Brainstem correlates of behavioral and compositional preferences of musical harmony

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Certain chords are preferred by listeners behaviorally and also occur with higher regularity in musical composition. Event-related potentials index the perceived consonance (i.e., pleasantness) of musical pitch relationships providing a cortical neural correlate for such behavioral preferences. Here, we show correlates of these harmonic preferences exist at subcortical stages of audition. Brainstem frequency-following responses were measured in response to four prototypical musical triads. Pitch salience computed from frequency-following responses correctly predicted the ordering of triadic harmony stipulated by music theory (i.e., major > minor >> diminished > augmented). Moreover, neural response magnitudes showed high correspondence with listeners' perceptual ratings of the same chords. Results suggest that preattentive stages of pitch processing may contribute to perceptual judgments of musical harmony. ***NeuroReport*** **22:212–216 © 2011 Wolters Kluwer Health | Lippincott Williams & Wilkins.**

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Introduction

In music, the combination of multiple pitches produces harmonies whose sonority may be agreeable (i.e., consonant) or disagreeable (i.e., dissonant) to the ear. Behavioral studies show that independent of musical ability, listeners prefer certain musical pitch relationships over others and assign them higher status in hierarchical ranking [1,2]. It is this hierarchy, which largely contributes to the sense of a musical key and pitch structure, critical principles for both the organization, and perception of Western tonal music [3].

Neural correlates of musical consonance for simple dyads (i.e., two-tone intervals) have been identified at a cortical level in humans using both event-related potentials [4] and functional neuroimaging [5]. These studies show that brain activity is sensitive to the pitch relationships found in music and is selectively enhanced for certain musical intervals relative to others according to their perceptual status and significance in music. Recent evidence also suggests that such correlates may exist in the very initial stages of the auditory pathway including auditory nerve [6] and brainstem [7]. Thus, preattentive mechanisms may play a role in forming simple musical pitch attributes. However, it is important to remember that music is created from more than the simple two-note intervals examined to date. Triads (i.e., three-note chords), for instance, are a ubiquitous component of musical harmony. Yet despite their importance to written and heard music, there is heretofore, no entirely convincing explanation for why listeners prefer certain chords over others [1,2,8]. We hypothesized that sensory-level, neurophysiological processing within the brainstem may contain adequate information relevant to these harmonic preferences in music.

As a window into the early stages of subcortical pitch processing we use the scalp-recorded frequency-following response (FFR). The FFR reflects sustained phase-locked activity from a population of neural elements within the midbrain (see [9] for review). Importantly, the FFR provides a robust index of the brainstem's transcription of speech [10] and musically relevant features of the acoustic signal [7,11,12]. Here, we compare behavioral ratings with spectro-temporal properties of the FFR evoked by musical triads to determine if correlates of musical harmony exist in preattentive stages of audition.

Methods

Participants

Ten normal hearing (i.e., thresholds ≤ 25 dB hearing level) adults participated in the experiment. Their ages ranged from 20 to 26 years ($\mu \pm \sigma$; 23.4 ± 2.1 years). All had formal musical training (13.6 ± 1.7 years) on one or more instruments and none reported any history of neurological or psychiatric illness. All participants gave informed consent in compliance with a protocol approved by the Institutional Review Board of Purdue University and were provided monetary compensation for their time.

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Stimuli

Four standard triads (i.e., three-note chords) common to Western music were constructed from pitches drawn from the equal tempered musical scale. Individual pitches were synthesized using a 200 ms tone-complex (six cosine phase harmonics of equal amplitude) of different fundamental frequencies (f_0s). Three pitches were then combined vertically to create the major (note f_0s; 220, 277, 330 Hz), minor (220, 261, 330 Hz), diminished (220, 261, 311 Hz), and augmented (220, 277, 349 Hz) triads, respectively. Each chordal stimulus was 200 ms in total duration (including a 10 ms rise–fall time).

Behavioral chordal ratings

Perceptual consonance ratings for the chordal triads were measured using continuous rating scales. The four triads were presented to each participant through circumaural headphones at a comfortable listening level (~ 70 dB sound pressure level). Participantts were instructed to rate the chords on a continuum ranging from 1 (maximally dissonant, i.e., unpleasant sounding) to 7 (maximally consonant, i.e., pleasant sounding) [1,2] and to use the scale's full range in making their judgments. The order of the chords was randomly assigned within and between participants. Listeners made their ratings using slider bars in a custom graphical user interface coded in MATLAB. They were allowed to replay each chord to compare them with one another and once content with their decisions, their final rating was recorded for each triad.

