Perception of Different Types of Roughness of Violin Tones

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The presented psychoacoustic experiment was focused on perception of roughness in violin tones. The research suggests a possible multi-dimensionality of perceived roughness linked to both the processes of sound generation influenced by irregularities in string oscillation and psychoacoustic roughness perception principles. The sounds of free violin G string, played with different bow speed and force (built-up of differing rough tones) were recorded with microphone. Simultaneously, the recordings of the violin string movement were done with high speed video camera. Nine standardized audio records were used as stimuli in listening tests with 18 subjects. Their roughness measure was obtained in ranking and rating test. The ratings of dissimilarity in roughness and verbal attributes descriptions were received in a pair comparison test. The resulting perception spaces were analyzed on space dimensionality. Different kinds of roughness described with different verbal descriptions were joined with stimuli positions in perception space and also with form of string motion near the violin bridge. The obtained perception space had 4 dimensions and it was possible to recognize minimally the same number of roughness types in separate sectors of the space. The results will be presented also in 3D graphs and string movement documentation.

1 Introduction

The roughness psychoacoustic quantity is used to quantify a complex phenomena associated with subjective perception of different temporal changes in sound. It plays an important role in sound-quality (timbre in music) evaluations. Some roughness concepts regard roughness as a result of envelope fluctuations in time and spectral domain and link auditory roughness to the sound waveform, other models have associated roughness with the physiological cause, such as the hypothesis offered in [1] explaining the interference of multiple harmonics of a complex tone in one critical band at the basilar membrane. Other hypotheses consider higher order auditory grouping [2] or neural bases of roughness [3]. Roughness is also studied in relationship with the concept of dissonance, sub-harmonic components of the sound, and with character of aperiodicities in sound signal, e.g. in [4, 5]. Since the perception of changes in sound can arise from several physical reasons, it could be assumed roughness is a multidimensional phenomenon, as also suggested by other authors, e.g. [6, 7]. The studies of pathologic voice quality based on listening tests show results of more then one factor or dimensionality in roughness ratings, e.g. [7]. Roughness multidimensionality emerged also in results of listening tests focused on timbre of violin tones (buzzing, subharmonicity [8]).

In the studies of bowed violin string [9] the time-domain of the string waveform was explored in detail by means of observation and modelling. Both periodic and aperiodic modulations and subharmonicity were observed in the string movement courses (varying extent of jitter, shimmer, spikes joined with distinct perceptual quality). Since the bowed instrument sounds due to repeating slip-stick release cycle of the string under the bow (with a periodicity of the fundamental of the played note) and because the timing and magnitude of the string release during play is not entirely regular, the string exhibits irregularities or aperiodicities in its vibrations that result in various time changes in sound signal waveform. The time changes are dependent to a large extent on the used bowing technique (on bowing place, speed, pressure force, broadness of the bow hairs in contact, e.g. [10, 11]).

The goal of the presented psychoacoustic experiment is to verify the assumption of multidimensionality of perceived roughness and to connect its multiple forms with the verbal descriptors used by listeners for description of different qualities and types of “rough” sounds. Following to the results of previous research of authors of this paper, real violin tones played by a musician were used, rated and verbally described. Different regimes of bowing where used in order to obtain a variety of different oscillations and roughness forms (according to [9]). The movement course of the string was tracked using a high speed camera to verify the roughness causation.

2 Experiment

In the first step of the experiment a larger number of different types of rough violin sounds were produced by changing of bowing technique during the standard play by musician. The produced sounds and corresponding string movements were both recorded simultaneously. Similarly sounding sound recordings were rejected in a listening pre-test so an acceptable number of representatives of different rough sound were obtained. The resulting and loudness and duration normalized sounds were used in rating listening test and also in pair comparison test. In statistical analysis of the test results an agreement of judgment of test respondents was assessed and the perception spaces were obtained by means of multidimensional scaling technique (for groups of respondents with similar judgment manner). The positions of different types of roughness in perception spaces were determined by verbal descriptions obtained in pair comparison test. The time courses of the captured string movements in different positions relative to the bridge were obtained by video tracking software and inspected.

