



PSYCHOACOUSTIC BASIS OF SOUND QUALITY EVALUATION AND SOUND ENGINEERING

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Abstract

In R & D departments of companies, the evaluation of sounds usually is based on physical measurements. However, in "real life", the ultimate judge for sounds is the human hearing system. A customer evaluates the sound of a product by his or her hearing system, not by physical measurement tools, whatever their sophistication may be.

In this situation, psychoacoustics is the scientific field of choice to bridge the gap between physical and subjective evaluations. In psychoacoustic experiments, firm relations between the physical representations of sounds and the correlated hearing sensations are established.

In practical applications of psychoacoustics, two main tasks can be distinguished:

First, questions of sound evaluation, usually for already existing sounds which often have to be improved and

Second, questions of sound quality engineering, where for a (new or modified) product or application a suitable sound has to be "tailored".

For the evaluation of sounds, basic psychoacoustic magnitudes like loudness and sharpness have proven successful, which assess volume or power and tone color of sounds, respectively. Using these descriptors, extremely different questions like the quality of piano sounds or the annoyance of snoring sounds can be assessed. In addition, psychoacoustic magnitudes related to the temporal structure of sounds like fluctuation strength or roughness can play an important part.

In sound quality engineering, for each sound, the right "recipe" has to be found, how to mix the different hearing sensations, to arrive at the desired sound. For the example of warning signals, a systematic approach, incorporating elements of decision tree studies, is discussed.

INTRODUCTION

The scientific field of psychoacoustics describes the relations between the physical representation of sounds and the hearing sensations elicited by them. In addition to developments in basic science, practical applications of psychoacoustic knowledge got more and more interest in recent years (see e.g. Deutsch 1999, Fastl 2005a).

For sound quality evaluation, psychoacoustic magnitudes like loudness or sharpness have proven successful (for reviews see e.g. Zwicker 1987, Widmann 1998, Fastl 2005b). Recently, trends in applied psychoacoustics of the last five years or so were summarized (Fastl 2006).

In sound engineering frequently the same principles as in sound quality evaluation are applied, however in reversed sequence. In extended psychoacoustic studies an optimal sound for a specific product is "tailored" and it is the task of the engineers to modify the physics of the sound generation in such a way as to arrive at a sound which is as close as feasible to the target sound.

In this paper, some psychophysical methods useful for both sound quality evaluation and sound engineering will be discussed. Psychoacoustic metrics like loudness, sharpness, fluctuation strength and roughness will be introduced, and examples for the evaluation of annoying and pleasant sounds, i.e. snoring sounds and sounds from grand pianos, respectively, will be given. A procedure is introduced which – for the same loudness-time function - largely obscures the information about the sound source, addressing questions of cognitive effects. Finally, sound engineering is treated using a type of decision tree approach for the example of warning signals.

METHODS

For sound quality evaluation and sound engineering psychophysical methods are used, which have proven successful in psychoacoustics. From a multitude of possible methods (e.g. Hellbrück and Ellermeier 2004, Fastl 2005a), only three are mentioned in this paper: The method of "random access" allows a quick information, whether a product sounds better than the product of a competitor. The method "magnitude estimation" can give an indication, how much the sound quality of products differ. For sound engineering, the method of "semantic differential" can give hints, what sounds are suitable to convey an intended message, e.g. as a warning signal.

Random Access

A ranking procedure, called random access, which has proven successful for questions of sound quality evaluation (e.g. Fastl 2000) is illustrated in figure 1. In the example displayed, six sounds denoted A through F have to be ranked with respect to their sound quality. When clicking on the loudspeaker icon, the respective sound, e.g. an idling motor, is heard. The task of the subject is to shift the icons A through F in

the empty fields denoted 1 through 6 in such a way that the sounds are ordered with respect to their sound quality. The subjects are free to listen to each sound as often as they like and to correct the sequence until a final status is reached. This large freedom of the subject, who has "random access" to the sounds to be ranked is one of the reasons that this procedure is nowadays preferred for a quick ranking of sound quality.

