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Consonance and Pitch

Neil McLachlan, David Marco, Maria Light, and Sarah Wilson
University of Melbourne

To date, no consensus exists in the literature as to theories of consonance and dissonance. Experimental data collected over the last century have raised questions about the dominant theories that are based on frequency relationships between the harmonics of music chords. This study provides experimental evidence that strongly challenges these theories and suggests a new theory of dissonance based on relationships between pitch perception and recognition. Experiment 1 shows that dissonance does not increase with increasing numbers of harmonics in chords as predicted by Helmholtz's (1863/1954) roughness theory, nor does it increase with fewer pitch-matching errors as predicted by Stumpf's (1898) tonal fusion theory. Dissonance was strongly correlated with pitch-matching error for chords, which in turn was reduced by chord familiarity and greater music training. This led to the proposition that long-term memory templates for common chords assist the perception of pitches in chords by providing an estimate of the chord intervals from spectral information. When recognition mechanisms based on these templates fail, the spectral pitch estimate is inconsistent with the period of the waveform, leading to cognitive incongruence and the negative affect of dissonance. The cognitive incongruence theory of dissonance was rigorously tested in Experiment 2, in which nonmusicians were trained to match the pitches of a random selection of 2-pitch chords. After 10 training sessions, they rated the chords they had learned to pitch match as less dissonant than the unlearned chords, irrespective of their tuning, providing strong support for a cognitive mechanism of dissonance.

Keywords: dissonance, model, pitch, perception, recognition

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The idea that music tuning systems could be based on simple ratios of string or pipe lengths was known in China and Greece over 2,000 years ago. Much later, in the 13th century A.D., simple ratio tunings were explicitly associated with the perceived smoothness of chords (Partch, 1974). For the remainder of the second millennium A.D., music theorists debated the benefits of various tuning strategies in terms of the relative roughness of intervals created at different steps of music scales (Chalmers, 1990; Partch, 1974).

Pythagorus linked the consonance he perceived for simple ratios of string length to the broader principle that simple number relationships underpin the order of the cosmos (Tenney, 1988). This principle led to a long tradition of mathematical theories of harmony in music and the visual arts in the West. Early in the scientific revolution, anatomists and psychophysicists developed mechanistic models of pitch and dissonance (Helmholtz, 1863/1954) that sought to explain the prevalence of small-integer ratio tunings in Western music. Later, computing and information theory were used to revise these theories into algorithmic models of auditory processes related to pitch and dissonance (de Cheveigné, 2005; Sethares, 1993). More recently, models of auditory processing have captured the attention of cognitive scientists and neuroscientists interested in linking acoustic and psychoacoustic processes to the ability to recognize and categorize sound and speech (Thompson, 2009). Recent models have shown how these categorization processes can influence perceptual systems at a fundamental level via mechanisms of neuroplasticity (McLachlan & Wilson, 2010). As we show in this article, from a broad perspective, understanding pitch and consonance addresses fundamental questions about human cognition that has applications to many fields of research, ranging from basic sensory processes to emotions.

Theories of Consonance and Dissonance

In 1863, Helmholtz (1863/1954) proposed that dissonance was created by the beating of closely tuned tones that give rise to perceptual roughness. The overtone frequencies of most naturally occurring tonal sounds are arranged in the harmonic series (i.e., at integer multiples of the fundamental or lowest frequency component). For tunings at integer ratios, the frequency differences between some pairs of harmonics are at zero while the differences for all other pairs are at local maxima (Figure 1). Helmholtz proposed that Western music intervals occur at close to integer ratios to minimize roughness due to the beating of closely tuned pairs of harmonics. Figure 1 shows the relationships of harmonics that minimize beating and roughness. Specifically, two complex harmonic tones are tuned at a frequency ratio of 3:2, so the

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Neil McLachlan, David Marco, Maria Light, and Sarah Wilson, School of Psychological Sciences, University of Melbourne, Melbourne, Victoria, Australia.

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Correspondence concerning this article should be addressed to Neil McLachlan, Melbourne School of Psychological Sciences, University of Melbourne, Melbourne, Victoria, 3010 Australia. E-mail: mcln@unimelb.edu.au

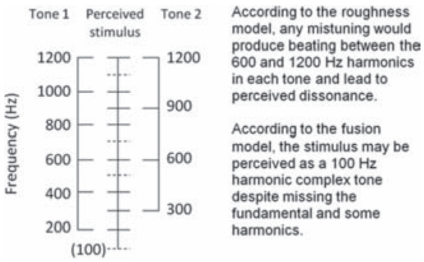

Figure 1. Schematic representation of two harmonic complexes tuned to a frequency ratio of 3:2 (a perfect fifth) predicted to be very consonant by the roughness and fusion models.

frequency differences between both the 600- and 1,200-Hz harmonics are zero, while the differences for all other pairs are at local maxima. A small mistuning of either complex leads to beating between the pairs of harmonics at 600 and 1,200 Hz, which would increase the perceived roughness and dissonance (Plomp & Levelt, 1965).

In 1898, Stumpf proposed the tonal fusion theory of consonance (DeWitt & Crowder, 1987; Ebeling, 2008; Guernsey, 1928; Huron, 1991) in which consonance is associated with perceptual fusion of pitches of harmonic complex tones that are tuned to integer frequency ratios and so have pairs of harmonics at common frequencies. In Figure 1, perceptual fusion would lead to the perception of a single harmonic complex with a fundamental at 100 Hz, despite the absence of some harmonics and the fundamental (dotted lines in Figure 1). According to Stumpf's theory, the similarity of the perceived stimulus in Figure 1 to a harmonic series could lead to misrecognition of the stimulus as a single harmonic complex as this is a more parsimonious sensory experience. Fusion is most likely to occur for music chords tuned close to small-integer ratios since they share more harmonics.

In 1928, Martha Guernsey reported a series of experiments that presented substantial challenges for both Helmholtz's roughness theory of dissonance and Stumpf's tonal fusion theory of consonance. Guernsey found no evidence that changing stimulus timbre affected consonance as predicted by these theories; instead she found strong effects of music training on consonance. This discovery led her to suggest that consonance was associated with familiarity for commonly used music chords.

In 1974, Terhardt distinguished the perception of sensory dissonance for simultaneous tones when independent of a music context from musical dissonance that is experienced when music deviates from an expected pattern of chords or notes. In the Western music tradition, these expected sequential patterns have been formulated as functional harmony (Piston, 1948). Experiment 1 in this article is concerned with developing and testing a neurocognitive model of sensory dissonance experienced for music chords in the absence of a musical context. In this experiment, we re-examined the dominant theories of dissonance in light of modern findings by extending the experimental paradigm employed by Guernsey. The results will be presented in four parts. Part 1 examines a key prediction of Helmholtz's theory that dissonance increases with the number of harmonics in the stimulus due to greater beating and roughness when chords are not tuned to simple integer ratios. Part 2 describes a new test of Stumpf's theory of consonance, in which the ability to match pitch height is predicted to be less certain for stimuli with greater tonal fusion. In Part 3, these pitch-matching results provide experimental support for a recent theory of concurrent pitch processing (McLachlan, 2011), which leads, in Part 4, to the development and testing of a new model of dissonance that incorporates pitch-matching mechanisms. In Experiment 2, we tested this model by training nonmusicians to match the pitches in a random selection of 2-pitch chords over 10 sessions. We then compared their dissonance ratings for these chords with dissonance ratings for the remaining 2-pitch chords.

Experiment 1: Pitch Matching, Familiarity, and Dissonance

Method

Participants. Seventy-one adults (46 women, 25 men; mean age = 22 years, *SD* = 7 years) participated in the study, and the data from 66 of these participants were included in the analyses after screening (see Procedure). Participants included undergraduate and postgraduate students from the University of Melbourne and the Melbourne Conservatorium of Music, as well as adults recruited from the general community. The mean number of years of participants' formal education was 14.6 (*SD* = 2.4). All participants completed a questionnaire about their music experience (J. W. Wilson, Lusher, Martin, Rayner, & McLachlan, 2012) and reported having normal hearing and no serious neurological conditions. Information about the study was provided and written informed consent was obtained.

When the level of music training was a variable in analyses, the participants were divided into three groups on the basis of their years of formal music training on a pitched musical instrument. Figure 2 shows the distribution of formal music training across the participants in the study. It indicates that they fell naturally into one of three groups: (a) no training (0 years of training; *n* = 14, three men, 11 women), (a) low training (up to 12 years of training; *M* training = 6 years; *n* = 40, 15 men, 25 women), and (c) high training (more than 15 years of training; *M* training = 19 years; *n* = 12, four men, eight women).

Materials. Three types of stimuli were created to investigate whether dissonance increased systematically with the number of harmonics present in the stimuli. They were (a) pure tones, (b) odd harmonic complexes composed of a fundamental plus equal-amplitude harmonics at three and five times the frequency of the fundamental, and (c) full harmonic complexes composed of a

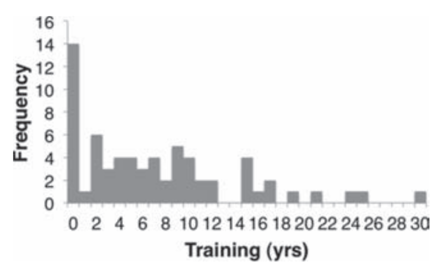

Figure 2. Frequency histogram representing years (yrs) of formal music training for all participants.

fundamental plus five equal-amplitude harmonics. Six 2-pitch and six 3-pitch chords with intervals of up to eight semitones were created from each stimulus type (Table 1), generating 36 chord stimuli in all. These chords provide a representative sample of varying dissonance and familiarity in accordance with categorizations of chord dissonance and chord usage in Western music (Krumhansl, 1990). Each chord was presented a sufficient number of times to allow pitch matching of each pitch in the chord in separate presentations in different blocks (see Procedure). In addition to the chords, three single-pitch stimuli of each stimulus type were presented for comparison with pitch-matching distributions for the chords (nine 1-pitch stimuli in all). This led to a total of 99 stimulus presentations. The pitches of the stimuli were evenly distributed within the Western chromatic scale over the range of 220–466 Hz (A_3 to $A^{\#}{}_4$).

Procedure. For each stimulus presentation, participants were first asked to match one of the pitches in the stimulus and then to rate the familiarity and the dissonance of the stimulus on separate Likert-type scales. All stimuli were presented to participants individually in an anechoic chamber at a sound pressure level of 70 ± 2 dB through two loudspeakers located on either side of a computer monitor (1 m in front and 0.5 m apart). Trials were presented randomly over three blocks of 25 trials and one block of 24 trials, with each block lasting approximately 10 min. Breaks were provided between blocks to minimize fatigue effects.

