FROM PSYCHOACOUSTICS TO SOUND QUALITY ENGINEERING

H Fastl AG Technische Akustik, MMK, TU Muenchen, Germany

1 INTRODUCTION

The scientific field of psychoacoustics quantitatively explains the relations between sound stimuli, well defined in the physical domain, and the hearing sensations elicited by such stimuli. Already more than 2500 years ago, the Greek philosopher Pythagoras when studying with his monochord musical consonance and dissonance, performed a typical psychoacoustic experiment: For Pythagoras, the physical magnitude was the length of the string stretched out along his monochord and supported by a bridge. By varying the position of the bridge he judged with his hearing system when plucking both ends of the string whether the resulting interval was a musical consonance or a musical dissonance. For simple ratios of the string divisions like 1:2 (octave), 2:3 (fifth) or 3:4 (quart), consonant musical intervals were obtained.
In modern psychoacoustics in principle the same procedure as used by Pythagoras is applied: stimuli well defined in the physical domain are produced, nowadays with the help of fancy digital sound processing algorithms. After D/A conversion the resulting sounds are presented to subjects via headphones or loudspeakers and their opinion is asked about the pitch, the loudness, the tone colour etc. of the sounds perceived.
In sound quality engineering frequently the same principles 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 production in such a way to arrive at a sound which is as close as feasible to the target sound.
In this paper psychophysical methods useful for both psychoacoustics and sound quality engineering will be discussed. Models of basic psychoacoustic magnitudes like loudness or sharpness as well as combined metrics will be introduced, and their application to sound quality design will be explained. For some examples of sound quality studies the results of subjective evaluations will be compared to predictions from physical models. Influences of the image of brand names as well as the meaning of sound on sound quality evaluation will be discussed. Finally the influence of visual effects on the rating of sound quality will be briefly touched.

2 METHODS

For sound quality evaluation psychophysical methods are used which have proven successful in psychoacoustics: Ranking methods indicate, whether a product sounds better than the product of a competitor. The method of Semantic Differential gives hints, why a specific sound is suitable to convey an intended message, e.g. as a warning signal. Finally, category scaling and magnitude estimation can give an indication, how much the sound quality of products differs. This is of particular relevance for cost/benefit evaluations.

2.1 Ranking procedure "random access"

A ranking procedure, called random access, which has proven very successful for questions of sound quality evaluation (e.g. Fastl[1,2]) 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 ranking of sound quality.

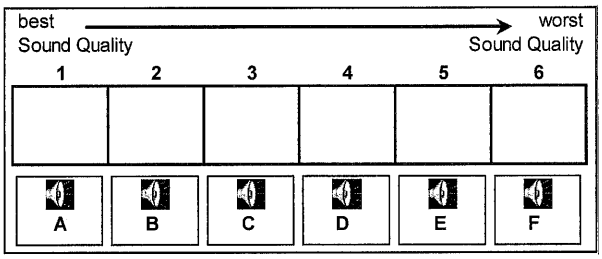

Fig. 1. Example for ranking of sound quality by the method random access (Fastl[2])

2.2 Semantic Differential

The method of Semantic Differential is used to test whether a sound is 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[3]). It is clear that warning signals should have high loadings on adjectives like dangerous, frightening, unpleasant, conspicuous 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

Fig. 2. Semantic Differential used in an international study on warning signals (Kuwano et al.[3])

2.3 Category scaling

Category scaling frequently is used for the assessment of the loudness of products. Five step scales as well as seven step scales are employed. Five step scales usually are labelled very soft,

soft, neither soft nor loud, loud, very loud. In comparison to the five step scale, the seven step scale has in addition the steps slightly soft as well as slightly loud. Therefore, the whole range between very soft and very loud has a finer grading in seven step grades than in five step grades.
A variant of category scaling frequently used in audiology or the assessment of noise immissions is the subdivision of a five step scale in ten subcategories each, leading to a 50 point scale (Hellbrück[4] Since the numerical representation of categories may suggest a ceiling effect sometimes the categories inaudible at the low end and too loud at the high end are added to the 50 point scale.

