ROUGHNESS AND DISSONANCE OF MUSICAL DYADS

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ABSTRACT

Dissonance of musical dyads arises due to rapid beats between the harmonics of complex tones. The sensation produced by rapid beats is called roughness in psychoacoustics. Roughness of dyads composed of harmonic complex tones was assessed using a psychophysical scaling method of absolute magnitude estimation. The dyads formed 35 musical intervals ranging from a unison to an octave, in various tuning systems.

Results demonstrate that roughness varies with the interval's frequency ratio what is a well-known phenomenon. An unexpected observation is that equally tempered intervals are perceived less rough than intervals with frequency ratios based on integer proportions. This finding may be explained by the effect of slow beats that are produced between the harmonics of the two complex tones when the interval's frequency ratio slightly departs from integer proportion. Slow beats are heard as loudness fluctuations and produce a pleasant quality of sound.

1. INTRODUCTION

It has been widely known that dissonance of musical dyads depends on the frequency ratio of the interval formed by the two tones. Sounds produced by most musical instruments are harmonic complex tones. When two complex tones are played simultaneously, the sound fluctuates in amplitude, due to beats that occur between their harmonics. The beat rate is equal to the difference in frequency between the two beating tones. Beats are perceived differently, depending on their rate. When the beat rate is below about 10 Hz, the beats are heard as loudness fluctuations. As the beat rate increases, the sound becomes unpleasant and is perceived as rough. The roughness sensation reaches a maximal strength when the beat rate is within a range of about 20-60 Hz, and diminishes, as the beat rate is further increased above 60 Hz [1, 2].

Roughness of a dyad composed of harmonic complex tones is produced by various combinations of the beating harmonics. Relation between the frequency ratio of such a dyad and roughness is nonmonotonic. As the frequency ratio of the two complex tones is varied several local maxima and minima of roughness can be observed. According to a theory formulated by von Helmholtz [3] and further expanded by other researchers [4], roughness reaches a minimum when the fundamental frequencies of the two tones are in small integer ratios. In such a case certain harmonics of the two complex tones coincide in frequency and the effect of beats is minimized.

The effect of beats on the roughness sensation was explored in a number of experiments which consisted in subjective judgment of dyads composed of two pure tones [1, 2]. In published studies, roughness of complex-tone dyads was predicted in a theoretical way, by summation of the roughness produced by various combinations of the harmonics [5]. The purpose of the present study was to determine the roughness of complex-tone dyads by auditory assessment of sensation magnitude.

2. METHOD

The dyads were composed of harmonic complex tones. Each complex tone comprised the fundamental and nine harmonics, and had a decreasing spectral envelope of 6 dB/oct. The fundamental frequency of the lower complex tone in a dyad was 261,6 Hz (C4 on the musical scale) and the fundamental frequency of the upper tone was an experimental variable. The set of stimuli included 35 dyads which formed 24 intervals spanning an octave range in equally-tempered, quarter-tone steps and 11 intervals with frequency ratios based on integer proportions. The frequency ratios of intervals and their size in cents are listed in Table 1. All dyads were 2 s in duration and were presented monaurally at a loudness level of 50 phons.

The dyads were generated digitally using a PC-compatible computer with a signal processor (TDT AP2) and a 16-bit D/A converter (TDT DD1) with a 50-kHz sampling rate. The signal at the converter's output was low-pass filtered (TDT FT5, f_c=20 kHz), attenuated (TDT PA4), and led to a headphone amplifier (TDT HB6), which fed one earphone of the Beyerdynamic DT 911 headset. The listeners were tested individually in a sound-proof booth.

The judgments of roughness were obtained using the method of absolute magnitude estimation [6]. The listener's task was to assign a number to the magnitude of roughness produced by each of the stimuli in a series. The order of stimuli was random in each presentation of a series. In accordance with the procedure of absolute magnitude estimation described by Zwislocki and Goodman [6], no restrictions were made as to the range of numbers used for the judgment of sensation magnitude, except that the listeners were required to use positive numbers. The listener activated a single presentation of sound by pressing a button on the response box in the booth and could listen to the sound at will before reporting the number through an intercom to the experimenter. The experimenter entered the number to the computer and a visual signal was presented on the response box to indicate a next judgment.