The pitch-matching task was adapted from B. C. J. Moore and Glasberg (1985). Before the presentation of each chord, participants were informed of the number of pitches (one, two, or three) and the target pitch they were required to match (lowest, middle, or highest). Target stimuli were followed by a single probe tone pitch that was repeated three times, as shown in Figure 3. Bidirectional lateral movement of a computer mouse by the participants altered the pitch of the probe tones (right movement increased pitch). The target stimulus and probe tones were repeated until participants clicked the mouse to indicate when they thought the probe tone matched the target, and the cycle was terminated. Purpose-built computer software was used to present the stimuli and record task responses. The software distributed 800 screen pixels evenly between 200 and 500 Hz, providing a frequency resolution of 0.375 Hz per pixel. Pitch matching of all component pitches in each stimulus was tested over 99 separate trials, pseudorandomly ordered so that concurrent presentations of the same chord were avoided.

Table 1
Intervals Used in This Study Showing Their Frequency Ratios and Common Music Names

Semitone interval	Frequency difference (%)		Chord names
2	12.2		Major 2nd
3	18.9		Minor 3rd
4	26		Major 3rd
6	41.4		Tritone
7	49.8		Perfect 5th
8	58.7		Minor 6th
2 & 7	12.2	49.8	Suspended 2nd triad
3 & 6	18.9	41.4	Diminished 5th triad
3 & 7	18.9	49.8	Minor triad
4 & 6	26	41.4	Flattened 5th triad
4 & 7	26	49.8	Major triad
4 & 8	26	58.7	Augmented 5th triad

At the completion of each pitch-matching trial, a rating screen appeared on the computer monitor for participants to grade the dissonance and familiarity of the target stimuli. Two separate 5-point Likert-type scales were used to measure perceived familiarity (1 = *not familiar*, 5 = *very familiar*) and perceived dissonance (1 = *not dissonant*, 5 = *very dissonant*). Dissonance was described to the participants as an experience that may be related to perceived roughness, harshness, unpleasantness, or difficulty in listening to the sound.

Prior to the experimental trials, participants completed a questionnaire to collect demographic, health, and music background data (S. J. Wilson, Pressing, Wales, & Pattison, 1999). All participants were also tested for absolute pitch ability using an established pitch-naming task (J. W. Wilson et al., 2012; S. J. Wilson, Lusher, Wan, Dudgeon, & Reutens, 2009), but no participant scored above chance (greater than 10 out of 50 correct responses). Participants then completed three practice trials on 2- and 3-pitch chords with assistance from the investigator to ensure adequate task comprehension, followed by a series of screening trials using pure tone stimuli. The screening continued up to a maximum of 10 trials with supervision until participants had accurately pitch matched a pure tone to within two semitones on three successive trials. Data from five participants who could not pass the screening task were excluded from analyses.

Part 1: Dissonance and Roughness

Background. To investigate the relationship between roughness and dissonance, Plomp and Levelt (1965) used pure tones to measure dissonance ratings for a range of nonmusical (unfamiliar) intervals between unison and an octave. Maximum dissonance ratings occurred at about 25% of the frequency resolution of the cochlea (or one critical bandwidth; Zwicker & Fastl, 1999), leading them to concur with Helmholtz (1863/1954) that dissonance is caused by the roughness of tones that are not resolved by the cochlea. This explanation of sensory dissonance has dominated the literature since (Fishman et al., 2001; Terhardt, 1974; Tufts, Molis, & Leek, 2005). For example, Sethares (1993) computed the dissonance of a range of music timbres and intervals by summing the pure tone dissonance values across all pairs of harmonics in a chord according to the model proposed by Plomp and Levelt (1965).

Kameoka and Kuriyagawa (1969) further extended the Plomp and Levelt (1965) model by suggesting that Stevens's (1957) power law should be applied to sum psychological percepts such as roughness. By varying the free parameters of the model, they were able to fit computed dissonance with behavioral data for a range of stimulus timbres with increasing numbers of harmonics. However, they did not systematically compare behavioral data between stimuli such as chords of pure and complex tones. This is important because summation of dissonance for all pairs of harmonics in a chord as proposed by Helmholtz (1863/1954), Plomp and Levelt (1965), and Kameoka and Kuriyagawa (1969) and later by Sethares (1993) predicts that the dissonance ratings for chords of harmonic complexes will be greater than for chords of pure tones tuned to the same pitches, since the overtones of the harmonic complexes are additional sources of beating. Previous data

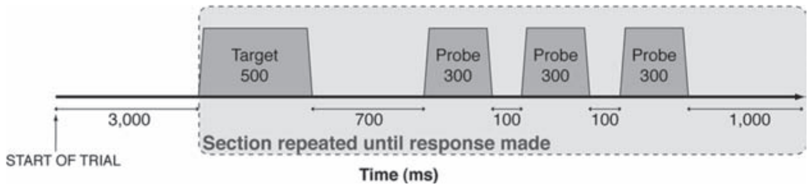

Figure 3. Schematic representation of the presentation of auditory stimuli. Each target stimulus and probe were synthesized with 30-ms linear onset and offset ramps and presented in a continuous sequence (shaded box) until participants matched the pitch of the probe to the target. Probes were synthesized in real time at frequencies governed by participant movement of the computer mouse. Axis is not shown to scale.

for chords of pure and complex tones collected by Kaestner in 1909 (replotted in Huron, 1991) and Guernsey (1928) did not support this important prediction of the Helmholtz theory.

Aims and hypotheses. A statistical analysis of the effect of the number of harmonics in chords on dissonance ratings is not available in the literature. Thus, in this analysis, the dissonance ratings for a range of chords comprising pure and complex tones were compared with the predictions of Sethares's (1993) dissonance algorithm, which is based on the model of Plomp and Levelt (1965) and the roughness theory of dissonance proposed by Helmholtz (1954). In accordance with the predictions of the Sethares algorithm, we hypothesized that the chords of harmonic complex tones would be rated higher in dissonance than chords of pure tones at the same pitches. We tested this hypothesis by comparing the dissonance ratings for the series of 2- and 3-pitch chords comprising pure tones and harmonic complexes.

Results. In order to test the hypothesis, we performed a repeated-measures analysis of variance (ANOVA) with planned repeated contrasts to compare dissonance ratings across the three stimulus types. The gray lines in Figure 4 show the predictions of the Sethares algorithm for 2-pitch chords of full harmonic complexes (solid), odd harmonic complexes (dashed), and pure tones (dotted). For pure tones, the algorithm simply reproduces the Plomp and Levelt's (1965) dissonance curve, whereas for harmonic complexes, dips in dissonance were predicted by the algorithm at integer frequency ratios due to local minima in roughness (Sethares, 1993). The black lines in Figure 4 show the participant dissonance ratings for full harmonic complexes (solid), odd harmonic complexes (dashed), and pure tones (dotted). The similarity of dissonance ratings for these stimulus types across 2-pitched chords is in stark contrast to the predictions of the Sethares algorithm. Consistent with this, a repeated-measures ANOVA revealed no main effect for stimulus type on dissonance ratings, collapsed across chord tuning for all 2- and 3-pitch chords, $F(1.3, 86.3) = 0.36$, $p = .61$, failing to support the Helmholtz roughness model of dissonance.

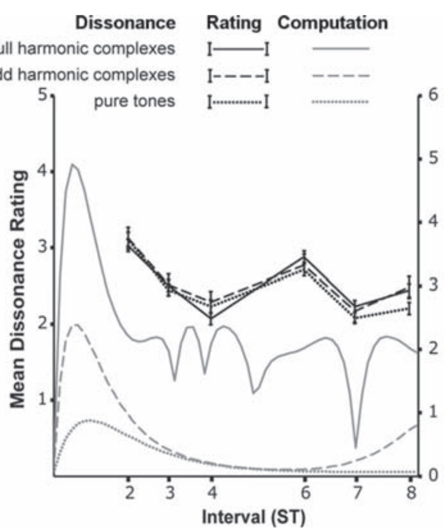

Figure 4. Mean dissonance ratings compared with computed dissonance using the Sethares algorithm for full harmonic complexes and pure tones tuned to intervals between two and eight semitones for 2-pitch chords. Error bars show ±1 standard error of the mean. ST = semitone. ST = semitone.

Discussion. Despite the long tradition of attributing dissonance to rapid beating of auditory neural responses, this study found no evidence for the Helmholtz roughness model of dissonance. In contrast, the lack of a statistical difference between the mean dissonance ratings for pure and complex harmonic tones confirms earlier findings by Guernsey (1928) and supports the findings of McDermott, Lehr, and Oxenham (2010) that individual preferences for consonance are not related to preferences for stimuli without beats.

Pairs of tones with a frequency difference of less than the resolution of the cochlea have been shown to cause beating of neural activity at both peripheral and higher levels of the auditory system in monkeys and humans (Fishman et al., 2001). Fishman and colleagues also reported that the amplitude of the neural beat frequencies increased for chords commonly reported to be dissonant. Close inspection of their data reveals that this effect was supported by the dissonant chords with intervals of less than a critical bandwidth (two semitones or less). If dissonance was due to beating of auditory neural firing rates, then it would be innate to all mammals. However, monkeys failed to discriminate between consonant and dissonant chords (McDermott & Hauser, 2004), which points to the importance of higher level mechanisms rather than stimulus-driven mechanisms (such as roughness) in the perception of dissonance.

Part 2: Consonance and Tonal Fusion

Background. According to Stumpf's tonal fusion theory of consonance (DeWitt & Crowder, 1987; Ebeling, 2008; Guernsey, 1928; Huron, 1991), when two harmonic complex tones are tuned to simple frequency ratios, they may be perceptually fused into a single harmonic series (Figure 1), resulting in underestimation of the number of pitches present and increased consonance. However conflicting degrees of pitch-number underestimation of various 2-pitch chords were reported by Malmberg (1918) and Guernsey (1928), and statistical evaluations of their data were not presented.

When tonal fusion was tested using modern statistical methods, DeWitt and Crowder (1987) found that people only underestimated pitch number for 3-pitch chords of harmonic complexes containing octave (2:1 frequency ratio) and perfect fifth (3:2 frequency ratio) intervals. Consistent underestimation of pitch number was not observed for any other 2- or 3-pitch chords. Given that these two intervals are considered the most consonant in Western music (and represent the simplest possible frequency ratios), this finding has been taken as evidence that tonal fusion leads to the perception of consonance.