Frequency-following response recording protocol

Details of data acquisition procedures can be found in previous reports from our lab [7] (see also Supplemental Methods, *http://links.lww.com/WNR/A105*). Briefly, FFRs were recorded from each participant in response to monaural stimulation of the right ear (81 dB sound pressure level) through a magnetically shielded insert earphone. FFRs were recorded using a common noninverting electrode placed on the midline of the forehead at the hairline referenced to: (i) the ipsilateral mastoid (A2); (ii) the contralateral mastoid (A1); and (iii) the 7th cervical vertebra. An electrode placed on the mid-forehead (Fpz) served as the common ground. These three channels produced nearly indistinguishable responses (Supplemental Methods, *http://links.lww.com/WNR/A105*) thus only results from the ipsilateral channel (i.e., high forehead – A2) are reported. Note, this ipsilateral vertical configuration is widely considered the optimal arrangement for recording brainstem FFRs [9,13]. Interelectrode impedances were maintained at less than or equal to 1 kΩ. Neural activity was amplified by 200 000 and band-pass filtered from 70–5000 Hz. Control of the experimental protocol was accomplished by a signal generation and data acquisition system (Intelligent Hearing Systems) using a sampling rate of 10 kHz. In total, each response waveform represents the average of 3000 artifact free trials over a 230 ms acquisition window.

Frequency-following response data analysis

FFRs were analyzed based on their neural periodicity [7] (for details, see Supplemental Methods, *http://links.lww.com/WNR/A105*). Weighted ($\tau = 10$ ms) autocorrelation functions (ACFs) were computed for each FFR to index the dominant periodicities present in the response. 'Neural pitch salience' was estimated from FFR ACFs using periodic template analyses whereby a series of harmonic interval sieves (100 μs wide bins) selected ACF activity at a given pitch period (i.e., $1/f_0$) and its multiples [7,14]. For each template, the salience for a given pitch was estimated by dividing the mean density of activity falling within the sieve bins by the mean density of activity in the whole ACF. The output from each template was then concatenated as a function of f_0 to construct a running salience curve representing the relative strength of possible 'pitches' present in the FFR. The maximum of this function was taken as a singular measure of neural pitch salience for a given chordal stimulus. The use of a single value to describe the total salience of the response mimics the fact that although chords are composed of multiple pitches, listeners perceive them as being merged or fused into a single unitary percept (e.g., 'pitch fusion' or 'pitch unity') [15]. Running neural pitch salience curves (i.e., output of the periodic sieve analyzer) are shown for the four triads in Fig. 1.