2.1 Listening tests

The tones were played on a open G string (Thomastik Dominant) on a single factory violin (Strunal CZ a.s.) in three positions relative to the bridge (sul tallone, modo ordinario and sul ponticello) with an approximate tone duration of 2s, with three varying bow pressure levels (detache, senza vibrato, arcata in su) and three repetitions. The set of sounds has been recorded in acoustically treated room in HAMU experimental acoustics laboratory (0.4 s balanced reverberation time) on a stereophonic 8 channel TASCAM recorder (pcm wav, stereo, A/D 32 bit, 96 kHz sample rate, calibrated on 0 dB_{SPL}), with Neumann KU100 dummy head at 1 m distance 45^{o} relative to the violin top plate, in the plain of the bridge. The string movement recordings, synchronized with sound, were realized with high speed camera (Vision research V611, 60k Fps).

The total of 27 obtained sound recordings was reduced in listening pre-test with 3 violin experts. The pre-test purpose was to select only essential number of sounds for covering the whole original extent of the rough sound variations without repetition of similar type of roughness. Nine representative sounds were chosen. Their recordings were converted to monophony in order to prevent the influence of spatial perception, and the signals were cut to a 500 ms duration with a 30 ms linear fade-in and a 50 ms fade-out passage to avoid the atypical non repeatable transient irregularities and normalized for the same loudness.

The listening tests consisted of two parts: 1) Assessment of sound's roughness measure in ranking and rating test;
2) Valuation of preference and dissimilarity and verbal description of difference between sounds in pair comparison test. Total number of 20 subjects participated in the listening tests (2 of them did not participate in the ranking and rating test), age ranged from 21-57 years. One half of test respondents were from a stable listening group of sound engineer and musicians at the Faculty of performing arts Prague (in next labeled *experts*). Other respondents were volunteer participants without musical education and without experience with listening tests consisting mainly of students of Charles University in Prague (*non-experts*). In all cases of a listening in the experiment, the sounds were reproduced with SENHEISER HD 580 Precision earphones. Both tests were carried out on a PC and programmed in the listening test editor software (*LiTeD*©) written at authors institute. The test schedules consisted in multiple sub-parts (login, acquaint, warming-up, own test, test break sections). The tests together lasted about 60-70 minutes performed in one session.

The ranking and rating test (print of its fundamental screens and description of respondent's activity see in Figure 1 left) gave measure of roughness (in Czech language: Rough = Drsný) on the scale 0 (Min = Nejméně) to 10 (Max = Nejvíce) without distinguishing of roughness types.

The pair comparison test (print screen and respondent's activity see in Figure 1 right) collected and measured dissimilarities between sounds (in Czech: dissimilarity = nepodobnost) on a scale 0 (no = žádný) to 5 (extrem = extrémní) with 0.5 step, verbal descriptions of perceived features and the sound preference (not utilized yet) for both sounds in a played pair. A list of 60 most frequent words used for description of musical sound (based on [12]) was available during the test (occasionally utilized by non experienced listeners).

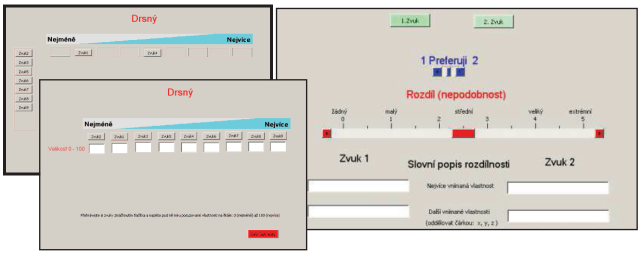

Figure 1: Screens of Ranking (left top) and Rating (left bottom) tests: Mouse clicking on buttons (at first on the left) play the sounds, the respondent moves the buttons at positions in order of roughness value (see horizontal graphic scale) one after the other, and enters matched roughness values to appropriate input boxes (white) after ranking of all sound buttons.

Screen of the pair comparison test (right): Mouse click on buttons plays the first (top left) or the second (top right) sound from the pair in free order, the respondent then moves the preference (under the top buttons) and dissimilarity (in the middle, 11 grade scale) sliders and enters words that verbally depict perceived type of dissimilarity in appropriate input box (white). Pair order of sound stimuli was organized under Ross algorithm [13].

2.2 Respondent agreement

Both tests had a statistically significant judgment agreement of all respondents (the intraclass correlation coefficient of 0.98). Scale utilization variance (example see in Figure 4 left) and evaluative model of the individual respondents was tested by means of a Spearman correlation of the test results data (example in Table 1; red marked correlation among the listeners was significant at $p < 0.01$). Spearman correlation values show least similarity for respondent 11, which was relatively more related to respondents 8, 10, 6, 13, 14, 15. This is in concordance with the results of the factor analysis, where this listener belonged to the group of respondents marked in the blue filled circle in factor space (see Figure 2). The respondents 11 and 20 did not participate in the ranking and rating test.

