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Consonance perception of complex-tone dyads and chords

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Summary
Sensory consonance and dissonance are perceptual attributes of musical intervals conveying pleasantness, tension, and harmony in musical phrases. For complex-tone dyads, corresponding to two musical notes played simultaneously, consonance is known to vary with the ratio in fundamental frequency (F0) between the two tones in the dyad. While such a relationship is well established for dyads, the subjective consonance of chords containing three or more simultaneous notes, that form the basis of most musical pieces, remains to be explored. The present study aimed at comparing consonance judgments for dyads and 3-note chords as a function of the F0 ratio between their element tones. Dyads and chords were generated by adding two or three complex tones containing 6 harmonics with equal amplitude and random phase. The base F0 of the first tone was randomly selected from an interval spanning $\pm 3/4$ of a semitone centered at 440 Hz. The second tone F0 varied between 0–12 semitones above the base F0. For chords, the third tone F0 was fixed either at 5 (Perfect 4th, P4) or at 7 (Perfect 5th, P5) semitones above the base F0. Ten normal-hearing listeners were presented with all possible dyad/dyad, dyad/chord, and chord/chord combinations in random order and were asked to judge which interval was most consonant in each paired comparison. The results for dyad/dyad comparisons were consistent with earlier findings, with the unison, octave, P5, and P4 intervals being perceived as the most consonant. For dyad/chord comparisons, dyads were more consonant in the intervals around the fixed third tone. Overall, chords were not found to be more dissonant than dyads. This suggests that the hypothesis according to which consonance decreases with the amount of interaction between present harmonics, arguing for a potential role of frequency selectivity for consonance perception of dyads, might not hold for chords.

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1. Introduction

In Western music, the sound produced as a result of the interaction between two musical tones played simultaneously can be perceived by a listener as consonant (pleasant/harmonious) or dissonant (unpleasant/inharmonious). While the perception of consonance has received much study, and several theories have been proposed (e.g., [1, 2]), it remains a current topic of research (e.g, [3]). Moreover, while the consonance of pure-tone and complex-tone dyads, corresponding to two simultaneous musical notes, has been widely studied and is known to vary with the ratio in fundamental frequency (F0) between the two tones in the dyad, there is less knowledge about the subjective consonance of chords, i.e., groups of three or more notes. Specifically, the relationship between the consonance of chords and dyads has rarely been studied directly (e.g., [4]), and the design of a unifying modeling framework that can account for the consonance and dissonance of musical sounds containing different numbers of simultaneous notes remains a challenge.

Hermann von Helmholtz suggested that consonance is related to beats, i.e., fluctuations in sound amplitude resulting from the frequency difference between the interacting tones, and roughness, an attribute of sound quality occurring for small frequency differences of simultaneous tones that listeners usually describe as unpleasant [1]. This explanation was further refined and related to the critical bandwidth of auditory filters by Plomp and Levelt [2], who suggested that the consonance between pure tones decreases up to a frequency spacing of about 1/4 of the critical bandwidth, and increases progressively for larger spacings. Such a relationship between auditory-filter bandwidth and dissonance judgments by normal-hearing and hearing-impaired listeners was also observed for complex-tone dyads in a study by Tufts et al. [4], whose observations suggested a role of peripheral frequency selectivity for dissonance perception.

Independently from [2], Kameoka and Kuriyagawa developed a quantitative framework to predict dissonance of tones and harmonic complexes [5]. Underlying this framework is the key assumption that the dissonance of a dyad or chord created from harmonic complexes is the sum of the dissonances resulting from all the possible combinations of harmonic pairs. Thus, this framework predicts that chords should always be more dissonant than dyads, as adding the third tone or harmonic complex to a dyad would add dissonances from the interaction of the added harmonics.

Other explanations have been given for the perception of consonance and dissonance. Indeed, a recent study of McDermott et al. suggests that harmonicity in the complex-tone spectra plays a key role in the perception of consonance [3] and can more strongly influence consonance perception than beating. Thus, these results might predict that chords created by adding a perfect fourth or perfect fifth note to a dyad would be judged as more consonant than the dyad, as the spectra would include more harmonicity, particularly if the dyad was dissonant.

