



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.

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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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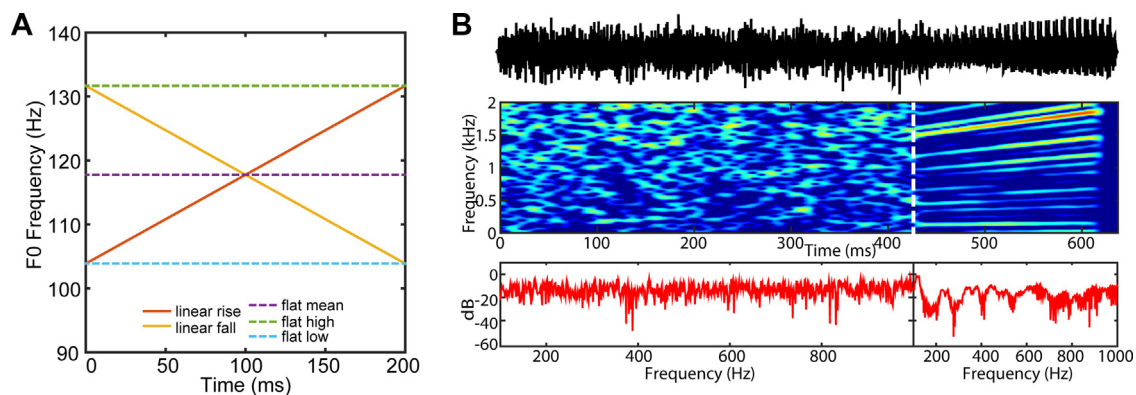


Fig. 1. Stimuli used to probe the POR's sensitivity to dynamic features of pitch. (A) F0 contours used to create time-varying IRN stimuli. Pitch patterns (linear rise/fall) were matched in average pitch height (i.e., same mean F0 as flat mean condition) but are contrastive in pitch direction. Whereas 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 \rightarrow 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 occurring 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 ± 3.6 yrs) 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 \rightarrow 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-

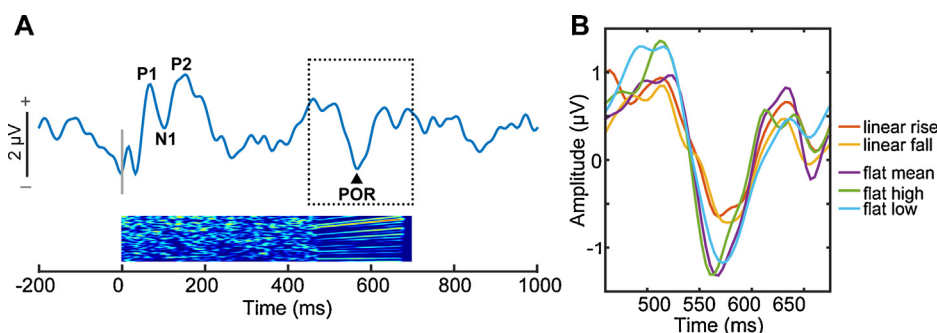


Fig. 2. Cortical pitch onset responses (PORs) to dynamic pitch patterns. (A) Example time course of the POR response (linear rise condition). The arrow demarcates the peak used to quantify POR magnitude. For reference, a stimulus spectrogram is shown below the timescale. Note the difference between early obligatory components (P1, N1, P2), elicited by the onset of acoustic stimulus energy, and the POR wave (~ 560 ms), reflecting the neural encoding of pitch. (B) Modulations in POR amplitude across pitch trajectories.

state contours had F0s of 132 Hz and 103, respectively. Contrasting responses to the rising/falling stimuli with the mean pitch pattern allowed us to assess the sensitivity of the POR to dynamic, time-varying pitch; contrasts between the high and low steady-state pitches allowed us to assess sensitivity to pitch height. Additionally, comparisons between the rising and falling contours allowed us to assess POR coding of the directionality of pitch change (i.e., up vs. down sensitivity).