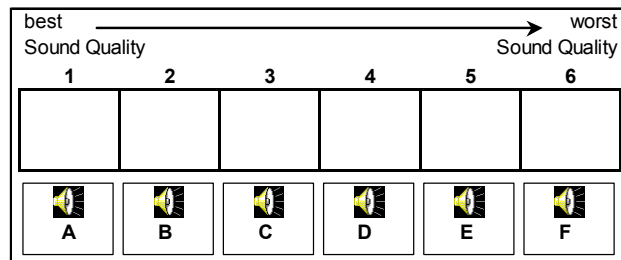


Figure 1 – Example for ranking of the sound quality by the method random access (from Fastl 2002)

Magnitude Estimation

For sound quality evaluations, frequently magnitude estimation with anchor sound is used, in which pairs of sounds are presented. The first sound A is called anchor sound and the second sound B test sound. Throughout an experiment the anchor sound is kept constant and the test sound is varied. To a psychoacoustic magnitude of sound A, e.g. its loudness, a numerical value, e.g. 100, is assigned. The task of the subject is to assign to the test sound B a numerical value which represents the relation in the psychophysical magnitude (loudness) between sound A and sound B. If for example sound B is perceived 30 percent softer than sound A, the subject should give the response 70. By magnitude estimates a direct relation of psychophysical magnitudes is obtained which is of advantage for cost/benefit analysis. Intra-individual as well as inter-individual differences of magnitude estimates usually are within 10 percent. However, sometimes the choice of the anchor sound may influence magnitude estimation significantly. Therefore it is suggested to use at least two anchor sounds, one with a large value of the psychophysical magnitude in question and the other with a small value.

Semantic Differential

The method of Semantic Differential is used e.g. in sound engineering to test what sounds are suitable for an intended purpose. In figure 2 an example is given of adjective scales used in an international study on the suitability of signals as warning signals (Kuwano et al. 2000). It is clear that warning signals should have high loadings on adjectives like dangerous, frightening, unpleasant etc.

adjective scales	
loud	soft
deep	shrill
frightening	not frightening
pleasant	unpleasant
dangerous	safe
hard	soft
calm	exciting
bright	dark
weak	powerful
busy	tranquil
conspicuous	inconspicuous
slow	fast
distinct	vague
weak	strong
tense	relaxed
pleasing	unpleasing

Figure 2 – Semantic Differential used in an international study on warning signals (from Kuwano et al. 2000)

The three psychophysical methods mentioned all have their advantages and disadvantages: Random access and semantic differential give more qualitative descriptions of sound quality. For quantitative assessment of sound quality, the method of magnitude estimation is recommended. However, effects of the frame of reference as well as influences of the choice of the anchor sound have to be taken into account.

PSYCHOACOUSTIC METRICS

For sound quality evaluation and sound engineering basic psychoacoustic magnitudes like loudness, sharpness, fluctuation strength, and roughness play an important role. Since the evaluation of those magnitudes in psychoacoustic experiments can be pretty time consuming, models simulating psychoacoustic magnitudes have been proposed.

Loudness

Usually the loudness of a product has a strong influence on its sound quality. Therefore the model of loudness proposed by Zwicker (1960) has been improved (Zwicker and Fastl 1983, Zwicker et al. 1985) and extended in recent years including its applicability to persons with hearing deficits (Chalupper 2002).

Figure 3 illustrates an actual implementation of a Zwicker-type loudness model, called Dynamic Loudness Model (DLM) (Chalupper and Fastl 2002). Essentials of

spectral processing are found in the critical band filter bank, the upward spread of masking as well as spectral summation. Temporal processing is represented in figure 3 by envelope extraction, post-masking, and temporal integration. Most important is the block loudness transformation: extremely simplified, this block represents that loudness is proportional to the square-root of sound pressure or the fourth root of sound intensity.

The distinguishing feature of the Dynamic Loudness Model (DLM) is that just by modifying the block loudness transformation, the loudness perception of normal hearing persons as well as persons with hearing deficits can be simulated (Chalupper and Fastl 2002). This new feature is of particular relevance for practical aspects of sound quality engineering, since in the ageing populations of industrialized countries, a large part of prospective customers of a product will show mild to moderate hearing loss. Unfortunately, even an increasing percentage of the younger generation these days shows hearing deficits, frequently due to extremely loud leisure activities.

