## ADDITIONAL SUPPLEMENTARY RESULTS

# Individual Differences Reveal the Basis of Consonance

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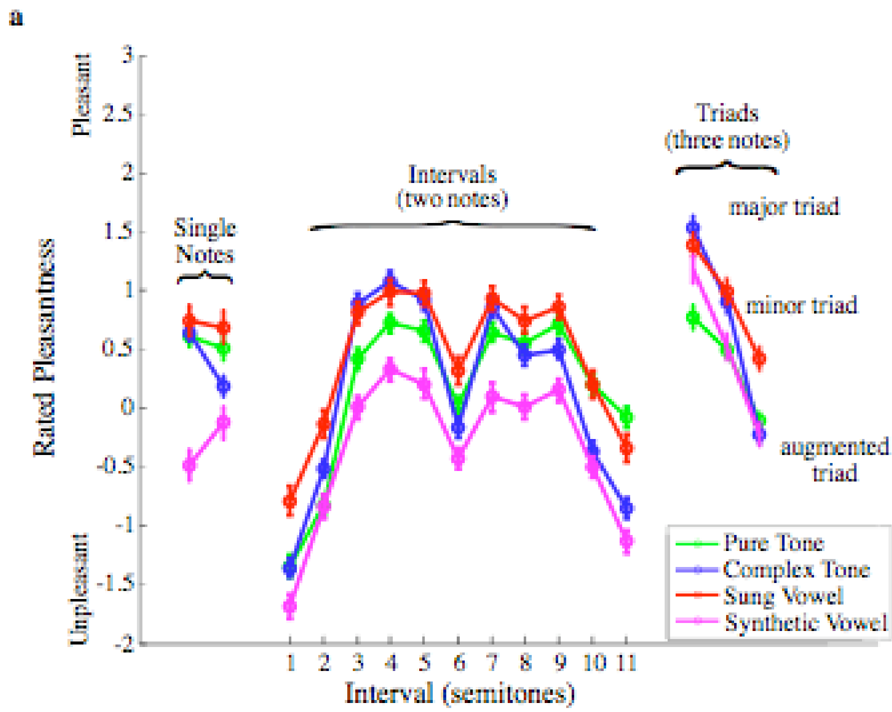
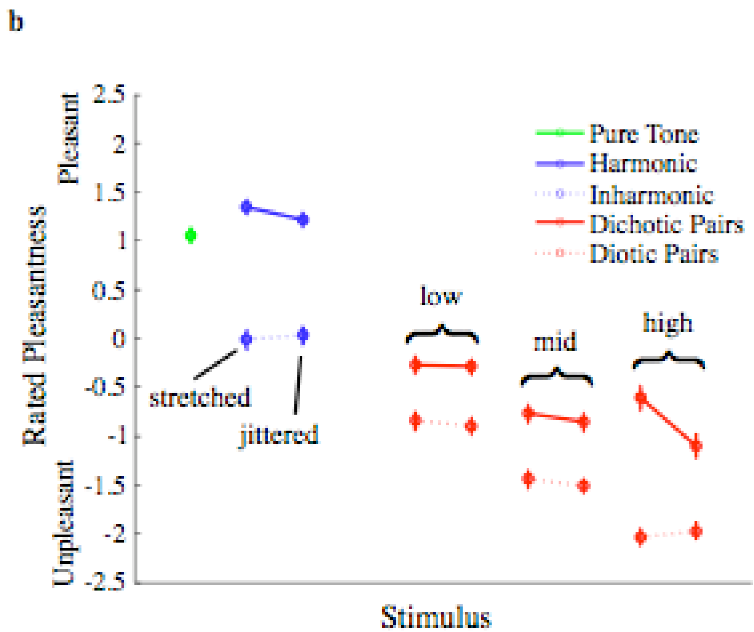
This document contains additional supplementary results that could not be included in the Supplement to our Current Biology paper due to Cell Press length restrictions.

