UNIVERSITY OF MINNESOTA
Driven to Discover

Exploring models of consonance perception

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Introduction

Consonance is pleasant and "stable" percept created when certain combinations of two or more tones are heard simultaneously. In contrast, dissonance is an unpleasant or "rough" percept created when certain combinations of two or more tones are heard simultaneously.

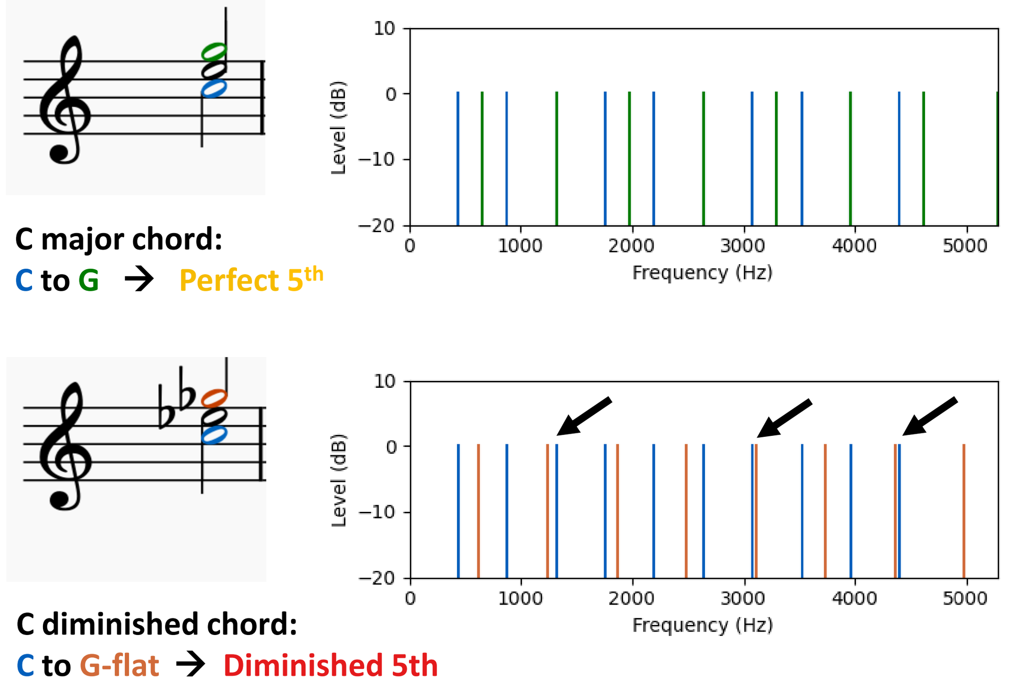


Figure 1. Musical notation, name, and schematic spectra for a consonant chord and a dissonant chord. The C major chord (top) is a strongly consonant chord and contains an interval of a perfect fifth. As can be seen in the schematic spectrum on the right, the components of this dyad are evenly spaced. The C diminished chord is a much less consonant chord and contains an interval of a diminished fifth. As can be seen in the schematic spectrum on the right, the components of this dyad are less evenly spaced. Black arrows indicate components that are nearby but not overlapping, which would likely produce the percept of beating.

Key factors

Prior work has shown that a range of factors contribute to the perception of consonance:

Roughness/beating
When two sinusoids with different frequencies enter the same auditory filter **beating** can occur. The components drift in and out of phase over time, and the combined waveform amplitude waxes and wanes. This modulation results in a sound quality known as **roughness**, which listeners usually define as unpleasant (Terhardt, 1974); (Daniel & Weber, 1997) and is thought to be more common in dissonant, but not consonant, sounds (Oxenham et al., 2010). In Figure 1, shows that dissonant chords typically have more nearby components that would evoke beating.

Harmonicity
In tones with multiple components, if components are all integer multiples of a fundamental frequency, then the tone is called **harmonic**. Otherwise, the tone is called inharmonic. Harmonicity is more common in consonant than in dissonant chords (Plack, 2010).

Familiarity
Some chords or intervals are more common than others in certain musical contexts. The degree of **familiarity** of a given interval or chord can influence its perceived consonance (Johnson-Laird et al., 2012).

Low-level acoustic features
Some low-level acoustic features, such as the spectral centroid or spectral slope of a sound, may influence the sound's perceived consonance.