However, close inspection of the stimuli used by DeWitt and Crowder (1987) reveals that consistent underestimation of pitch number only occurred for stimuli in which the harmonics of highest frequency pitches were all at the same frequency as harmonics of one or both of the lower frequency pitches. These chords contained either an upper interval of an octave (twice the frequency of the middle pitch) or a lower interval of an octave and an upper interval of a fifth (two and three times the frequency of the lowest pitch), and so effectively participants were presented with a single harmonic series of varying harmonic amplitudes for these intervals. The statistical effects reported by DeWitt and Crowder likely were due to these particular stimuli and do not provide strong evidence that tonal fusion could account for varying dissonance ratings of other music chords.

Systematic underestimation of pitch number recently has been observed for other less common 3-pitch chords of harmonic complexes with reduced numbers of harmonics in each complex but was not observed for 2-pitch chords of complexes with reduced numbers of harmonics (Marco, McLachlan, & Wilson, 2008; McLachlan, Marco, & Wilson, 2012). This suggests that for unfamiliar chords, pitch-number estimation is influenced by the density of spectral components in the stimulus. This may result in lower pitch-number estimation for 3-pitch stimuli when the number of harmonics is reduced, but not for 2- pitch stimuli since 1-pitch stimuli are easily recognized and distinguished from 2-pitch stimuli.

Aims and hypotheses. Since pitch-number estimation has not provided conclusive evidence for the tonal fusion theory of consonance, a new paradigm was developed to test this theory in the current study. Tonal fusion should lead to more pitch-matching errors for consonant chords as participants attempt to match the pitch of these chords to the fundamental frequency of the partial harmonic series produced by tonal fusion (see Figure 1) or some octave of this fundamental frequency. We investigated the accuracy of matching the probe tone to each pitch in a range of chords traditionally considered to be consonant or dissonant and hypothesized that if tonal fusion decreases perceived dissonance, then pitch-matching errors will be greater for chords rated as less dissonant.

Results. Since no effect for stimulus type was found for dissonance ratings in Part 1, dissonance ratings were collapsed across the three stimulus types. In keeping with previous pitch-matching studies (Ross, Olson, & Gore, 2003; Ross, Olson, Marks, & Gore, 2004), results were recoded to reflect absolute deviation from target, resulting in a single-tail positive distribution. The median of the absolute pitch matching data for each chord then is sensitive to the accuracy of pitch matching.

A Friedman's ANOVA revealed a significant difference in pitch-matching error between stimulus types, $\chi^2(2) = 28.46$, $p < .01$. Paired comparisons revealed that pitch-matching error was significantly greater for full versus odd harmonic stimuli, $z = 4.59$, $p < .01$, and full versus pure tone stimuli, $z = 4.24$, $p < .01$ (Bonferroni adjusted), but there was no significant difference in pitch-matching error between pure and odd harmonic stimuli, $p > .05$. Differences in pitch-matching error across stimulus type were also tested within each musician group. It was found that significant differences in performance were evident in the no- and low-training groups, $\chi^2(2) = 7.43$, $p < .05$, and $\chi^2(2) = 25.80$, $p < .01$, respectively, but not in the high-training group, $\chi^2(2) = 0.17$, $p > .05$. These findings are consistent with the tendency of nonmusicians to be influenced by the spectral centroid of complex tones rather than the fundamental frequency when making pitch height judgments (Seither-Preisler et al., 2007).

Since the tonal fusion theory of consonance should hold for all three stimulus types, we first analyzed the data collapsed across stimulus type. Figure 5 shows pitch-matching error and dissonance ratings collapsed across stimulus type for each chord. Overall, the pitch-matching errors are similar in magnitude to previous data reported for concurrent pitches by Assmann and Paschall (1998), and the pattern of the dissonance ratings is the inverse of pleasantness ratings reported for the same intervals in McDermott et al. (2010). Contrary to the predictions of the tonal fusion theory, the curves plotted for pitch-matching error and mean dissonance ratings parallel each other, indicating that pitch-matching error increased for more dissonant chords. This observation was confirmed by a strongly positive Pearson correlation of median pitch-matching error and mean dissonance ratings for the chords, $r = .84$, $p < .01$. Pearson correlations were all positive and significant (all $p < .05$) when calculated separately for all stimulus types in each musician group.

The chords were then divided into groups of low and high dissonance chords by comparison of the mean dissonance ratings for each chord with the median of the dissonance scale (the value 3). Single-value t tests (Bonferroni corrected) indicated that the minor and major third, the perfect fifth and minor sixth 2-pitch

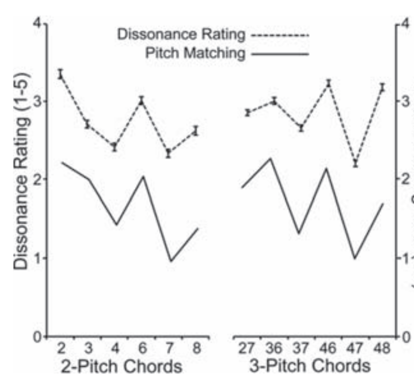

Figure 5. Mean dissonance ratings and median pitch-matching error across music chords. Error bars show ±1 standard error of the mean. ST = semitone.

Table 2
Comparison of the Mean Dissonance Ratings for Each Chord With the Median Rating Score by Single Sample t Tests

Chord	Semitone interval	Mean dissonance rating (*SD*)	*t*	Effect size (r^2)
Major triad	**4 & 7**	**2.21 (0.87)**	**7.41**	**.46**
Perfect 5th	**7**	**2.33 (0.82)**	**6.65**	**.40**
Major 3rd	**4**	**2.40 (0.82)**	**5.92**	**.35**
Minor 6th	**8**	**2.61 (0.79)**	**3.99**	**.20**
Minor triad	**3 & 7**	**2.67 (0.70)**	**3.80**	**.18**
Minor 3rd	**3**	**2.71 (0.68)**	**3.50**	**.16**
Major 2nd	2	3.34 (0.84)	3.35	.15
Flattened 5th triad	4 & 6	3.25 (0.68)	3.03	.12
Augmented 5th triad	4 & 8	3.20 (0.75)	2.15	.07
Diminished 5th triad	3 & 6	3.02 (0.67)	0.45	<.00
Suspended 2nd triad	2 & 7	2.87 (0.60)	0.22	<.00
Tritone	6	3.01 (0.71)	0.06	<.00

Note. Items are listed in descending order of the *t* statistic. Values in bold indicate chords with mean dissonance ratings significantly lower than the median with Bonferroni corrections applied. Dissonance scale ranges from 1 (*low dissonance*) to 5 (*high dissonance*).

chords, and the minor and major triad and the suspended second 3-pitch chords were all rated less dissonant (Table 2). This classification is consistent with dissonance ratings reported in previous literature (Krumhansl, 1990). A paired-samples *t* test was then used to test whether pitch-matching error collapsed across stimulus type was greater for less dissonant intervals. However, this showed that pitch-matching error was significantly less for the group of less dissonant chords, $t(65) = 11.19$, $p < .001$, partial $\eta^2 = .66$. Pitch-matching error across all participants was significantly less for the group of less dissonant chords when similar *t* tests were conducted independently on all three stimulus types (all $p < .05$). Given these effects are opposite to those predicted by the tonal fusion theory, the data fail to support the hypothesis that decreased dissonance (increased consonance) is associated with increased pitch-matching error, and the tonal fusion theory more broadly.

Discussion. There is limited theoretical basis or experimental evidence to support Stumpf's theory of tonal fusion and the claim that underestimation of pitch number is associated with consonance (DeWitt & Crowder, 1987). The data reported in this analysis refute the tonal fusion model of consonance in which pitch-matching error should increase for chords of less dissonance. Instead, they show that pitch-matching error decreases for chords of lower dissonance.

It should be noted that in this study, participants were informed of the number of pitches present in each stimulus prior to undertaking the experimental tasks. This was done to prevent possible confusion about which pitch was the target, given pitch-number estimation for three pitch chords is very unreliable (Marco et al., 2008; McLachlan et al., 2012; Thurlow & Rawlings, 1959). According to the tonal fusion theory, dissonance ratings should be uniformly high for all chords if awareness of the number of pitches present in the stimulus prevented fusion. This effect was not evident in the present data. Alternatively, if tonal fusion occurs automatically at precortical levels of auditory processing, awareness of the number of pitches present in the stimulus would have minimal relevance.

Recent models of auditory processing suggest that the grouping of harmonics occurs as part of recognition mechanisms prior to fine pitch processing (McLachlan, 2009; 2011; McLachlan & Wilson, 2010). These grouping mechanisms operate at the frequency resolution of the cochlea and are sensitive to unexpected or unfamiliar changes to stimuli such as a reduction in the number of harmonics in each complex of a chord (McLachlan et al., 2012). Generally, this implies that the pitches of a chord are unlikely to be independently perceived and then enumerated. Instead, the complete chord may be recognized, and fine pitch-processing mechanisms then sequentially primed by attentional mechanisms (McLachlan, 2011; McLachlan & Wilson, 2010). In support of this idea, a participant's pitch-number estimation has been found to be more accurate for chords that are more familiar to the participant (McLachlan et al., 2012; Thurlow & Rawlings, 1959).

Part 3: Familiarity and Pitch Estimation of Chords

Background. It is well established that the ability to segregate or stream sounds increases with the familiarity of the sounds (Bregman, 1994; Brungart, Simpson, Ericson, & Scott, 2001), likely reflecting the importance of recognition mechanisms in the early stages of auditory processing (McLachlan & Wilson, 2010). Consistent with the findings of B. C. J. Moore (1973), McLachlan (2009) proposed that two mechanisms are involved in pitch height estimation. Processing of spectral information associated with recognition mechanisms is the first to initiate and primes an array of pitch neurons near the auditory core (Bitterman, Mukamel, Malach, Fried, & Nelken, 2008) with a low-resolution pitch estimate. A competitive network of lateral inhibition then ensures that more finely tuned periodicity information that arrives at the cortex after successive waveform periods contributes to just one pitch estimate.

Accuracy of pitch height discrimination for 1-pitch stimuli is better in musicians (Micheyl, Delhommeau, Perrot, & Oxenham, 2006; Thurlow, 1963) and may reflect their improved use of periodicity information. Periodicity processing commences with stimulus-driven sustained chopper neuron responses in the ventral cochlear nucleus (Frisina, Smith, & Chamberlain, 1990). Synchronization of these responses likely occurs in the inferior colliculus (Meddis and O'Mard, 2006) where efferent cortical pathways modulate neural sensitivity in response to the activation of long-term memory templates by recognition mechanisms (McLachlan & Wilson, 2010; Strait, Chan, Ashley, & Kraus, 2012).

