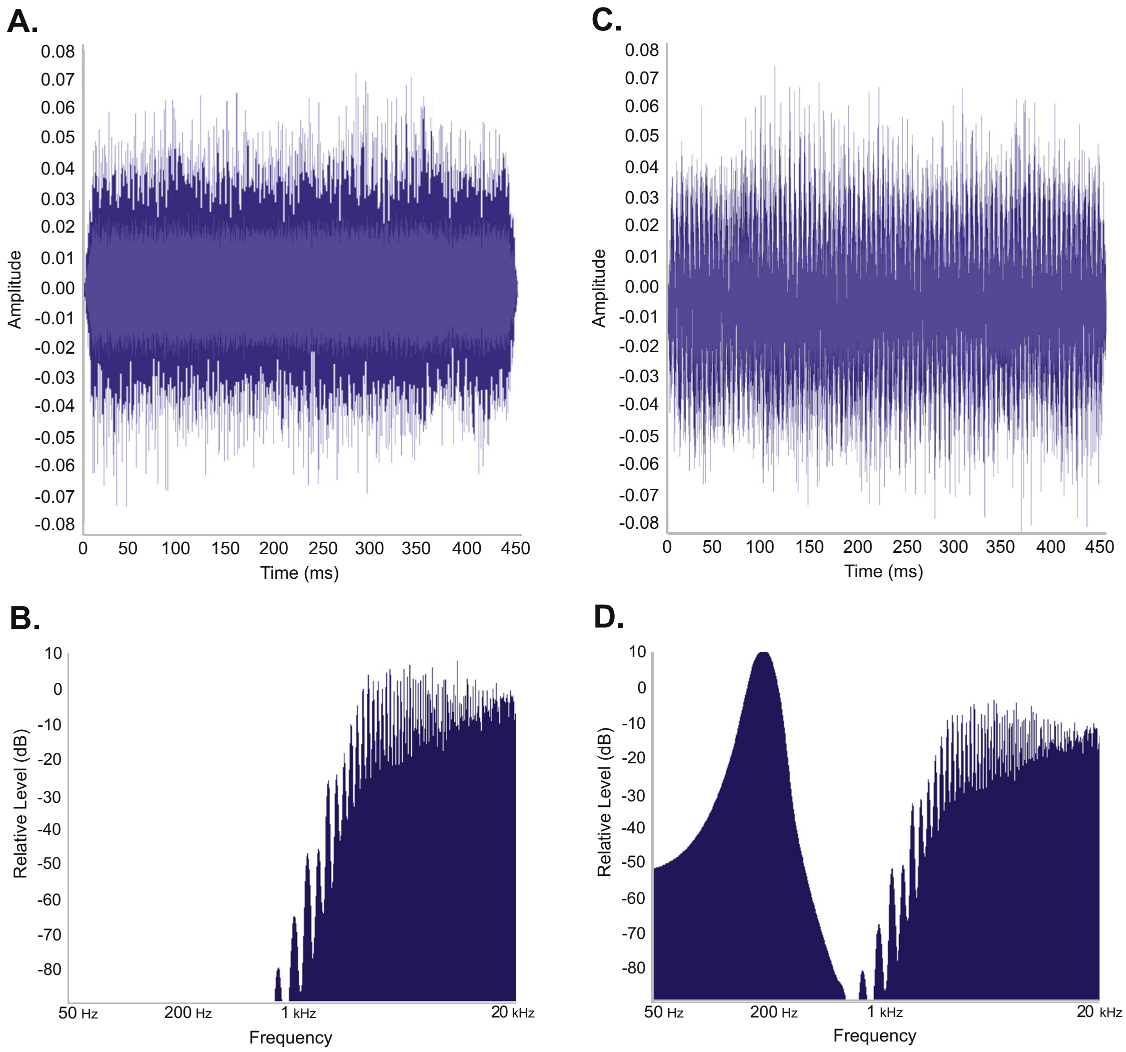

Fig. 1. Panels A and B show the waveform and power spectrum for the target stimulus used in the training and experimental phases of *Experiment 1*, and in the experimental phase of *Experiment 2*. Panels C and D show the waveform and power spectrum for the target stimulus used in the training condition of *Experiment 2*, reflecting the addition of a 200 Hz puretone. In both cases, power spectra were created using a Hanning window.

presence of a change in pitch). All adults scored 100% correct (12/12 hits, 0/12 false alarms).

