Recent developments in sound quality evaluation

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This keynote introduces various contributions to a structured session on sound quality organized by the present author. In the last decade, basic research as well as practical applications of sound quality increased substantially. This holds true for sound quality of emissions e.g. in product sound as well as for sound quality of immissions e.g. in the environment. For product sound, two cases of sound quality are considered: one, where sound quality is the dominant, generic feature of a product like musical instruments or loudspeakers, and a second, where sound quality is a by-product like the sound of Dieselengines or - to give a more exotic example - the sound quality of snoring. As concerns sound immissions, wanted sounds typical for a soundscape and unwanted sounds typical for noise immissions can be distinguished. However, also sounds blending perfectly into a soundscape like the noise of a chain saw in the soundscape of a forest, may be pretty annoying. For both product sound and sound quality of the environment, influences of the meaning of sounds have to be considered. Additional extra-aural effects like the image of brand names or audio-visual interactions can significantly influence sound quality judgements.

1 Introduction

This paper sketches some recent trends in sound quality evaluation. Aspects of sound quality are discussed in the domain of emissions as well as in the domain of immissions.

As concerns sound emissions, examples are given, where sound quality is a generic feature of a product. In particular the question is addressed, whether the inharmonicity of partials in the sound of an electric guitar produces a "better" sound quality compared to strictly harmonic partials. As a somewhat exotic example of a case, where sound quality is a by-product, sound quality of snoring is assessed.

With respect to immissions, evaluations of the sound produced by different types of a waterfall are discussed in view of questions of soundscapes. On the other hand, sound quality of noise immissions is assessed for the example of railway bonus.

Keeping the loudness-time function the same but obscuring the signature of the sound source, the relevance of cognitive factors in sound quality evaluation are studied.

Finally, the influence of effects which bear no direct relation to acoustical features are studied: On the one hand aspects of the image of brand names, and on the other hand effects of audio-visual interactions.

2 Aspects of sound quality evaluation

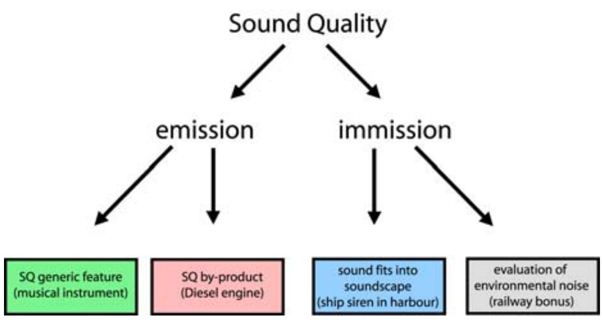

Figure 1: Aspects of sound quality evaluation

The sketch outlined in figure 1 gives an overview of relevant aspects of sound quality evaluation. The field of sound quality branches into questions of sound emission and questions of sound immission.

For the sound emissions, two important subfields emerge: on the one hand cases, where sound quality is a generic feature like in the sound quality of musical instruments. On the other hand, cases are considered, where sound quality is just a by-product like the sound quality of Diesel engines.

As concerns immissions, sound quality again can be split into two subcategories. On the one branch, concerning soundscapes, the question is how seamless a specific sound fits into the whole acoustic atmosphere. For example the sound of leaves in the wind definitely belongs to the soundscape of a forest, but also the sound of a chain saw can be part of this soundscape. While the sound of the leaves usually will be appreciated, the sound of the chain saw can annoy quite a number of people.

The second branch of immissions representing environmental noise usually is linked to low values of sound quality. Nevertheless, within noise immissions even at same energy equivalent A-weighted level, differences in evaluations may occur: For example sounds from railways are frequently preferred to sounds from road traffic. This effect is termed “railway bonus”.

In summary then, sound quality plays an important part for evaluations of both sound emissions and sound immissions.

3 Examples of sound quality evaluation

In this section examples are given on all aspects of sound quality mentioned in section 2. In particular, sound quality of musical instruments, of snoring, of waterfalls as well as noise immissions will be addressed.

3.1 Sound quality of strings of an electric guitar

Wound strings of musical instruments produce spectra which are slightly inharmonic [1, 2, 3]. The question is now, whether this is a physical effect which can not be avoided, or whether the inharmonicity adds to the sound quality of tones in a musical context. In order to address this question, experiments where performed in which strictly harmonic spectra as well as sligthly inharmonic spectra of the strings of an electrical guitar were synthesized. The temporal envelope of the simulated guitar sounds was chosen in accordance with measurements of solid-body-guitars by Fleischer [4].