Table 1: The values of the correlation coefficient

	Spearman Rank Order Correlations (Pair test: 36 pairs, 20 respondents) Marked correlations are significant at p <.01000																			
Resp.No:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1.0	0.8	0.6	0.4	0.4	0.7	0.6	0.6	0.6	0.3	0.2	0.6	0.7	0.5	0.6	0.6	0.6	0.5	0.7	0.6
2	0.8	1.0	0.6	0.5	0.5	0.6	0.7	0.6	0.6	0.6	0.2	0.7	0.6	0.5	0.6	0.6	0.7	0.5	0.7	0.8
3	0.6	0.6	1.0	0.4	0.5	0.6	0.7	0.4	0.4	0.5	0.4	0.6	0.6	0.6	0.7	0.7	0.8	0.7	0.6	0.7
4	0.4	0.5	0.4	1.0	0.3	0.5	0.4	0.3	0.3	0.3	0.3	0.4	0.5	0.5	0.7	0.4	0.4	0.5	0.7	0.5
5	0.4	0.5	0.5	0.3	1.0	0.5	0.3	0.3	0.6	0.5	0.2	0.5	0.6	0.5	0.6	0.6	0.5	0.5	0.6	0.5
6	0.7	0.6	0.6	0.5	0.5	1.0	0.6	0.6	0.8	0.4	0.4	0.7	0.6	0.6	0.6	0.5	0.7	0.7	0.6	0.7
7	0.6	0.7	0.7	0.4	0.3	0.6	1.0	0.4	0.6	0.6	0.3	0.6	0.4	0.4	0.5	0.6	0.7	0.6	0.5	0.7
8	0.6	0.6	0.4	0.3	0.3	0.6	0.4	1.0	0.6	0.5	0.5	0.6	0.6	0.4	0.4	0.4	0.5	0.4	0.6	0.6
9	0.6	0.6	0.4	0.3	0.6	0.8	0.6	0.6	1.0	0.5	0.4	0.6	0.7	0.5	0.5	0.5	0.5	0.5	0.6	0.7
10	0.3	0.6	0.5	0.3	0.5	0.4	0.6	0.5	0.5	1.0	0.5	0.6	0.5	0.4	0.5	0.5	0.5	0.4	0.5	0.6
11	0.2	0.2	0.4	0.3	0.2	0.4	0.3	0.5	0.4	0.5	1.0	0.4	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.3
12	0.6	0.7	0.6	0.4	0.5	0.7	0.6	0.6	0.6	0.6	0.4	1.0	0.5	0.5	0.5	0.6	0.6	0.5	0.6	0.6
13	0.7	0.6	0.6	0.5	0.6	0.6	0.4	0.6	0.7	0.5	0.4	0.5	1.0	0.6	0.7	0.6	0.6	0.5	0.7	0.6
14	0.5	0.5	0.6	0.5	0.5	0.6	0.4	0.4	0.5	0.4	0.4	0.5	0.6	1.0	0.7	0.5	0.6	0.5	0.5	0.4
15	0.6	0.6	0.7	0.7	0.6	0.6	0.5	0.4	0.5	0.5	0.4	0.5	0.7	0.7	1.0	0.7	0.7	0.7	0.8	0.6
16	0.6	0.6	0.7	0.4	0.6	0.5	0.6	0.4	0.5	0.5	0.3	0.6	0.6	0.5	0.7	1.0	0.7	0.6	0.7	0.6
17	0.6	0.7	0.8	0.4	0.5	0.7	0.7	0.5	0.5	0.5	0.4	0.6	0.6	0.6	0.7	0.7	1.0	0.7	0.7	0.7
18	0.5	0.5	0.7	0.5	0.5	0.7	0.6	0.4	0.5	0.4	0.4	0.5	0.5	0.5	0.7	0.6	0.7	1.0	0.7	0.7
19	0.7	0.7	0.6	0.7	0.6	0.6	0.5	0.6	0.6	0.5	0.4	0.6	0.7	0.5	0.8	0.7	0.7	0.7	1.0	0.7
20	0.6	0.8	0.7	0.5	0.5	0.7	0.7	0.6	0.7	0.6	0.3	0.6	0.6	0.4	0.6	0.6	0.7	0.7	0.7	1.0