McLachlan (2011) has extended this dual mechanism model of pitch processing to chords, proposing that recognition of chord timbre would prime fine-pitch processing but only for one pitch in the chord due to competitive lateral inhibition in the pitch array (Figure 6). The other pitches would then be estimated by associating the activated long-term memory template of the chord timbre with the primed pitch in auditory short-term memory. Attentional processes that operate at the level of auditory short-term memory (McLachlan & Wilson, 2010) could then prime processing of periodicity information in the pitch array (Bitterman et al., 2008) if finer resolution is required for these other pitches. Highly trained musicians may also be able to use relative pitch (RP) templates to more accurately prime the remaining pitches in the chord in auditory short-term memory using the verbal labels for the chord intervals.

The pitch matching of concurrently presented vowels has been shown to improve dramatically as the pitch distance between the

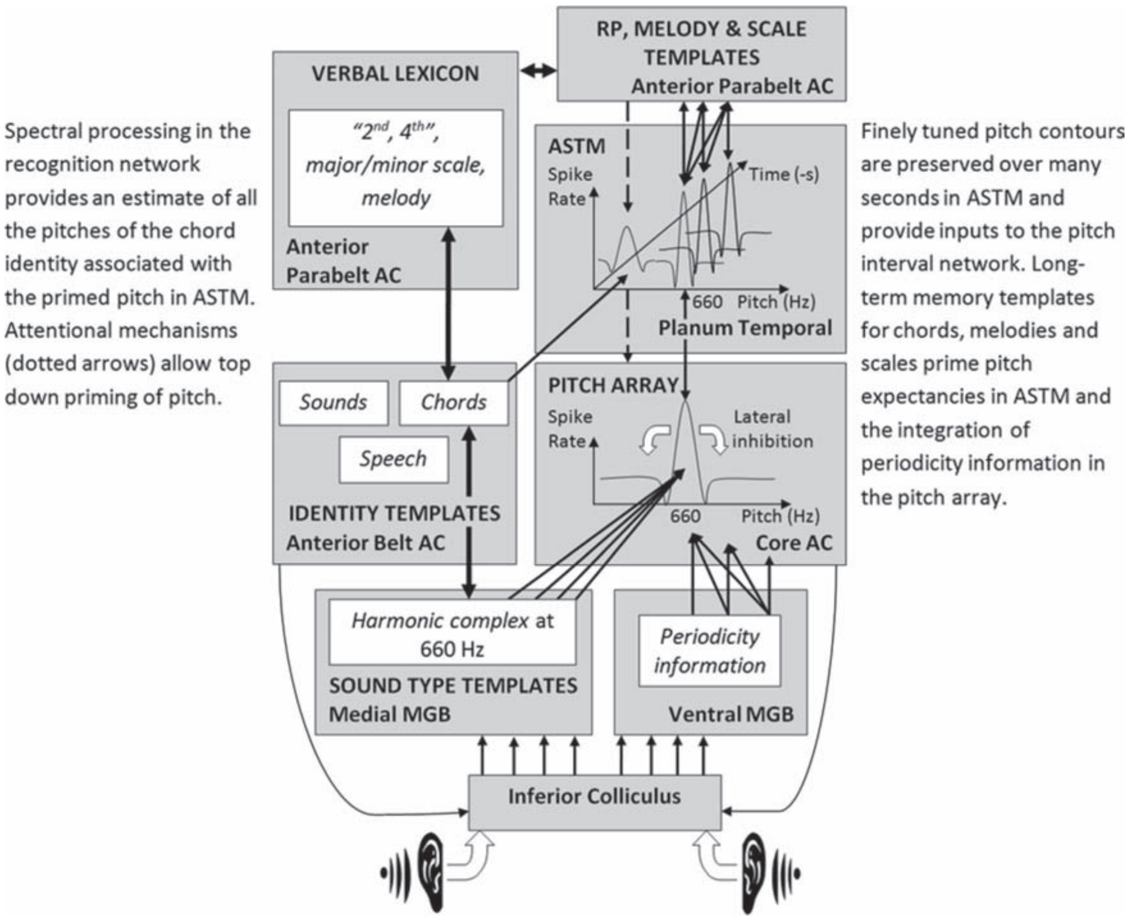

Figure 6. Schematic representation of the pitch-priming mechanism for concurrent pitches proposed by McLachlan (2011). AC = auditory core; MGB = medial geniculate body of the thalamus; ASTM = auditory short-term memory; RP = relative pitch.

vowels increases above two semitones (Assmann & Paschall, 1998), leading to models of concurrent vowel identification based on pitch segregation processes (Assmann & Summerfield, 1990; Meddis & Hewitt, 1992). Training has been shown to improve segregation of concurrent vowels across a range of pitch intervals (Alain, Snyder, He, & Reinke, 2007). This is consistent with the McLachlan (2011) pitch model since training is likely to generate long-term memory templates for chords. For unfamiliar chords, failure of recognition mechanisms would typically lead to pitch priming at frequencies that are unrelated to pitch estimates based on waveform periodicity, producing cognitive incongruity between the two pitch mechanisms and unreliable pitch estimation.

Aims and hypotheses. McLachlan (2011) proposed that spectral pitch estimation primes periodicity based pitch estimation for one of the pitches of a chord and then the remaining pitches are primed by attentional processes if required. The first hypothesis of Part 3 predicts that the familiarity of chords will increase with music training and will be positively related to the accuracy of pitch matching across all stimulus types of 2- and 3-pitch chords. Hypothesis 2 tested the McLachlan (2011) model with the specific prediction that pitch estimation for one target position would be more accurate across all chords. We tested Hypothesis 2 by comparing the pitch-matching errors for the highest and lowest pitches across the 2- and 3-pitch chords.

Results. Figure 7 shows histograms of the raw pitch estimations for each pitch in the two-, six-, and seven-semitone 2-pitch chords compared with estimates for single-pitch stimuli by the three music training groups. These 2-pitch chords have been selected to demonstrate the three main types of error distributions that were evident across all of the data from the 2- and 3-pitch chords as follows: (a) normal distributions about the target pitch that reflect the resolution of pitch perception exemplified by the distributions around the 1-pitch stimuli by highly trained musicians, (b) large skews in pitch estimates such as observed in distributions for the seven-semitone chord by the no- and low-training groups and in two-semitone chords by all three groups, and (c) matches for the lower target pitch at the higher stimulus pitch, which are particularly evident in the responses to the six-semitone chord. According to McLachlan (2011) these errors respectively relate to (a) the precision of fine pitch processing based on periodicity cues, (b) failure of stimulus recognition and spectral pitch estimation mechanisms, and (c) failure of attentional processes to select the correct pitch to match. Consequently, we will refer to these as *resolution*, *recognition*, and *attentional er-*

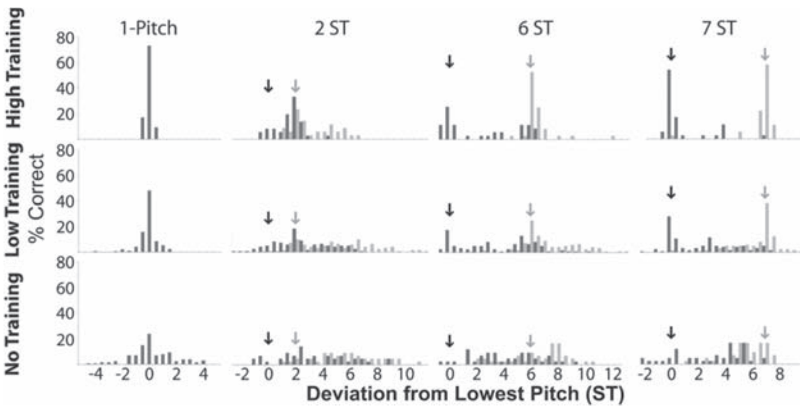

Figure 7. Pitch-matching distributions for the low (black) and high (gray) pitches of two-, six-, and seven-semitone (ST) intervals by the no-, low-, and high-training groups. Arrow heads denote low (black) and high (gray) target pitches.

rors, respectively. Octave errors were not observed in this data due to the range of frequencies of the probe tones.

The three types of pitch-matching errors suggest that multiple measures of the pitch-matching distributions are necessary to describe the relationships between familiarity and pitch-matching ability. The median of the pitch-matching distributions was used in Part 2 as it was sensitive to all three types of pitch-matching errors when the data were recoded as an absolute value. However, in this analysis, we were interested in the proportion of stimulus presentations in which the two pitch-estimation mechanisms were congruent. Thus, we used the percentage of pitch estimations that fell within the resolution of periodicity-based pitch processing. Since highly trained musicians make fewer recognition and attentional errors (Figure 7), we determined the precision of periodicity processing from their pitch-matching distribution for 1-pitch stimuli, defined as two standard errors from the target pitch. This value was found to be ± 0.41 semitones for the high-training-musician group compared with 2.25 for the low-training-musician group and 3.28 for the nonmusician group. Pitch estimations within the tolerance of the high-training-musician group were scored as correct, and then the percentage of correct responses was computed across participants within each training group for each chord tuning.

Figure 8 shows the mean familiarity and percentage of correct pitch-matching estimations for each chord and level of training collapsed across stimulus types (pure tones, odd and full harmonic complexes). It indicates that familiarity and the percentage of correct pitch matches generally increased with the level of music training, with pitch matching better for chords rated as more familiar. To address the first hypothesis, we performed four mixed between- and within-group ANOVAs. We performed two ANOVAs separately for the 2- and 3-pitch stimuli with each of the dependent variables of mean familiarity ratings and percentage of correct pitch-matching responses. Training group (three levels) and chord tuning (six levels) were the independent variables for each analysis.