Methods

We analyzed the outputs of existing implementations of various consonance models to examine similarities and differences between different models of consonance (Harrison and Pearce, 2020; Eerola and Lahdelma, 2021). Each tested model is described briefly below:

Roughness/beating

Huc78, *Hutchinson & Knopoff* (1978; 1979): Extension of the Plomp and Levelt (1965) consonance model to consider interference between all pairs of harmonics (and not only adjacent harmonics).

Seth93, *Sethares (1993)*: Extension of the Plomp and Levelt (1965) consonance model, considering in particular how timbre affects consonance.

Vass01, *Vassilakis (2001)*: Extension of the Hutchinson and Knopoff (1978) model that reconsiders how relative component amplitudes relate to consonance

Wan13, *Wang et al. (2013)*: Computes roughness as a weighted sum of the modulation index at the output of each channel of a simple auditory periphery model

Hur94, *Huron (1994)*: Predicts consonance of complex chords as the combination of the consonance ratings of each dyad within the chord

Harmonicity

Par88, *Parncutt (1988):* Computes the root of a chord using chord-root model and then predicts consonance as a function of different possible or plausible roots a chord may have.

Par94, *Parncutt and Strasburger (1994)*: computing both "pure tonalness" (a measure of audibility) and "complex tonalness" (a measure of audibility of the strongest pitch in the mixture).

Mil13, *Milne (2013)*: Computes cosine similarity between a simplified "internal spectrum" of a chord and individual template notes, predicts the consonance cosine similarity of the best match.

Gil09, *Gill and Purves (2009)*: Predicts consonance by measuring the extent of overlap between the spectrum of a chord and a template complex tone centered on a fundamental of a chord root.

Sto15, *Stolzenburg (2015)*: Computes consonance based on the simplicity of ratios between components in the chords.

Familiarity

Jl12, *Johnson-Laird et al. (2012)*: Predicts consonance according to a set of rules: favors chords (1) on the major scale, (2) with a major triad, (3) separated by intervals or a third or a fifth.

CorpJa, *Eerola and Lahdelm (2020):* Prevalence ranking of chords in jazz music corpus

CorpCl, *Harrison and Pearce (2018)*: Prevalence ranking of chords in a selection of sonatas and string quartets by Mozart, Chopin, Haydn, Bach, and Beethoven.

CorPo, *Eerola and Lahdelm (2020):* Prevalence rankings of chords in popular music corpus

Har19_corp, *Harrison and Pearce (2018)*: Prevalence rankings of chords from the 739-piece Billboard corpus (Burgoyne, 2012).

TonDis, *Eerola and Lahdelm (2020):* indicates whether a chord can be built from a major scale

Acoustic

SpecCe & SpecRo, *Lahdelma and Eerola (2016); Smit et al. (2019)*: both indicate measurements of the spectrum's distribution over frequency

SpecIr, *Jensen (1999)*: Quantifies the irregularity of overlapping partials

SpecSh, *Zwicker and Fastl (1990); Claire Churchill (2004)*: The model first computes the signal's loudness using an algorithm then computes sharpness across these frequency bands using Zwicker's formula. emphasizing sounds with higher frequency contents as having sharper timbre.

Combined

Har19_comp, *Harrison and* Pearce *(2020)*: this model combines roughness, harmonicity and familiarity model predictions to optimally predict behavioral consonance ratings.