**Contents**

**A. Mean stimulus ratings for Cohort 2.**

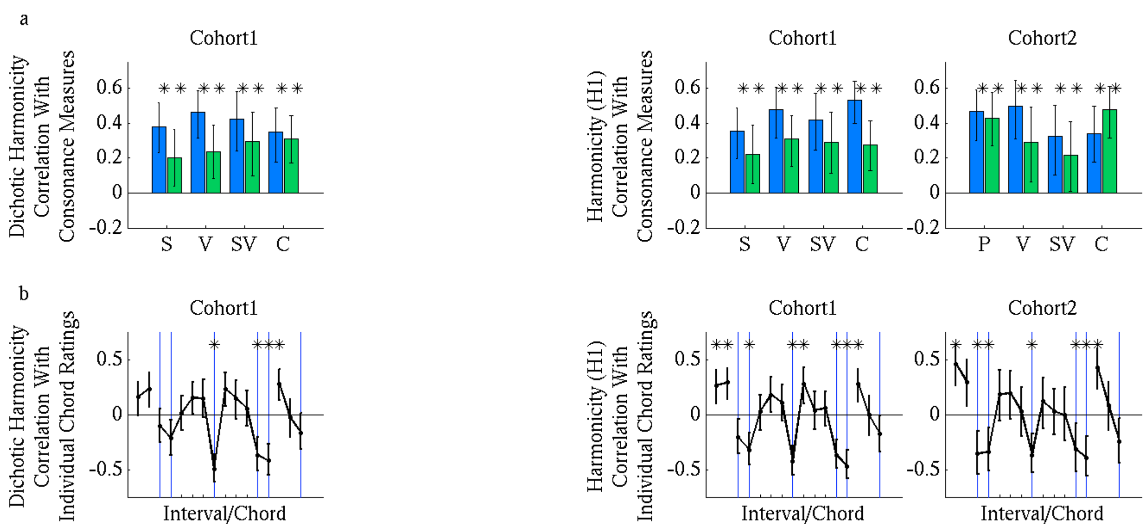



**Supplementary Figure 6.** Mean ratings for Cohort 2 **(A)** Mean pleasantness ratings of individual notes and chords, for Cohort 2. **(B)** Mean pleasantness ratings of acoustic test stimuli, for Cohort 2. Conventions are as in Figures 1 and 2.

**B. Correlation results for dichotic harmonicity stimuli.**

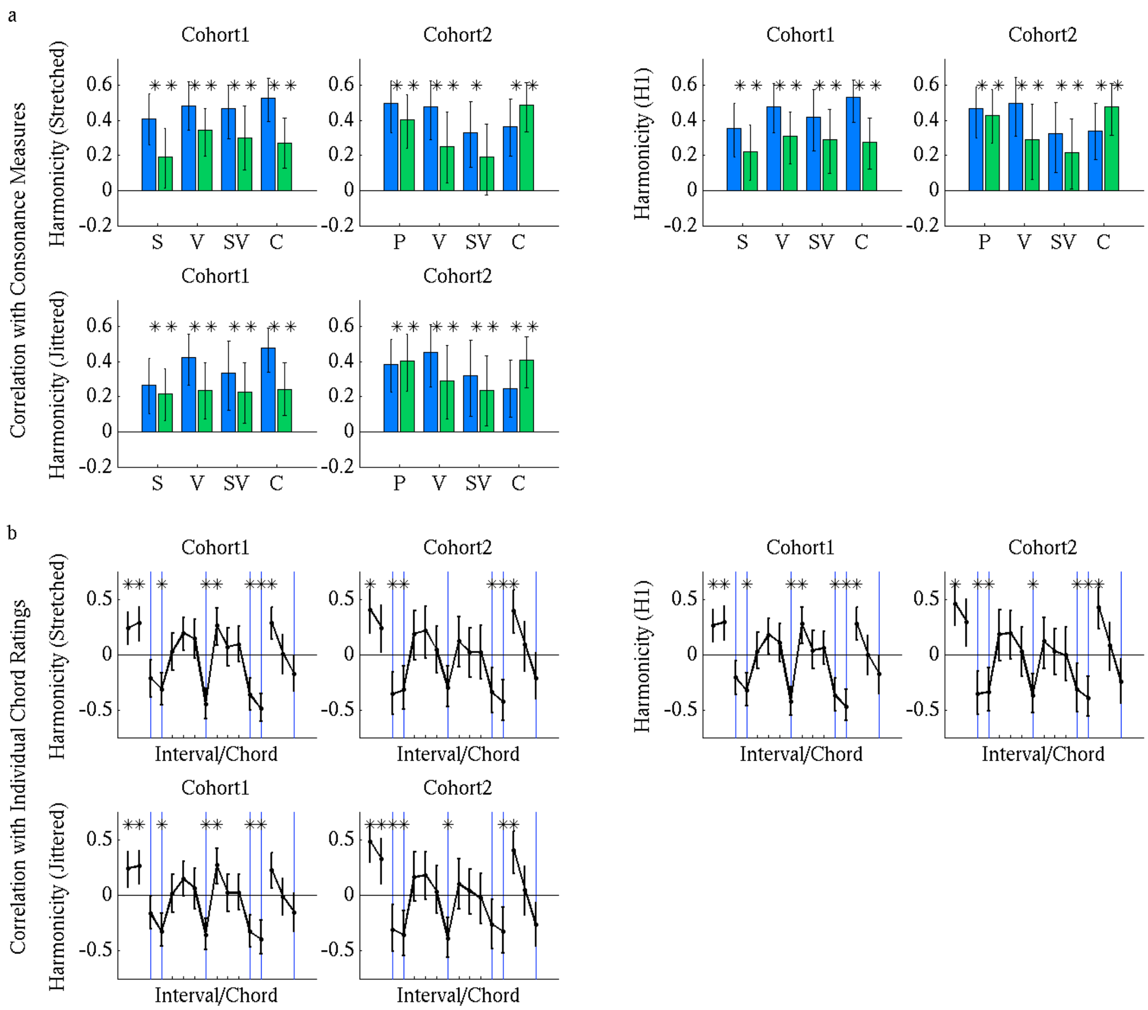
Although beating is greatly reduced when frequency components are more than a critical band apart, there are some such conditions in which beats are nonetheless heard, typically when frequency components are related by ratios that deviate slightly from small integer ratios[1]. It is thus conceivable that our inharmonic test stimuli might have produced perceptible beating for some subjects, which could in principle have contributed to the harmonicity preference measured by our main H1 measure. Dichotic presentation of frequency components is known to greatly reduce even these other forms of beats[2], and thus the H2 measure served as a control for this issue. As an additional control, we included conditions where the even and odd numbered frequency components of the harmonicity test stimuli were played to opposite ears[3]. The correlation results for the measure computed from these dichotic stimuli were similar to those for the diotic stimuli. All correlations with our consonance measures were significant (p<.05), and the pattern of correlations with individual chord ratings was qualitatively similar to that for the diotic H1 harmonicity measure. It thus seems unlikely that effects related to beating contributed substantially to the harmonicity correlations.