Analysis of familiarity ratings showed significant main effects for chord tuning—2-pitch, $F(5, 59) = 6.01$, $p < .01$, $\eta^2 = .34$; and 3-pitch, $F(5, 59) = 7.45$, $p < .01$, $\eta^2 = .39$—and for training—2-pitch, $F(2, 63) = 14.83$, $p < .01$, $\eta^2 = .32$; and 3-pitch, $F(2, 63) = 12.79$, $p < .01$, $\eta^2 = .29$—but no significant interaction effects. We recoded the pitch-matching data using a square root transformation to meet parametric assumptions of normality, homogeneity of variance, and sphericity. Analysis of pitch-matching responses also showed significant main effects for chord tuning—2-pitch, $F(5, 315) = 15.53$, $p < .01$, $\eta^2 = .20$; and 3-pitch, $F(5, 315) = 16.41$, $p < .01$, $\eta^2 = .21$—and for training—2-pitch, $F(2, 63) = 14.94$, $p < .01$, $\eta^2 = .32$; and 3-pitch, $F(2, 63) = 14.59$, $p < .01$, $\eta^2 = .32$—but no significant interaction effects. Pair-wise comparisons (Bonferroni corrected) showed that highly trained musicians scored significantly greater than musicians with less training (both $p < .05$), who in turn scored significantly greater than the no-training group (both $p < .05$) for both familiarity and pitch matching.

Pair-wise comparisons (Bonferroni corrected) were also performed on familiarity ratings and pitch-matching responses sepa-

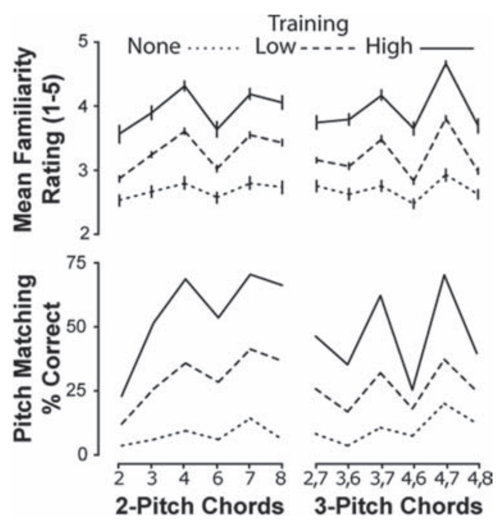

Figure 8. Mean familiarity ratings and percentage of correct pitch estimations for intervals of 2- and 3-pitch chords by participants with high levels of music training (solid lines), low levels of music training (dashed lines), and no music training (dotted lines). Error bars show ± 1 standard error of the mean.

rately across the 2- and 3-pitch chords. The large number of comparisons and the graduated differences between chords show a general pattern of findings that is summarized in online supplemental Table 1. Specifically pitch-matching accuracy was significantly poorer for the chords that were rated as significantly less familiar across all training groups. The order of familiarity ratings shown here closely follows the order of chord usage in Western music listed in Krumhansl (1990).

Pearson's correlations were also undertaken to measure relationships between familiarity and pitch-matching accuracy. The overall correlation between mean familiarity ratings and the percentage of correct pitch-matching estimations collapsed across all chord tunings and levels of music training was strong and significant (r = .96, p < .01). This relationship held when separate correlations were performed for each level of training (none, r = .73, p < .01; low, r = .87, p < .001; and high, r = .86, p < .001) demonstrating that familiarity ratings made a significant contribution to the variance of pitch-matching accuracy for chords independent of the level of training. The observation that the strength of these correlations increased from nonmusicians to musicians reflects the large increase in the rates of correct pitch matches for chords rated as familiar by musicians shown in Figure 8. To ensure the statistical robustness of the effects observed, we also computed correlations from the pitch-matching data set derived from each participant for each chord, which showed remarkably similar effects (none, r = .77, p < .01; low, r = .89, p < .01; high, r = .87, p < .01). These data provide strong evidence for the first hypothesis: that familiarity of chords increases with music training and is strongly related to pitch-matching accuracy.

The second hypothesis—that pitch estimation for one target position (e.g., highest or lowest pitch) will be more accurate across all chords—was tested using a mixed between- and within-groups ANOVA with independent variables of target position (two levels) and music training group (three levels). The music training variable was included because of the significant differences in the accuracy of pitch estimation reported earlier. The ANOVA showed main effects for target position, $F(1, 63) = 23.6$, p < .01, partial η^2 = .27, and group, $F(2, 63) = 13.8$, p < .01, partial η^2 = .30, but no interaction. The means revealed that pitch-matching accuracy was consistently greater for the high-target pitch position (M = 35.19, SD = 24.65) than the low-target pitch position (M = 25.51, SD = 28.51). Inspection of the data for the middle pitches of the 3-pitch chords revealed that pitch-matching accuracy for this target pitch never exceeded the accuracy of either of the other target pitches (see Figure 1 in the online supplemental material). Consistent with the previous analysis, post hoc Bonferroni contrasts again showed greater pitch-matching accuracy for the group with high training than for the group with low training (p < .01), and for the group with low training than for group with no training (p < .01).

A further analysis was undertaken to evaluate the possibility that patterns of masking of harmonics could differentially affect the salience of the highest and lowest pitches. In auditory stimuli that contain harmonics that are not resolved by the cochlea, the auditory nerve activation associated with one harmonic could mask the activation associated with others (Zwicker & Fastl, 1999). Patterns of masking about a harmonic are asymmetrical and wider at higher frequencies. It follows that different levels of masking of harmonics associated with the highest and lowest pitches of chords of complex tones could differentially affect the salience of target pitches (Parncutt, 1989). Masking will have greater effect on pitch salience in stimuli with more harmonics and so should have more effect on pitch-matching accuracy for full harmonic complexes than for pure tones. A mixed between- and within-groups ANOVA was performed on pitch-matching accuracy as a function of the target position and stimulus type to test for an effect of masking. The analysis was performed on the pitch-matching data of the high-training group as the nonmusician group performance was close to chance. The ANOVA showed a main effect for target pitch position, $F(1, 11) = 14.46$, p < .01, partial η^2 = .57, with the percentage correct for the high pitch (M = 66.65, SD = 14.68) again greater than the low pitch (M = 46.70, SD = 25.06), but no main effect for stimulus type. Furthermore, no interaction between these variables was observed, suggesting that masking did not contribute to better performance for the higher target position.

Since pitch matching was more accurate for the high target pitch, according to McLachlan (2011) it is likely that these pitches are primed by a recognition mechanism. It follows that the attentional mechanism postulated in Figure 6 would prime the lower pitches in the chords. Attentional errors (pitch matches at the wrong target pitch) should then occur more often for the low-target positions than for the high-target position. We investigated this idea by computing the mean percentage of pitch estimates at nontarget pitches for high- and low-target positions across all chords, stimulus types, and musician levels and by comparing the mean error rates using a paired samples t test. Consistent with the McLachlan model of concurrent pitch processing, the mean percentage of pitch estimations at nontarget pitches was greater for the low target position (M = 15.62, SE = 1.16) than the high target position (M = 2.95, SE = 0.44), $t(65) = 9.89$, p < .001, partial η^2 = .60.

Discussion. The finding that music training improves pitch-matching accuracy for common chords has not been previously reported, despite the importance of this skill for musicians. The strong positive correlation between familiarity and pitch-matching accuracy for chords provides new experimental support for the proposition that recognition mechanisms are integral to pitch processing (McLachlan, 2009, 2011; McLachlan & Wilson, 2010). In particular, the finding that fewer pitch-matching errors were made for the highest pitch of each chord, even in the absence of masking, provides strong support for the prediction that only one pitch in a chord can be directly estimated by recognition mechanisms (McLachlan, 2011). This finding is consistent with the results of Platt and Racine (1990), who found that the highest pitch was always the most salient pitch percept produced by isolated 3-pitch chords and that this effect increased with music training. These findings are consistent with the tradition in Western music composition of placing harmonic accompaniment at pitches below the melodic line (Piston, 1948). Finally, the mean percentage of pitch estimations at nontarget pitches was greater for the low-target position, which is consistent with these errors being associated with a subsequent attentional mechanism after the highest target pitch was primed by recognition mechanisms.

The effect of music training on pitch-matching accuracy for chords is consistent with improved identification of concurrent vowels with training reported by Alain et al. (2007). Learning effects have also been reported for pitch discrimination limens of single tones (Micheyl et al., 2006) and for the tendency to locate a pitch at the fundamental of a set of higher order harmonics (Seither-Preisler et al., 2007).

The proposition that recognition mechanisms prime pitch processing is also supported by recent findings that show enhanced synchronization of auditory brainstem electrical encephalographic (EEG) responses in musicians with the waveforms of instruments on which they trained (Strait et al., 2011). The object-attribute model (McLachlan & Wilson, 2010) describes a mechanism by which increasing certainty of the identity of a sound timbre could stream this sound from background noise by modulating the sensitivity of inferior colliculus neurons. Efferent pathways from recognition mechanisms in the auditory belt and the pitch array near the auditory core (Figure 6) would enhance neural sensitivity in critical band lamina of the inferior colliculus (Ehret & Schreiner, 2005) at frequencies predicted by the long-term memory template for the sound.

Part 4: Dissonance and Pitch Estimation of Chords

Background. Guernsey (1928) summarized psychological theories of consonance and dissonance found in the literature up to the early twentieth century. These ranged from theories of dissonance as a negative affect associated with stimulus unfamiliarity and ambiguity, to consonance as enculturation, to commonly used intervals. For example, H. T. Moore (1914) suggested that when a chord is first encountered, it may induce *perceptual conflict* that reduces as the ear becomes accustomed, until eventually hearing the chord becomes pleasurable. This pleasure then diminishes with repetition, leading musicians to explore new intervals. This theory accounts for slow changes in the perceived dissonance of music intervals over time in Western music (Guernsey, 1928).

Guernsey's (1928) experimental data showed striking increases in pleasantness ratings for more common music intervals in musicians, leading her to conclude that training and musical genre are important factors that condition the perception of consonance. Recent research has confirmed Guernsey's finding that the ability to discriminate consonant and dissonant chords increases in individuals with music training (Brattico et al., 2009; McDermott et al., 2010). In particular, McDermott et al. (2010) found that individual preference for harmonicity was strongly correlated with a preference for chords that are traditionally considered to be consonant, as well as the level of music training.

Seashore and Mount (1918) suggested that the ability to perceive consonance is a general test of innate musical intellect and depends primarily on pitch discrimination ability. This idea has recently been supported by neurophysiological findings from Passynkova, Neubauer, and Scheich (2007), who observed a positive correlation between stimulus dissonance and the EEG coherence of left anterior and right posterior brain regions, which in turn negatively correlated with stimulus familiarity ratings. This led Passynkova and colleagues to suggest that the inability to segregate closely tuned pitches may contribute to the experience of dissonance, since this would generate high stimulus ambiguity.