In the present study, listeners directly compared the consonance of dyads and chords against each other using a paradigm inspired by [4]. The aim was to clarify whether dissonance is directly related to the amount of harmonic interactions within peripheral auditory filters, in which case chords should overall be more dissonant than dyads, or whether other factors such as harmonicity or pitch strength should be considered in models of consonance perception.

2. Method

A total of 10 listeners with varying degrees of musical training (ranging from none to seven years of training) participated. None of the listeners reported any history of hearing loss and all had normal audiometric thresholds ($\leq$ 25 dB HL, 500–8000 Hz).

The procedure and stimuli were inspired by that used in [4]. Participants sat in a sound-insulated booth and listened to pairs of dyads and/or chords. For each pair, listeners judged which was more consonant. As in [4], participants were instructed that a consonant sound was "pleasant, smooth, pure, and harmonious". Stimuli were presented monaurally to the right ear using Senheiser HD580 headphones.

The set of intervals used to construct the dyads and chords are presented in Table I. Each dyad consisted of two harmonic complex tones. Each harmonic complex contained six components (i.e., a fundamental and 5 harmonics). All twelve components were were of equal amplitude and random starting phase. Similarly, the chords consisted of three harmonic complexes, each with six components. For the perfect fourth (P4) chords, one of the harmonic complexes corresponded with the five semitone interval. Similarly, for the perfect fifth (P5) chord, one of the harmonic complexes corresponded with the seven semitone interval.

Table I. Semitone separation, name, and corresponding frequency ratio of the intervals used in this study. *Note that an incorrect ratio for the perfect fifth was used. The correct ratio should have been 1.498.

Semitone Separation	Interval Name	Frequency Ratio
0	Unison	1.000
1	Minor 2nd	1.059
2	Major 2nd	1.122
3	Minor 3rd	1.189
4	Major 3rd	1.260
5	Perfect 4th	1.335
6	Tritone	1.414
7	Perfect 5th	1.489*
8	Minor 6th	1.587
9	Major 6th	1.682
10	Minor 7th	1.782
11	Major 7th	1.888
12	Octave	2.000

Each dyad and/or chord was 600 ms in duraction and each pair was separated by a silent interval of 250 ms. Over the course of the experiment, each participant listened to a total of 1482 pairs. All possible dyad/chord combinations were presented twice (i.e., in both orders, A vs. B and B vs. A). For each pair, the F0 of the root was randomly chosen. The values were uniformly distributed between 421.35 Hz and 459.48 Hz, which corresponded to 3/4 of a semitone below and above 440 Hz, respectively.

Due to a typing error, the frequency ratio of the presented perfect 5th was offset relative to the one originally intended. Thus, the presented perfect 5th was not a true perfect 5th. The frequency ratio used in the experiment was 1.489 rather than 1.498. This introduced an error of approximately 0.6%. While small, the difference in terms of consonance is still audible.

3. Results

For each participant, a running score was kept for each of the dyad and chords. When a listener judged a dyad (or chord) to be more consonant, the score for that dyad (or chord) was incremented. The total score was then normalized by the total number of presentations of that dyad (or chord). Thus, a normalized score of 1 corresponded to the case where that dyad (or chord) was always judged as more consonant. Conversely, a normalized score of 0 corresponded to the opposite case, where the dyad (or chord) was always judged as less consonant (i.e., more dissonant).

The normalized results, averaged across listeners, are plotted in Figure 1. The results in the left panel

