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ROUGHNESS OF TWO SIMULTANEOUS HARMONIC COMPLEX TONES IN VARIOUS PITCH REGISTERS

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The purpose of the study was to determine the dependence of perceived roughness on the frequency ratio of two simultaneous harmonic complex tones. A set of 36 dyads forming musical intervals of various tuning systems was presented in three pitch registers. Twelve sound engineering students judged each dyad for roughness by the method of absolute magnitude estimation. Results show that roughness considerably varies with the frequency ratio of the two complex tones, what is a well-known phenomenon. A new finding, being in contrast to published theories of roughness, is that some of the equally-tempered intervals are perceived less rough than their counterparts based on integer frequency ratios. This effect is attributed to slow beats that arise between the harmonics of two complex tones when the frequency ratio of the tones slightly departs from the integer ratio.

Keywords: psychoacoustics, music perception, roughness, dissonance.

1. Introduction

This study was carried out to determine how the auditory sensation of roughness depends on the frequency ratio of two simultaneous harmonic complex tones. The sensation of roughness produced by such tones is an effect of beats that occur between their harmonics. Traditionally, consonance has been associated in music with intervals represented by a ratio of small integers. According to von HELMHOLTZ's [1] theory, dissonance is an effect of roughness evoked by beats. Combined sounding of two harmonic complex tones with a small integer frequency ratio is consonant because the two tones either coincide in frequency and evoke no beats or the beats occur at a rate that does not produce roughness. A previous study [4] has demonstrated that most equally-tempered intervals are perceived less rough than their integer-ratio counterparts, an effect being in contrast to published theories of roughness [1, 3]. MIŚKIEWICZ *et al.* [2] explored intervals with a 261.6-Hz (C4) frequency of the lower tone. The present study extends the above experiment to other pitch registers.

2. Method

The stimuli were dyads formed by combining two harmonic complex tones, each composed of the fundamental and nine harmonics, with a decreasing amplitude envelope of 6 dB/oct. All component tones were gated on with a 0 phase. Each dyad was 2 second long, including a 25-ms rise and fall. The fundamental frequency of the lower tone was the same in all 36 dyads and the frequency of the upper tone depended on the interval. The frequency ratios, interval sizes (in cents) and names are given in Table 1. The set of 36 intervals listed in Table 1 was presented in three pitch registers: in the second octave of the musical scale (lower tone C2, frequency $f_L = 65.4$ Hz), the fourth octave (C4, $f_L = 261.6$ Hz) and the sixth octave (C6, $f_L = 1046.4$ Hz).

The sensation of roughness was assessed by the estimation of the absolute magnitude [4]. The listener was seated in a sound-insulating booth and had to assign a positive number to the magnitude of roughness produced by each dyad. The listener activated every presentation of the dyad by pressing a button on the response box and could listen to the sound at will before reporting the number to the experimenter through an intercom. The experimenter entered the number to the computer and a visual signal was displayed on the response box in the booth to indicate the next judgment. A series of judgments comprised 36 intervals presented in a one pitch register, in random order.

The dyads were generated using a PC-compatible computer with a signal processor (TDT AP2) and a D/A converter (TDT DD1). The signal at the converter's output was low-pass filtered (TDT FT5), attenuated (TDT PA4), amplified (TDT HB6), and led to a pair of earphones (Beyerdynamic DT 911). All dyads were presented at a loudness level of 70 phons, determined with the use of an artificial ear (B&K 4153), a 1/4-inch microphone (B&K 4134), and a spectrum analyzer (B&K 4144) equipped with software for the measurement of loudness, according to Zwicker's method. Earphone calibration was 103.8 dB SPL for a 1-V input.

The judgments of roughness were obtained from 12 students of sound engineering, 20–23 years old, with normal hearing. A listening session lasted about 45 minutes and comprised three series of judgments for different pitch registers. The order of registers within a session was chosen randomly. Each listener participated in five sessions. Altogether, 60 judgments were obtained for each stimulus (12 listeners $\times$ 5 series of judgments).

3. Results and discussion

The results of roughness scaling are shown in Fig. 1, in a separate panel for each pitch register. In each panel, the main abscissa is the size of the interval (in cents) and the secondary abscissa shows the frequency ratio of the two tones. The data are geometric means of 60 estimates multiplied by a constant chosen for a pitch register so that the maximum roughness value obtained for a series of 36 intervals equals 1.

Table 1. Frequency ratios, interval sizes (in cents), and names of musical intervals used in the study.