Sixteen music students served as listeners. Each of them completed five series of judgments, so that a total of 80 judgments was obtained for each stimulus (16 listeners × 5 series of judgments).

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	Frequency ratio	Interval in cents	Interval
1	1.0000	0	unison
2	1.0125	22	syntonic comma
3	1.0293	50	tempered quarter tone
4	1.0595	100	tempered semitone
5	1.0905	150	
6	1.1225	200	tempered major second
7	1.1554	250	
8	1.1892	300	tempered minor third
9	1.2000	316	just minor third
10	1.2241	350	
11	1.2500	386	just major third
12	1.2599	400	tempered major third
13	1.2660	408	Pythagorean major third
14	1.2968	450	
15	1.3348	500	tempered perfect quarter
16	1.3740	550	
17	1.4142	600	tritone
18	1.4557	650	
19	1.4983	700	tempered perfect fifth
20	1.5000	702	Just fifth
21	1.5422	750	
22	1.5874	800	tempered minor sixth
23	1.6000	814	just minor sixth
24	1.6339	850	
25	1.6670	885	just major sixth
26	1.6818	900	tempered major sixth
27	1.7311	950	
28	1.7500	969	harmonic minor seventh
29	1.7818	1000	tempered minor seventh
30	1.8000	1018	just minor seventh
31	1.8340	1050	
32	1.8750	1088	just major seventh
33	1.8877	1100	tempered major seventh
34	1.9431	1150	
35	2.0000	1200	octave

Table 1. Frequency ratios and size in cents of musical intervals used in the experiment.

3. RESULTS

Figure 1 shows the values of roughness as a function of the interval size in cents. Each data point represents the geometric mean of 80 judgments. The geometric means were multiplied by a constant such that the maximum roughness value in Fig. 1 equaled 1.

As seen in Fig. 1, the roughness of a dyad considerably varies, depending on the interval formed by the constituent complex tones. The maximum value of roughness is obtained for an interval of 150 ct (3/4-tone), and the lowest roughness values are observed for a unison (a single complex tone) and an octave.

The present data made it possible to verify a theory which postulates that roughness and dissonance of two simultaneously sounding complex tones reach a minimum when their frequency ratio is expressed by small integers. This theory, developed by von Helmholtz [3] and further expanded by other researchers [4], has been recalled by musicians to argue that integer-ratio intervals are more consonant than tempered intervals.

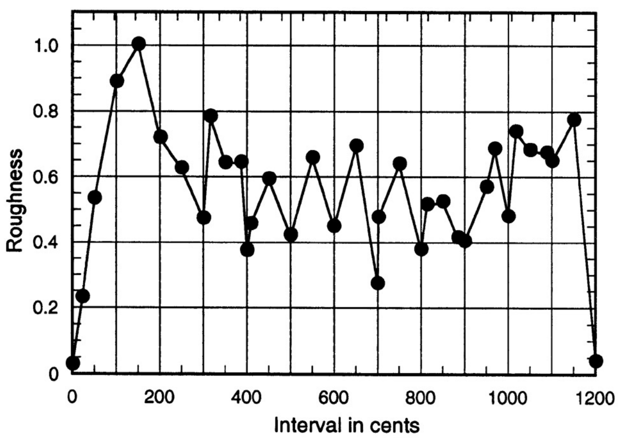

Figure 1: Roughness of dyads as a function of the interval size in cents. Each data point represents the geometric mean of 80 judgments (16 listeners × 5 series of judgments).