Results

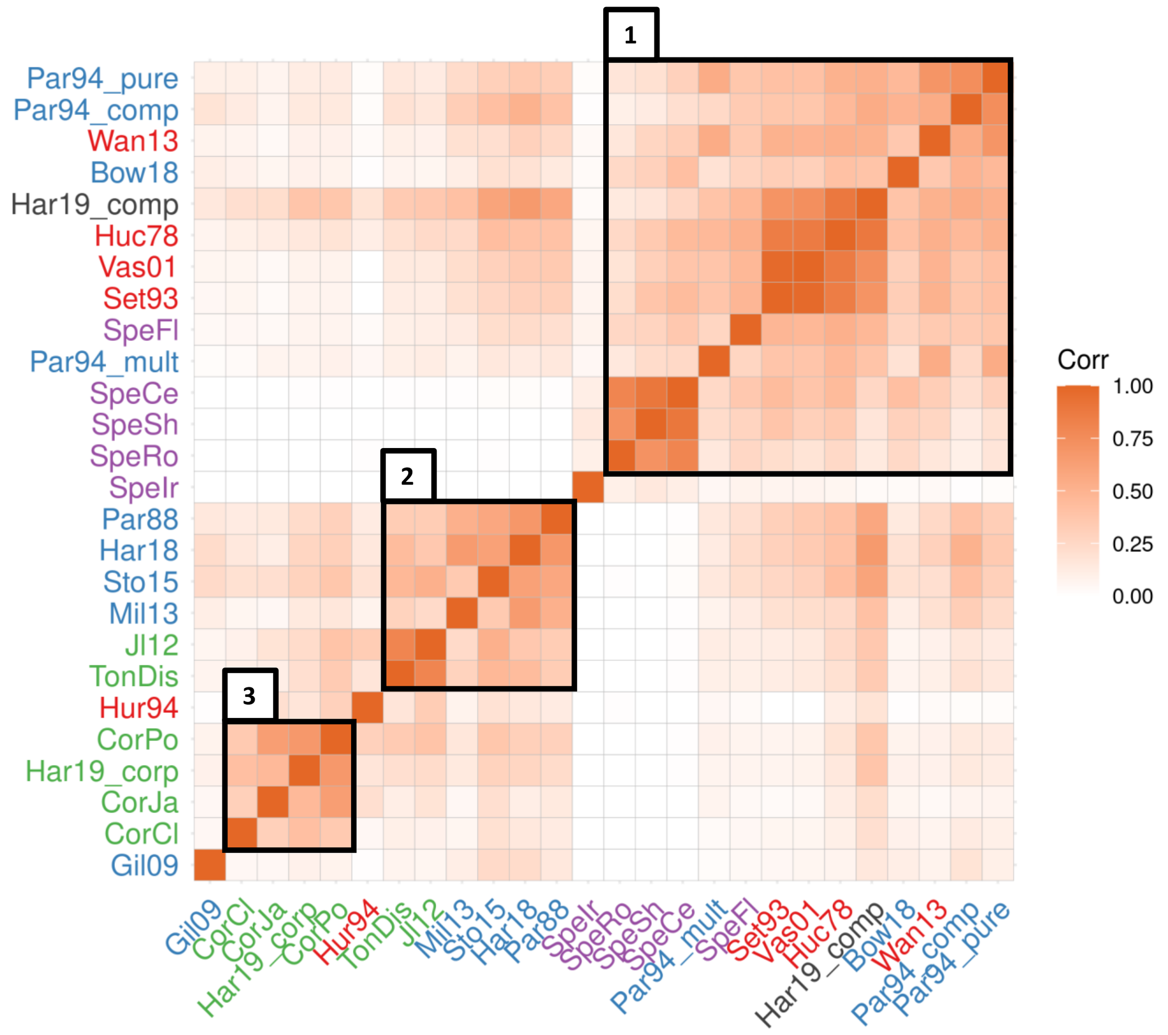
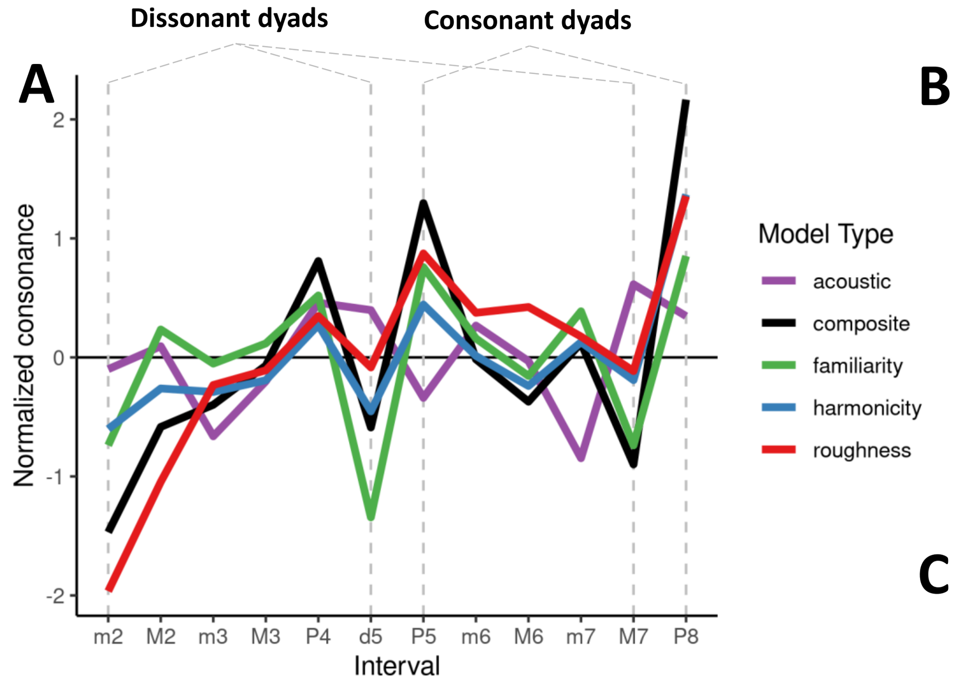