The McLachlan (2011) model of pitch processing in chords proposes that failure of recognition mechanisms would typically lead to pitch priming at frequencies unrelated to pitch estimates based on periodicity. Extending the proposition by Passynkova et al. (2007), negative affect due to cognitive incongruity between the two pitch mechanisms could be experienced as dissonance when recognition mechanisms fail. Music training increases familiarity for commonly used chords, which would lead to less pitch-matching errors and so reduced dissonance for these chords. This prediction is consistent with the decrease in dissonance associated with music training for common chords observed by Guernsey (1928), Brattico et al. (2009), and McDermott et al. (2010). Since musicians are more able to use periodicity information than are nonmusicians (Strait et al., 2012), it also follows that they would experience more incongruity between pitch processing mechanisms and consequently more dissonance when recognition mechanisms fail.

Recognition mechanisms also are likely to fail for pitch intervals less than a critical bandwidth (the resolution of the cochlea). An interval of two semitones is slightly less than a critical bandwidth and is the interval at which dissonance ratings begin to increase for decreasing frequency differences of both musical and nonmusical intervals of pure and complex tones (Guernsey, 1928; Kameoka & Kuriyagawa, 1969; Plomp & Levelt, 1965). This finding has been used to support the Helmholtz roughness model of dissonance, but given that the resolution of the cochlea is a physiological limitation on concurrent pitch processing (McLachlan, 2011), it could also support a model of dissonance based on incongruence between pitch processing mechanisms.

Aims and hypotheses. Drawing together the findings of previous research and the three previous parts of Experiment 1, our hypothesis for Part 4 was that as music training increased, (a) dissonance would decrease for common chords due to higher familiarity and better pitch processing but (b) would increase for uncommon chords due to musicians' greater reliance on periodicity-based pitch information.

Results. Figure 9 shows the percentage of correct pitch-matching estimations (based on the ±0.41 semitone tolerance used in Part 3) and the mean dissonance ratings for each chord and level of training collapsed across the stimulus types (pure tones, odd and full harmonic complexes). As reported in Part 3, the percentage of correct pitch matches increased with the level of music training

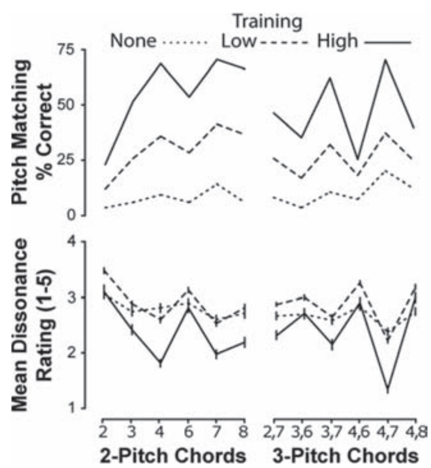

Figure 9. Percentage of correct pitch estimations and mean dissonance ratings for intervals of 2- and 3-pitch chords by participants with high levels of music training (solid lines), low levels of music training (dashed lines), and no music training (dotted lines). Error bars show ±1 standard error of the mean.

and was better for chords rated as more familiar. In keeping with the findings of Guernsey (1928) and later researchers, dissonance decreased for more familiar chords as music training increased.

To address the hypothesis that dissonance would decrease for common chords but increase for uncommon chords with music training, we first divided the chords according to well-established data on the frequency of chord usage in Western music (Krumhansl, 1990). The common chord group comprised the major and minor third, perfect fifth, and minor sixth 2-pitch chords, and the major and minor triads (Table 3). Bonferroni-adjusted single-sample *t* tests comparing mean familiarity ratings of the high training group for each chord to the median of the familiarity data across all chords confirmed that familiarity ratings were higher for the more common chords, as shown in Table 3.

To test the hypothesis, we first performed a mixed between- and within-groups ANOVA with independent variables of music training (three levels) and chord usage (two levels). Then we performed one-way ANOVA planned contrasts to investigate any significant main effects. Dissonance ratings were collapsed across stimulus type in accordance with the results in Part 1. This ANOVA showed an interaction between chord usage and training level, $F(2, 63) = 3.61$, $p < .05$, partial $\eta^2 = .10$, and main effects for both chord usage, $F(1, 63) = 39.37$, $p < .01$, partial $\eta^2 = .39$, and training level on dissonance ratings, $F(2, 63) = 5.44$, $p < .01$, partial $\eta^2 = .15$. To further investigate the interaction, we performed two one-way ANOVAs to examine the effect of training on dissonance ratings for the high- and low-usage chord groups; Dunnett's one-tailed test was used to assess the direction of the predicted effects. For the high-usage chords, lower dissonance ratings were observed for the high training group than for either of the other groups ($p < .01$), whereas for low-usage chords, higher dissonance ratings were observed for the low training group ($p = .05$) than for either of the other groups.

This pattern of data suggests that there is a general tendency toward higher dissonance ratings in the earlier stages of music training that is counteracted as musicians become highly trained and more familiar with music chords. These effects can be observed in Figure 9 as generally elevated dissonance ratings by the low-training group compared with the no-training group, but substantially reduced dissonance ratings by the high-training group for familiar chords in particular. To ensure that the time spent on the pitch-matching task did not influence dissonance or familiarity ratings, we recorded the average number of target sound repetitions in the pitch-matching trials for each chord by each music training group (see online supplemental Figure 2). The average number of repetitions did not vary with chord type but generally increased with the level of music training, likely reflecting more care taken by highly trained musicians to make correct pitch matches.

Correlations between pitch-match accuracy and dissonance ratings were analyzed to further investigate the effect of music training on dissonance ratings. Overall, a significant negative correlation was found between the percentage of correct pitch-matching estimations and dissonance ratings collapsed across all chords and levels of music training ($r = –.71$, $p < .01$). Furthermore, the correlations within each training group were all stronger than the overall correlation, being highest for the high-training group ($r = –.90$, $p < .01$), followed by the low-training group ($r = –.87$, $p < .01$) and the no-training group ($r = –.73$, $p < .05$). This relationship also held when we obtained correlations using the percentage of correct responses for each participant (high, $r = –.91$, $p < .01$; low, $r = –.90$, $p < .05$; none, $r = –.66$, $p < .05$). The increase in the strength of correlations as training level increased provides further support for the proposition that increasing reliance on periodicity information with music training increases negative affect when pitch matching is inaccurate.

Correlations between familiarity and dissonance ratings were also analyzed to investigate the proposition that dissonance is due to failure of recognition mechanisms to prime pitch processing, rather than simply a preference for familiar chords. Mean familiarity and dissonance ratings were strongly correlated ($r = –.69$, $p < .01$) when collapsed across chord tuning and music training. However, when we controlled for the effect of the percentage of correct pitch-matching estimations using a partial correlation, this relationship was no longer significant ($r = –.02$).

An additional analysis showed that the percentage of pitch matches at nontarget stimulus pitches was not correlated to familiarity ratings ($r = .09$). This is consistent with the McLachlan (2011) model of concurrent pitch processing that postulates that lower frequency pitches in the chord are primed by a separate attentional mechanism that occurs after the initial recognition mechanism (as shown in Figure 6) and with the analysis of relative rates of attentional errors for high- and low-target pitches reported in Part 3. Consistent with the cognitive incongruence model of dissonance, the percentage of these attentional errors was not correlated to dissonance ratings ($r = .33$), since spectral pitch estimates at nontarget stimulus pitches would still be congruent with waveform periodicity present in the stimulus. In other words, although the participant attended to the wrong pitch, periodicity information in the stimulus nevertheless coincided with the primed pitch estimate and so perceived dissonance was low instead of high.

Discussion. Across the analyses performed, the hypothesis that as the amount of music training increased, dissonance would decrease for common chords due to higher familiarity and pitch-matching accuracy was supported. The hypothesis that as the amount of music training increased, dissonance would increase for

Table 3
Comparison of the Mean Familiarity Ratings by the High Training Group for Each Chord With the Median Rating Score by Single Sample t Tests

Chord	Semitone intervals	Familiarity rating mean (*SD*)	*t*	Effect size (r^2)
Major triad	**4 & 7**	**4.70 (0.38)**	**15.41**	**.96**
Major 3rd	**4**	**4.45 (0.67)**	**7.56**	**.84**
Minor triad	**3 & 7**	**4.21 (0.66)**	**6.33**	**.78**
Perfect 5th	**7**	**4.34 (0.83)**	**5.60**	**.74**
Minor 6th	**8**	**4.19 (0.89)**	**4.66**	**.66**
Minor 3rd	**3**	**3.99 (0.86)**	**4.02**	**.59**
Diminished 5th triad	3 & 6	3.82 (0.78)	3.65	.55
Suspended 2nd triad	2 & 7	3.75 (0.93)	2.80	.42
Augmented 5th triad	4 & 8	3.70 (0.98)	2.48	.36
Tritone	6	3.71 (1.04)	2.37	.34
Flattened 5th triad	4 & 6	3.64 (0.99)	2.26	.32
Major 2nd	2	3.63 (1.18)	1.83	.23

Note. Items are listed in descending order of the *t* statistic. Values in bold indicate chords of high usage listed in Krumhansl (1990).

uncommon chords due to the greater reliance on periodicity pitch estimates was partially supported. With respect to the proposed cognitive incongruence model of dissonance, this pattern of data is consistent with a general tendency toward higher dissonance ratings as musicians become better able to use periodicity-based pitch mechanisms. It is also consistent that this tendency is counteracted by better priming of periodicity pitch mechanisms for high-usage chords as musicians become more familiar with these chords. In other words, these data are consistent with the theory that dissonance is a negative affect related to a mismatch between pitch information arriving at the auditory cortex from recognition mechanisms and periodicity processing in the brainstem and mid brain. This mismatch would lead to disruption of perceptual and cognitive processing of pitch and increased stimulus ambiguity causing negative affect.

Figure 10 summarizes the relationships among key variables that underpin the new model of dissonance and pitch matching described in Parts 3 and 4. The findings in Part 3 showed that increased chord usage and music training led to higher familiarity ratings, which, in turn, were strongly correlated with the percentage of correct pitch estimations. Music training also reduced the variance of pitch-matching estimates for single-pitch stimuli, likely reflecting increased reliance on periodicity pitch cues. For chords containing two-semitone intervals, poor auditory resolution likely contributed to poor pitch-matching performance and higher dissonance ratings even at the highest level of music training, so in keeping with Plomp and Levelt (1965), we included auditory resolution as a separate causal factor in the model.