2.1.3. *Procedure*

After the procedure was explained and the consent form was signed by a parent, each infant was tested individually, seated on his/her parent's lap facing the experimenter inside an Industrial Acoustics Co. sound-attenuating booth with a GSI loudspeaker to the infants' left. The loudspeaker was located above a box containing four compartments, each of which housed a mechanical toy and lights. The box had a smoked Plexiglas front such that the toys were not visible unless the lights in that compartment were illuminated. Infants were tested using the go/no-go conditioned head-turn response procedure in which head turns toward the loudspeaker are reinforced with an illuminated, moving toy only if the turn occurs within 2 s of the onset of a change in the sound. Sound stimuli with 44,100 Hz sample rate and 32-bit resolution were presented by an Apple G4 computer, through an NAD C352 stereo integrated amplifier, while both the parent and the experimenter wore headphones and heard continuous music that masked the stimuli.

When the child's attention was focused on the experimenter, she called for a trial using a button box that was concealed from the view of both the infant and their parent, connected to a computer via a custom-built interface to a NI PCI-DIO96 I/O card. Head turns by the infant toward the loudspeaker were recorded to computer by the experimenter pressing another button on the button box.

During the *training phase*, all trials were change trials in which a single presentation of the 167 Hz IRN background stimulus was replaced by the 200 Hz IRN. If an infant made a turn toward the loud speaker of at least 45° within 2 s of the onset of a change stimulus (i.e. during the period between the onset of a change stimulus and the onset of the subsequent background stimulus), the computer illuminated one of the toys located beneath the loud speaker and caused it to move for 2 s. Once the reinforcement had ended and the experimenter had regained the infant's attention, the experimenter called for the next trial. During the *training phase*, the target stimulus level was 6 dB higher (64 dB[A]) to help the infant learn the contingency between a head-turn response to a 200 Hz F0 and the visual reinforcement (the illuminated, moving toy). In order to pass training, the infant needed to make 4 consecutive correct head turns to the change in F0 within 20 trials.

During the *testing phase*, twenty-four trials (12 change trials and 12 no-change trials) were presented in quasi-random order for each subject with the constraint that no more than two no-change trials were presented consecutively. For change trials, the 167 Hz IRN background stimulus was replaced by a 200 Hz IRN stimulus of equal amplitude. For no-change trials, the background 167 Hz IRN stimulus continued. Turns recorded during change trials were coded as hits, while turns made within 2 s of the onset of no-change trials were considered false alarms. Hit and false alarm rates were converted to individual *d*' sensitivity measures for each infant. Because hit rates of 12/12 or false alarm rates equal to 0/12 would result in infinite *d*' values, these values were replaced with values of $(12 - 0.5/n)$ or $(0 + 0.5/n)$, respectively, where n is the number of signal trials (Macmillan and Kaplan, 1985). In addition, the hit and false alarm rates across all infants were combined to create a measure of group sensitivity.

2.2. Results and discussion

Half of the infants tested were unable to complete this experiment, suggesting that the discrimination was difficult. Of the remaining five infants, only two had *d*' values greater than chance ($d' = 0$). Macmillan and Kaplan (1985) have suggested that averaging hits and false alarms across subjects can yield a reliable, unbiased estimate of average *d*' when the number of trials available for each listener is limited, such as in the present study. In this case, combining the data across listeners yielded a group sensitivity of $d' = 0.24$. This poor performance is in contrast with perfect performance for the pilot adult subjects as described in the stimulus section.