**Supplementary Figure 7.** Correlation results for dichotic harmonicity stimuli. **(A)** Correlations of dichotic and diotic harmonicity measures with measures of consonance preference. **(B)** Correlations of dichotic and diotic harmonicity measures with average ratings of individual chords. The results for the diotic measure (on the left) are replotted from Figure 3 to aid comparison. The dichotic harmonicity stimuli were only used with Cohort 1. Conventions are the same as those in Figure 3.

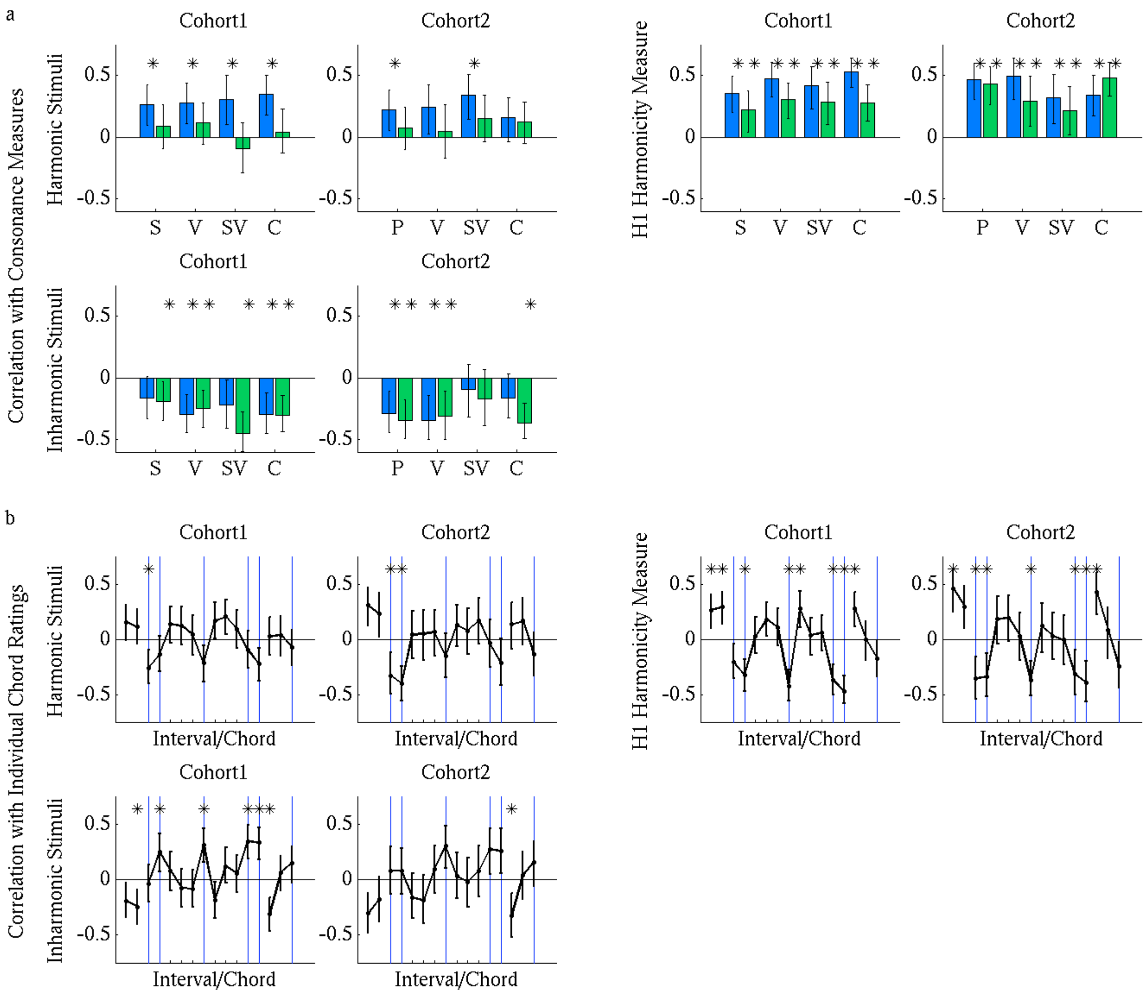
### C. Correlation results for individual harmonicity stimuli.