Results

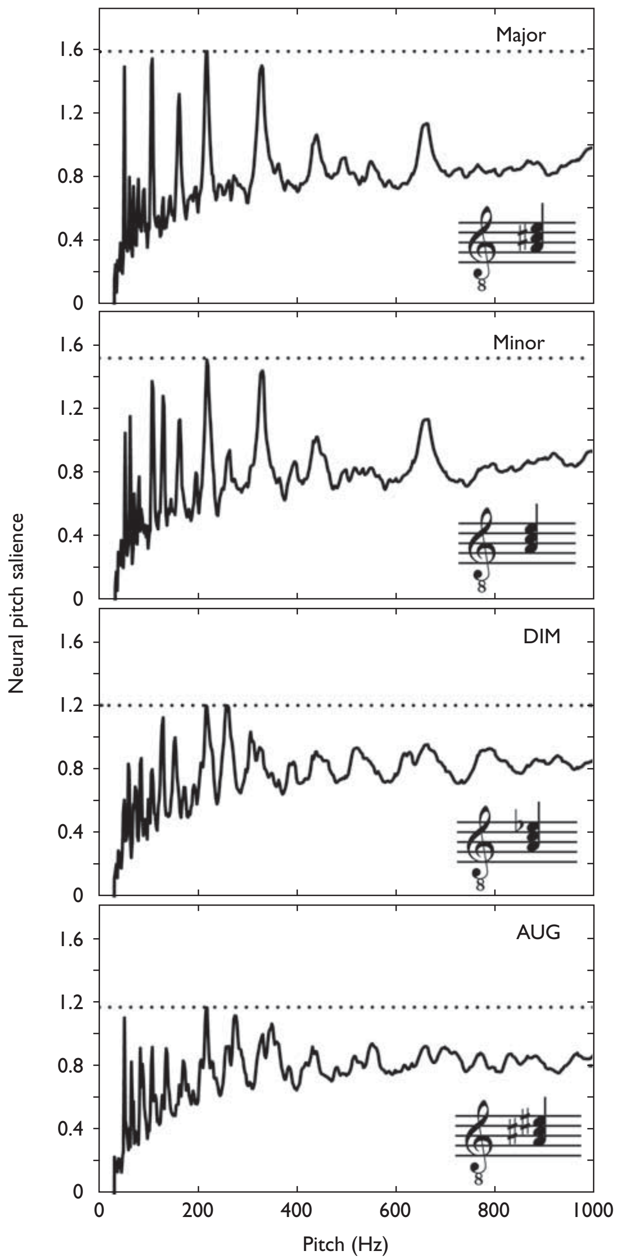
Behavioral triadic consonance ratings

Mean behavioral consonance ratings for the four triadic harmonics are shown in Fig. 2a. A Kruskal–Wallace nonparametric ANOVA (used because rank observations failed normality) revealed a significant main effect of chord type on perceptual ratings [$\chi^2(3) = 31.98$, $P < 0.0001$]. Bonferroni corrected multiple comparisons (Wilcoxon rank sum tests; $\alpha_{\text{individual}} = 0.01$) revealed that the consonance ratings of chords followed an ordering which closely matched their importance in music theory, i.e., major > minor > diminished = augmented. Subjects generally preferred the consonant major and minor triads over the dissonant diminished and augmented harmonies suggesting that chords of the former pair were judged more pleasant sounding than those of the latter. The ordering of ratings observed here (i.e., major > minor > diminished ≥ augmented) is consistent with previous reports of musical chord preferences by both musician/non-musician and Western/non-Western listeners [1,2,7].

Brainstem pitch salience reveals differential encoding of musical chords

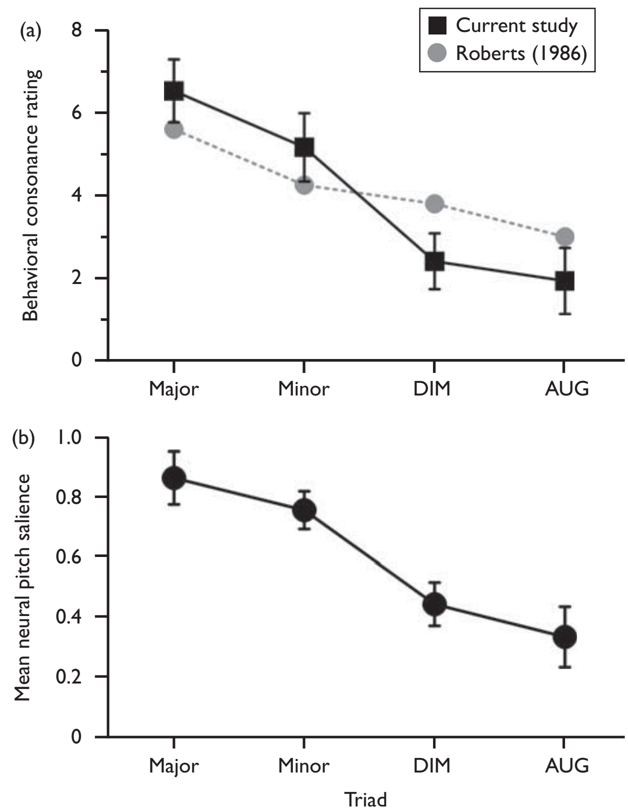
Mean neural pitch salience derived from individual FFRs are shown for each of the four triads in Fig. 2b. An omnibus analysis of variance showed a significant effect

Fig. 1



Running neural pitch salience curves (i.e., output of periodic sieve analysis) computed from frequency-following responses (FFRs) to major, minor, diminished, and augmented harmonies. Each curve quantifies the salience of all possible pitches encoded in the FFR (see Methods for details). The peak magnitude (dotted lines) represents a singular measure of salience for the eliciting musical chord. Insets show the musical notation for each stimulus. AUG, augmented; DIM, diminished.