	Frequency ratio	Interval size (ct)	Interval name
1	1.0000	0	unison
2	1.0125	22	syntonic comma (81:80)
3	1.0293	50	equally-tempered quarter tone
4	1.0595	100	equally-tempered semitone
5	1.0905	150	
6	1.1225	200	equally-tempered major second
7	1.1554	250	
8	1.1892	300	equally-tempered minor third
9	1.2000	316	just minor third (6:5)
10	1.2241	350	
11	1.2500	386	just major third (5:4)
12	1.2599	400	equally-tempered major third
13	1.2660	408	Pythagorean major third (81:64)
14	1.2968	450	
15	1.3333	498	just fourth (4:3)
16	1.3348	500	equally-tempered perfect fourth
17	1.3740	550	
18	1.4142	600	tritone
19	1.4557	650	
20	1.4983	700	equally-tempered perfect fifth
21	1.5000	702	just fifth (3:2)
22	1.5422	750	
23	1.5874	800	equally-tempered minor sixth
24	1.6000	814	just minor sixth (8:5)
25	1.6339	850	
26	1.6670	885	just major sixth (5:3)
27	1.6818	900	equally-tempered major sixth
28	1.7311	950	
29	1.7500	969	harmonic minor seventh (7:4)
30	1.7818	1000	equally-tempered minor seventh
31	1.8000	1018	just minor seventh (9:5)
32	1.8340	1050	
33	1.8750	1088	just major seventh (15:8)
34	1.8877	1100	equally-tempered major seventh
35	1.9431	1150	
36	2.0000	1200	octave (2:1)

As shown in Fig. 1, roughness markedly fluctuates as the interval between the two tones is increased from a unison (0 ct) to an octave (1200 ct). The maximum roughness values are produced by intervals of 650 ct (second octave, uppermost panel), 1150 ct (fourth octave, middle panel) and 1050 ct (sixth octave, lowest panel). The lowest values of roughness are obtained for the unison in all three pitch registers. The course of roughness as a function of the interval size is generally similar in all three panels in Fig. 1.

To enable a comparison of roughness produced by intervals based on integer frequency ratios and by equally-tempered ones, Fig. 2 shows pairs of bars representing

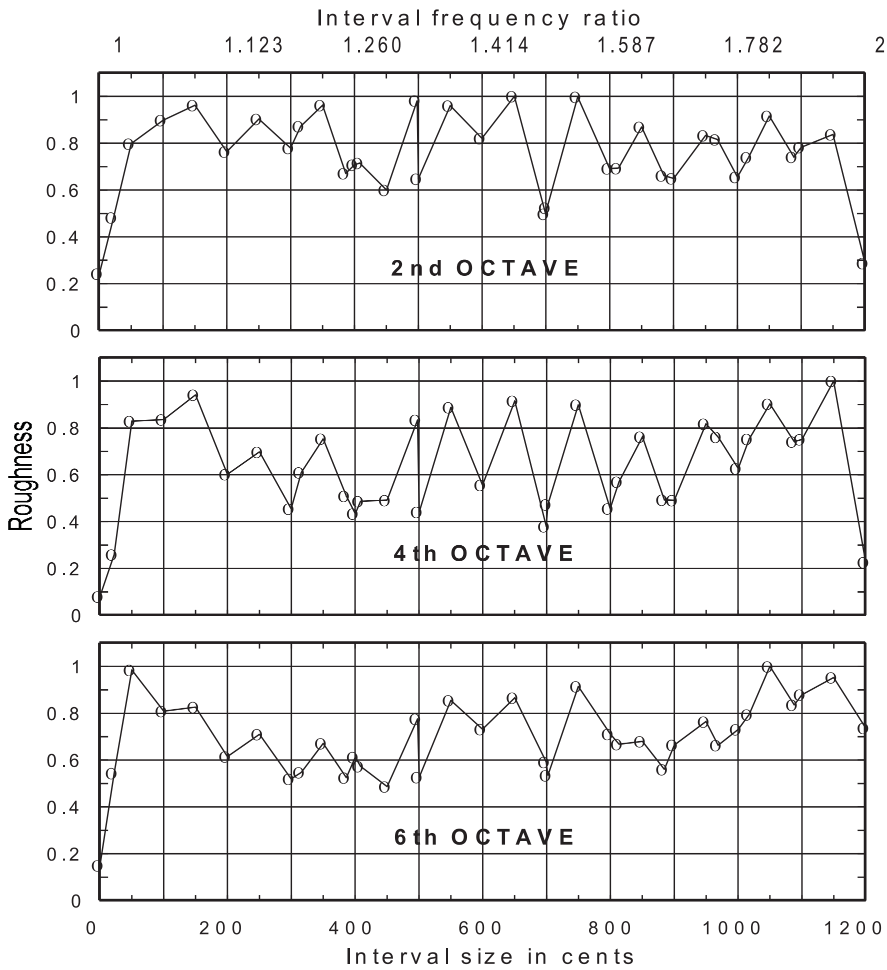

Fig. 1. Roughness of complex-tone dyads. Geometric means of 60 judgments. The three panels show respectively the data obtained for the 2nd, 4th and 6th octave. The geometric means of numerical values assigned to each dyad have been multiplied by a constant such that the maximum roughness obtained for a set of 36 intervals in a given octave equals 1.