2.4 Magnitude estimation

An advantage of the method of magnitude estimation is that no ceiling effects show up and it has (theoretically) an infinite resolution (e.g. Zwicker and Fastl[5]). In the procedure, 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 20 percent softer than sound A the subject should give the response 80. 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.
The psychophysical methods mentioned so far all have their advantages and disadvantages: Random access and semantic differential give more qualitative descriptions of sound quality. For quantitative assessment of sound quality, methods like category scaling and magnitude estimation are recommended. While traditional category scaling is confined to five step or seven step scales, magnitude estimation in principle has an infinite resolution. However, in practice, effects of the frame of reference as well as influences of the choice of the anchor sound have to be taken into account.

3 MODELING PSYCHOACOUSTIC MAGNITUDES

For sound quality engineering basic psychoacoustic magnitudes like loudness, sharpness, roughness, and fluctuation strength 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.

3.1 Loudness

Usually the loudness of a product has a strong influence on its sound quality. Therefore the model of loudness proposed by Zwicker[6] has been improved (Zwicker and Fastl[7], Zwicker et al. [8]) and extended in recent years including its applicability to persons with hearing deficits (Chalupper and Fastl[9]).

Since Zwicker's classic loudness model is standardized in DIN 45 631 and ISO 532B, it seems sufficient to mention here some key features of the procedure like transformation of frequency scale into Bark scale, taking into account effects of masking, and the direct relation between the area of the loudness pattern and perceived loudness. In later versions of the loudness model[7] also effects of temporal masking are incorporated.
Figure 3 illustrates an actual implementation[9] of a Zwicker-type loudness model. 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 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 new implementation called dynamic loudness model (DLM) is that just by modifying the block loudness transformation the loudness perception of both normal hearing as well as hearing impaired persons can be simulated (Chalupper and Fastl[9]). 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 costumers of a product will show mild to moderate hearing loss. Unfortuately, even an increasing percentage of the younger generation these days shows hearing deficits, frequently due to extremely loud leisure activities.

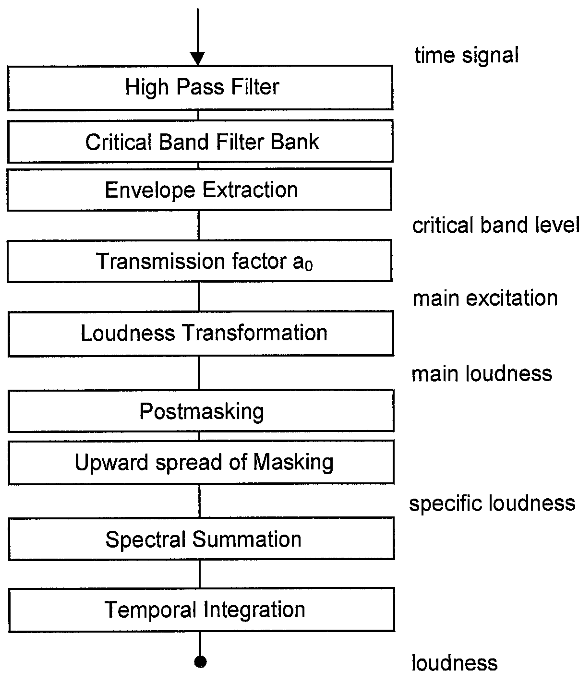

Fig. 3. Block diagramm of a dynamic loudness model (DLM) proposed by Chalupper and Fastl[9]

In essence, the loudness transformation for normal hearing persons differs from that of hearing impaired persons as follows: at low levels, the loudness perception of hearing impaired persons is much softer than for normal hearing persons, but at high levels, according to the recruitment phenomenon, the loudness perception of hearing impaired persons "catches up". Just above threshold of audibility the gradient of loudness is very steep and an increase in level by a few dB can lead to a drastic increase of loudness which can be pretty annoying for the hearing impaired person. Although modern hearing aids try to compensate this effect by digital processing even the most advanced hearing instruments can not restore normal hearing completely.

