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Musicians demonstrate experience-dependent brainstem enhancement of musical scale features within continuously gliding pitch

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ABSTRACT

In contrast to language, where pitch patterns consist of continuous and curvilinear contours, musical pitch consists of relatively discrete, stair-stepped sequences of notes. Behavioral and neurophysiological studies suggest that both tone-language and music experience enhance the representation of pitch cues associated with a listener's domain of expertise, e.g., curvilinear pitch in language, discrete scale steps in music. We compared brainstem frequency-following responses (FFRs) of English-speaking musicians (musical pitch experience) and native speakers of Mandarin Chinese (linguistic pitch experience) elicited by rising and falling tonal sweeps that are exemplary of Mandarin tonal contours but uncharacteristic of the pitch patterns typically found in music. In spite of musicians' unfamiliarity with such glides, we find that their brainstem FFRs show enhancement of the stimulus where the curvilinear sweep traverses discrete notes along the diatonic musical scale. This enhancement was note specific in that it was not observed immediately preceding or following the scale tone of interest (passing note). No such enhancements were observed in Chinese listeners. These findings suggest that the musician's brainstem may be differentially tuned by long-term exposure to the pitch patterns inherent to music, extracting pitch in relation to a fixed, hierarchical scale.

Musical pitch patterns differ substantially from those used in other domains, including language. Linguistic pitch patterns, for instance, are continuous and curvilinear [9] whereas in Western music, notes unfold in a discrete, stair-stepped manner [3]. The discrete nature of musical pitch stems directly from the fact that in Western tonal music, the octave is divided into 12 equally spaced pitch classes (i.e., semitones). Subsets of these pitches are then used to construct the intervals, chords, and hierarchical scales that define tonality and musical key [11].

Although curvilinear pitch contours can occur in specific musical instruments (e.g., trombone), these tend to be exceptions rather than the norm. Slides/sweeps and other such continuous changes are isolated events used primarily for ornamentation to embellish the otherwise discrete notes of a musical line [3]. It is universally accepted that pitch patterns in music are built upon a foundation of discrete, stair-stepped contours and that local "curvilinear" deviations from that model are simply decorations [3,7]. Indeed, the discrete nature of musical pitch – and the intervals it creates – is a necessary ingredient for both the perception and memorization of musical melodies [6,7].

Musicians spend countless hours listening to and manipulating tones of the musical scale. As such, they develop an internalized, cognitive representation (i.e., categories) for these discrete notes in otherwise continuously changing pitch [4,21]. This mental "grid" is quite robust to manipulation in that even distorted pitches are heard (i.e., mapped) in relation to an internalized musical scale [16]. Neurophysiological evidence supports this notion of an "internalized scale". As indexed by the mismatch negativity (MMN), musicians show heightened sensitivity to intervallic (cf. discrete) alterations in pitch compared to untrained listeners [19].

Indeed, recent evidence suggests that musicians may extract discrete features of the musical scale even at the level of the brainstem. In a cross-domain experiment, Bidelman et al. [1] examined frequency-following responses (FFRs) in both musicians and tone language speakers (Mandarin Chinese) in order to compare the effects of long-term pitch experience from music (musicians) and language (Chinese) pitch experience on subcortical encoding of pitch-relevant information. In one condition, FFRs were evoked by presenting listeners with a continuous linguistic (nonmusical)

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pitch sweep spanning the interval of a major third (DO → MI). Importantly, the passing tone of this sequence (i.e., DO-*RE*-MI[1]) was in no way demarcated as it would be had it occurred in a typical (discrete) musical sequence, i.e., the stimulus swept through this note without pause. Yet, despite the fact that such a glide is uncharacteristic of pitch patterns found in music, musicians' FFRs showed selective enhancement for the intermediate passing tone (RE) of the sweep. No such music-specific enhancements were observed in Chinese listeners, despite their enhanced representation for curvilinear pitch patterns [10,18]. These findings suggest that musicians may extract perceptually relevant features of the musical scale even at a subcortical level of processing.

However, such inferences were based on only a single, sweeping stimulus. In the present study, we hypothesize that if in fact musicians do have selective brainstem enhancement to intermediate, discrete scale tones within a sweeping pitch contour, then this effect must satisfy three criteria: (1) it must persist with changes in the absolute pitch height of the sweep (i.e., invariance with transposition); (2) it must persist regardless of sweep direction (ascending vs. descending); (3) it should be localized such that it is specific to musical pitches, i.e., the enhancement should not occur directly before or after the scale tone in question. Three pitch sweeps are used to test these manipulations and the selective scale tone enhancement effect. We compare brainstem FFRs between musicians and native speakers of Mandarin Chinese because both groups have exhibited subcortical enhancements in the encoding of complex pitch relative to English-speaking nonmusicians [1]. Here, Chinese nonmusicians serve as a control group to rule out that the observed scale tone enhancements are not simply related to pitch experience per se, but rather, are specific to musicians.

Fourteen English-speaking musicians (8 male, 6 female) and 14 native speakers of Mandarin Chinese (6 male, 8 female) participated in the experiment. The two groups were closely matched in age, years of education, handedness, and had normal hearing. Musicians were practicing amateur instrumentalists having ≥9 years of continuous instruction on their principal instrument (12.4 ± 2.4 yrs), beginning at or before the age of 11 (8.3 ± 2.2 yrs) (Table S1). None had any prior experience with a tone language. Chinese participants were born and raised in mainland China. None had received formal instruction in English before the age of 9 (12.1 ± 2.5 yrs) nor had > 3 years of musical training on any combination of instruments. Participants gave informed consent in compliance with a protocol approved by the Institutional Review Board of Purdue University.