The set of dyads used in the present study included the following intervals with integer frequency ratios:

- just minor third: frequency ratio 6:5, interval size 316 ct,
- just major third (5:4, 386 ct),
- perfect fifth (3:2, 702 ct),
- just minor sixth (8:5, 814 ct),
- just major sixth (5:3, 884 ct),
- harmonic minor seventh (7:4, 969 ct),
- just minor seventh (9:5, 1018 ct),
- just major seventh (15:8, 1088 ct).

Figure 2 shows a comparison of roughness values obtained for the above intervals and for the respective tempered intervals.

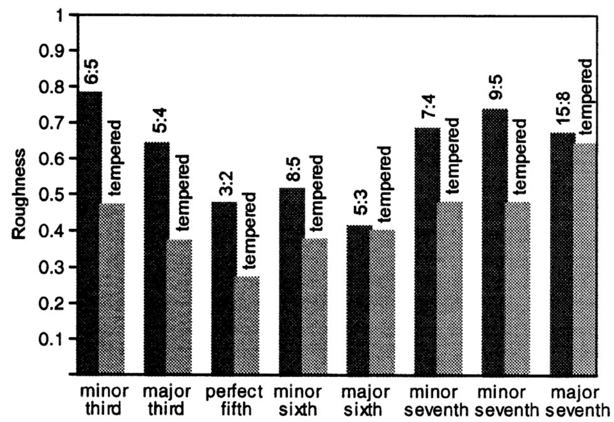

Figure 2: A comparison of roughness values determined for intervals with integer frequency ratios and for tempered intervals. The data shown are taken from Fig. 1.

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As seen in Fig. 2, the roughness values determined for tempered intervals are lower than those obtained for intervals with integer frequency ratios. The difference is largest for the perfect fifth, the major third, and the minor third. Roughness of the above intervals with integer frequency ratios is about 1.7 times larger than the roughness of tempered intervals. The smallest difference in roughness between integer-ratio and tempered intervals is observed for the major sixth and the major seventh.

A *t*-test for grouped data was performed to examine whether the differences in roughness were statistically significant for the pairs of intervals compared in Fig. 2. The values of probability, p, were less than 0.001 for the minor third and the major third, less than 0.01 for the perfect fifth and for the two pairs of the minor seventh, and less than 0.03 for the minor sixth. The differences in roughness were therefore statistically significant for the above intervals. In the pairs of the major sixth and the major seventh, the p values exceeded the 0.05 level, so the differences in roughness could not be considered significant.

In order to further explore the effect of beats on roughness, we calculated the beat rates and beat amplitudes for the dyads used in our experiment. Figure 3 shows the data for an interval of 150 ct (a three-quarter tone), for which the maximum roughness value was obtained, and for an octave, in case of which a minimum of roughness was found. The beat rates are represented by the location of the bars on the abscissa, and the beat amplitudes are indicated by the dots on the bars. The value of 0 dB on the ordinate is the amplitude of beats produced by the fundamentals of the two complex tones. The amplitudes of beats produced by various pairs of harmonics are indicated by separate dots on the bars.

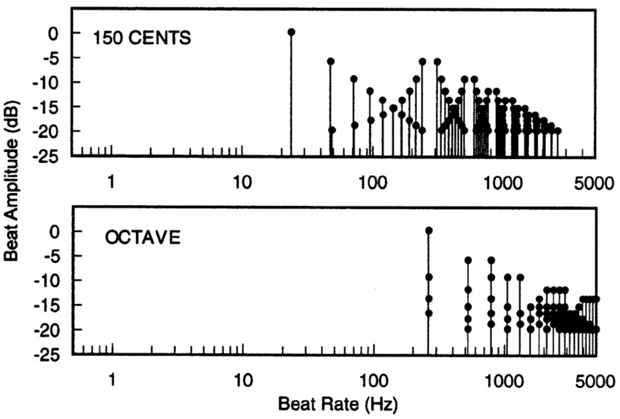

Figure 3: Beat rates and beat amplitudes produced by pairs of partials of dyads forming an interval of 150 ct (upper panel) and an octave (lower panel). The value of 0 dB on the ordinate indicates the amplitude of beats produced by the fundamentals of the two complex tones.