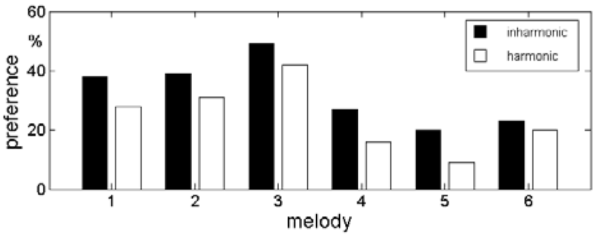

Figure 2: Preference of short melodies when string sounds of an electric guitar are realized with harmonic (unfilled colums) versus inharmonic (filled colums) spectra.

In particular for the lower strings of the guitar (E2, A2), the inharmonic spectra produce clearly audible beats. From the digitally synthesized material, six short melodies were composed and presented to subjects in pairs. The subjects had to answer the question, whether they prefer the first or the second realization of a melody within a pair. Results of the corresponding psychoacoustic experiment are given in figure 2.

The results displayed in figure 2 suggest that irrespective of the melody played, the realization of the E-guitar sound by inharmonic spectra is slightly preferred compared to a realization with strictly harmonic spectra. This means that the inharmonicity of wound strings is not a physically inevitable flaw, but slightly inharmonic spectra are preferred in a musical context.

3.2 Sound quality of snoring

These days many evaluations of sound quality are performed for sound emissions of products, where the sound quality is not a genuine feature, but just a by-product. For example in the automotive industry, currently numerous studies on the sound quality of Diesel engines are performed (e.g. [5, 6]). However, in this paper we want to give a more exotic example about the sound quality of snoring. In cooperation with colleagues from the ENT-Clinic of the Ludwig-Maximilians-Universität München, snoring sounds of different origin and different intensity were recorded [7]. These sounds were edited and evaluated in psychoacoustic experiments with respect to basic psychoacoustic magnitudes like loudness or sharpness. In addition, all snoring sounds were evaluated with respect to their annoyance. Several metrics were checked, whether the annoyance of snoring sounds can be predicted on the basis of other psychoacoustic magnitudes. It turned out that the product of loudness and sharpness can account for the annoyance of the snoring sounds. Data for the subjective evaluations are given in figure 3.

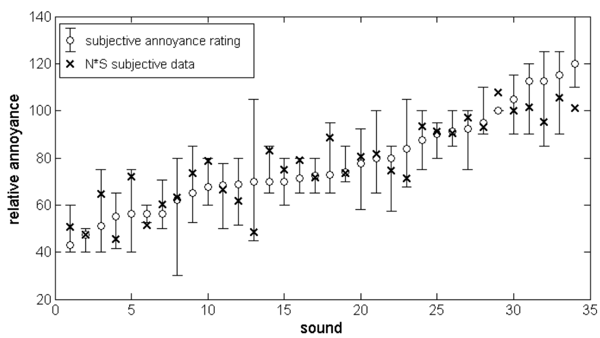

Figure 3: Relative annoyance of snoring sounds. Circles: subjective evaluation of annoyance, Crosses: relative annoyance calculated from the subjective evaluations of loudness N and sharpness S

The results displayed in figure 3 show that the annoyance of different snoring sounds can differ by a factor of about three. Sometimes very large interquartile ranges show up (e.g. sound 8 or sound 13) which are due to inter-individual differences in the scaling of the annoyance for the respective snoring sound. By and large, the subjective annoyance data (circles) can be predicted on the basis of the subjective evaluation of loudness and sharpness of the snoring sounds (crosses). As a rule, the calculated annoyance data (crosses) are within the interquartiles of the subjective annoyance data (circles).

The results displayed in figure 4 allow a comparison of the subjective evaluation of snoring sounds (circles) with predictions from physical, instrumental measurements of loudness and sharpness of the same sounds (crosses).