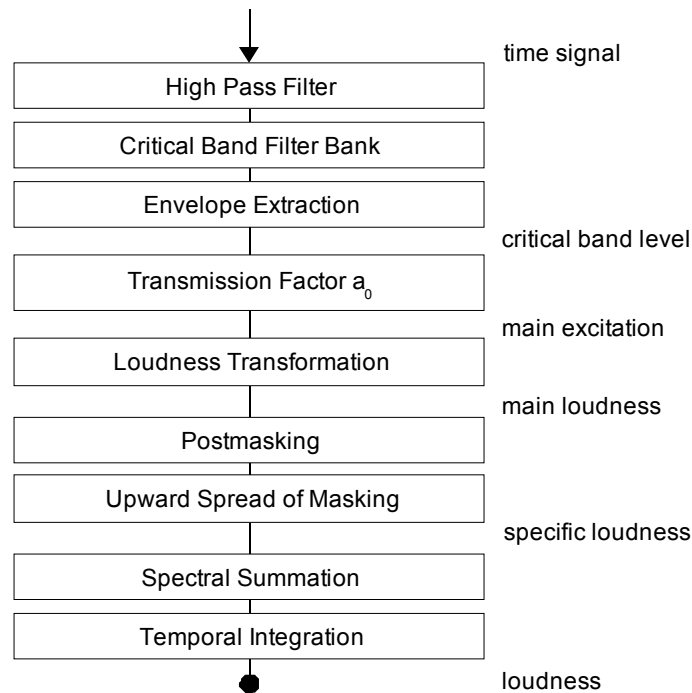


Figure 3 - Block diagram of the Dynamic Loudness Model (DLM) proposed by Chalupper and Fastl (2002)

Although the psychoacoustic magnitude loudness with its unit “sone” is more and more used in professional sound quality evaluation and sound engineering, even with experts sometimes the “feeling” for the sone-scale is not so developed as for the dB(A)-scale. Therefore, a loudness-thermometer (Fastl et al. 2006) was proposed, which gives sone-values for typical everyday sounds. For comparison, the dB(A)-values of the same sounds are also given in figure 4.

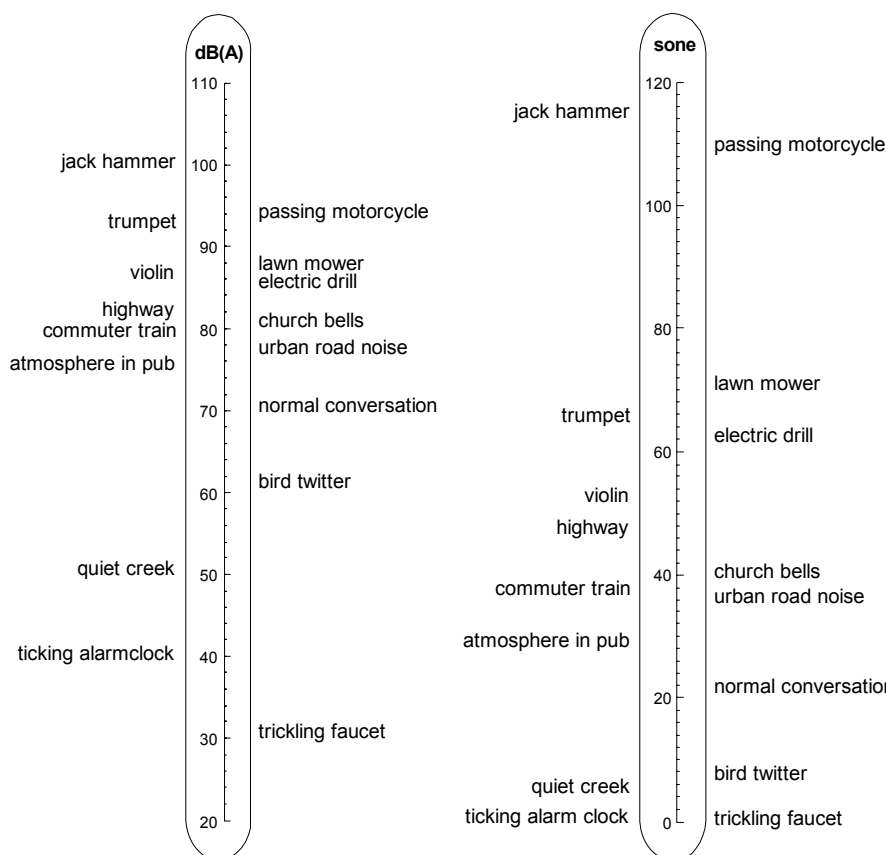


Figure 4 – Level-thermometer (left) in comparison to loudness-thermometer (right) (after Fastl et al. 2006).

The data displayed in figure 4 indicate that irrespective of the scale used, a jack hammer is considered to be pretty loud and a trickling faucet to be rather soft. However, closer inspection reveals that some sounds exchange their position along the dB(A)-scale versus the sone-scale. For example, the trumpet shows a higher dB(A)-value than the lawn mower, but the sequence is reversed in the sone-scale. Likewise, a violin produces the same dB(A)-value as an electric drill, but shows a lower value on the sone-scale. These differences can be due to different spectral distributions of the related sounds, which are not accounted for by the single channel analysis of a sound level meter. In contrast, loudness meters with their multi-channel analysis can account for minute spectral differences with their representation in different tone colours, in line with features of the human hearing system.