Pitch segments were filtered between 80 and 4000 Hz to match the bandwidth of the preceding noise. The two segments were then equated in RMS amplitude and crossfaded ($5 \text{ ms } \cos^2$ ramps) with overlapping ramps. This ensured that at the transition from noise to pitch, the envelope of the composite stimulus remained flat (Fig. 1B). This also ensured there were no perceptible discontinuities in intensity or other cues (e.g., clicks) between noise and pitch segments and the total acoustic energy remained constant over the stimulus duration. The resulting percept of these stimuli was thus a smooth transition from noise to pitch. Critically, this stimulus segmentation separated the onset of pitch from the onset of the stimulus as a whole thereby allowing us to examine the encoding of dynamic pitch without the overlap of obligatory onset responses [7,11,17]. An example spectrotemporal profile for the linear rising pitch token is shown in Fig. 1B.

2.3. Electrophysiological data acquisition and analysis

Participants reclined comfortably in an electro-acoustically shielded booth to facilitate recording of neurophysiologic responses. They were instructed to relax and refrain from extraneous body movement, ignore the sounds they hear (to divert attention away from the stimuli), and were allowed to watch a muted subtitled movie to maintain a calm yet wakeful state. Stimulus presentation was controlled by MATLAB[®] 2013 routed to a Tucker–Davis (TDT) RP2 interface. Stimuli were delivered binaurally at an intensity of 82 dB SPL through electromagnetically shielded insert earphones (ER-2, Etymotic Research). Listeners heard 200 exemplars of each stimulus (ISI = 750 ms). Stimulus order was randomized within and across participants.

Neuroelectric activity was recorded differentially between Ag/AgCl disc electrodes placed on the scalp at the high forehead at the hairline ($\sim \text{Fpz}$) referenced to linked mastoids (A1/A2). Another electrode placed on the mid-forehead served as common ground. This bipolar montage was selected as the POR shows maximal scalp distribution at frontal-midline scalp locations [7] and allows direct comparisons with other single-channel POR studies [16]. Interelectrode impedance was maintained $\leq 5 \text{ k}\Omega$. Continuous EEGs were digitized at 5 kHz (SynAmps RT amplifiers; Compumedics Neuroscan) using an online passband of DC – 2000 Hz. Responses were

then stored to disk for offline analysis. EEGs were then epoched [–200 to 1100 ms window] and averaged in the time domain to obtain separate ERPs for each stimulus condition. Sweeps containing activity exceeding $\pm 25 \mu\text{V}$ were rejected as artifacts prior to averaging. Neural responses were then bandpass filtered (2–30 Hz; zero phase) for subsequent quantification.

For the frequency range of stimuli used in this study (103–132 Hz), the POR wave to steady-state pitch appears as a frontally-distributed negativity ~ 130 –150 ms after the onset of acoustic periodicity [7,17,27]. POR latency and amplitude were measured within the 500–620 ms time window after the time-locking stimulus onset (i.e., arrow Fig. 2). This search window encapsulated the onset and offset of periodicity in our stimuli and thus, the expected latency of the cortical POR response to pitch [7,11,17]. The time at which the maximum negativity occurred was taken as a measure of POR latency (i.e., absolute latency: ~ 525 ms; relative latency from onset of pitch: ~ 125 ms).

3. Results

Cortical POR time waveforms elicited by the five pitch patterns are shown in Fig. 2. A clear P1-N1-P2 onset complex is observed in the 50–200 ms time window reflecting the obligatory brain response to onset of acoustic stimulus energy. Following the transition from a noise precursor (0–450 ms) to the initiation of pitch (450 ms), a prominent negativity emerged at the ~ 560 ms time mark corresponding to the pitch-specific POR response [cf. 7,14,17].