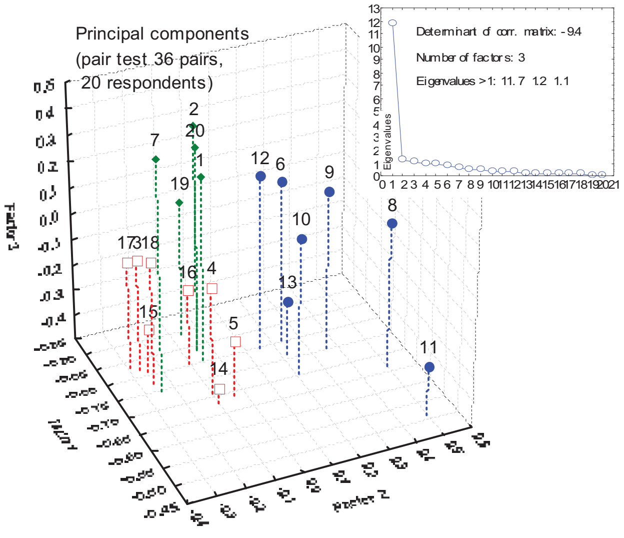

Figure 2: Plot of factor loadings of respondent data from the pair comparison test with Scree plot of eigenvalues.

The subjects were grouped in two main clusters also both by K-means (see Table 2) and Tree cluster analysis (see Figure 3). Different clustering methods gave similar cluster base. Interpretation revealed that the respondents in the second cluster (in red/green) had listening test experience (this could be a result of developed judgment model and refined scale utilization of the respondent). Only respondents 5, 12, 13, 20 were clustered diversely. Since they were non experienced listeners, theirs data were added to non-experts group (in blue) of respondents.

Table 2: Grouping of respondents by K-mains clustering

	non-experts									experts										
Group	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2
Resp.No.	6	8	9	10	11	20	5	12	13	1	2	7	19	3	4	14	15	16	17	18

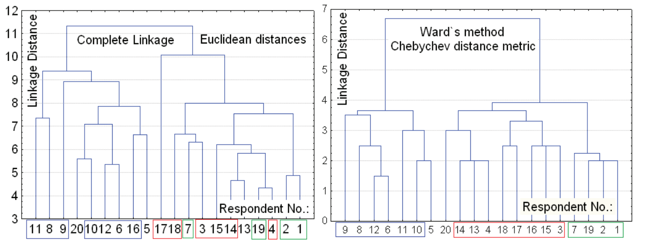

Figure 3: Grouping of respondents by Tree clustering. Complete linkage method with Euclidian distances (left) and Ward’s method with Chebychev distance metric (right).

The average dissimilarity rating of each sound pair for all respondents and for both discerned groups of respondents was calculated (graph of group averages, see in Figure 4 right) and placed into dissimilarity matrixes.

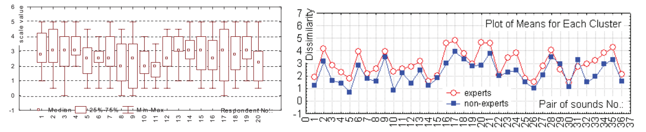

Figure 4: Scale utilization in the pair comparison test (left). The averaged dissimilarity values (right) for non-experts and experts groups as emerged from cluster analysis of respondent data (confirmed with intra subject correlation).

2.3 Perceptual spaces interpretations

The dissimilarity matrixes of all respondents and both groups (non-experts, experts) were analyzed by non-metric multidimensional scaling method MDS [ ]. The quality of the MDS solution was assessed by the D-hat values and by comparison of objects distances in the MDS solution spaces with original dissimilarity values. Solutions with less dimensionality had a progressively increasing disagreement; e.g. the order of observed dissimilarity of certain sound pairs was 7-4, 8-7, 6-3, but the 2D solution distances had order 8-7, 6-3, 7-4 (see Figure 5). Based of the results of the computed-observed comparison (presented on a Sheppard diagram), the fit of the solution was sufficiently good in 4 dimensions and worst in 2 dimensions.

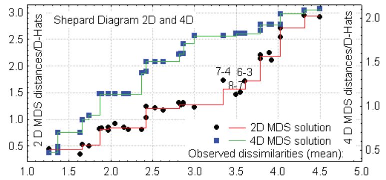

Figure 5: The graph of computed distances versus observed dissimilarity for 2D and 4D MDS solution from all respondent values averages.