Sharpness

The psychoacoustic magnitude sharpness plays an important part in sound quality engineering since it can be regarded as measure of tone colour (cf. von Bismarck 1974). If the right amount of sharpness is added to a sound it gives it a character of powerfulness. However, too much sharpness will render a sound aggressive. If the loudness pattern of a sound is available, its sharpness can be relatively easily calculated. The corresponding procedure is illustrated in figure 5. The left panel illustrates the spectral distribution of a narrow-band noise, a broadband noise and a high pass noise. The right panel in figure 5 shows the corresponding loudness patterns, which - in order to account for the increased sharpness of high frequency sounds - are weighted by a function g . In order to derive from the resulting patterns the sharpness, the first momentum is calculated. The respective values are indicated in the right panel of figure 5 by vertical arrows. It becomes clear from figure 5 that, when adding to a high pass noise low frequencies, the centre of gravity moves downwards leading to a smaller value of sharpness (cf. dotted vs. dashed arrow). This means for practical questions of sound engineering that the sharpness and hence the aggressiveness of a product sound can be reduced by adding low frequency components. If the loudness of the original sound is not too high, the reduction in sharpness and hence aggressiveness can overcompensate the increase in loudness with respect to overall sound quality.

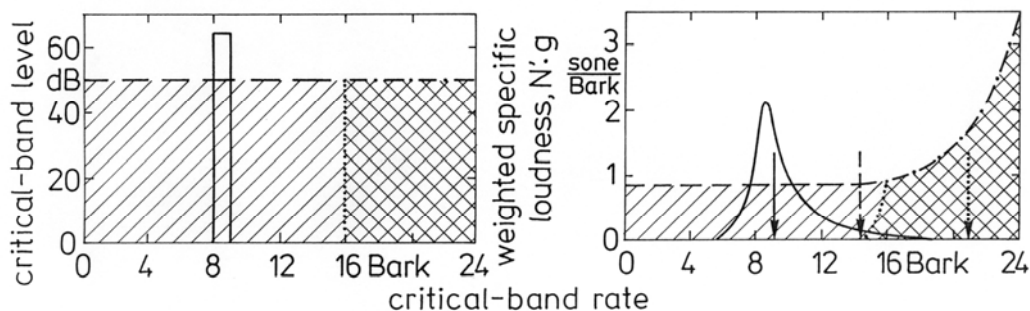


Figure 5 - Illustration of the model of sharpness (from Zwicker and Fastl 1999).

Fluctuation strength and Roughness

The psychoacoustic magnitudes fluctuation strength and roughness describe temporal variations of sounds. While fluctuation strength is elicited by slower sound variations up to about 20 Hz, roughness is perceived at faster variations (e.g. Terhardt 1968). However, there is no strict boundary between both psychoacoustic magnitudes and sounds of e.g. 25 Hz temporal variation produce fluctuation strength *and* roughness.

Fluctuation strength reaches a maximum for modulation frequencies around 4 Hz. This holds true for AM as well as FM sounds (Fastl 1982). Fluctuation strength plays a crucial role in the assessment of human speech: the envelope fluctuation of

fluent speech also shows a maximum around a modulation frequency of 4 Hz. This roughly corresponds to the number of syllables pronounced per second. As can be expected in nature, the human speech organ produces speech sounds with dominant envelope fluctuations at such a rate for which the human hearing system is most sensitive.

In sound engineering, fluctuation strength is indispensable for the creation of warning signals. Actually, most warning signals used in daily life show large values of fluctuation strength.

On the other hand, roughness is used in sound quality engineering for example to stress in a motor sound the feature of sportiness. Roughness reaches a maximum for modulation frequencies around 70 Hz (Terhardt 1968). In essence roughness can be described by the temporal masking pattern of sounds (Fastl 1982). This reasoning is illustrated in figure 6. The hatched areas show the temporal variation of a sound modulated in amplitude by a degree of modulation of almost 100 % when the level is displayed as a function of time. For 16 bit amplitude resolution, the "valleys" between the peaks reach a minimum near minus 90 dB.