The findings in Part 4 showed that the percentage of correct pitch estimations (reflecting the *congruence* of spectral and periodicity pitch mechanisms) was inversely correlated with dissonance ratings. According to the cognitive incongruence model, this also has the effect of increasing dissonance for unfamiliar low-usage chords as musicians begin to rely on periodicity cues for pitch. Furthermore, attentional errors were not significantly correlated with familiarity ratings, suggesting that this source of error was independent of the initial spectral pitch mechanism. Finally, when we controlled for the relationship between familiarity and pitch-matching accuracy, there was no partial correlation between familiarity and dissonance ratings.

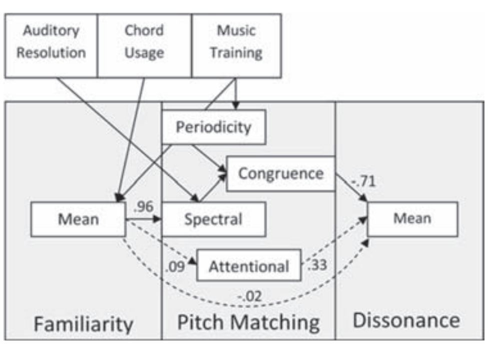

Figure 10. Schematic representation of the cognitive incongruence model of dissonance. The three cognitive mechanisms proposed to be involved in the pitch matching of concurrent pitches are represented by the boxes labeled periodicity, spectral, and attentional. Congruence represents the percentage of correct pitch estimates (estimates within 0.41 semitones, or the resolution of periodicity processing mechanisms). Dotted arrows represent nonsignificant correlations.

Long-standing and popular models of consonance and dissonance that are based on the physical properties of stimuli have been strongly refuted in this study, and a new model of consonance based on enculturation has emerged. This theory was developed from data generated in a cross-sectional, quasi-experimental paradigm in which participants were asked to make sequential judgments of pitch, familiarity, and dissonance for each stimulus. It is difficult to ascertain causality from a quasi-experimental design, and data collected over a sequence of tasks may have order effects; thus, it is clear that a longitudinal experimental design would provide a stronger test of our new theory. If nonmusicians are trained to match the pitches of a random subset of Western chords with intervals greater than two semitones, their dissonance ratings after training with these chords should be less than for unlearned chords, irrespective of the chords tuning.

Experiment 2: Learning Consonance

From a learning framework, theories of dissonance can be broadly classified into those in which dissonance is treated as an innate response and those in which it is treated as a learned response. Innate theories began with Pythagoras and include the theories of Helmholtz and Stumpf described in Parts 1 and 2. However, neither of these theories can account for changes in the perceived dissonance of chords that have occurred over the centuries since Western music was first notated (Guernsey, 1928) or for changes in perceived dissonance associated with music training observed in Experiment 1. Nor can these theories—since both are based on the harmonic relationships within a stimulus—explain the observation that dissonance ratings are the same for chords of pure tones and harmonic complexes as reported in Experiment 1 and observed by Guernsey (1928). These points show the importance of a learned model, such as the cognitive incongruence model of dissonance.

The cognitive incongruence model proposes that dissonance ratings should decrease as people become more familiar with particular chords and better able to recognize the relationships between their constituent pitches, regardless of the chord tuning. This line of reasoning points to the involvement of recognition mechanisms based on spectral information in the first stages of pitch processing of chords (McLachlan, 2011; McLachlan & Wilson, 2010). Conversely, if sensory dissonance is innate, then it would depend on chord tuning and be independent of an individual's ability to recognize the pitch intervals of a chord and match its pitches. To test the cognitive incongruence model of dissonance, we asked nonmusicians to undertake 10 daily training sessions on matching the pitches of five 2-pitch chords of pure tones that were randomly selected from intervals between two and 11 semitones. One-semitone intervals were not used as they are less than the spectral resolution of the cochlea, which is a physiological limit for processing the pitch of music chords (Assmann & Paschall, 1998; McLachlan, 2011). We measured the differences in the participants' ratings of dissonance for learned and unlearned chords before and after training.

Method

Participants. Nonmusicians were defined as people who had received no formal training in playing musical instruments or singing. Of the 24 nonmusicians who were recruited for the study, 19 completed all sessions and were included in the analysis (10 men, nine women; M age = 28.5 years, SD = 11.03). The mean number of years of formal education was 16.8 (SD = 2.22). Participants were given a laptop computer and a set of high-quality headphones to use at home for the duration of the study. Participants completed a practice diary and were prompted to practice every day by text messaging. Information about the study was provided, and written informed consent was obtained.

Procedure. The pitch-matching task was the same as that used in Experiment 1. In the first and last sessions (Sessions 1 and 10), participants listened to 100 stimuli that included 80 examples of the 10 two-pitch chords (eight pitch-shifted examples of each chord) and 20 single-pitch stimuli. Single-pitch stimuli were included as control stimuli to ensure that participants were performing the task to the best of their ability. Participants first matched one of the pitches and then received automated auditory and visual feedback on their error. In the automated feedback, participants heard each stimulus pitch individually followed by their response, and their error was displayed on a scale that ranged from –15 to 15 semitones, with zero signifying a perfect match. Finally, the stimulus was repeated, and participants were asked to rate the dissonance on a 5-point Likert scale. All participants were told that dissonance was an experience that may be related to perceived roughness, harshness, unpleasantness, or difficulty in listening to the stimulus.

In the intermediate training sessions (Sessions 2–9), each participant was required to pitch match 10 pure tones and 60 examples of five chords that were randomly selected from the original set of 10 chords. This meant that each participant continued to train on 12 pitch-shifted examples of a unique set of five randomly selected chords, while the remaining five unlearned chords were only presented in Sessions 1 and 10. Participants were not asked to rate the dissonance of stimuli in Sessions 2–9. The approximate duration of Sessions 1 and 10 was 40 min, and the approximate duration of Sessions 2–9 was 15 min.

Stimuli. The target stimuli were synthesized from 500-ms-duration pure tones with 50-ms onset and offset ramps at randomly selected Western music pitches between 220 and 880 Hz. Trials were pseudorandomly ordered so that presentations of the same chord were widely separated.

Results

Comparison of data collected before and after pitch training. Pitch-matching error was computed as the mean absolute distance from the target across all responses for each chord. Figure 11 shows that the mean pitch-matching error and the mean dissonance decreased more for learned chords than for unlearned chords after training. Mean pitch-matching error and mean dissonance also decreased for pure tones after training.

A repeated-measures ANOVA of pitch-matching errors revealed a significant interaction between time (Session 1 vs. Session 10) and chord type (learned vs. unlearned), $F(1, 18) = 9.09$, $p < .01$, $\eta^2 = .44$, indicating that the improvement for learned chords was greater than for unlearned chords. There were also

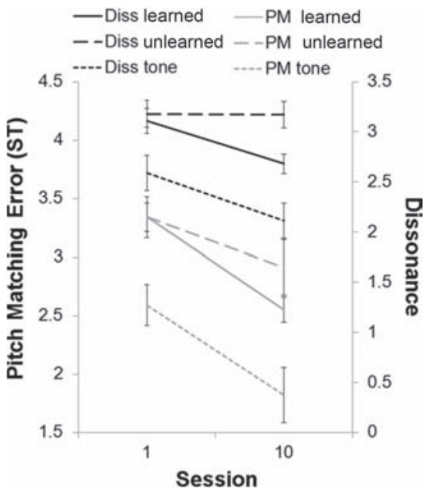

Figure 11. Mean dissonance (Diss) ratings and the mean pitch-matching (PM) error for learned (solid lines) versus unlearned (dashed lines) chords in Sessions 1 and 10. Error bars indicate ±1 standard error of the mean. ST = semitone.

significant main effects of time, $F(1, 18) = 16.94$, $p < .001$, $\eta^2 = .60$, and chord type, $F(1, 18) = 4.36$, $p < .05$, $\eta^2 = .19$. Paired t tests revealed that pitch-matching error for learned chords was significantly lower in Session 10 (M = 2.55, SD = 0.47) than in Session 1 (M = 3.34, SD = 0.52), $t(18) = 5.58$, $p < .001$. Pitch-matching error for unlearned chords was also significantly lower in Session 10 (M = 2.91, SD = 0.58) than in Session 1 (M = 3.34, SD = 0.58), $t(18) = 3.61$, $p < .01$, indicating that participants improved in pitch matching for both chord types, although the improvement was greater for the learned chords.

Similarly, a repeated-measures ANOVA of mean dissonance ratings revealed a significant interaction between time and chord type, $F(1, 18) = 12.68$, $p < .01$, $\eta^2 = .37$, indicating that the decrease for learned chords was greater than for unlearned chords. There was also a significant main effect of chord type, $F(1, 18) = 14.38$, $p < .001$, $\eta^2 = .16$),but not time. Paired t tests revealed that the mean dissonance rating for learned chords was significantly lower in Session 10 (M = 2.68, SD = 0.42) than in Session 1 (M = 3.11, SD = 0.55), $t(18) = 2.61$, $p < .05$, but not for unlearned chords, indicating that dissonance only decreased for learned chords.

Figure 11 also shows that the mean dissonance rating and pitch-matching error for pure tones decreased between Sessions 1 and 10. Paired t tests revealed that both the mean pitch-matching error for single tones was significantly lower in Session 10 (M = 1.82, SD = 1.03) than in Session 1 (M = 2.59, SD = 0.76), $t(18) = 3.26$, $p < .01$, and the mean dissonance rating was significantly lower in Session 10 (M = 2.11, SD = 0.77) than in Session 1 (M = 2.59, SD = 0.77), $t(18) = 2.28$, $p < .05$.

Since there was a moderate amount of variability in the pitch-matching improvement across participants, we subtracted pitch-matching errors and dissonance ratings at Session 10 from Session 1 to correlate the change in these variables across all participants with a Pearson's coefficient. A strong correlation was found between decreases in pitch-matching error and decreases in dissonance ratings for learned chords ($r = .65$, $p < .01$) but not for the unlearned chords (r = .33, p = .163). The finding that pitch-matching error and dissonance ratings decreased more for learned chords regardless of their tuning provides strong support for the cognitive incongruence model of dissonance and further refutes theories of dissonance that predict an innate preference for small-integer ratio chords.

Rates of learning. Figure 12 shows the pitch-matching error for the learned chords and pure tones over the 10 training sessions compared with the pitch-matching error for the unlearned chords in Sessions 1 and 10. A repeated-measures ANOVA with planned repeated contrasts found the decrease in pitch-matching accuracy for the learned chords was significant between Sessions 1 and 2, $F(1, 18) = 51.69$, $p < .001$, $\eta^2 = .74$, but not between any other consecutive sessions. Since participants had been exposed to all chords used in the study in Sessions 1 and 10, some learning occurred for the unlearned chords and likely resulted in the reduced pitch-matching errors in Session 10, despite the 8-day period between exposures to these chords. A paired-samples t test revealed no significant difference between the mean pitch-matching error for learned chords at Session 2 and unlearned chords at Session 10, confirming that the learning effect of the first exposure to these chords was largely maintained over the 8 intervening days.