The suitability of the MDS solutions was also judged by the elbow criterion on a Scree plot of D-hat stress values (Figure 6 top left). The Scree plot graph of non experts group does not have a well resolved elbow. Its D-hat stress values are higher than values of the experts group except for 2D solution. A sudden increase of stress occurs for expert group at the decrease of MDS dimensionality from 4 to 3. These results indicate the experts and non-experts did not heed equal number of judged or perceived attributes which differentiate the sounds in pairs.

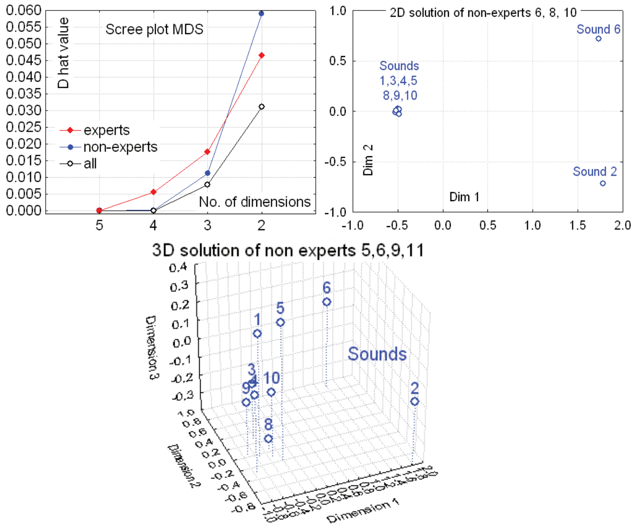

Figure 6: Scree plot of MDS solutions (all, non-experts, experts) from 5 to 2 dimensions (top left); MDS space from non-experts 6, 8, 10, which where able to differentiate only sounds 2 and 6 from the other, here 2D solution is suitable (top right); 3D MDS solution was suitable for non-experts 5, 6, 9, 11, which differentiate not only sounds 2, 6, but also sounds 1, 5, 8 from each other (bottom).

To inspect that, data from individual respondents (and than from several smaller groups) were also MDS analyzed and these additional MDS spaces were compared. Two examples of sound stimuli placement in the 2D (Figure 6 top right) and 3D (Figure 6 bottom) MDS solutions illustrate that listeners not experienced in listening tests (usually also non musicians) did not distinguish the subtle differences between the violin sounds in pairs, so the sounds appeared more similar (theirs sound positions are in MDS spaces almost the same). The dissimilarity data for the presented examples were averaged in small groups of respondents (in lists).

For the experts group it was evident that smaller than 4D MDS solution is not suitable for unbiased preservation of the dissimilarities. The stress for averaged data of all respondent also increases with decreasing dimensionality; it is however smaller than for the non-experts group in all cases. Averaging of all respondents data do not increases the stress of the 4D solution (ranks of averaged large distances keep similarity with theirs ranks from experts group) and decreases the stress in 2D solution in comparison to experts only (not distinguishing of the subtle differences by non-experts disturbs the need of higher dimensionality for unbiased preservation of experts data). Described approaches assess the optimal MDS space dimensionality for successful representation of obtained dissimilarity matrixes: for the experts group = 4 dimensions, for non-experts 2 (or 3) dimensions. Averaging of data from all respondents causes errors of results in both groups (obtained group data had to be analyzed separately).

The multidimensional sound configurations resulting from MDS solutions of appropriate dimensionality were used as perception spaces that visualize hidden relationships among used stimuli (one example of a sound configuration in a perception space from averaged data of experts is presented in Figure 8).

The roughness values from ranking and rating test were averaged for all respondents and both groups (see roughness columns in Table 3).