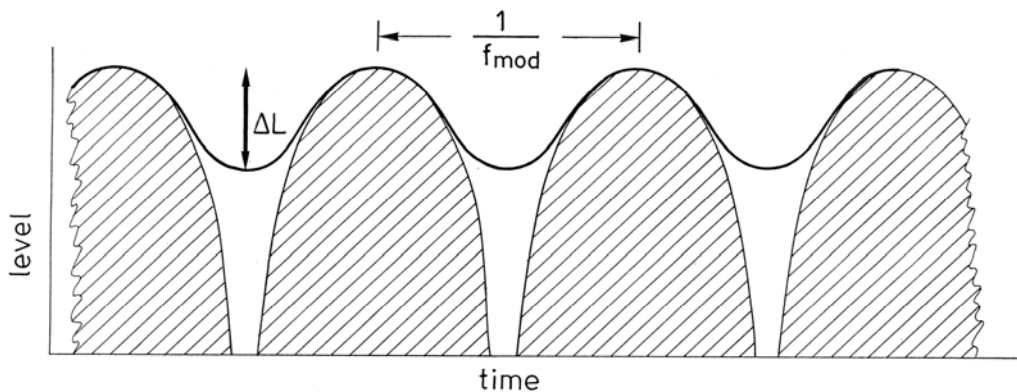


Figure 6 - Illustration of the input to the model of roughness (from Fastl 1982)

In contrast to the modulation depth of the physical signal, the modulation depth of the temporal masking pattern ΔL reaches much smaller values because of the effects of post-masking, i.e. the decay of psychoacoustic excitation in the hearing system. This limited level resolution is illustrated in figure 6 by the solid curve. The temporal distance of the peaks is inversely related to the modulation frequency. In principle the roughness of a sound can be described by the product of the modulation depth ΔL of the temporal masking pattern and the modulation frequency f_{mod} .

$$R \sim \Delta L \cdot f_{\text{mod}} \quad (1)$$

Since this product carries the unit dB/sec, the hearing sensation roughness is proportional to the speed of the variation of the temporal masking pattern.

SOUND QUALITY EVALUATION

Since many examples for sound quality evaluation can be found in the proceedings of noise conferences and in our list in the web, in this paper only two extremely different examples will be given. The first example deals with the annoyance of snoring sounds, the second example with the sound quality of grand pianos.

Annoyance of snoring sounds

In cooperation with colleagues from the ENT-Clinic of the Ludwig-Maximilians-Universität München, snoring sounds of different origin and different intensity were recorded (Dreher et al. 2004).

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 (Fastl 2005b). Data for the subjective evaluations are given in figure 7.

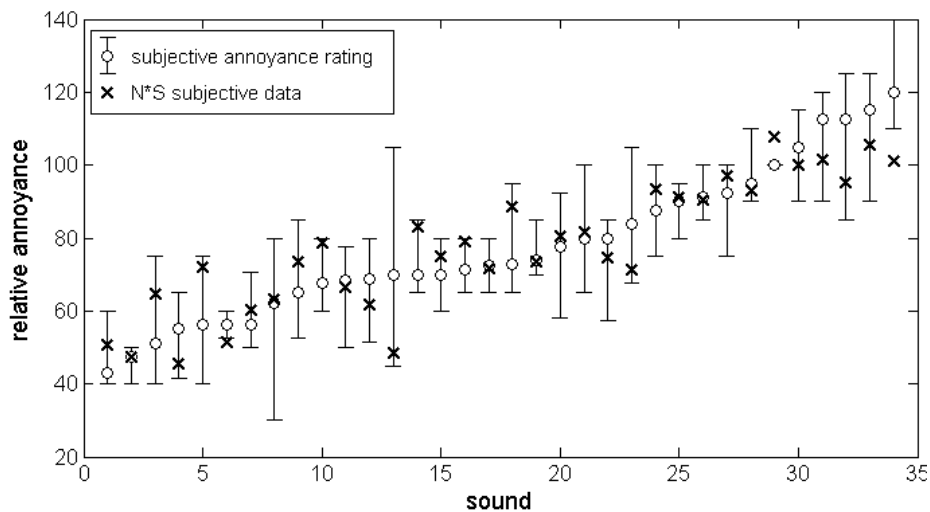


Figure 7 - Relative annoyance of snoring sounds. Circles: subjective evaluation of annoyance (medians and interquartiles), Crosses: relative annoyance calculated from the subjective evaluations of loudness N and sharpness S

The results displayed in figure 7 indicate 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).

Sound quality of grand pianos

Another, less exotic example of sound quality evaluation is the rating of the sound quality of grand pianos. In psychoacoustic experiments, the sound quality of grand pianos from Bösendorfer, Ibach, Steinway and Yamaha was evaluated. As a result of extended studies (Valenzuela 1998) a procedure was developed which allows the rating of the sound quality of grand pianos by physical measurements. Results displayed in figure 8 allow a comparison of subjective and physical evaluation.