Fig. 2



Perceptual and neurophysiological responses to musical triads. (a) Mean behavioral consonance ratings for the four most common triadic harmonies of Western music. Chords considered consonant according to music theory (i.e., major, minor) are preferred over those considered dissonant (i.e., diminished, augmented) and show an ordering expected by music practice (i.e., major > minor >> diminished > augmented). Chordal ratings for musicians reported in [2] are shown for comparison. (b) Mean neural pitch salience derived from frequency-following responses. Values are normalized to the largest pitch salience measured across participants. Neural responses mimic the perceptual ratings of musical chords in that consonant triads produce greater pitch salience than dissonant triads and follow the same ordering. Error bars indicate ± 1 standard deviation. AUG, augmented; DIM, diminished.

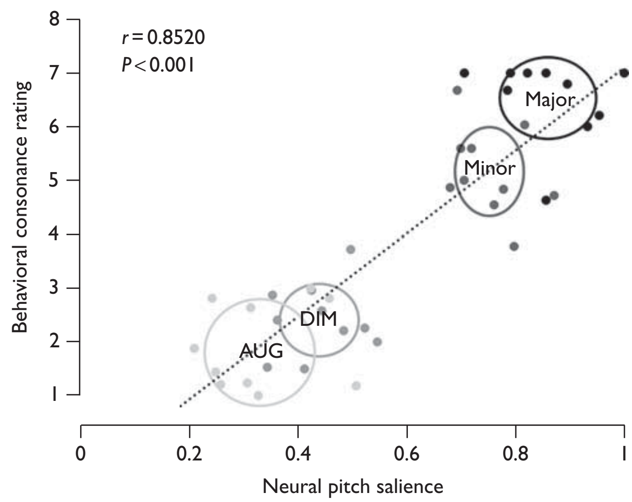
Table 1 Compositional prevalence and acoustical correlates of triadic harmony

Chord	Prevalence (%)[a]	Degree of harmonicity (%)[b]	Acoustic pitch salience[c]
Major	50.8	46.67	1.59
Minor	36.5	46.67	1.54
Diminished	8.32	31.11	1.20
Augmented	< 1.37	31.26	1.18

[a]Frequency of occurrence from a sample of 18–19th century music reported by [16].
[b]Computed as the mean percent similarity of the chordal notes to a single harmonic series ([17], p. 2).
[c]Computed using periodic sieve analysis applied to the chord's acoustic waveform ([7]; see Methods).

of chord type on neural pitch salience [$F(3,27) = 93.14$, $P < 0.0001$]. Bonferroni adjusted multiple comparisons showed that the magnitudes of neural pitch salience elicited by the chordal stimuli followed an order identical to that of the behavioral data, that is, major > minor > diminished > augmented. This ordering is also identical to the prevalence with which these chords occur in musical composition and practice (see Table 1). As expected, the two consonant harmonies (major, minor)

Fig. 3



Brainstem neural pitch salience computed from frequency-following responses (FFRs) predicts behavioral chordal consonance ratings. Each point represents an individual listener's FFR/behavioral response; the centroid of each ellipse gives the grand average for each chord. The major and minor chords elicit a larger neural pitch salience than the diminished and augmented chords and are also judged more pleasant by the listener. Note the systematic clustering of the major–minor (consonant) and diminished-augmented (dissonant) sonorities and their maximal separation from one another in the neural-perceptual space. Standard errors are represented by the radius of each ellipse in either the neural or behavioral dimension, respectively. AUG, augmented; DIM, diminished.

elicited stronger neural activity than the dissonant triads (diminished, augmented). It is interesting to note that chords, which elicited more robust FFRs (i.e., major, minor) are also those typically considered more structural, or 'pure', in tonal music.

Figure 3 shows behavioral consonance ratings plotted against neural pitch salience for each of the four triads. Neural and behavioral data were significantly correlated (Pearson's $r = 0.85$, $P < 0.001$) suggesting that subcortical processing can, in part, predict an individual's behavioral judgments of triadic harmonies. The ordering of chords in the neural-perceptual space shows differential encoding; consonant musical chords (major, minor) judged more pleasant by listeners subsequently yield more robust neural pitch salience than dissonant chordal relationships (diminished, augmented).