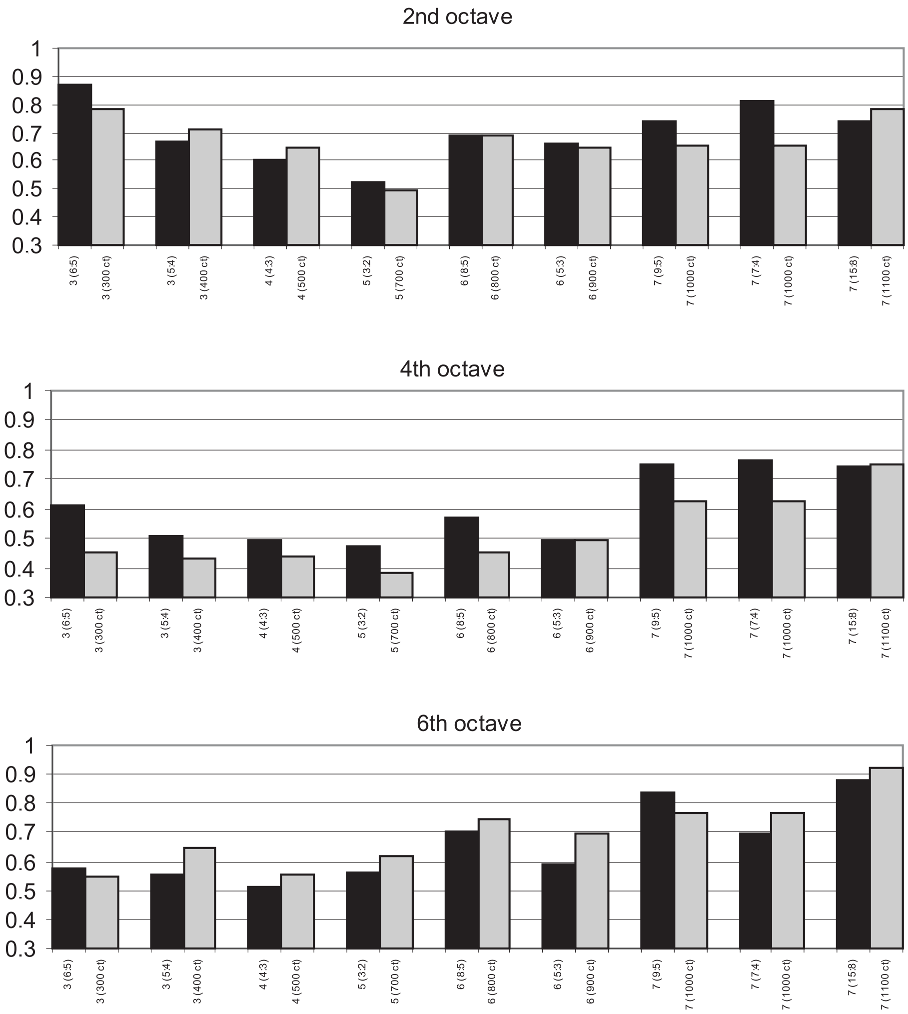

Fig. 2. Comparison of roughness values obtained for integer-ratio intervals (left bar in each pair) and equally-tempered intervals (right bar in each pair). The roughness values were replotted from Fig. 1.

the roughness values obtained for the two kinds of intervals. The data in the three panels in Fig. 2 were replotted from Fig. 1. The data obtained for intervals falling within the 4th octave (Fig. 2, middle panel) are in close agreement with the results of a previous experiment conducted with the use of the same stimuli [2]. The present data show once again that most equally-tempered intervals produce less roughness than their integer-ratio counterparts. MIŚKIEWICZ *et al.* [2] explained the lesser roughness of equally-tempered intervals by the effect of very slow beats that occur when the interval slightly departs from an exact integer-frequency ratio. The differences in roughness between integer-ratio and equally-tempered intervals (Fig. 2, uppermost panel) are less clear-cut in the 2nd octave than in the 4th octave. The results for the 6th octave are generally consistent with the von HELMHOLTZ's [1] theory of roughness: in seven out of nine pairs of intervals the higher value of roughness was obtained for the equally-tempered interval, an effect opposite to that observed in lower pitch registers.

The change of roughness relations between intervals in different pitch registers is an expected effect when one considers the psychoacoustic principles of roughness. When an interval is transposed to a different register the frequency ratios between the two tones remain the same but the frequency differences and the beat rates change and so does the sensation of roughness.

4. Conclusions

In the low and middle pitch registers, most equally-tempered intervals are perceived less rough than their counterparts based on integer frequency ratios due to slow beats that occur between the partials of two harmonic complex tones when the interval departs from exact integer ratio. In high pitch registers equally-tempered intervals produce more roughness than integer-ratio intervals, as the difference between two tones in frequency is larger than in lower registers and the beats between the harmonics are too fast to be perceived as smooth fluctuations. Roughness was explored in the present study with the use of synthesized dyads. To extend the present findings to real conditions encountered in music, the data should be verified with the use of the samples of musical instrument sounds.

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