These results suggest that infants do not perceive the pitch of these high-pass filtered IRN stimuli. However, it is possible that infants' perception is naturally drawn to the very salient noisy timbral quality of these stimuli, and that they would show perception of their pitch if their attention could be drawn to their pitch. The goal of Experiment 2 was to determine whether it is possible to train infants to perceive the pitch of IRN stimuli.

3. Experiment 2

3.1. Methods

3.1.1. Participants

Sixteen healthy 8-month-old infants (13 males; age = 258 ± 3 days [mean ± SD) participated. All infants were born within 2 weeks of full term, were healthy at the time of testing, and no parent reported a history of chronic ear infection or hearing impairment. An additional two infants did not pass the training phase of the experiment and one infant failed to complete the experiment due to fussiness. All research protocols were approved by the McMaster Research Ethics Board.

3.1.2. Stimuli

The stimuli in the experimental phase were identical to those of Experiment 1. In the training phase, the IRN stimuli were also as for Experiment 1, but for the target (change) IRN stimuli, which had an F0 of 200 Hz, a 200 Hz sine tone was added. Both the IRN and sine tone components had levels of 55 dB (A) such that the overall presentation level of the target stimulus remained at 58 dB (A). Waveforms and spectrograms for the target stimuli used in the training and experimental phases of experiment 2 are shown in Fig. 1.

3.1.3. Procedure

The experimental phase was identical to that for Experiment 1. The training phase was also identical to that for experiment 1, with the following exception: During the training phase, the stimulus on change trials was the 200 Hz IRN/puretone stimulus rather than the 200 Hz IRN stimulus. This deviant stimulus was presented at the same loudness as the baseline stimulus (58 dB[A]) in an effort to ensure that infants learned the contingency between visual reinforcement and the 200 Hz F0, rather than between reward and a change in stimulus loudness.

Table 1
Sensitivity scores (*d*') for each infant in Experiment 2.

Subject	*d*'
1	1.35
2	1.30
3	1.11
4	1.11
5	0.97
6	0.86
7	0.76
8	0.71
9	0.67
10	0.46
11	0.42
12	0.42
13	0.22
14	0.00
15	0.00
16	−0.21

3.2. Results

Table 1 shows the obtained *d*' values. The median individual *d*' value across infants was 0.69, and all but three infants had *d*' values greater than zero, suggesting that the majority of 8-month-olds were able to detect a change from an IRN stimulus with an F0 of 167 Hz to one with an F0 of 200 Hz. A one-sample Wilcoxon Signed Rank Test revealed that this median value was significantly above chance level ($p = 0.01$). Combining the data across listeners yielded a group sensitivity of $d' = 0.58$. It is possible that imposing a limit of no more than 2 consecutive no-change trials in the experimental phase (which functions to prevent infants from becoming bored with the paradigm), could artificially inflate the hit rate. However, in the current study, the hit rate following 2 consecutive no-change trials was actually slightly lower than on other change trials (44.2 vs. 50%, respectively). Fig. 2 shows the hit and false alarm rates for each infant. It is important to note that, while the majority of infants had hit rates that exceeded their false alarm rates, the performance of the 8-month-olds tested here was far worse than that of the adults described in Experiment 1, who performed at ceiling level.

4. Discussion

We used a conditioned head-turn procedure to measure the sensitivity of 8-month-old listeners to an F0 change in IRN stimuli containing information only outside the region of spectral resolution. These IRN stimuli typically elicit a weak pitch sensation in

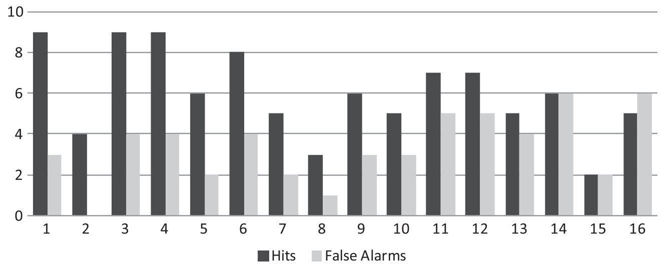

Fig. 2. Hit rates (dark bars) and false alarm rates (light bars) for each infant in the current study, arranged in order of decreasing sensitivity. Thirteen of sixteen infants showed hit rates that exceeded their false-alarm rates.