The stimuli for the H1 measure were generated in two ways – first, by stretching the spectrum of one harmonic tone, and second, by adding small offsets to the frequencies of a second harmonic tone (as shown in Figure 2d). As an additional demonstration of consistency, here we separate the two types of inharmonic complex tone stimuli into different acoustic measures. Each measure subtracted the ratings of the corresponding harmonic and inharmonic test stimuli (the shifted inharmonic complexes were omitted, as these were only used with Cohort 1). Both types of inharmonic stimuli produce measures that yield robust correlations with consonance preferences (Supplementary Figure 8). The pattern of correlations with individual chord ratings was similar for the two measures, providing further evidence that the effects are not specific to a particular stimulus.



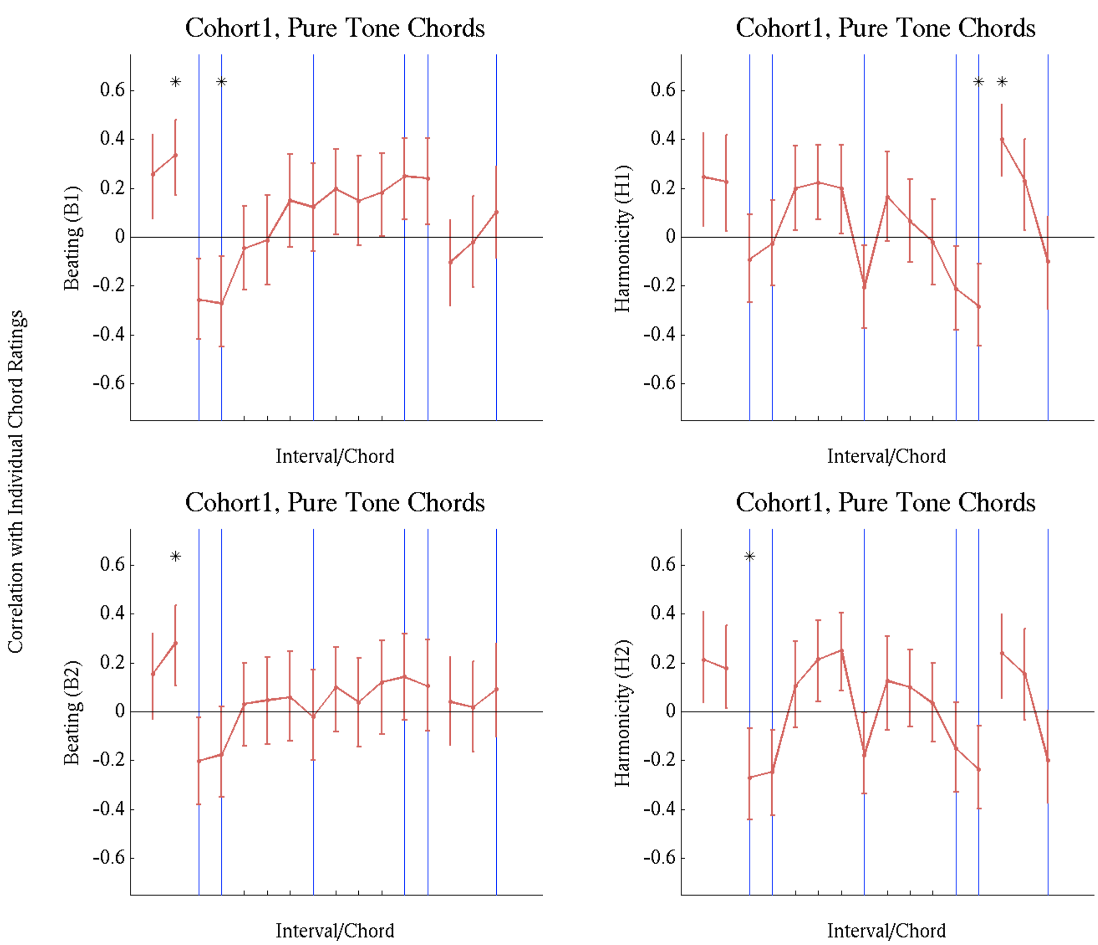

**Supplementary Figure 8**. Correlation results for additional harmonicity measures. **(A)** Correlations of additional harmonicity measures with measures of consonance preference. Results for the H1 harmonicity measure are plotted on the right to aid comparison. **(B)** Correlations of additional harmonicity measures with average ratings of individual chords. Conventions are as in Figure 3.

We also computed consonance correlations for the harmonic stimuli alone, and the inharmonic stimuli alone (Supplementary Figure 9). It is apparent that the ratings of the harmonic stimuli tend to be positively correlated with our consonance measures, whereas those of the inharmonic stimuli are negatively correlated with them. The correlation patterns for the harmonic and inharmonic stimuli are roughly mirror images of each other. The correlations of the H1 harmonicity measure, derived from subtracting the harmonic and inharmonic ratings, are larger and more consistent than those for either the harmonic or inharmonic stimuli alone, indicating that our measure isolating harmonicity is more closely related to consonance than is either stimulus alone.




**Supplementary Figure 9**. Correlation results for individual harmonicity test stimuli. **(A)** Correlations of average ratings of harmonic and inharmonic stimuli (and the harmonicity measure we derived from them, repeated on the left to aid comparison) with measures of consonance preference. **(B)** Correlations of average ratings of harmonic and inharmonic stimuli with average ratings of individual chords. Results for harmonicity measure are repeated on left. Conventions are as in Figure 3.