3.2 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[10]). 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 4. The left panel shows the spectral distribution of a narrow-band noise, a broadband noise and a high pass noise, the right panel illustrates the related loudness patterns. However, in order to account for the increased sharpness of high frequency sounds a weighting function g is applied. 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 4 by vertical arrows. It becomes clear from figure 4 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. However, it has to be kept in mind that this addition of low frequency components increases the total loudness. Nevertheless, 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.

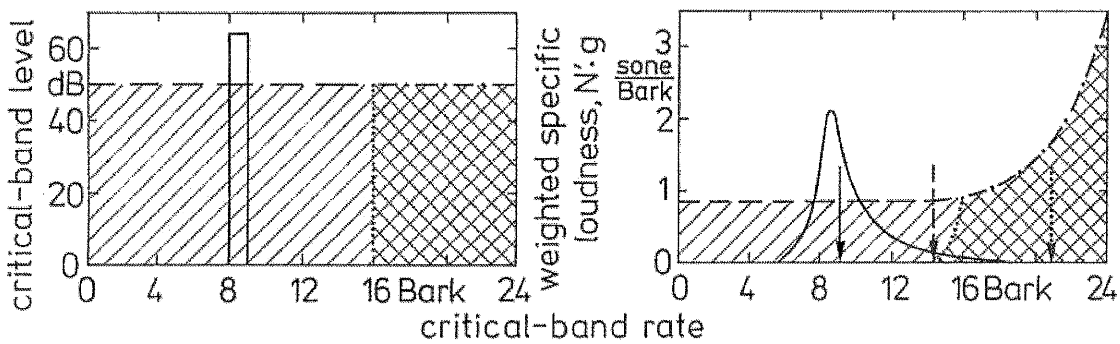

Fig.4. Illustration of the model of sharpness (Zwicker and Fastl[5])

3.3 Roughness

The psychoacoustic magnitude roughness is used in sound quality engineering for example to stress in a motor-sound the feature of sportiness. Roughness is governed by temporal variations of a sound and reaches a maximum for modulation frequencies around 70 Hz (Terhardt[11]). In essence roughness can be described by the temporal masking pattern of sounds (Fastl[12]). This reasoning is illustrated in figure 5. 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. Theoretically the "valleys" between the peaks reach a minimum near minus infinity dB. In practical applications however, the minimum level is governed by the dynamics of the system producing the stimuli which reaches for 16 bit amplitude resolution some 90 dB. 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 5 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}.

$$R \sim \Delta L \cdot f_{\mathrm{mod}} \qquad (1)$$

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.