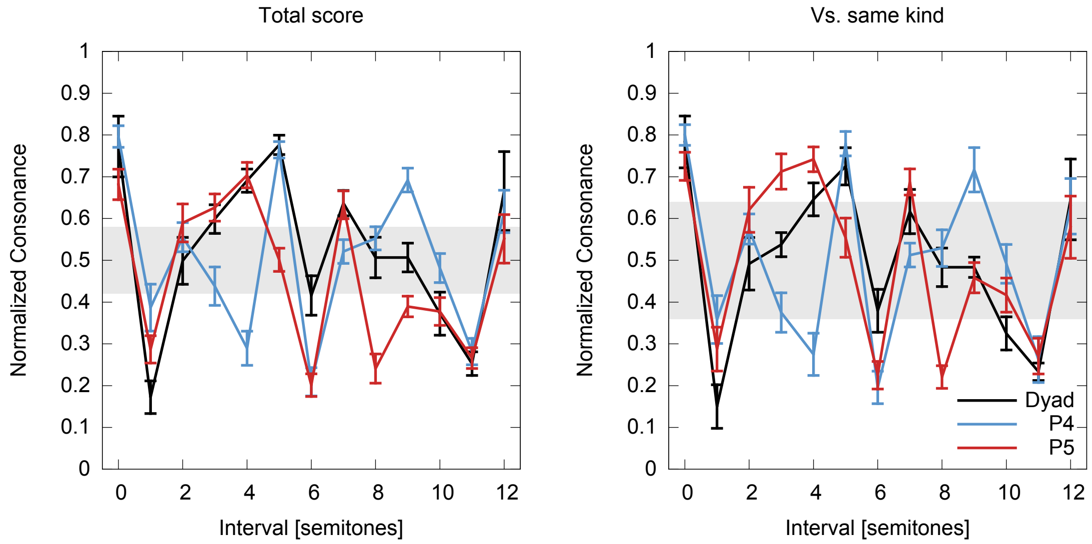

Figure 1. Normalized mean total consonance scores (left) and mean consonance scores vs. same type (right). Points that lie outside the grey region are significantly different from chance ($p < 0.05$, Bonferroni corrected for multiple comparisons). Errorbars indicate one standard error.

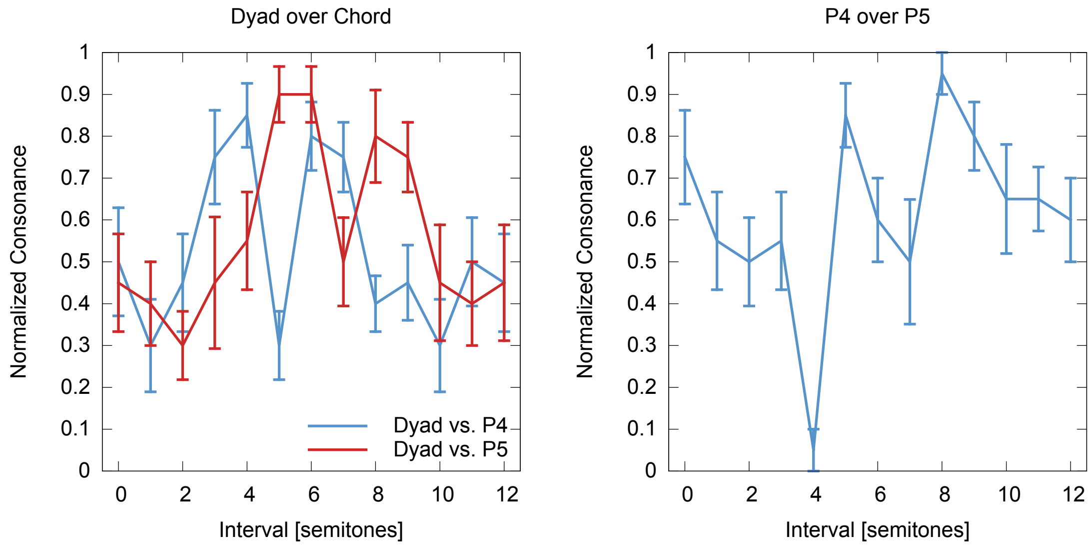

Figure 2. Normalized mean consonance scores of dyads vs. chords of the same interval (left) and P4 vs. P5 chords of the same interval (right). Errorbars indicate one standard error.

are from judgements of all combinations, while the results in the right panel are from judgements of the same type (i.e., dyad vs. dyad, P4 vs. P4, or P5 vs. P5).

For dyads, the most consonant intervals were the unison, perfect 4th, perfect 5th, and octave (i.e., intervals of 0, 5, 7, and 12 semitones, respectively). Conversely, the minor 2nd and major 7th (i.e., intervals of 1 and 11 semitones, respectively) were the most dissonant.

For the P4 chords, the most consonant intervals were the unison, perfect 4th, major 6th, and octave (i.e., intervals of 0, 5, 9, and 12 semitones, respectively). Conversely, the minor 2nd, major 3rd, tritone, and major 7th (i.e., intervals of 1, 4, 6, and 11 semitones, respectively) were the most dissonant.