adult listeners, but one that can be readily detected. Four of the ten infants tested in experiment 1 failed to complete the training phase of the experiment, suggesting they were unable to learn the contingency between the change in the F0 of the IRN stimuli and the visual reinforcement provided. For those infants who completed the experimental phase, the low group average sensitivity ($d' = 0.24$) suggests that the IRN stimuli were not being successfully discriminated.

IRN stimuli have a salient noisy timbral quality. In the training phase of experiment 2, the deviant stimulus was designed to draw attention to pitch in an effort to prime the infants to attend to pitch differences. The group average sensitivity ($d' = 0.58$) was statistically above chance level, and exceeded the sensitivity previously reported for complex tones containing only unresolved harmonics ($d' = 0.44$; Clarkson and Rogers, 1995). However, this sensitivity is well below that reported for infants for similar F0 changes in harmonic stimuli with spectrally resolved components, even when the component at F0 is missing ($d' = 1.25$, Clarkson and Rogers, 1995; $d' = 1.80$, Clarkson and Clifton, 1995). Collectively, the results reported in experiments 1 and 2 suggest that as a group, 8-month-old infants can perceive the pitch of IRN stimuli with no resolvable harmonics, when first primed to attend to stimulus pitch. However, the pitch sensation for such stimuli is weak compared to that for complex tones with resolvable harmonics.

It is possible that the spectral ripples present in IRN stimuli might create distortion products at or near the fundamental frequency of the sound as a result of cochlear non-linearities. However, for harmonic tones, these distortions are large only for specific phase relationships between components (Pressnitzer and Patterson, 2001) that are weak or absent in IRN stimuli (Sayles and Winter, 2008). Moreover, evidence suggests that if IRN produces audible distortion products, they are at such a low level as to be essentially negligible (Winter et al., 2001). The most robust distortion product occurs at a frequency equivalent to 2f1−f2 (the cubic distortion product; Gorga et al., 1996). Given the high-pass filter settings used in the current experiment (the cutoff frequency was at the 13th harmonic of the 200 Hz stimulus), the lowest distortion product produced by harmonics 13 and 14 would be near the 10th harmonic, and thus beyond the region of resolvable spectral pitch cues.

It is also possible that despite the high-pass filter used in the current experiment, that lower, possibly resolved harmonics may have been audible (e.g. the 8th harmonic located at 1.6 kHz in Fig. 1). Given that the IRN stimulus was presented at 58 dB, the spectrum level within the passband of the filter (1.6–2 kHz) is 15.6 dB (Yost, 2007). The equivalent rectangular bandwidth (ERB) at 1600 Hz is 197.4 Hz (Glasberg and Moore, 1990), and the filter provides an attenuation at this frequency of 24.71 dB. Thus, the 8th harmonic in the present study is being presented at roughly 13.84 dB. Because auditory thresholds of 6- to 12-month-old infants have been measured as 12 dB at 2 kHz and 24 dB at 1 kHz (Werner-Olsho et al., 1988), it is unlikely that spectral cues arising from lower harmonics contribute to pitch sensation in the present study, particularly when the masking effects of higher frequency spectral content is considered. This, combined with the low overall presentation level, suggests that the discriminations observed in Experiment 2 were based on temporal pitch cues, rather than on spectral content or cochlear distortions in the region of resolved information.