**D. Correlations of acoustic measures with pure tone chords.**
Cohort 2 heard chords constructed from pure tone notes (one of the four pairs of chord tests they completed). These ratings are useful to examine individually as there are clear predictions for what the chord roughness should be – the two smallest intervals (minor and major second; 1 and 2 semitones) should produce considerable beating, and all intervals above the major third (4 semitones) should produce negligible beating as they are separated by more than a critical band. The correlation magnitudes (and statistical significance) were low, because the individual chord ratings for a single timbre had high variance, but the patterns of correlation with our beating test measure were consistent with what is expected. Correlations were negative for the small intervals that produce large amounts of beating, but were positive for intervals exceeding a major third, as well as for single notes (which also lack beats). This suggests that in cases where there are strong beats or a clear absence of beats, roughness can influence perceived pleasantness, and that our beating measure produces correlations that reflect this. The lack of strong correlations between our beating measures and consonance thus likely indicates that there are not large differences in beating between most consonant and dissonant intervals. It is notable that the harmonicity correlations are not functions of interval size, but rather reflect dissonance, with negative correlations for all the dissonant chords.

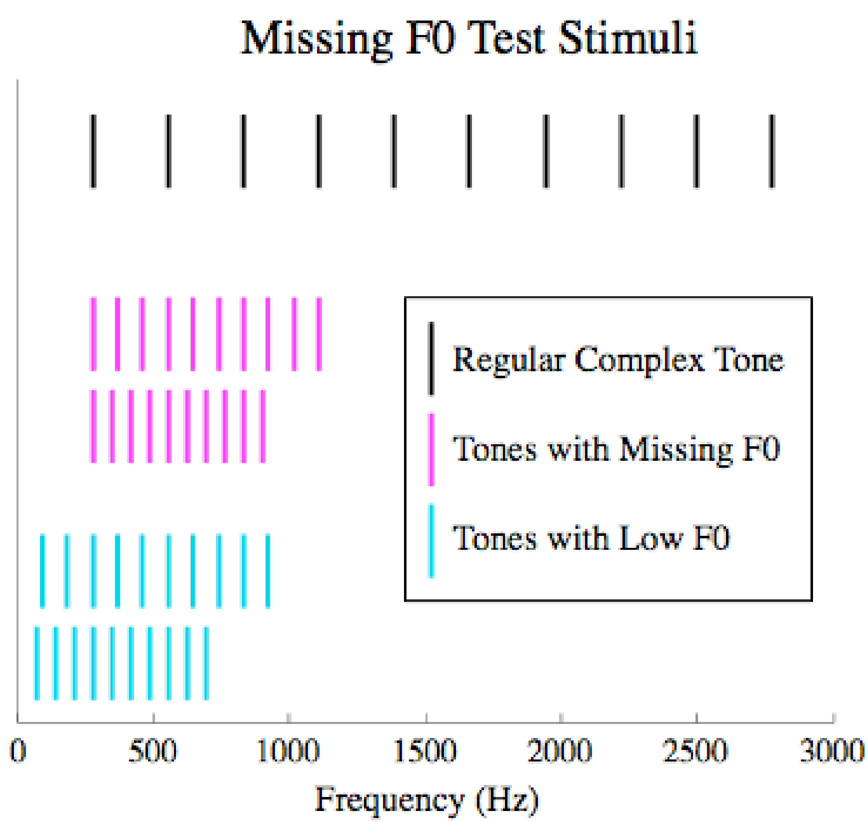



**Supplementary Figure 10**. Correlations of diagnostic measures with average ratings of pure tone chords. Conventions are as in Figure 3c.

**E. Correlations of missing fundamental test measures with consonance.**
Here we present the results of an additional set of acoustic test measures designed to probe the importance of the "fundamental bass" pitch in consonance. These measures did not produce significant correlations with our measures of consonance preference, but we present them as additional evidence that harmonicity is uniquely predictive of consonance.

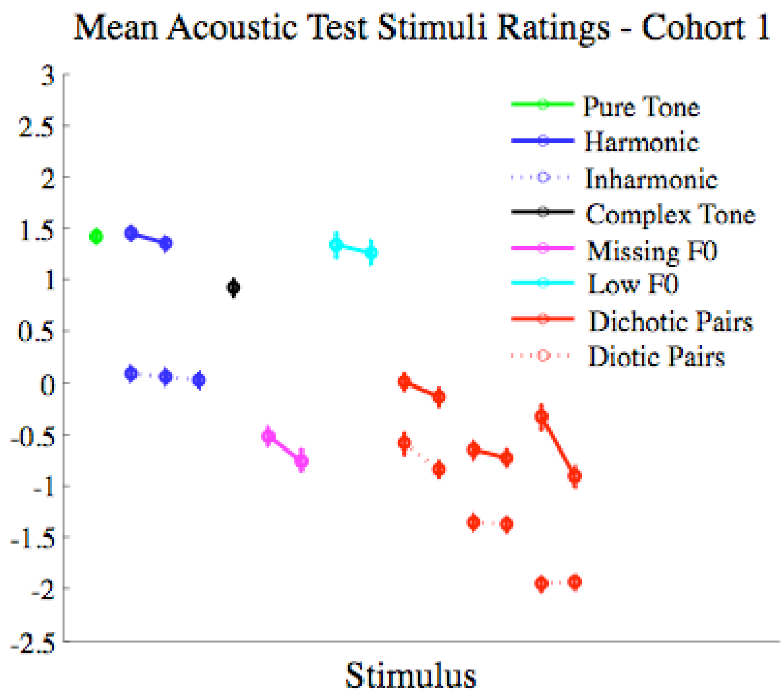
Because the frequencies of many consonant chords are a subset of the harmonic series, they have been proposed to support the perception of a "fundamental bass" pitch corresponding to the fundamental frequency of the harmonics, similar to the pitch of the "missing fundamental" that is routinely perceived in complex tones that lack a physically presented fundamental frequency (F0). Many have thought that this fundamental bass pitch might play an important role in consonance and harmony[4-6].