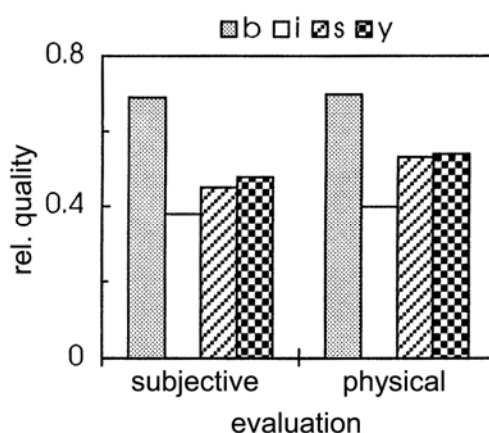


Figure 8 – Rating of the sound quality of four grand pianos from different manufacturers. Subjective evaluation (left) and physical evaluation (right) (after Valenzuela 1998)

The data displayed in figure 8 indicate that the procedure proposed by Valenzuela can predict the subjective rating of the sound quality of grand pianos. Interestingly enough, the procedures for rating annoyance of snoring sounds and sound quality of grand pianos use the same ingredients: loudness and sharpness. However, without going into too much detail it should be stated that the procedure developed by Valenzuela (1998) uses in addition to sharpness a weighted distribution of specific loudness with a maximum around 1 kHz.

Recognition of sound source

When evaluating sound quality, cognitive effects like the recognition of the sound source may play an important part. In a global market it is of importance to take into account possible cultural differences. Cross-cultural studies with subjects in Japan and Germany (Kuwano et al. 1997) showed that sometimes one and the same sound can be rated differently by subjects from different cultural backgrounds. For example the sound of a bell was interpreted by the German subjects as the sound of a church-bell leading to connotations of pleasant or safe. On the contrary, Japanese subjects

were reminded by the bell sounds to sounds of a fire engine or a railroad crossing leading to feelings like dangerous or unpleasant. The corresponding data of the study with the method of semantic differential are displayed in figure 9 (adopted from Kuwano et al. 1997). Data for Japanese subjects are connected by solid lines, data of German subjects by dotted lines.

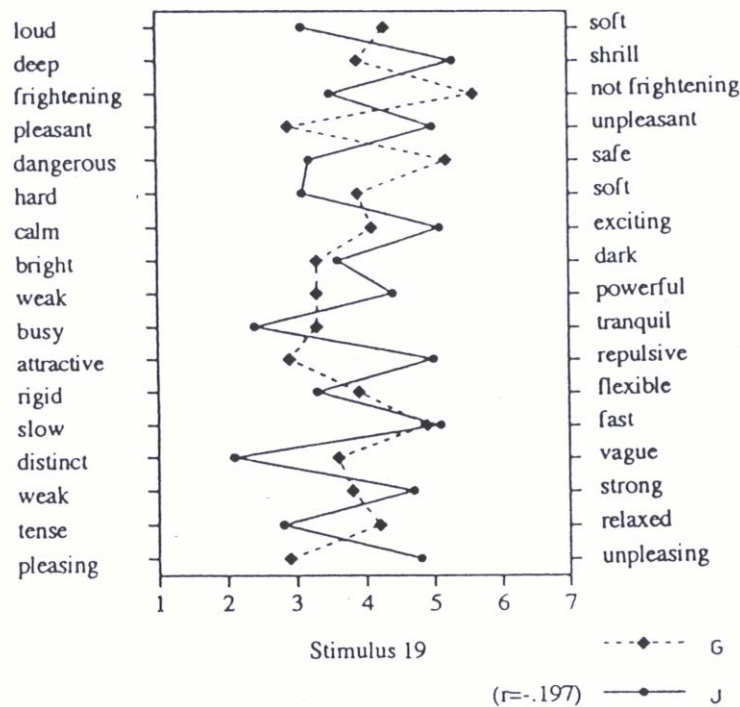


Figure 9 - Semantic differential for a bell sound. Data for Japanese subjects are connected by solid lines, for German subjects by dotted lines. (from Kuwano et al. 1997)

The data for the German subjects suggest their feelings that the bell-sound is not frightening, but pleasant, safe, attractive, relaxed, and pleasing. On the contrary, Japanese subjects feel that the bell sound is shrill, frightening, unpleasant, dangerous, exciting, busy, repulsive, distinct, strong, tense, and unpleasing.

In order to overcome such problems, a procedure has been proposed (Fastl 2001) which largely removes the information about the sound source from a stimulus. A block-diagram displayed in figure 10 illustrates the correlated procedure. From an original sound, e.g. a bell sound, a spectral analysis is performed by an FTT algorithm. The Fourier-time transform FTT (Terhardt 1985) is a spectral analysis which uses in contrast to FFT a sliding temporal window corresponding to a frequency-dependent bandwidth in line with the frequency resolution of the human hearing system. In the next steps, after spectral broadening and hence obscuring the spectral details, the sound is re-synthesized by inverse FTT. In this way a sound with

the same spectral envelope and the same loudness-time function is created from which, however, the information about the sound source is removed.