A mixed-model ANOVA (pitch pattern as fixed effect, subjects as random effect) revealed that POR latency was modulated by the stimulus pitch pattern [$F_{4,48} = 4.10$, $p = 0.006$] (Fig. 2A). As would be expected from our stimuli (i.e., identical noise precursor across tokens), both N1 latency (negative deflection at 95–110 ms) [$F_{4,48} = 2.06$, $p = 0.100$] and amplitude [$F_{4,48} = 1.33$, $p = 0.270$] were invariant across stimuli. This confirms the functional distinction between the N1 and POR negativities [14,17]; the former reflects activity to the onset of stimulus energy whereas the latter reflects neural encoding of pitch periodicity.

To evaluate the POR's sensitivity to various properties of dynamic pitch, three a priori planned contrasts were conducted adjusted for multiple comparisons via false-discovery rate (FDR) [4]: (i) time-variance: mean vs. rise/fall; (ii) pitch height: low vs. high; (iii) pitch direction: rise vs. fall. These contrasts revealed that POR latency distinguished static from time-varying contours [$F_{1,12} = 5.31$, $p_{\text{FDR}} = 0.039$] (static < time-varying) and the height of steady-state pitch patterns [$F_{1,12} = 11.46$, $p_{\text{FDR}} = 0.008$] (higher < lower) (Fig. 3A and B). However, POR latency was insensitive to the directionality of dynamic pitch glides [$F_{1,12} = 0.51$, $p_{\text{FDR}} = 0.480$] (rise = fall) (Fig. 3C). No reliable stimulus effect was

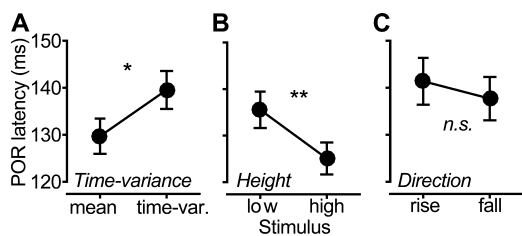


Fig. 3. PORs are sensitive to time-variance and the height of dynamic pitch patterns but not their direction. (A) Mean POR latency contrasting responses to stimuli with identical average F0 but differing in time-variance (i.e., flat mean vs. rise/fall). Earlier PORs are elicited for steady-state compared to time-varying pitch. (B) Mean POR latency contrasting pitch height (i.e., high vs. low). Earlier PORs are elicited for higher compared to lower pitches. (C) Mean POR latency contrasting the direction of time-varying pitch (i.e., rise vs. fall). No change in POR latency is observed for pitch glides of different direction. Error bars = \pm s.e.m. * $p_{FDR} < 0.05$, ** $p_{FDR} < 0.01$.

observed in POR amplitude [$F_{4,48} = 0.34$, $p = 0.850$]. Collectively, these findings indicate that the POR (latency) is sensitive to pitch height and time-varying pitch but not the direction of pitch change, per se.

4. Discussion

In the current study, cortical pitch onset responses (PORs) were characterized in response to isolated properties of dynamic pitch including height, time-variance, and direction. The present findings show that the POR deflection (~ 120 – 140 ms after initiation of pitch), is sensitive to both the overall height and time-varying nature of pitch trajectories. Yet, our data fail to provide evidence that the POR is sensitive to the direction of dynamic pitch changes. That is, the POR response does not appear to differentiate rising from falling pitch.

Collectively, our findings corroborate the notion that the POR is sensitive to pitch height [7,17], evoking earlier responses for stimuli with higher compared to lower F0s. Earlier responses to higher relative to lower pitch might be attributable to the well-known tonotopic organization of human auditory cortex and more apical (and hence delayed) cochlear initiation site for lower compared to higher tones [e.g.,21,22]. While distinction between frequency (a physical acoustic attribute) and pitch (a perceptual correlate) must be recognized, previous MEG studies suggest that the “tonotopic” profile of human auditory cortex reflects the pitch rather than frequency of the periodic stimuli [22] (see also [7]). Nevertheless, future studies are needed to clarify whether the POR’s sensitivity to the F0 contours observed here reflects pitch-specific processing per se, or a more general sensitivity to tracking time-varying spectral cues.