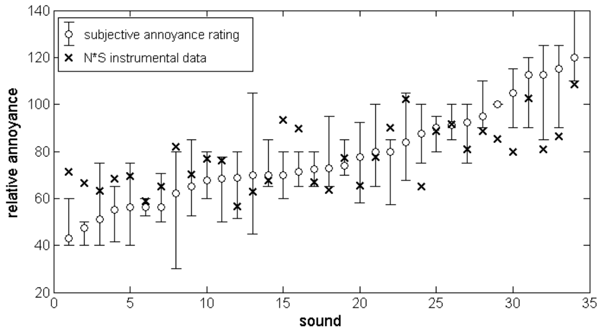

Figure 4: Relative annoyance of snoring sounds. Circles: subjective evaluation of annoyance, Crosses: calculated data from instrumentally measured values of loudness N and sharpness S

The results displayed in figure 4 suggest that the prediction of the annoyance of snoring sounds on the basis of *instrumental* measurements of loudness and sharpness are in only 50 percent of the cases in line with subjective annoyance evaluations. On the other hand, as displayed figure 3, based on *subjective* evaluations of loudness and sharpness, annoyance of snoring sounds can be predicted in more than 90 percent of the cases. This means that for the somewhat exotic example of snoring sounds, instrumental values of loudness and sharpness can deviate from the subjective evaluations of these psychoacoustic magnitudes.

3.3 Sound quality of waterfalls

In connection with the planning of a soundscape, systematic studies of the sounds produced by waterfalls were performed [8]. A difference in height of 1.4 meters was bridged either by four straight steps, four steps with basins, or by a gentle grade. The layout of the respective waterfall is illustrated in the insets of figure 5.

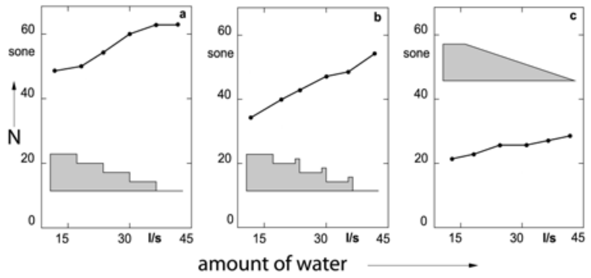

Figure 5: Loudness N of waterfalls as a function of the amount of water for three constructions: (a) four straight steps, (b) four steps with basins, (c) gentle grade

The results displayed in figure 5 clearly show that with increasing amount of water, the loudness increases. For the three different constructions of the waterfall, substantially different values of loudness are obtained, and the dependence of loudness on the amount of water is also different. While for (b), i.e. four steps with basins, an almost linear relation between the amount of water and loudness shows up, for construction (a), at high amounts of water some saturation of loudness seems to occur. With the gentle grade (c), the influence of the amount of water on the resulting loudness is relatively small.

Each of the three constructions considered produces a distinctly different tone color of the respective waterfall. These effects are illustrated in figure 6 for the four straight steps and the four steps with basins.

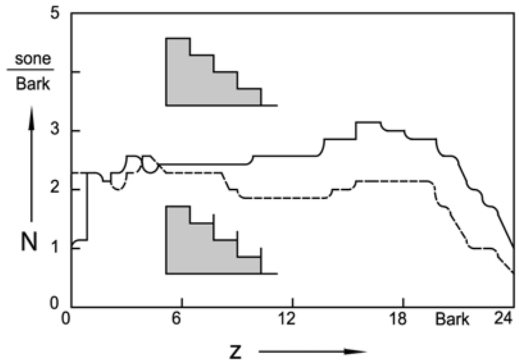

Figure 6: Loudness patterns for a waterfall with four straight steps (solid) and a waterfall with four steps with basins (dashed)

The data displayed in figure 6 illustrate that for the four straight steps (solid), the sound of the waterfall contains significantly more energy at higher frequencies above 1 kHz (8.5 Bark) than the waterfall with four steps with basins. While the construction with four straight steps produces sounds similar to typical natural waterfalls comparable to white noise, the construction with four steps with basins elicits sounds which resemble the murmuring of a brook.

As becomes clear from the data plotted in figure 5, the gentle grade produces the smallest loudness. However, despite larger loudness, frequently the construction (b) with four steps with basins was preferred because of the character of the sound, reminding the subjects to pleasant landscapes with murmuring brooks.

3.4 Sound quality of noise immissions

Noise immissions usually deal with unwanted sound and as a rule the sound quality is pretty low. However, even at same energy equivalent A-weighted sound pressure level, differences in the perceived loudness of noise immissions from railway noise versus road traffic noise can show up. This effect, which has been termed “railway bonus” is found in field studies [9, 10] as well as in laboratory studies [11, 12]. Results of related experiments are displayed in figure 7.