For the P5 chords, the most consonant intervals were the unison, major 3rd, perfect 5th, and octave (i.e., intervals of 0, 4, 7, and 12 semitones, respectively). Conversely, the minor 2nd, tritone, minor 6th, and major 7th (i.e., intervals of 1, 6, 8, and 11 semitones, respectively) were the most dissonant.

While the results in the left and right panels of Figure 1 are quite similar, a direct comparison of dyads and chords with the same interval is plotted in Figure 2. In the left panel, the normalized results indicate the relative frequency of the dyad being judged as more consonant than the chord. Thus, scores near 0.5 indicate that the dyad and chord were judged to be similar in consonance. In the right panel, the normalized results indicate the relative frequency of the P4 chord being judged as more consonant than the P5 chord.

4. Discussion

In the present study, participants listened to pairs of dyads and/or chords and, for each pair, judged which was more consonant than the other. Overall, the pattern of results for the dyads is in agreement with previous studies (e.g., [2, 5, 4]).

In comparing the normalized dyad consonance scores, the results for the total score as a function of interval (left panel of Figure 1) are quite similar to the normalized score when the comparisons are limited to only other dyads (right panel of Figure 1). A similar pattern is observed between the total score and the vs. same kind scores for P4 and P5 chords. Taken together, these results do not suggest that dyads are systematically more or less consonant than chords.

A more complex picture emerges when dyads and chords with the same interval are compared (Figure 2, left panel). When dyads and P4 chords of the same interval are compared directly, they are judged to be similar in consonance (i.e., the normalized consonance score is approximately 0.5) for all intervals except 3, 4, 6, and 7 semitones (blue curve). A similar pattern is observed for dyads and P5 chords, except that the intervals where dyads are judged to be more consonant are 5, 6, 8, and 9 semitones (red curve). Thus, a dyad is perceived as more consonant than the corresponding P4 or P5 chord if the interval between the second and third tone of the chord is within two semitones.

For second chord notes more than 2 semitones away from the third P4 and P5 notes (i.e., intervals of 0, 1, 2, 10, 11, and 12 semitones), the consonance of dyads and either chord type do not differ (scores of approximately 0.5 in the left panel of Figure 2). No large dyad vs chord difference is observed either when the second note is equal to the third (5 semitones for P4, 7 semitones for P5), i.e., conditions in which the frequencies of all harmonics are identical for the dyad and the corresponding chords and only harmonic amplitudes differ. These observations also indicate that, when the second and third note in the chord are sufficiently far apart in terms of F0, chords are neither more consonant nor more dissonant than corresponding dyads.

When P4 and P5 chords are directly compared (Figure 2, right panel), similar consonance ratings are obtained except when the interval between the second and third note is greater than 1 semitone.

Overall, the behavioural measures suggest that dyads are not more consonant than chords, except in the intervals close to the fixed third tone of the particular chord. This is in contrast to the framework developed by Kameoka and Kuriyagawa [5] that suggests that dissonance of a set of sinusoids is equal to the sum of the dissonance of all combinations of harmonic pairs. While the introduction of a 1- or 2-semitone interval within a chord is detrimental to consonance, suggesting a contribution of a close spacing between harmonics to dissonance, such a contribution cannot be generalized in an additive fashion to all tested semitone intervals. Thus, other aspects of auditory perception must play a role in the subjective consonance of chords and dyads.

5. Conclusions

In general, dyads are not systematically more consonant or dissonant than chords unless the interval between the second and third tone of a three-tone chord is within two semitones (in which case dyads are perceived as more consonant). This implies that assumptions regarding the general additivity of dissonance (e.g., [5]) are likely incorrect. The present findings suggest that a model of consonance perception based solely on the amount of peripheral interaction between harmonic components within the critical bandwidth of auditory filters would fail at correctly predicting consonance judgments of both complex-tone dyads and chords. A comparison of consonance predictions from such a model with those of modeling approaches based on harmonicity (e.g., [3]) or pitch strength (e.g., [6]) may reveal whether one or a combination of these different attributes can best account for the subjective consonance and dissonance of any combination of complex tones.

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