The perception of pitch for inharmonic tones and IRN stimuli relies to a large extent on the temporal mechanism for pitch extraction (e.g., Butler and Trainor, 2012). While pitch discrimination performance degrades for both infants and adults as inharmonicity increases, infant performance appears to drop off much more rapidly than does adult performance (Clarkson and Clifton, 1995). Similarly, the results reported here with the IRN stimuli suggest very low performance for infants compared to adults (e.g., our adult subjects showed perfect discrimination of the stimuli of the present paper; Barker et al., 2011; showed 70.7% accuracy when discriminating between 100 Hz and 160 Hz IRN stimuli in a 3AFC paradigm [see their Fig. 3]). While differences between the adults piloted in this study, and those tested by Barker et al. (2011) may have arisen due to a number of differences in stimuli and/or experimental design, these studies collectively demonstrate that adult discrimination is markedly better than that observed for infants in the present study. This observation is consistent with Clarkson and Clifton's (1995) suggestion that the mechanism responsible for extracting and/or interpreting temporal pitch cues may take longer to develop than the mechanism acting on resolved spectral cues. The peripheral auditory structures necessary to encode spectral pitch cues are functional at birth, with pure tone frequency discrimination undergoing rapid development postnatally (Olsho et al., 1982). While much less is known about the structures necessary to extract and perceive temporal pitch cues, the results presented here suggest that temporal pitch mechanisms are present, yet not functionally developed in 8-month-old infants. Age-related maturational factors surely contribute to infants' degraded performance relative to that of adults. However, adults have also had a lifetime of listening experience extracting signals such as speech in challenging listening environments where spectral cues may be degraded or unavailable. This experience with temporal cues likely underlies their performance in tasks like the one presented in the current study. The importance of experience is also evident from the fact that a small amount of directed training in infants in the present study led to better performance for stimuli with minimal spectral cues.

Examining individual differences, it appears that the sample of infants tested in experiment 2 may represent a continuum from infants who show robust discrimination to those who seemingly cannot discriminate between the IRN stimuli presented (see Fig. 2). Given that only 24 trials were obtained from each infant, we have not included statistical analyses at the individual level. If it is indeed the case that pitch perception given unresolved spectral content is limited by the development of the mechanism responsible for extracting and/or interpreting temporal pitch cues, this gradation in behavior may reflect differential development of this mechanism across infants. Further suggestion that the temporal mechanism might be improving during this period of development is that the infants in the present study (mean age = 258 days) were somewhat older than those tested using harmonic complex stimuli by Clarkson and Rogers (1995; mean = 221 days). Thus, the somewhat better performance of infants in the present study than of the infants in the Clarkson and Rogers study might reflect an increased sensitivity of the temporal mechanism with increased age.

Perhaps one of the most interesting findings of the present study was that a very short period of training that focussed attention on the pitch of the IRN stimuli facilitated infants' ability to discriminate pitch. While the presence of the sine tone during the training phase was a salient feature which discriminated the target stimulus from the background stimulus, the increase in performance during the testing phase (when the sine wave had been removed) suggests that it succeeded in emphasizing stimulus pitch. This finding raises the possibility that infant performance on a number of tasks, including discriminating the pitch of harmonic complexes without resolvable harmonics, might be improved through focused training.

There are some aspects of the current experimental design that may have led to an overestimate or underestimate of infants' discrimination. However, each of these design parameters are necessary for infant testing. More importantly, the design used in this study is the same as the design used previously (e.g. Montgomery and Clarkson, 1997; Clarkson and Clifton, 1995), allowing for direct comparison of the results of those studies to the present findings.

In summary, the present study provides behavioral evidence that following a training period designed to emphasize stimulus pitch, most 8-month-old infants can discriminate the pitches of IRN stimuli whose spectral content is limited to the region beyond which individual harmonics can be resolved by the cochlea. As in adults, pitch perception in infants is degraded when resolvable spectral content is absent, but this degradation appears to be more marked for infants than adults. Taken in conjunction with the results of previous studies, it appears that the extraction of pitch without information in the resolvable region, and the temporal mechanism for pitch extraction, are not yet mature in 8-month-old infants.

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