Our results further extend previous findings by revealing that in addition to height sensitivity, the POR is modulated by time-varying features of dynamic pitch patterns. This was evident by the fact that response latencies occurred earlier for static (i.e., flat) F0 stimuli compared to time-varying F0 contours (rise and fall), despite controlling for overall differences in pitch height (average F0 of mean, rise, fall was matched at 117.5 Hz; Fig. 1). Faster responses for steady-state relative to time-varying F0 patterns may reflect the effects of temporal integration on the formation of auditory object representations. It is conceivable that the auditory system might compute a stable representation of pitch much earlier for static compared to time-varying pitch given that former is a stationary signal (with regard to F0), requiring less time to compute the heard pitch. Indeed, previous electrophysiological studies demonstrate shorter N1 response latency for linear frequency sweeps of short compared to longer ramp durations [1]. Under this notion, dynamic, time-varying signals might require longer temporal integration windows [e.g.,16] as larger frequency changes would be

required to reach a comparable output level of a putative “pitch integrator” [2,3]. Estimates from behavioral studies suggest that the auditory system requires at least ~ 20 ms (a rate of change of 25 octave/sec) to identify the presence of frequency modulation [18]. Given that the duration of all of our stimuli fell well outside this psychophysical boundary, a pitch integrator mechanism could account for the prolongation in POR latency observed between steady-state and gliding pitches.

The present study also shows that the POR is largely insensitive to directional changes in pitch; response latencies were identical between rising and falling pitch sweeps. Psychophysical studies have been equivocal on a possible asymmetry in sensitivity between upward and downward sweep detection. Some studies have demonstrated that listeners are more sensitive at detecting changes in rising compared to falling pitch [18,26]. In contrast, others have reported no perceptual asymmetries between rising and falling glides [3,8,19]. Still others have shown the opposite pattern where listeners achieve higher sensitivity for downward compared to upward sweeping pitch [12,26]. However, as noted by Luo, et al. [18], a behavioral up/down asymmetry in frequency modulation perception is likely clouded by subjective bias (and/or language experience) of the observer. Electrophysiologically, human brainstem responses to time-varying pitch show similar neural phase-locked responses regardless of the direction of pitch sweeps [6,8]. Our current findings using cortical PORs are most compatible with these previous neural data, which similarly fail to demonstrate directionality sensitivity. Thus, it is possible that the neurophysiological encoding of rising and falling pitch is largely symmetric, with up/down asymmetries only emerging due to subjective biases in behavioral tasks. Future studies are needed to examine psychophysiological asymmetries in rising/falling pitch across both neural and behavioral levels.

While prominent latency effects were observed, time-variance and pitch height did not reliably modulate response amplitude. Reasons for this lack of an amplitude effect is unclear. However, this could be attributable to the higher intra- and inter-subject variability of ERP amplitudes compared to latency and the fact that amplitude effects are less salient when viewed in electrode- compared to source-level recordings [7,17]. Additionally, dynamic pitch properties could modulate POR amplitude in a topographic manner or based on the behavioral relevance of the stimuli to the listener [e.g.,7,16]. Future multichannel studies are needed to address these possibilities and extend initial findings reported herein.

Collectively, 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. Based on response characteristics, it is likely that the POR would be useful for examining musical pitch or gender identity in speech, both of which exploit relative changes in pitch height. This common pitch attribute is ideal, for example, when attempting to examine differential neural processing of pitch between music and language [e.g.,5]. Similarly, given the POR’s ability to distinguish steady-state from time-varying pitch, the response might be useful for estimating (electrophysiologically) thresholds for time-varying spectral information (e.g., formant transitions) which can be compromised with hearing loss [e.g.,24] or language impairments [e.g.,13]. However, the POR would probably fail to capture important aspects of pitch such as musical contour, linguistic pitch prosody, or lexical tones given its invariance to pitch direction.

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