To explore the possible importance of implied low-frequency F0s, we presented Cohort 1 with three additional types of test stimuli: regular complex tones (with harmonics 1-10), complex tones with missing F0s (harmonics 3-12 and 4-13, with F0s lower than the complex tone by factors of 3 and 4, such that the lowest frequency in the tones was the same), and regular complex tones with low F0s (corresponding to the implied F0s of the missing F0 complexes). Schematic spectra are shown in Supplementary Figure 11. We thought that consonance preferences might be correlated with preferences for the tones with missing F0s (relative to regular complex tones with physically present F0s).



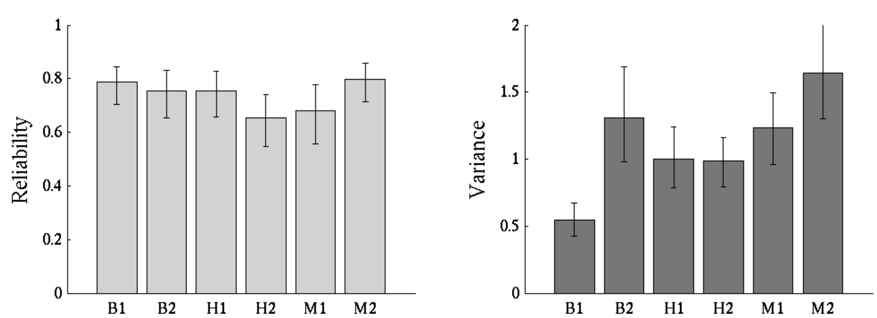

**Supplementary Figure 11**. Schematic spectra of missing fundamental test stimuli.

Supplementary Figure 12 shows the mean ratings of these stimuli alongside those of the other acoustic test stimuli. The missing F0 tones are rated lower, on average, than the other complex tones. From these ratings we constructed two additional acoustic measures: one subtracting the missing-F0 tone ratings from that of the regular complex tone (M1), and one subtracting the missing-F0 tone ratings from those of the low-F0 tones (M2). Both of these differences were large, on average, as is apparent from the figure – comparable in size to those of the other acoustic measures.




**Supplementary Figure 12**. Mean ratings of missing fundamental test stimuli (the lower of the two F0s is plotted on the right for both the missing and low F0 stimuli), with other diagnostic stimuli replotted for comparison. Conventions are as in Figure 2e&f.

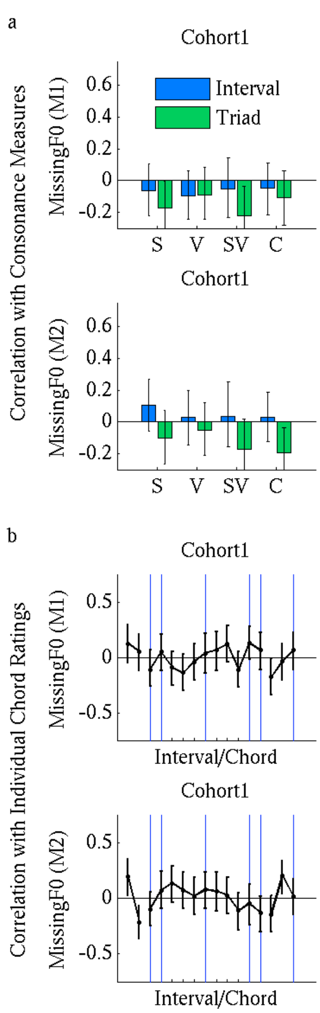
The reliabilities of both measures were comparable to those of our other acoustic measures, and the variance of each measure was, if anything, somewhat higher (Supplementary Figure 13).




**Supplementary Figure 13**. Reliability and variance of the two missing fundamental measures, with those of the other measures replotted for comparison (beating (B1&B2), harmonicity (H1&H2), missing F0 (M1&M2)).