Table 3: Roughness evaluation and verbal description

Sound No.	Rank+rate test roughness all	experts	non-exp.	Pair comparison test Cracked	Strident	Buzzing	Rustle	Blear	Dark-Bright	Narrow	Quinted
1	4.6	4.4	4.8	1	1	1.5	2.5	4	4.5	1	0
2	9.5	9.4	9.5	10	3	0	0.5	1	3	3	0
3	3.3	2.1	4.4	0	3	7.5	0	0	1	0	0
4	1.9	2.4	1.5	0	0	2.5	1.5	4.5	6	6	0
5	6.1	6.4	5.8	4	2.5	0.5	3	4	5	3	0
6	8.3	7.9	8.7	7	8	0	1	0.5	0	1	0
8	5.3	3.9	6.6	0	2.5	7	1	1	1.5	9	0.5
9	2.0	1.5	2.4	0	0.5	4	0.5	3	3.5	1	0
10	4.4	4.6	4.1	1	1	4.5	1	2	2	3	8

The verbal descriptors of perceived attributes for each sound obtained from individual respondents in the paired comparison test were merged. Since the description was spontaneous (even though spontaneous associations could be optionally supported by a list of words suitable for sound colour description) a total of 586 different words was obtained. The synonymy linkages were particularized in discussions with the respondents after the end of the listening tests. For most frequently used descriptors the averaged frequency of occurrence at separate sounds was calculated (some selected words see in pair comparison test columns in Table 3). Since respondents describe all perceived differences between sounds, it can not be directly discerned which words describe roughness. Nevertheless it is possible to reject some specific words from the interpretation of rough sounds on the basis of its denotative meanings (e.g. dark-bright or narrow belong to other psychoacoustic dimensions; quinted describes inseparable sounding of tone harmonic structure with a narrow band noise between 1. and. 2. harmonics = quintus to frequency of 1. harmonic). The amounts of perceived sound attributes (obtained descriptors) were embedded to perception spaces.

In the process of perception spaces interpretations the multiple regression method must have been used for embedding of the obtained amounts of verbalized sound attributes to the space, because higher dimensionality (>3D) of the MDS solution does not allow for direct observation of an attribute gradation through the sound placement in such a space. The regression and interpretation results here are presented only for the experts group (due to their larger information ability). For the fit between the observed values and values predicted by regression equation for the particular attributes, see Figure 7 (the roughness values from ranking and rating test are also embedded). Since the obtained attributes participate in perception of the sounds (chosen in tests as stimuli) relatively jointly within the range of distinguishable gradation (except sounds with an attribute extreme), and experts were able to distinguish this attribute extent, the fit is highly propitious (see values of Adjusted R2 in Table 4 and 95% confidence intervals in Figure 7). The regression results confirm the need of 4D MDS solution, which exhibits best fit and the lowest R2 from the other MDS dimensionality and also from the other respondents grouping.

Table 4: Adjusted R2 and regression coefficients B (Dim 1, 2, 3, 4 and Intercept) for selected attributes

	cracked	strident	buzzing	rustle	blear	dark-bright	narrow	roughness
Adj.R2	0.98	0.88	0.81	0.96	0.73	0.82	0.94	0.96
1 Dim	4.85	1.99	-3.00	0.15	-0.57	-0.49	0.21	3.57
2 Dim	-1.14	-1.29	-1.88	1.90	2.37	2.25	-2.17	0.49
3 Dim	-0.32	3.64	0.45	0.21	-1.08	-1.99	5.06	0.16
4 Dim	0.86	-0.75	-3.54	0.55	2.36	3.34	0.18	-0.91
Intercept	2.56	2.39	3.06	1.22	2.22	2.94	3.56	4.75

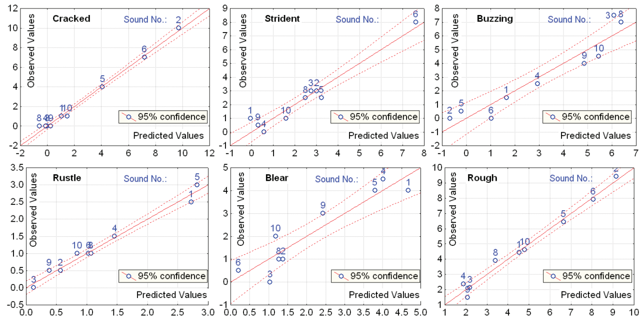

Figure 7: The fit between the observed values and predicted by regression equation for the particular attributes.

Perception space interpretations achieved by embeddings of regression lines of specified attributes to expert's 4D MDS solution are shown in Figure 8 top (view is only 3D: left Dim 1, 2, 3, right Dim 1, 2, 4). Depicted paths of separate attributes (each in different colour) are specified by positions of the sounds with the maximum (the big circle end of embedded attribute line) and minimum (small point) attribute amount.