The examples of dyads with the minimum and the maximum roughness values (Fig. 3) agree with von Helmholtz's theory of roughness. However, such an agreement of judgments with the theory cannot be observed when data obtained for integer-ratio and tempered intervals are compared. As an example, shown are in Fig. 4 the beat frequencies and beat amplitudes for a just fifth and a tempered fifth. In the case of a just fifth (upper panel), the lowest beat frequency is 130.8 Hz, and is remote from the range of beat frequencies that produce a pronounced sensation of roughness. In the case of tempered fifth, the lowest beat frequencies are 0.9, 1.8, and 2.7 Hz.

In contrast to what has been known from von Helmholtz's [3] theory, the roughness of the tempered fifth was judged lower than the roughness of the just fifth (see Fig. 2). This finding may be explained by the effect of slow beats that in the tempered fifth (Fig. 4). Slow beats produce a pleasant character of sound, resembling the effect of vibrato. It has been demonstrated that the sensation of roughness is very highly correlated with unpleasantness of sound. Some authors argue that roughness may be assessed on the basis of judgments obtained for unpleasantness [5]. In the case of the tempered fifth, the effect of slow beats is an increase in pleasantness of sound and, in consequence, a decrease in roughness.

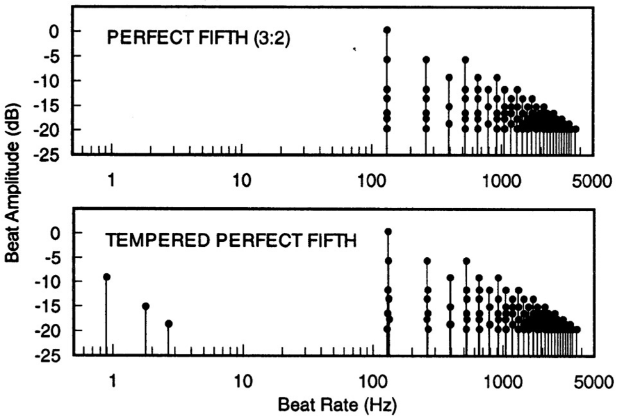

Figure 4: Beat rates and beat amplitudes produced by pairs of partials of two harmonic complex tones forming a just perfect fifth (upper panel) and a tempered perfect fifth (lower panel). The data are plotted in a similar manner as in Fig. 3.

Figure 5 shows the beat rates and the beat amplitudes calculated for six pairs of intervals compared in Fig. 2, for which the differences in roughness were found statistically significant. Plotted are data for intervals with integer frequency ratios and for tempered intervals.

As seen in Fig. 5, the lowest beat rates are less than 20 Hz in the tempered minor third, the tempered major third, the tempered fifth, and the minor sixth. In the intervals based on integer frequency ratios the lowest beat rates are much higher than those observed for tempered intervals and do not produce loudness fluctuations. The lowest beat frequency for the tempered minor seventh is about 30 Hz, yet this interval is judged less rough than the two integer-ratio sevenths (Figs 2 and 5). In this case the lower roughness value of the tempered interval may be partly attributed to the fact that the integer-ratio sevenths are dissonant and produce a relatively strong sensation of roughness.