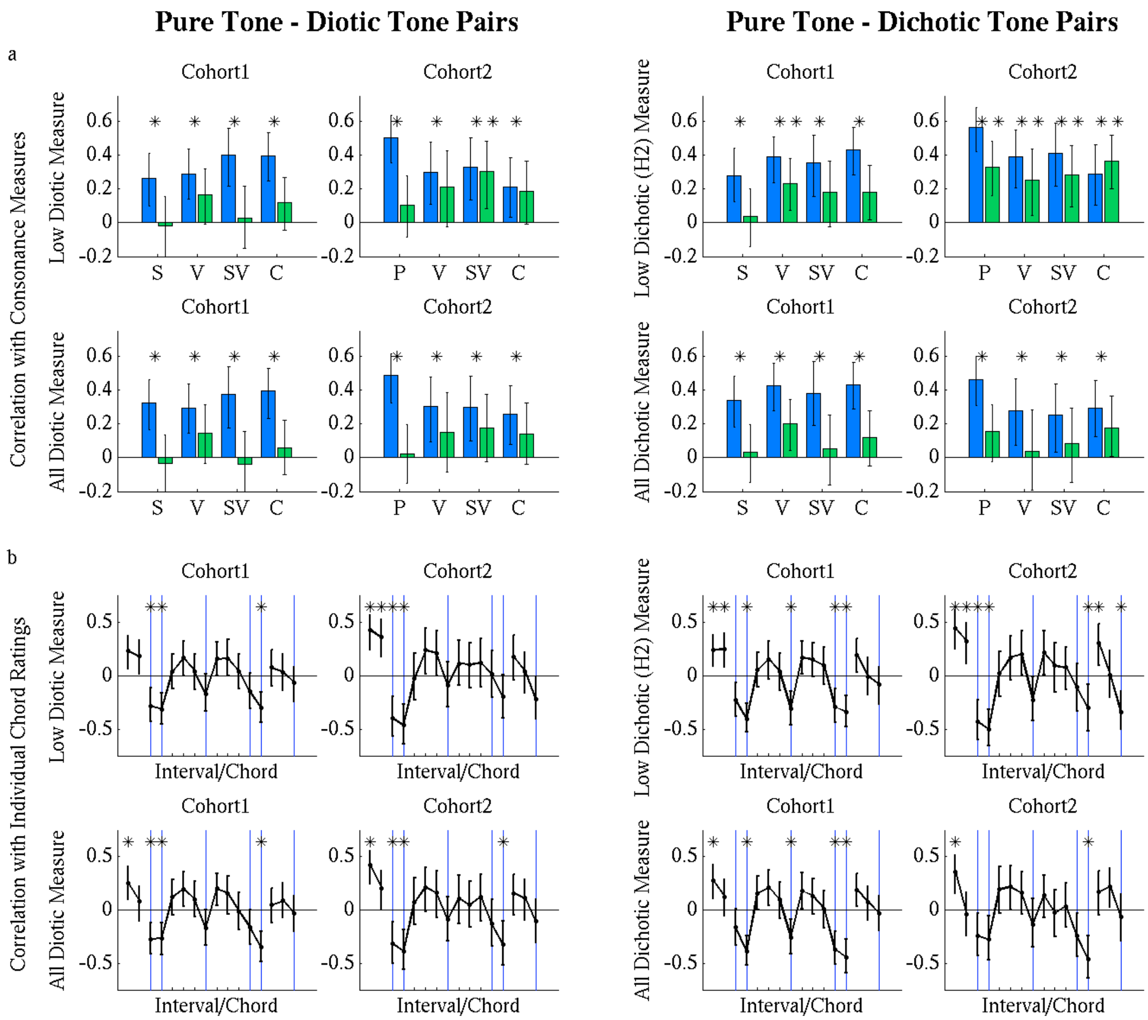
Despite the comparable effect size, variance, and reliability, the missing F0 measures did not produce significant correlations with our consonance measures (Supplementary Figure 14). Note that because the test measures subtracted the missing F0 ratings from those of standard complex tones, a link between the fundamental bass and consonance preferences would have been reflected in negative correlations between our missing F0 test measures and the consonance measures (as stronger preferences for consonant intervals over dissonant should have been linked to stronger preferences for missing F0 tones over regular tones). There are weak trends in this direction, but none of the correlations reached statistical significance.

There are many reasons why our measure might not have adequately captured the relevant acoustic property of the fundamental bass (for instance, the missing F0 tones differed from typical consonant chords in containing consecutive harmonics, which resulted in a rough timbre, probably explaining the low overall ratings relative to the other tones evident in Supplementary Figure 12). However, the lack of substantial correlations with our consonance measures, or with individual chords, is additional evidence that not all aesthetic effects, even those that are large in magnitude, reliable, and with large individual differences, are correlated with consonance. Harmonicity appears to have a privileged status in this regard.



