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Research paper

Sensitivity of the cortical pitch onset response to height, time-variance, and directionality of dynamic pitch

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HIGHLIGHTS

- Pitch onset response (POR) to pitch height, time-variance, and directional changes.
- Latency sensitive to pitch height (high < low), time-variance (steady-state < dynamic).
- PORs are insensitive to direction of pitch sweeps (rise = fall).
- PORs useful for studying cortical coding for some but not all pitch stimuli.

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ABSTRACT

Event-related brain potentials (ERPs) demonstrate that human auditory cortical responses are sensitive to changes in static pitch as indexed by the pitch onset response (POR), a negativity generated at the initiation of acoustic periodicity. Yet, it is still unclear if this brain signature is sensitive to dynamic, time-varying properties of pitch more characteristic of those found in naturalistic speech and music. Neuroelectric PORs were recorded in response to contrastive pitch patterns differing in their pitch height, time-variance, and directionality (i.e., rise vs. fall). Broadband noise followed by contiguous iterated rippled noise (producing salient pitch sweeps) was used to temporally separate neural activity coding the onset of acoustic energy from the onset of time-varying pitch. Analysis of PORs revealed distinct modulations in response latency that distinguished static from time-varying pitch contours (steady-state < dynamic) and pitch height (high < low). However, PORs were insensitive to the direction of pitch sweeps (rise = fall). Our findings suggest that the POR signature provides a useful neural index of auditory cortical pitch processing for some, but not all pitch-evoking stimuli.

1. Introduction

The ability to track dynamic pitch is important for deciphering the prosodic features of speech, the melodic elements in music, and segregating multiple speakers in the auditory scene [23]. Consequently, understanding the neural basis of pitch is of interest to understand how fundamental elements of the sound environment are mapped to meaning. Multichannel event related potentials (ERPs) provide direct assays of neuronal activity and thus, the potential to further clarify the nature of cerebral mechanisms engaged in processing pitch. Prominent ERP components elicited by auditory stimuli emerge within a few hundred milliseconds following stimulus onset (e.g., obligatory P1-N1-P2). However, these components are both generated and modulated by a wide range of stimuli and thus, reflect the encoding of energy onset [20] in addition to any one specific acoustic feature (e.g., pitch).

Recently, auditory cortical pitch encoding has been examined via the pitch onset response (POR), a negative deflection in the ERPs occurring after the onset of pitch-bearing sounds [7,10,11,14,15,17]. The POR is often studied using a stimulus paradigm that disentangles the overlapping obligatory onset response from pitch-specific brain components [17]. In this paradigm, a continuous sound is constructed from a segment of noise followed by a segment of iterated rippled noise (IRN). IRN is created by delaying broadband noise and adding it back onto itself matched in intensity and overall spectral profile. This delay-and-add process yields a noisy pitch percept corresponding to the reciprocal of the time delay (d), whose perceptual salience scales

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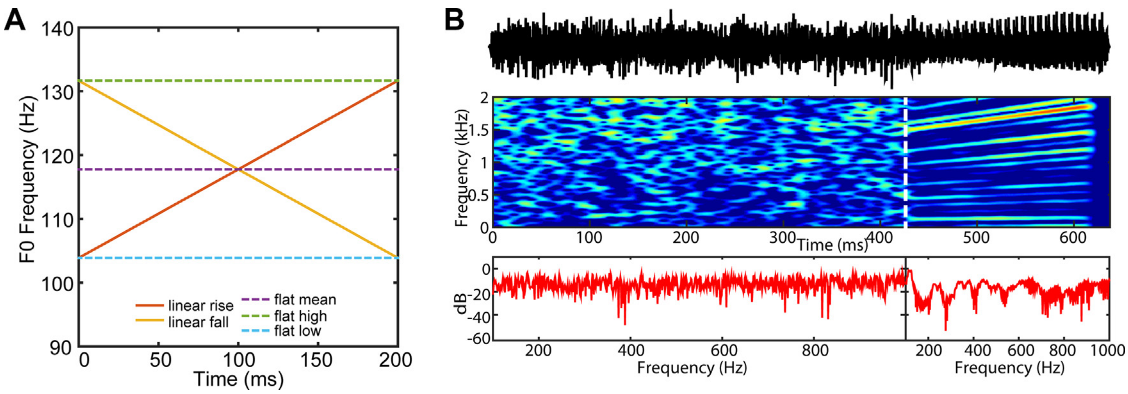

Fig. 1. Stimuli used to probe the POR's sensitivity to dynamic features of pitch. (A) F0 contours used to create time-varying IRN stimuli. Pitch patterns (linear rise/fall) were matched in average pitch height (i.e., same mean F0 as flat mean condition) but are contrastive in pitch direction. Whereas flat low, mean, and high conditions (dotted lines) are time-invariant but are contrastive in pitch height. (B) Spectrotemporal characteristics. Time waveform (top row) and spectrogram (middle row) of the linear rise stimulus. Dotted line demarcates the transition from random noise to iterated rippled noise (IRN) that contains clear pitch (450 ms post-stimulus onset). (bottom row) Spectra computed within the two stimulus segments. Note the absence of acoustic periodicity in the precursor noise but clear periodicity in the latter pitch segment, i.e., clear bands of energy at the fundamental frequency (103–132 Hz) and its harmonics.

with the number of iterations (n) [28]. The recursion process produces temporal regularity in the noise and a sinusoidal ripple in its long-term power spectrum yielding a harmonically rich sound with clear pitch. Preceding IRN with noise allows for the separation of neural responses to acoustic onset from activity related to the onset of pitch periodicity.