Discussion

There are two main observations of this study: (i) neural phase-locked activity in the brainstem seems to preserve information relevant to the perceptual attributes of triadic harmony and (ii) the strength of this aggregate neural activity seems to be correlated with the perceptual consonance (and preferences) of musical chords perceived by listeners.

Across all individuals, we found that consonant musical harmonies, that were judged to be more pleasant sounding than dissonant harmonic relationships, elicited FFRs with more robust pitch relevant information. It is also important to point out that the characteristics of both the neural and behavioral responses we observe are graded (i.e., major > minor >> diminished ≥ augmented). Harmonic relationships are not encoded in a strict binary manner (i.e., consonant vs. dissonant) but rather, are processed differentially based on their *degree* of perceptual consonance. It is of interest to note that the chordal relationships we find to elicit larger brainstem FFRs are not only deemed more pleasant sounding by listeners (present data, [1,2,18]) but also occur more frequently in tonal composition [16,19,20] (Table 1).

To explain the preferences of harmonic tone combinations, psychophysical models generally require the inclusion of more abstract aspects of music perception (e.g., 'intervallic tension', 'affective valence' [1]) to fully account for the consistent rankings of triads reported across a wide range of studies and subject pools [1,2]. Yet, considering a singular measure of either the acoustic periodicity (ACF magnitude) or harmonicity [17] of our chordal stimuli alone, it is possible to predict the correct rank order of triads based on either their behavioral preferences or their compositional prevalence (Table 1). Thus, waveform periodicity itself provides important information to initiate the perceived consonance of triadic harmony (e.g., [8]). We infer that this acoustic signature supplies relevant periodicity to the neural responses we observe at a subcortical level (*cf.* [7]).

Our results offer new evidence that correlates of musical pitch percepts also exist in sensory-level, neurophysiologic processing [6]. For consonant triads, interspike intervals within the population activity of the midbrain occur at precise, harmonically related pitch periods thereby producing a higher degree of coherence in their neural representation and hence, maximizing pitch salience. In contrast, dissonant triads evoke less coherent neural periodicity and subsequently elicit much lower neural pitch salience (Figs 1 and 2b). Our salience metric is closely related to the psychophysical phenomenon of 'pitch fusion' or 'tonal affinity', which measures the degree to which two or more pitches resemble a single tone or harmonic series [15,17] (Table 1). Insomuch as our listeners' behavioral rankings reflect their perception of a chord's fusion/harmonicity, their behavioral preferences for the triadic harmonies (Fig. 2a) may be reflected in the degree of pitch salience (i.e., 'neural fusion') found in their corresponding brainstem responses (Figs 2b and 3).

Although we do not claim the brainstem *produces* the percept of pitch, our data do imply that it may *contribute* to forming, or at least maintaining, musically relevant neural representations of the input signal. Brain networks engaged during music involve a series of computations applied to the neural representation at different stages of processing (e.g., [12,21]). Physical acoustic periodicity is transformed to musically relevant neural periodicity very early along the auditory pathway (e.g., auditory nerve [6]) and transmitted and enhanced in subsequently higher levels in the auditory brainstem ([7]; present study). Although the percept of musical harmony ultimately lies with higher, cognitive mechanisms, the robust pitch-relevant information we find encoded in the brainstem would presumably, eventually feed the complex cortical architecture responsible for generating and controlling such percepts [11,22]. The brainstem-behavior connections we observe here for musical chords along with those reported previously for two-tone musical intervals [6,7], provides further evidence that some of the most basic pitch attributes governing music may be rooted in sensory features that emerge very early along the auditory pathway [6,7,23]. Acoustical and other explanations notwithstanding, a neurobiological predisposition for simpler, consonant musical harmonies may be one reason why such relationships have been favored by composers and listeners throughout history (Table 1) [3].

Conclusion

Subcortical responses to musical chords showed that pitch relationships relevant to harmony perception are automatically encoded at a preattentive, sensory-level of auditory processing. Pitch relevant information preserved in brainstem FFRs is well correlated with chordal stability (i.e., consonance) ratings obtained behaviorally suggesting that a listener's judgment of pleasant or unpleasant sounding harmonies may be rooted in low-level sensory processing. It is possible that the preferential use of certain chords in compositional practice may have originated based on the fundamental processing and constraints of the auditory system.

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