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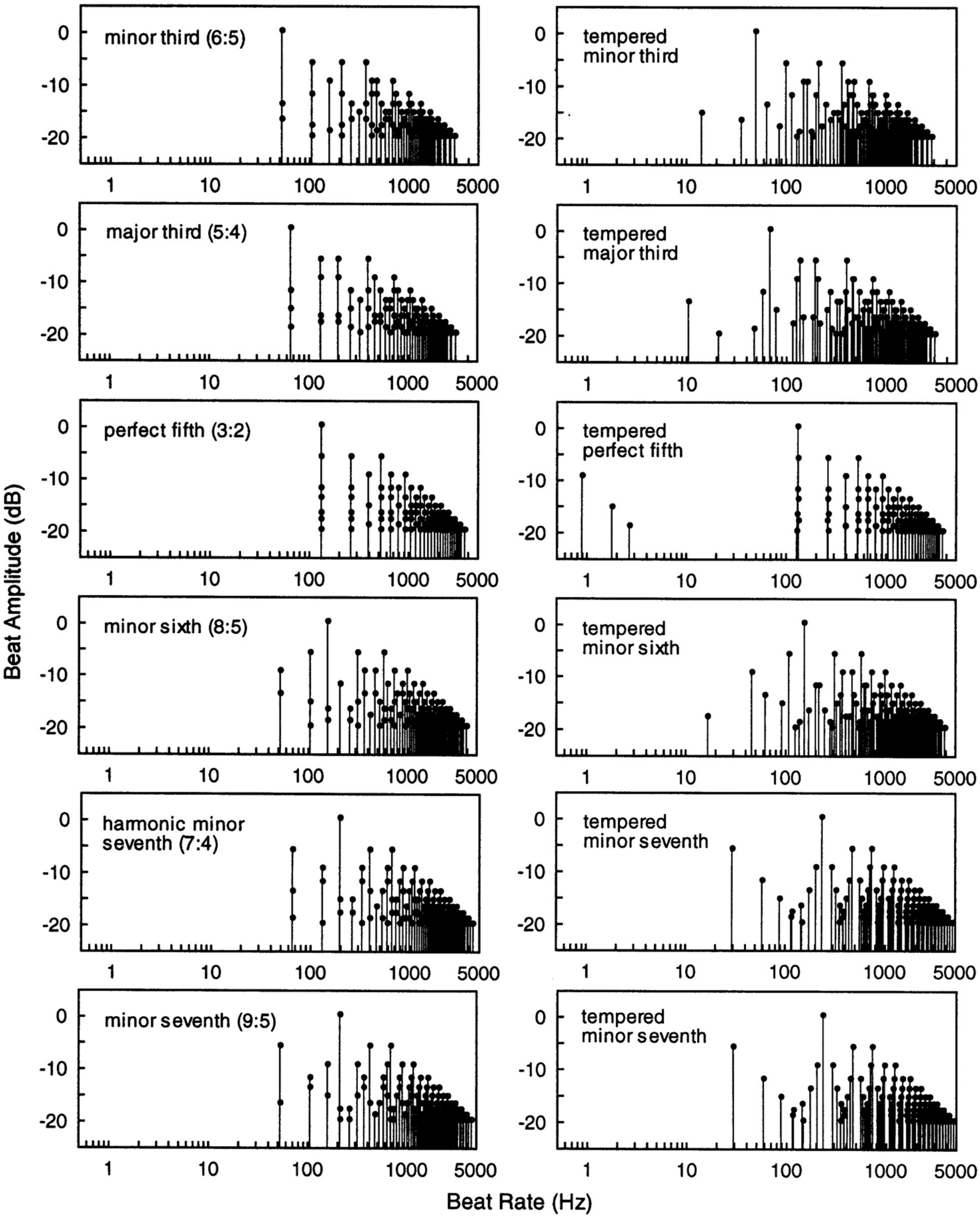

Figure 5: Beat rates and beat amplitudes produced by the partials of two harmonic complex tones. Left column: intervals based on integer frequency ratios, right column: tempered intervals. The value of 0 dB on the ordinate indicates the amplitude of beats produced by the fundamentals of the two complex tones.

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4. CONCLUSIONS

The present study has demonstrated that slow beats between the harmonics of two complex tones cause a decrease in roughness of musical dyads. As a result of this phenomenon, many intervals of the equally tempered scale are perceived less rough than their counterparts with integer frequency ratios. This finding leads to the conclusion that the theories of roughness and musical dissonance should be modified to include the effect of loudness fluctuations which occur when the interval frequency ratio slightly departs from exact integer proportion.

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