Figure 2. Squared correlation values between different models of consonance across the chord database. Color indicates model type. Ordering of models along the axes was decided by a hierarchical clustering algorithm implemented in R using the *fastcluster* package (Müllner, 2013) Black highlight boxes were added by hand to highlight notable clusters. A few interesting clusters are noted:

- Roughness models and low-level acoustic models mostly cluster together along with some harmonicity models (1)
- Several but not all harmonicity models clustered together (2) with some familiarity models
- Corpus-based familiarity models clustered together and correlated weakly with other models (3)



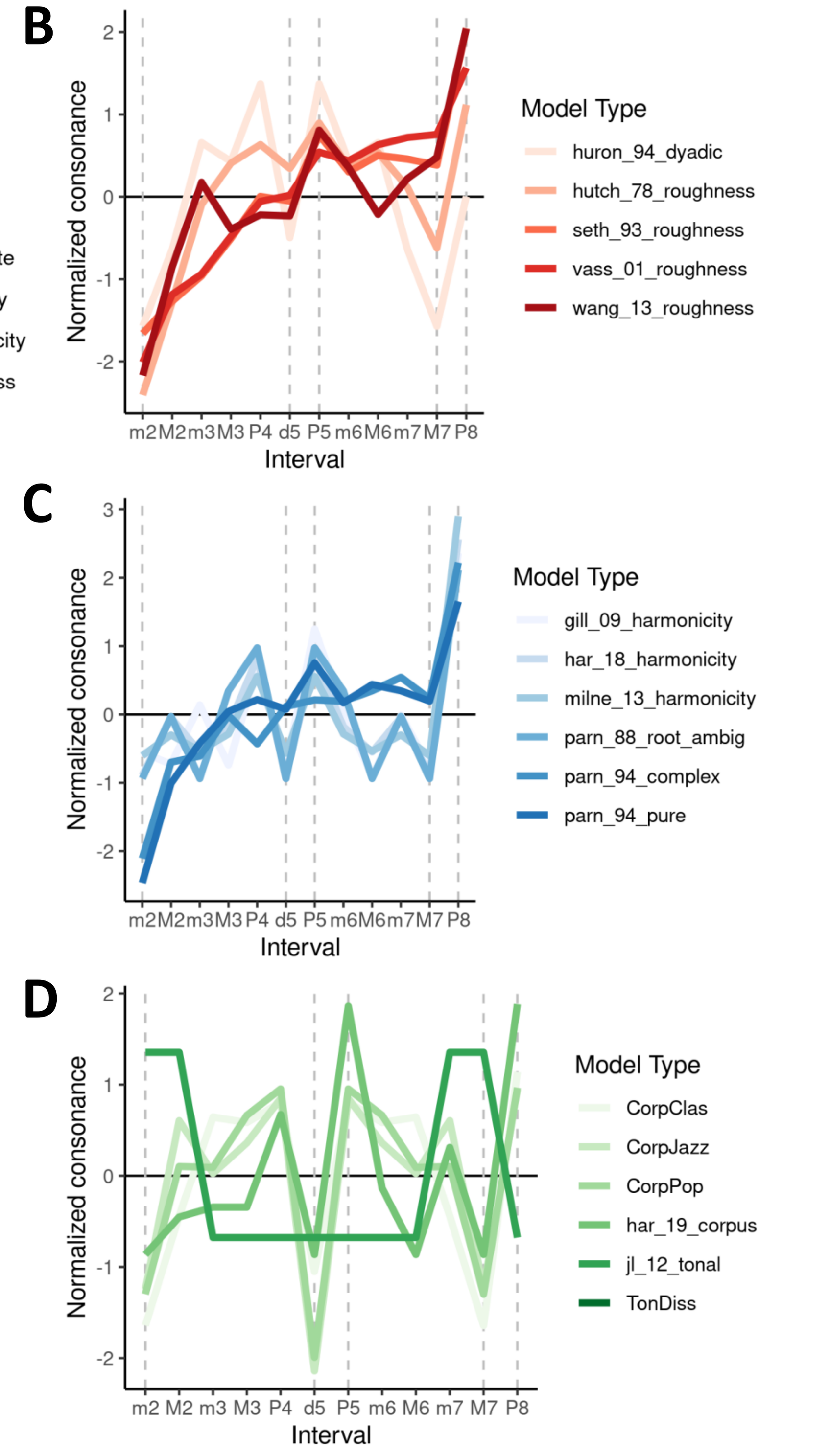
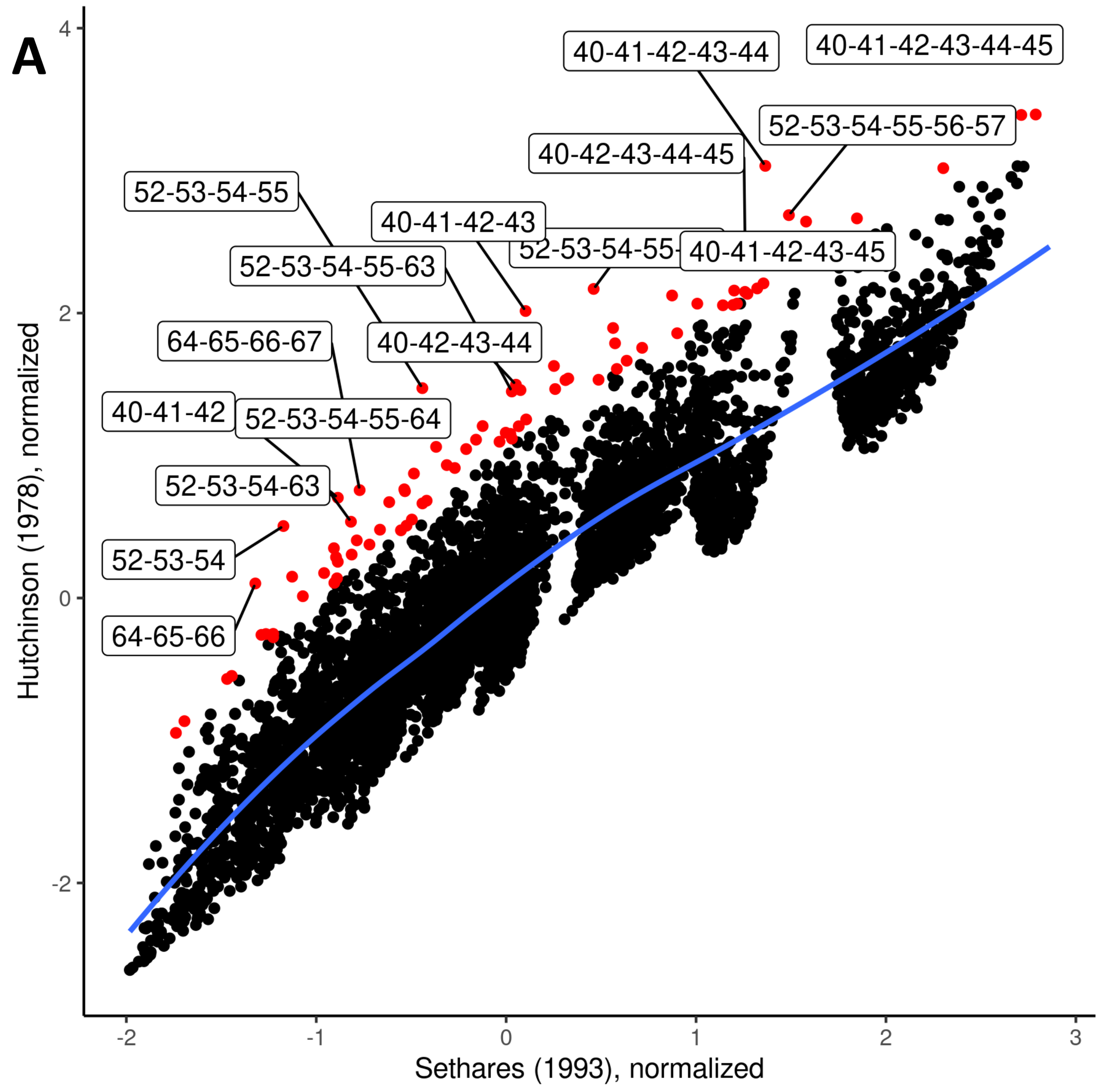


Figure 3. A. Average predicted consonance for each dyad on the chromatic scale. Predictions from individual models were first z-scored across the dyads and then predictions from each type of model were averaged. **B, C, D.** Predicted consonance for each dyad on the chromatic scale from the roughness models (**B**), harmonicity models **(C)**, or familiarity models (**D**). Predictions from each individual model were z-scored.

