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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