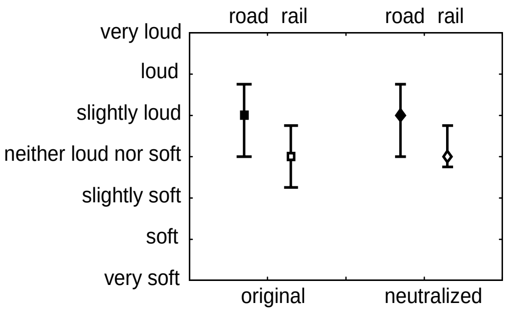

Figure 7: Loudness of road traffic noise versus railway noise of same energy equivalent A-weighted level for original sounds (left), and neutralized sounds (right)

The left part of figure 7 clearly shows he effects of railway bonus: For the same A-weighted energy equivalent level, road traffic noise is rated “slightly loud” whereas railway noise is rated “neither loud nor soft” (filled and unfilled squares).

Several possible reasons for the railway bonus have been discussed: On the one hand, there exist differences in spectrum and time structure (e.g. [13]) which can be assessed on a physical basis. On the other hand, cognitive factors may play a role that railway noise is preferred to road traffic noise.

In order to assess the magnitude of such possible influences, a procedure was developed which keeps the loudness-time function the same, but largely obscures the information about the sound source [14]. The corresponding effect was called “neutralizing” and has proven successful in studies of noise emissions [15, 16] as well as noise immissions [17, 18].

Figure 8 illustrates the effects of the “neutralizing procedure”. First, as displayed in the left part of figure 8, from the original sound, an FTT spectrum is produced (cf. [19]). After spectral boadening, the neutralized sound is re-synthesized, leading to the FTT spectrum displayed in the right part of figure 8 (for details see [14]).

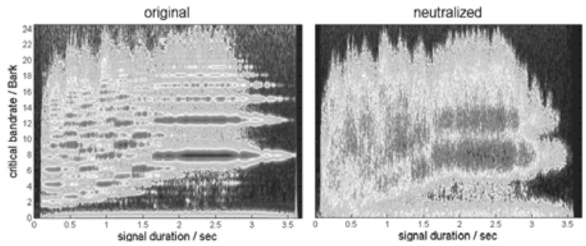

Figure 8: FTT spectra of original sound (left) and corresponding neutralized sound (right).

A comparison of left and right part of figure 8 reveals that spectral detail of the original sound represented by horizontal lines is lost in the neutralized version, where the information is blurred. Therefore, it is not easy to name the sound source of the neutralized sound, and hence, positive or negative aspects attached to the sound source will no longer influence the sound quality judgement.

Using this procedure, both the road traffic noise and the railway noise were neutralized. The right part of figure 7 shows the loudness evaluation of these neutralized sounds (filled and unfilled diamonds). Again, an effect of railway bonus can be seen, i.e. the road traffic noise produces a larger loudness than the railway noise, even in their neutralized versions. This result might seem to suggest that cognitive factors play a minor role for the phenomenon of railway bonus.

In order to get more information about this reasoning, a study using the semantic differential was performed [20]. Table 1 shows the results.

The data listed in table 1 largely correspond for original versus neutralized sounds. However for the adjectives pleasant/unpleasant, tense/relaxed, as well as pleasing/unpleasing differences between original and neutralized versions show up. Obviously the neutralized versions of road traffic noise *and* railway noise are unpleasant, tense and unpleasing.

These data suggest that some cognitive effects may influence the railway bonus. However, most part of the railway bonus can be traced back to physical differences in spectrum and time structure.

Table 1: Semantic differential for road traffic noise versus railway noise in original and neutralized version.

	original	neutralized
	road vs. rail	road vs. rail
loud/soft	**0.0185**	**0.0234**
deep/shrill	**0.0000**	**0.0017**
frightening/not frightening	**0.0197**	**0.0314**
pleasant/unpleasant	**0.0004**	0.1796
dangerous/safe	**0.0006**	**0.0298**
hard/soft	0.1400	0.1808
calm/exciting	**0.0147**	**0.0124**
bright/dark	**0.0000**	**0.0006**
weak/powerful	**0.0002**	**0.0002**
busy/tranquil	**0.0039**	**0.0145**
conspicuous/inconspicuous	0.9343	1.0000
slow/fast	0.2572	0.1742
distinct/vague	0.2268	0.4466
weak/strong	**0.0010**	**0.0004**
tense/relaxed	**0.0009**	0.1099
pleasing/unpleasing	**0.0001**	0.2373

4 Image of brand names

In addition to acoustic magnitudes, other features may influence sound quality ratings. In the following an example is given on the influence of the image of brand names. In a larger study [21], the sound quality of closing car doors was rated by subjects. In addition, the subjects had to give brand names of the cars where they thought the sound of the closing door would come from [22]. As an example figure 9 shows the responses for luxurious sedans. Corresponding data were obtained for sporty cars, economy cars, pickups and others.