A few features of note can be observed:

- Roughness models often do not capture some established trends in dyad consonance (e.g., d5 is dissonant and P5 is consonant), whereas harmonicity and familiarity models generally do
- Acoustic features (e.g., spectral centroid) are not systematically related to chord consonance
- Large discrepancies between models within categories observed in some cases (e.g., roughness of M7, Figure 3b)

Results (continued)



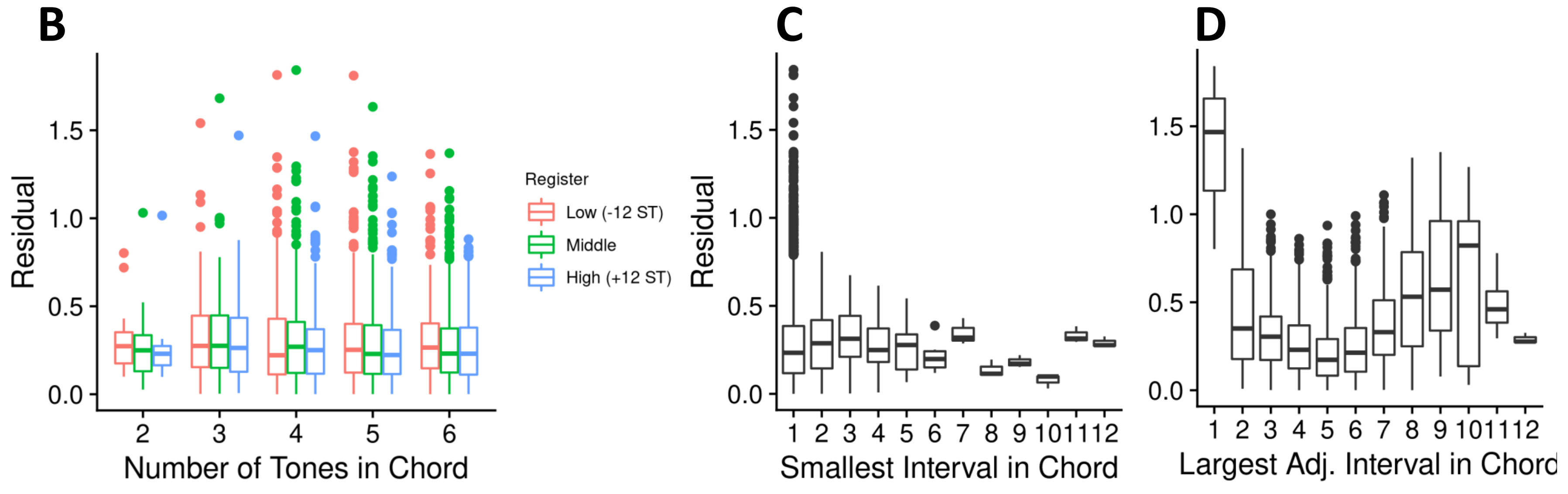


Figure 4. A. Correlation between z-scored consonance predictions for two example roughness models (Set93 and Huc78). A curve was fit through the scatterplot using *loess* in R and used to predict the outputs of one model from the other. Chords with residuals that were at least 3 standard deviations above the mean were marked with red dots. Some of these chords were labeled with their constituent notes in MIDI notation. **B.** Boxplots of the model residuals versus the number of tones in each chord and the register of the chord. **C.** Boxplots of the model residuals versus the smallest interval in the chord. **D.** Boxplots of the model residuals versus the largest adjacent interval in each chord.

- The number of tones in the chord and the register of the chord were not related to inter-model agreement
- Chords with smaller intervals resulted in less inter-model agreement

Conclusions

- **Figure 2:** Roughness and harmonicity models largely separate into two distinct clusters
  - Both types generally correlate with Har19_comp, which is successful in predicting behavioral consonance ratings
  - Suggests that consonance is a combination of roughness and harmonicity
- **Figure 3:** Surprisingly large disagreements are observed within categories between models in the predicted consonance of dyads
- **Figure 4:** Various models of consonance that are highly correlated still disagree about predicted consonance of individual chords
  - This could be exploited by researchers to develop experimental stimulus sets to efficiently identify which model better predicts human perception
- **Take home message:** Datasets and code provided by Harrison and Pearce (2020) and Eerola and Lahdelma (2020) highlight complexity of consonance perception and constitute useful tools for researchers in the field

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