Table 5: Angles between the embedded regression lines

	strident	buzzing	rustle	blear	dark-bright	narrow	roughness
cracked	65	127	95	100	93	85	32
strident		88	101	129	133	27	61
buzzing			125	130	133	79	116
rustle				39	51	105	82
blear					16	121	104
dark-bright						125	103
narrow							89

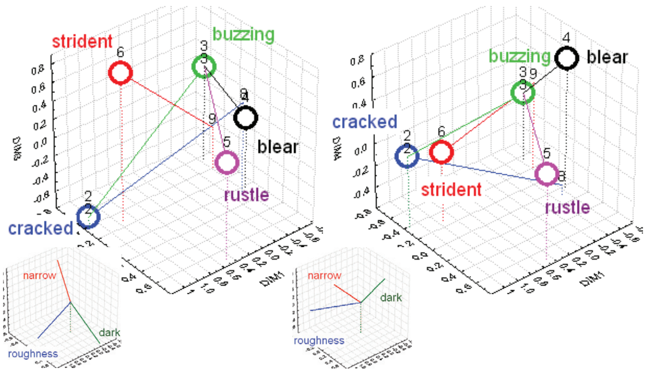

Figure 8: The 4D perceptual space interpretation: embedded regression lines of stated attributes (top; big circle = higher amount); embedded psychoacoustic dimensions (bottom); (left Dim 1, 2, 3, right Dim 1, 2, 4).

The possible independency of attributes was assessed by computed angles between regression lines (see Table 5). Right angles (90±15° are red marked) of: buzzing (sounding as zzz) × strident (gradation of sharpness), cracked (irregular variations) × rustle, strident × rustle, cracked × bleary (muffled dull mutations) indicate, that this sound attributes are potentially discrete psychoacoustic quantity (dimensions). Oblique angles (between 20~70^o or 110~160^o) may not signify dependency in relationship (e.g. because the number of used stimuli can be low to fill the perception space homogeneously in such attribute direction, or the real space dimensionality could be higher than used) their relationships are however context dependent and require subsequent supplementary study.

Embeddings of respected classical psychoacoustic dimensions (Figure 8 bottom) to perception space reveal: 1) The roughness (judged in rating test as an entirety) is not collinear with any of the obtained attributes. Both the cracked and buzzing perceptions contribute to perceived amount of roughness (buzzing a bit less; angles 32 ^{o}, -64 ^{o} respectively). Both rustle and blear do not contribute to roughness (right angles). 2) Strident is related to narrowness (27^o), to brightness (-47 ^{o}; opposite to dark) and also to roughness (61^o). This is in accordance with a finding [14] that percept of sharpness (here graded as strident) is a combination of percepts: bright, narrow and rough. 3) Dark and blear are collinear (16^o) and dark and rustle are not independent (51^o).

2.4 String motion irregularities

Visual comparisons of the time courses of the string motion at a single point near the bridge confirm the findings in [9, 10] about regularity (buzzing) and irregularity (cracked) causes of the rough violin tones (see Related document).

3 Conclusion

Even though a statistically significant agreement ($p<0.01$) of judgment of all respondents in listening test was obtained, the listeners without test experience (usually also non musicians, here named non-experts) did not distinguish the subtle differences between violin sounds. The non-experts, in comparison to experts, did not heed comparable number of judged or perceived attributes which differentiate the perception of sounds in pairs. Smaller than 4D MDS solution of expert's data was not suitable for unbiased preservation of the dissimilarities from the listening test. The fit of obtained attributes was highly propitious (probably because experts were able to distinguish attributes in pairs with certainty and that the sounds in tests represented the extent of attributes relatively homogeneously with sufficient gradation with only a few exceptions). The roughness perception judged as an entirety was not identical to the cracked, buzzing and strident percepts, but all these are in narrow relations to it. Buzzing and strident were mutually independent attributes. The narrowness, brightness and roughness each contribute to the strident percept (expanded sharpness). The sounds with more blear were also darker, which could divert a regression line of dark in the perception space and this way also the relations of dark to buzzing or to rustle (need of supplementary study). The figures in the related documents show string motion irregularities possibly associated with the cracked percept and regular courses possibly causing buzzing.

Acknowledgments

Supported by the Ministry of Education, Youth and Sports of the Czech Republic in the Long Term Conceptual Development of Research Institutes grant of the Academy of Performing Arts in Prague: The "Sound quality" project.

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4 Related documents

The time courses of the string movements (Figures R1 to 9)