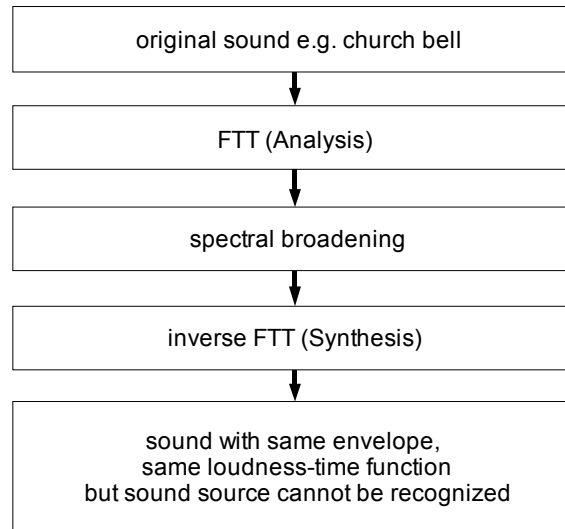


Figure 10 - Block diagram illustrating the procedure to obscure the information about the sound source of a stimulus (after Fastl 2001)

As an example for the procedure to obscure the information about the sound source, figure 11 shows the FTT-spectrum of the original bell sound in the left panel and the related FTT-spectrum of the processed sound in the right panel.

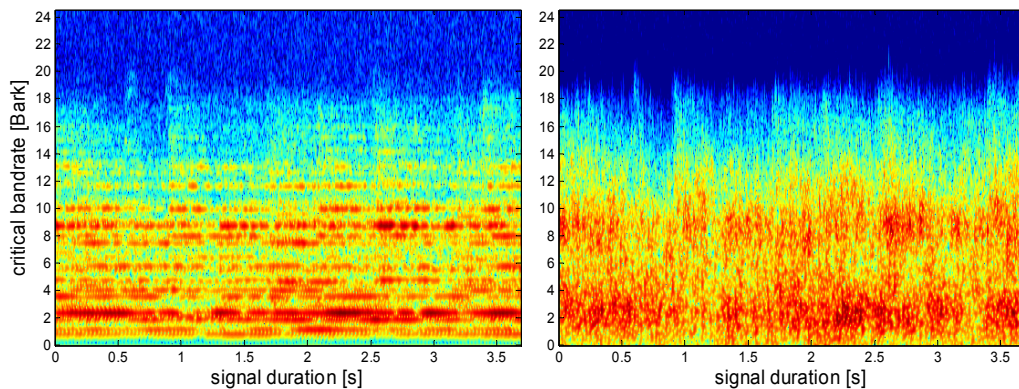


Figure 11 - Example for obscuring the information about the sound source. FTT-spectrum of the original sound church bell (left) and the related FTT-spectrum of the processed sound (right) in which the information about the sound source is obscured.

The data displayed in figure 11 clearly reveal the spectral broadening realized by the procedure illustrated in figure 10. The original bell sound (left) shows tonal components which are represented in the FTT-spectrum as horizontal lines. In contrast, the FTT-spectrum of the processed sound (right) shows only horizontal structures typical for noise bands. Therefore, the tonal character of the bell sound is lost and – despite the same loudness-time function - the processed sound does not include information about the sound source, i.e. a church bell. Hence, the cognitive factors can no longer influence the rating and subjects in Japan and Germany evaluate the processed “noise” alike.

Not only the semantic differential but also the rating of loudness and annoyance can be influenced by removing from sounds the information about the sound source (see e.g. Hellbrück et al. 2002, 2004, Zeitler et al. 2003, 2004, Ellermeier et al. 2004a, 2004b).

SOUND ENGINEERING

The basic psychoacoustic knowledge useful in sound quality evaluation is also helpful for questions of sound engineering. In particular, for the refinement of a sound of an already existing product, the procedures described above can be used as guidelines. If, however, a sound has to be “tailored” from scratch, a systematic approach similar to a decision tree has proven successful. For the example of a warning signal, a possible approach is illustrated in figure 12.