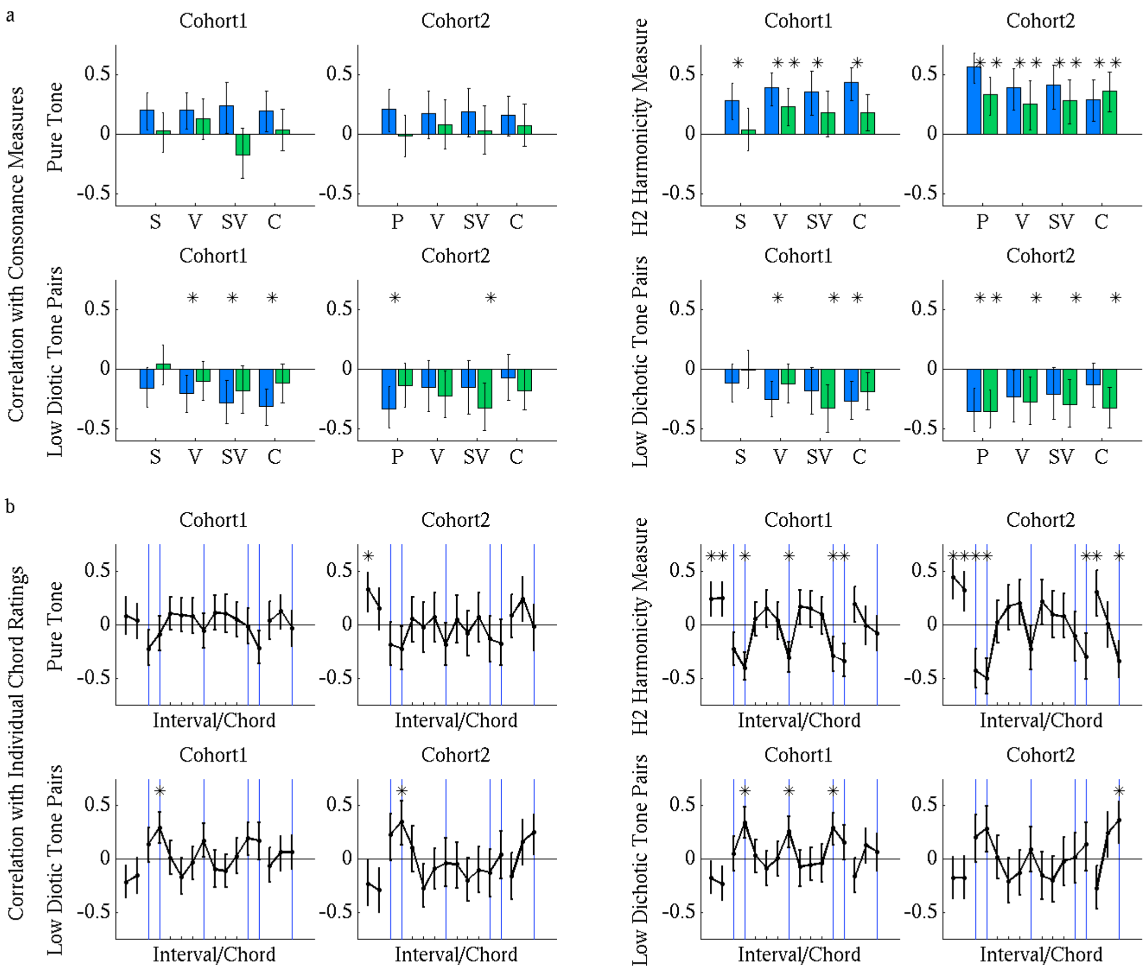

**Supplementary Figure 14**. Correlations of missing fundamental test measures with consonance. **(A)** Correlations of missing fundamental test measures with consonance measures (top left: regular complex tone – missing F0 tones (M1); bottom left: low F0 tones – missing F0 tones (M2)). Conventions are as in Figure 3. **(B)** Correlations of missing fundamental test measures with ratings of individual chords. Conventions are as in Figure 3.

**F. Correlation results for additional tone-pair test measures.**
To supplement the results of the H2 test measure discussed in the main text, we computed correlations for test measures utilizing diotic tone pairs instead of dichotic, and for measures combining low-, mid- and high-frequency tone pairs instead of just the low (which were used in the main test measure because they were matched to the pure tones in frequency). As shown in Supplementary Figure 15, we find that test measures derived from pure tones and diotic pure tone pairs (which presumably reflect beating as well as harmonicity) produce similar correlations to our H2 measure (which presumably just reflects differences in harmonicity given that dichotic tone pairs were used). The results were similar when all tone pairs were used instead of just the low-frequency pairs.




**Supplementary Figure 15**. Correlation results for additional tone-pair test measures. **(A)** Correlations of additional tone-pair measures with measures of consonance preference. **(B)** Correlations of additional tone-pair measures with average ratings of individual chords. Conventions are as in Figure 3.

We also computed correlations for the pure tone stimulus by itself, and for the tone pairs by themselves, to examine whether one of them was driving the correlations more than the other. Both stimulus classes individually produced weaker correlations than did the acoustic measure that resulted from combining them, but the pure tone was (weakly) positively correlated with our consonance measures, whereas both the diotic and dichotic tone pairs were negatively correlated (Supplementary Figure 16). It is notable that the correlation patterns are fairly similar for the diotic and dichotic tone pairs, as though the presence or absence of beats makes little difference for predicting chord pleasantness.




**Supplementary Figure 16**. Correlation results for individual tone-pair test stimuli. **(A)** Correlations of pure tones, tone-pairs, and H2 harmonicity measure with measures of consonance preference. **(B)** Correlations of pure tones, tone-pairs, and H2 harmonicity measure with average ratings of individual chords. Conventions are as in Figure 3.

Supplementary References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