Three time-varying fundamental frequency (F0) sweeps which are exemplary of Mandarin tonal contours, but uncharacteristic of the pitch patterns typically found in music, were created using an iterated rippled noise (IRN) algorithm [17] (Fig. 1). The first, standard (STD), was a replicate of the rising tonal sweep employed in our previous study [1]. Its F0 spanned a major third from A♭2 to C3 on the piano, 104 to 131 Hz, respectively. The second (UP), was identical to the STD sweep except that it was transposed upward by two semitones, i.e., a musical whole step. Its F0 spanned a major third from B♭2 to D3, 116 to 146 Hz, respectively. The third (DOWN), represented a mirrored version of the STD sweep, i.e., a falling tonal sweep, whose F0 spanned a major third from C3 to A♭2, 131 to 104 Hz, respectively. Thus, all three F0 contours traverse a major third in either the ascending (DO-RE-MI) or descending (MI-RE-DO)

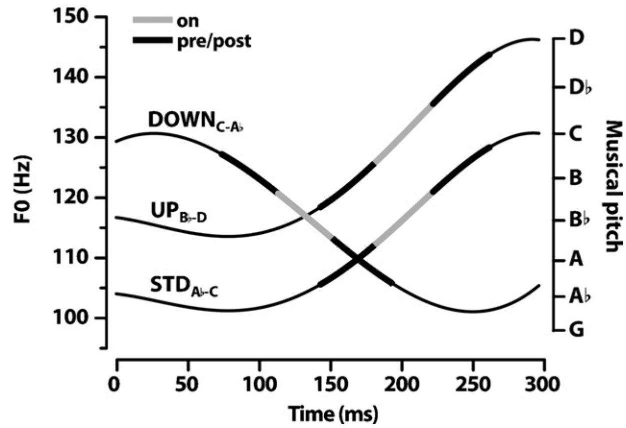

Fig. 1. Fundamental frequency (F0) contours of the stimuli. Each condition represents a continuous pitch sweep uncharacteristic of prototypical musical pitch patterns, which are typically discrete and stair-stepped. Compared to the standard (STD) condition, UP is transposed upward by two semitones, whereas DOWN represents a mirrored version which descends in pitch. All three F0 contours span a major third in either the ascending (DO-RE-MI) or descending (MI-RE-DO) direction. Analysis segments of interest (Pre, On, Post) are demarcated along the trajectory of each contour.

direction. However, the exact location of where the pitch contour intersects the passing note (RE) differs across stimuli. Compared to STD, UP moves this passing tone upward in absolute frequency whereas DOWN shifts it earlier in time (Fig. 1).

For all three stimuli, a high number of iterations (n = 32) was used in the IRN algorithm with the gain set to 1. At 32 iterations, IRN stimuli exhibit clear bands of spectral energy at the fundamental and its harmonics thus producing a salient sensation of pitch [20]. Yet, unlike speech or music, these stimuli are devoid of formant structure or a recognizable instrumental timbre [1]. The duration of all three waveforms was fixed at 300 ms (10 ms $\cos^2$ ramps). All waveforms were matched in overall RMS amplitude, bandwidth (30–3000 Hz), and were presented at a sample rate of 40 kHz.

Participants reclined comfortably in an electro-acoustically shielded booth to facilitate recording of brainstem responses. FFRs were elicited from each participant by monaural stimulation of the right ear at a level of 80 dB SPL (rarefaction polarity; 2.43/s repetition rate) through a magnetically shielded insert earphone (ER-3A). Presentation order was randomized within/across participants and controlled by a signal generation and data acquisition system (Intelligent Hearing Systems).

FFRs were obtained using a vertical electrode montage, the optimal configuration for recording neural activity in rostral brainstem [8]. Ag–AgCl scalp electrodes placed on the midline of the forehead at the hairline (~Fpz) and right mastoid (A2) served as the inputs to a differential amplifier. Another electrode placed on the mid-forehead served as common ground. The raw EEG was amplified by 200,000 and filtered online (30–5000 Hz). Interelectrode impedances were maintained ≤1 kΩ. Individual sweeps were recorded using an acquisition window of 320 ms at a sampling rate of 10 kHz. Neural responses were further band-pass filtered offline (80–2500 Hz). In total, each FFR waveform represents the average of 3000 artifact-free stimulus presentations (see also, Supplementary Methods).

We defined three 40-ms time segments of interest (Fig. 1) along the span of each stimulus pitch contour directly before (Pre), during (On), and after (Post) the RE passing tone in the DO-RE-MI sequence. To quantify FFR encoding of F0, FFTs were computed within each of the three time segments per stimulus: 145–185 ms (Pre), 186–226 ms (On), and 227–267 ms (Post) for both the STD and UP pitch sweeps and 75–115 ms (Pre), 116–156 ms (On), and 157–197 ms (Post) for the DOWN sweep. For each subject

[1] Defined musically, a passing tone is defined as an intermediate scale tone occurring between two chord tones. Passing tones typically fill in a melodic skip (i.e., interval) by conjunct stepwise motion. Here and throughout we use movable DO solfège to denote *scale degrees* (DO = scale tone #1, RE = #2, MI = #3) and not specific *pitch classes* (DO = C, RE = D, MI = E) as in a fixed DO system. For example, in movable DO nomenclature, RE is always the second note of the major/minor scale irrespective of key; in fixed DO, it is always the pitch D.