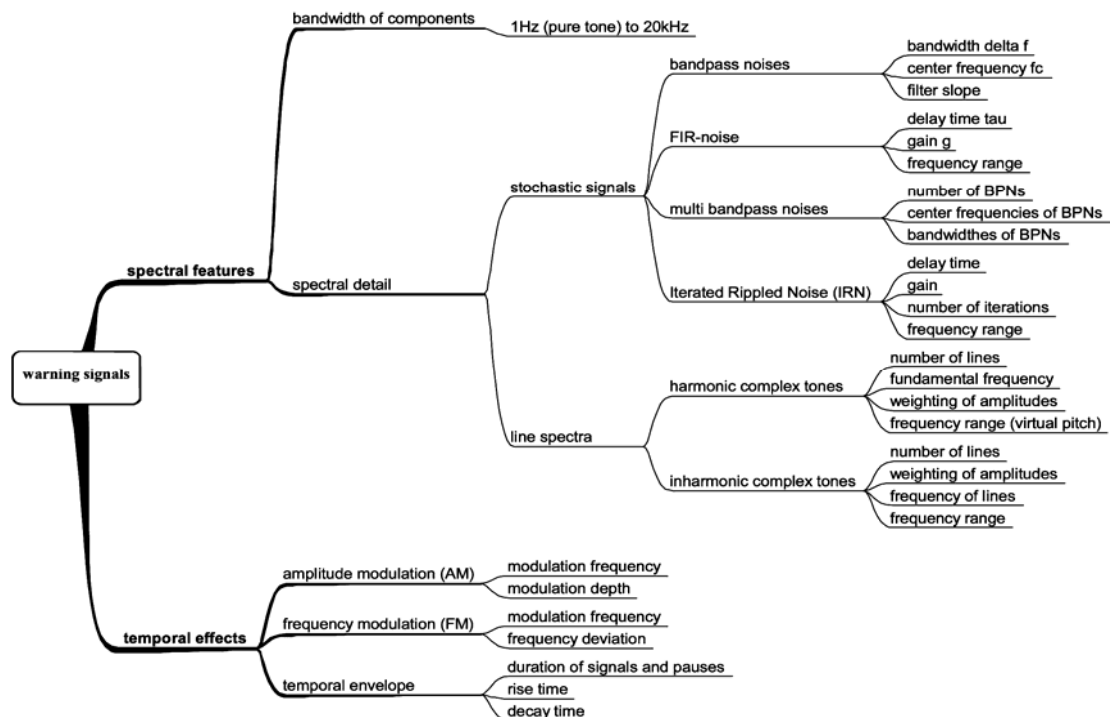


Figure 12 – Sound engineering of a warning signal. Possible alternatives are treated in a manner typical for decision trees

When engineering synthetic signals for a specific purpose, e.g. warning signals, the possible alternatives are considered step by step.

First, spectral features and temporal effects have to be selected. As concerns the temporal effects, the temporal envelope, i.e. the gating of the signal is of utmost importance. Duration and arrangement of signals and pauses with their respective rise- and decay-times play an important part. In addition to these coarse temporal effects, finer grating of the time structure e.g. by AM or FM is of importance. Modulation frequency, modulation depth and frequency deviation have to be chosen to fit the purpose of the warning signal, e.g. whether immediate action is necessary, or if the signal is rather of indicative nature.

As concerns the spectral features, the bandwidth of the whole signal and how it is composed are decisive for its suitability for a specific purpose. While line spectra can be modeled to produce pleasant sounds for more indicative signals, stochastic signals can be used to tailor rather intrusive sounds. For example with iterated rippled noise (IRN) a whole continuum from tonal, pleasant sounds to very noisy intrusive sounds can be realized. However, with the right combination of gating and AM or FM, also with line spectra pretty intrusive sounds can be realized. Therefore, a general “recipe” how to realize the “best” warning signal for a specific purpose can not be given; rather, the choice depends both on the experience of the person engaged in the sound engineering, and the preferences of the customer.

CONCLUSION

The application of psychoacoustic principles in sound quality evaluation and sound engineering has become more and more accepted in the last decade or so. Twenty years ago, applications of psychoacoustics in noise evaluation were rather exceptional (e.g. Blauert 1986). However, in the meantime, the application of knowledge from psychoacoustics (e.g. Zwicker and Fastl 1999) or even from musical acoustics (e.g. Fastl 2002) in sound quality design is increasing. The relevance of cognitive effects is assessed not only in view of psychological and sociological aspects but also from an engineering point of view. In a global market with many competing products of almost the same functionality, the noise produced can become an important feature. Moreover, sub-consciously, frequently not only the quality of the sound as such is evaluated. Rather, the sound produced by a product is taken as an indication of the quality of the product itself! A typical example would be that a “tinny” closing sound of a car door would imply that the vehicle is cheap and unreliable. In summary, it is to be expected that the application of psychoacoustics in sound quality evaluation and sound engineering still will increase in the future.

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