Magnetoencephalographic (MEG) responses to these stimuli show clear onset components, reflecting an obligatory response to the initial noise segment and further subsequent deflections following the initiation of pitch [10,11,17]. Interestingly, this latter pitch-specific response (i.e., POR) is strikingly asymmetric in that the reverse stimulus transition (pitch → noise) produces no discernible response [14,17]. Source analyses [7,10,11,17] corroborated by human depth electrode recordings [25] of neuroelectric activity (i.e., M/EEG) localize the POR's generators to anterolateral portions of auditory cortex. Studies demonstrate a strong dependence of POR latency and magnitude on specific features of pitch [e.g., salience, fundamental frequency (F0)]; earlier, more robust responses are evoked by salient compared to weaker pitch percepts [17,27]. Strikingly similar responses are produced by either monaurally or binaurally (e.g., Huggins pitch) generated pitch, suggesting that even disparate pitch percepts converge into a common cortical representation reflected by the POR [7,9].

Of particular interest are studies demonstrating that the neuroelectric POR can be used to investigate neural encoding of ecologically relevant pitch including musical and linguistic tonal stimuli [7,16]. Indeed, we have recently shown that PORs are mapped topographically within primary auditory cortex according to the perceptual consonance of multi-tone musical pitch intervals [7]. Similarly, cross language comparisons reveal a differential sensitivity in POR magnitude accordingly to listeners' language experience; larger and earlier responses are observed for native speakers of tonal (e.g., Mandarin Chinese) compared to non-tonal (e.g., English) languages [16]. These studies indicate that the POR might be a useful to explore not only sensory processing of musical and linguistic pitch but also how listening experience and perceptual outcomes act upon early cortical neural representations.

To date, POR studies have primarily employed steady-state (flat) pitch patterns [e.g.,7,14,17]. This limitation has made it unclear if the response is sensitive to dynamic, time-varying attributes of pitch as occuring in speech or music. Of the handful of studies examining responses to time-varying pitch trajectories, stimuli have been partly confounded by changes along multiple acoustic dimensions (e.g., duration and rate of pitch change; differences in mean fundamental frequency across stimuli) [cf. 15,16]. These shortcomings have made it difficult to ascertain what features of pitch actually drive modulations in the response. To this end, cortical PORs were recorded in response to dynamic F0 contours differing contrastively in their pitch height (low vs. high tones), time-variance (static vs. rising contours), or directionality (i.e., rising vs. falling sweeps). Critically, stimuli were controlled along other pitch dimensions to isolate PORs to these three experimental manipulations. Our findings show that the POR distinguishes pitch height and steady-state from time-varying pitch but is largely insensitive to the directionality of dynamic pitch contours.

2. Methods

2.1. Participants

Thirteen young adults (9 female; age: 24.9 ± 3.6yrs) participated in the experiment. All participants exhibited normal hearing sensitivity (i.e., <25 dBHL) bilaterally at octave frequencies between 250 and 8000 Hz and reported no previous history of neuropsychiatric illness. Participants gave written-informed consent in compliance with a protocol approved by the Institutional Review Board at the University of Memphis.

2.2. Stimuli

Five pitch stimuli were created following IRN using procedures described in our previous report [7] (Fig. 1). Each 700 ms stimulus consisted of two consecutive segments (i.e., noise → pitch): a noise precursor (which contained no sensation of pitch), contiguous with a segment containing the time-varying periodicity (and thus evoking the sensation of dynamic pitch) (Fig. 1). The noise precursor consisted of a 450 ms segment of filtered Gaussian noise (80–4000 Hz). The pitch segment was 250 ms in duration and was created using IRN. Here, $n = 64$ iterations were used to create IRN with salient pitch [5,7,14]. IRN delay (d) was varied to produce the various static and dynamic pitch patterns (Fig. 1A). Two pitch patterns were time-varying (linear rise and fall) and three were flat, steady-state contours (high, low, mean). The rising contour was a linear ramp with ascending F0 from 103 to 132 Hz over the 250 ms duration; the falling contour was its descending counterpart, traversing from 132 to 103 Hz. The mean token featured a steady-state pitch of 117.5 Hz, the average F0 of both the rising and falling contours. Hence, rise, fall, and mean tokens were equated in overall pitch height. The remaining high and low steady-