Figure 12 also shows that the pitch matching for pure tones was better overall than for chords and generally improved over the 10 training sessions. However, the large sustained drop in pitch-matching error observed immediately after Session 1 for the learned chords was not observed for single-pitch stimuli. A repeated-measures ANOVA with planned repeated contrasts revealed no significant differences in pitch-matching error between Sessions 1 and 2 for the single-pitch stimuli.

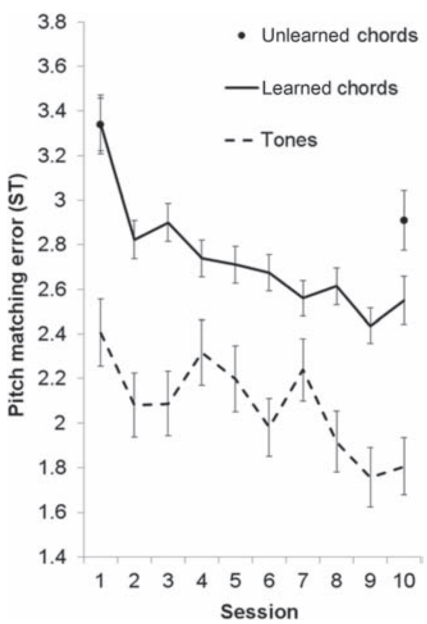

Figure 12. Pitch-matching error across 10 sessions for learned chords compared with pure tone stimuli (dashed line) and unlearned chords in Sessions 1 and 10. Error bars indicate ± 1 standard error of the mean. ST = semitone.

Discussion

The finding that improved pitch-matching accuracy for the learned chords was associated with decreased dissonance ratings for these chords, irrespective of their tuning, supports the cognitive incongruence model of dissonance. Learning for chords was faster between Sessions 1 and 2 compared with any other consecutive sessions, or the learning rate for pure tone stimuli. This is consistent with reports of rapid improvements in identification rates for concurrent vowels presented at different pitches (Alain et al., 2007) and is consistent with the establishment of unique long-term memory templates for music chords based on spectral information (McLachlan, 2011; McLachlan & Wilson, 2010).

Most participants were initially able to match the pitch of pure tones at about the resolution of the cochlea (around 2.5 semitones in the frequency range of the stimuli). However after 10 daily training sessions, the mean pitch-matching error for pure tones reduced to around 1.8 semitones, which is less than the resolution of the cochlea. Data presented in Experiment 1 and in Hutchins and Peretz (2012) have shown that after longer or more focused training, people can achieve pitch-matching errors of less than 0.5 semitones for single-pitch stimuli using a similar pitch-matching paradigm. This finding is consistent with the well-established theory that pitch representations are refined by waveform periodicity information (de Cheveigné, 2005) and suggests that the use of waveform periodicity information in pitch processing is learned.

The observed decrease in pitch-matching error for unlearned chords between Sessions 1 and 10 was not associated with decreased dissonance ratings. This is consistent with the finding in Part 4 of Experiment 1 that dissonance ratings generally increase for uncommon chords during early music training. According to the cognitive incongruence theory, increased reliance on periodicity processing in musicians creates stronger negative affect (dissonance) when recognition mechanisms fail and the periodicity information is incongruent with the expected pitch. It follows that the overall improvements in pitch-matching ability after training led to decreases in dissonance for both pure tones and learned chords, but not for the unfamiliar, unlearned chords for which recognition mechanisms were likely to fail.

The decrease in dissonance ratings for pure tones is difficult to reconcile with dissonance theories based on roughness (Helmholtz, 1954) or tonal fusion (DeWitt & Crowder, 1987). However, it is consistent with findings of greater congruence of brainstem EEG recordings with waveform periodicity for familiar timbres (Strait et al., 2012) and consonant (or familiar) chords (Bidelman & Krishnan, 2011). Furthermore, individual preferences for consonance have been found to be unrelated to preferences for stimuli without beats (McDermott et al., 2010).

General Discussion

This article makes a significant contribution by demonstrating that learning to perceive consonance involves cognitive processes. In particular, these include recognition mechanisms that facilitate the parsing of pitch information in more familiar stimuli. Support for a learned theory of dissonance does not imply that aversion to chords of less than two-semitone intervals is not innate, since these intervals are less than the spectral resolution of the cochlea (Plomp & Levelt, 1965). Many studies have reported innate preferences in infants, animals, and birds for simple integer ratio chords (Chiandetti & Vallortigara, 2011; Izumi, 2000; Zentner & Kagan, 1998) compared with one-semitone interval chords. While this shows that one-semitone chords are innately dissonant, it does not necessarily follow that simple integer ratio chords are innately consonant. Other studies that have reported innate preferences for these chords in infants included octave intervals as simple integer ratio chords (Masataka, 2006; Trainor, Tsang, & Cheung, 2002). An octave interval is a doubling of frequency, so all the harmonics of the higher pitch are at the same frequency as harmonics of the lower pitch, and the interval sounds like a single pitch rather than a chord (Izumi, 2000).

Musical tunings based on numerical ratios of frequency have been widely used since Pythagoras introduced tuning based on successive 2/3 proportions of string length. It is not surprising then that simple mathematical relationships can be found between the harmonics of common Western music chords. These relationships may result in the common periodicity of harmonics in chords (Ebeling, 2008), underestimation of the number of pitches in a chord due to the coincidence of harmonic frequencies (DeWitt & Crowder, 1987), and reduced beating between harmonics (Sethares, 1993). However, in light of the strong effect of training on consonance perception, correlations between consonance and the relative simplicity of tuning ratios (Schellenberg & Trehub, 1994) may simply reflect enculturation to this tuning tradition, rather than provide evidence that consonance is caused by any of the phenomena described earlier (Guernsey, 1928).

The frequent use of accurately reproduced intervals within a music culture would support the development of long-term memory templates for commonly used music chords and scales. Since the Middle Ages, the accurate musical reproduction of intervals could be achieved by the removal of beat frequencies between harmonics, which fixes the intervals of the fundamental frequencies (or pitches) to small-integer ratios such as 5:4 and 3:2. The extensive use of this technique provides a plausible neurobiological basis for the evolution of the traditions of tuning and harmony to which Western musicians have become acculturated. More generally, chord and scale templates may form with repeated exposure to any tuning system provided it is sufficiently stable over time. This explains why modern Western musicians find chords based on the 12-tone equal-tempered scale consonant, despite deviations from small-integer ratio tunings.

Having been persuaded by the roughness model of sensory dissonance, Terhardt (1974) proposed a distinction between this form of dissonance and musical dissonance that was associated with the disruption of melodic and harmonic expectancies over time. Deutsch (1999) proposed that long-term memory templates for scales are hierarchically encoded with greater emphasis placed on more common musical intervals. McLachlan and Wilson (2010) subsequently showed how these templates could prime pitch processing in primary cortex via auditory short-term memory to create melodic and harmonic expectancies. In support of this proposition, Smith, Kemler Nelson, Grohskopf, and Appleton (1994) showed that nonmusicians could categorize intervals when they were imbedded in popular songs for which they are likely to have melodic templates, but not when intervals were presented in isolation. In contrast to Terhardt's theory, the model of sensory dissonance that we proposed in this article suggests that both sensory and musical dissonance arise from negative affect generated by incongruence between pitch processing and pitch and melodic priming mechanisms. In particular, we proposed that sensory dissonance arises from incongruence with priming by chord templates, whereas musical dissonance arises from incongruence associated with priming by melodic or scale templates.

The cognitive incongruence model of dissonance is consistent with studies that have revealed that cortical mechanisms are involved in dissonance perception (Brattico, Tervaniemi, Valimaki, van Zuijen, & Peretz, 2003; Peretz, Blood, Penhune, & Zattore, 2001; McDermott & Hauser, 2004) and with earlier findings of increased dissonance for pure tones that are poorly resolved by the cochlea (Plomp & Levelt, 1965). In particular, the two-semitone interval lies within one critical bandwidth and so is poorly resolved by the cochlea. Rather than attributing the dissonance of this interval to the beating of auditory neural responses (Fishman et al., 2001; Plomp & Levelt, 1965), however, the cognitive incongruence model suggests that the dissonance of this interval arises from poor auditory resolution of spectral information. This proposition is supported by previous research that has found pitch-matching accuracy for concurrent vowels decreases substantially for intervals of two semitones or less (Assmann & Paschall, 1998) and is consistent with the McLachlan and Wilson (2010) model of auditory processing in which successful stimulus recognition based on the resolution of the auditory nerve is a necessary precursor to fine pitch processing.

Other researchers have inferred cortical involvement in dissonance perception from correlations among neuroimaging data, electrophysiological recordings, and dissonance judgments in a case study of selective deafness to dissonance (Brattico et al., 2003; Peretz et al., 2001). Furthermore, neuroimaging research has shown that increased hippocampal and parahippocampal activity is associated with the experience of dissonance (Blood, Zatore, Bermudez, & Evans, 1999; Wieser & Mazzola, 1986). These structures are known to be involved in the integration of sensory, semantic, and mnemonic operations, particularly when stimulus ambiguity must be resolved (Hoenig & Scheef, 2005). Taken together, these findings accord with the notion that recognition mechanisms are integral to concurrent pitch processing and that dissonance increases when these mechanisms fail.

The cognitive incongruence model of dissonance is consistent with the implication-realization model of emotional arousal to music (Narmour, 1992) in that both theories propose that emotional arousal is generated by validation or invalidation of moment-to-moment predictions about how a piece of music will unfold. However, it differs from Narmour's theory in that the predictions are not generated by bottom-up Gestalt-like sensory grouping processes (Cross, 1995) but rather by the activation of long-term memory templates that have been generated by enculturation to a music tradition.

In conclusion, the idea that harmony in music and the visual arts derives from physical relationships of simple integer ratios has been pervasive in the West since Pythagoras. However, our findings suggest that harmony results from the adaptation of sensory systems to reproducible and recognizable stimuli, regardless of their physical properties. This explains the modern preference for the equally tempered scale in Western music, despite few small-integer ratio tunings and the diversity of music tunings that do not conform to simple mathematical proportions that have emerged in isolated societies all over the world.

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