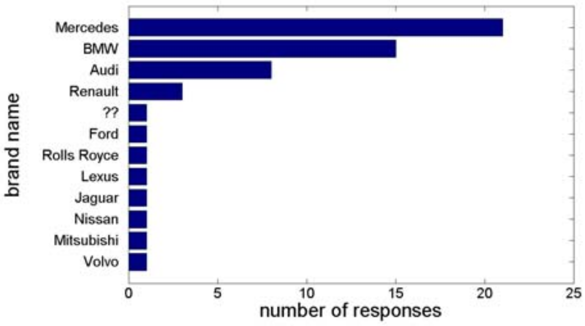

Figure 9: Brand names given for sounds of closing doors of luxurious sedans.

The results displayed in figure 9 clearly show that German subjects connote luxurious sedans with car manufacturers like Mercedes, BMW or Audi.

It is quite elucidating to compare these data with ranking of car manufacturers by the German automobile association ADAC. Results of a corresponding analysis are displayed in table 2.

Table 2: Ranking of car manufacturers in comparison to rating of car door closing sound by subjects

Ranking of car manufacturers	*Rating 1-4 in each class by subjects*
1. Mercedes	Luxurious 1
2. BMW	Sporty 1, Luxurious 2, Others 3
3. Audi	Luxurious 3
4. Volkswagen	Economy 1, Pick up 3, Others 4
5. Porsche	Sporty 2
6. Toyota	Economy 4
7. Peugeot	-
8. smart	-
9. Renault	Luxurious 4
10. Ford	Economy 3, Pick up 4
11. Opel	Economy 2
12. Skoda	Others 2

A comparison of the ranking of car manufacturers by ADAC and the rating of the car door closing sounds shows a clear correspondence in the different vehicle classes: For example, Mercedes is ranked first place from the ADAC and gets the best rating for luxurious sedans, or Audi is ranked third by ADAC and has the third place for luxurious sedans. Volkswagen, ranked number 4 by ADAC, has the best rating by the subjects for economy cars and so forth. This close correspondence between ranking of car manufacturers by ADAC and rating of the car door closing sounds by subjects suggests that the image of brand names can play an important part in sound quality evaluations.

5 Audio-visual interactions

In view of further influences on sound quality evaluation, which are not directly tied to acoustics, an example of audio-visual interactions should be mentioned. Subjects were presented the sound of the pass-by of a German ICE high-speed train. In addition to the sound, pictures of the high-speed train were presented either in its original color white or in red, blue or light green [23]. Despite the same acoustic stimulus, the loudness of the train was rated differently for different colors. Some data are displayed in figure 10, where the relative loudness is given for trains of different color.

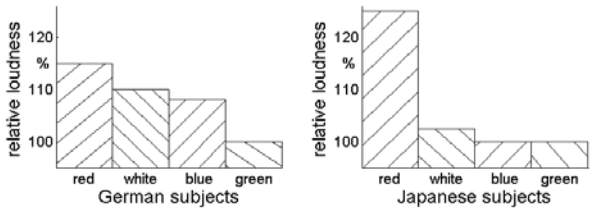

Figure 10: Loudness rating for ICE trains with different color. Results for German subjects (left) and for Japanese subjects (right)

Results displayed in the left part of figure 10 show that for German subjects, the red ICE train is by about 15 percent louder than an ICE train in light green [24]. The right part in figure 10 illustrates that for Japanese subjects, the red ICE train is by 25 percent louder than an ICE train in light green [25]. This means that irrespective of cultural background – despite identical acoustical stimulus – a red ICE train produced a larger loudness than a light green ICE train. Readers interested in further effects of audio-visual interactions are referred to the literature [26, 27].

6 Summary

Questions of sound quality play an important part both for emissions and immissions. Of course, sound quality is of particular relevance for products where sound quality is a generic feature like musical instruments, loudspeakers etc. However, also for products where sound quality is only a by-product like car indoor noise, sound quality has become an essential feature for customer satisfaction. With respect to noise immissions, soundscapes contain typical sounds which per se usually are an integral part of the soundscape, but sometimes can be also annoying. Noise immissions as a rule deal with unwanted sound; however, the degree of annoyance largely depends on the sound quality. For sound quality evaluations of both emissions and immissions, cognitive features, questions of image of brand names as well as audio-visual interactions can play an important part.

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