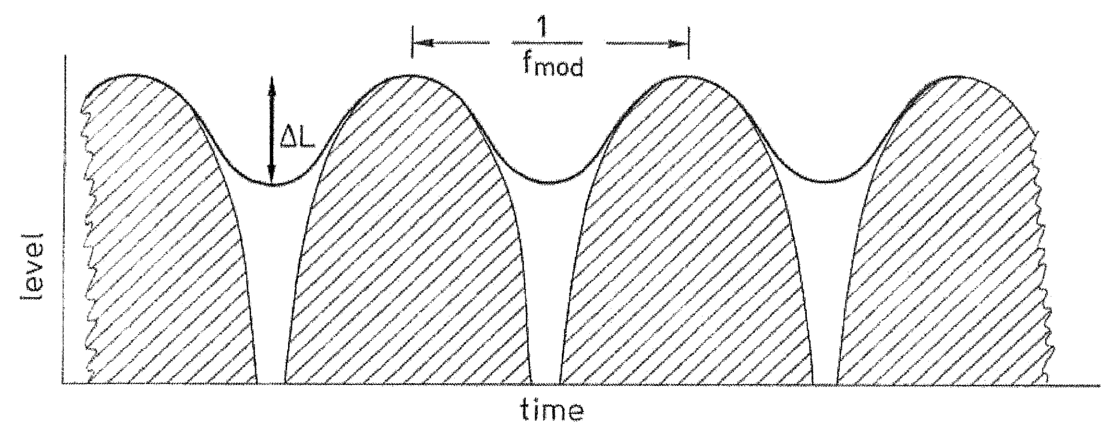

Fig. 5. Illustration of the input to the model of roughness (Fastl[12])

3.4 Fluctuation strength

The hearing sensation fluctuation strength is similar to the psychoacoustic magnitude roughness. However, fluctuation strength reaches a maximum for modulation frequencies around 4 Hz (Fastl[12]). The input to the model of fluctuation strength is the same as the input to the model of roughness displayed in figure 5. However, in addition to the modulation depth of the temporal masking pattern ΔL, the relation of the modulation frequency f_{mod} to a modulation frequency of 4 Hz is of relevance. Therefore basically fluctuation strength can be calculated as follows:

$$F \sim \frac{\Delta L}{\frac{4Hz}{f_{\mathrm{mod}}} + \frac{f_{\mathrm{mod}}}{4Hz}} \tag{2}$$

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.

3.5 Combined metrics

A combination of psychoacoustic magnitudes has proven successful for the prediction of the annoyance of sounds from noise emissions as well as noise immissions (Widmann[13]). The corresponding formula reads as follows.

$$PA = N_5 \quad 1 + \sqrt{w_S^2 + w_{FR}^2}$$

with

- N_5 percentile loudness in sone,
- $w_S = \frac{S}{acum} \quad 1.75 \quad 0.25 \lg \frac{N_5}{sone} + 10$ for S> 1.75 acum

(3)

describing the effects of sharpness S and

- $w_{FR} = \frac{2.18}{N_5 / sone} \quad 0.4 \quad \frac{F}{vacil} + 0.6 \quad \frac{R}{asper}$

describing the effects of fluctuation strength F and roughness R.

From the formula it becomes clear that the loudness is a dominant feature of annoyance. The percentile value N_5 indicates that a value near the maximum loudness is of importance for sound quality ratings. However, sharpness as well as roughness and fluctuation strength also may play an important role.
When thinking for example of a dentist's drill, not only the loudness but even more the sharpness is responsible for the annoyance. Likewise, water drops from a faucet which has not been completely closed (in particular when heard at night) are not annoying because of their loudness, but because of the regularity and hence the fluctuation strength of the sound produced.
Although the model of psychoacoustic annoyance proposed by Widmann[14] can account for many practical situations it is not designed to solve all questions of sound quality. Of course, Widmann's model contains the essential ingredients for sound quality evaluation namely loudness, sharpness, roughness, and fluctuation

strength. However, the "recipe" of the appropriate mixture of basic psychoacoustic magnitudes may vary for different families of product sounds.
Another composite model based on several psychoacoustic magnitudes put forward by Terhardt[15] has proven successful to rate the pleasantness of sounds, and in particular also of speech and music (cf. Terhardt and Stoll[16]). However, clearly audible tonal components get in the model of Terhardt a bonus whereas for questions of noise immissions, tonal components get a tone penalty. This means that care has to be taken when applying Terhardt's model of sensory pleasantness to questions related to noise immissions.

4 SOUND QUALITY

Since a multitude of examples for sound quality evaluation has been described in the literature (e.g. www.mmk.ei.tum.de/noise.html) only few examples will be given in this section. Our first example illustrated in figure 6 deals with motor adjustments (Patsouras et al. [17]). By modern car electronics it is pretty easy to control many features of the motor. In the example displayed in figure 6 a diesel motor was driven either "hard" or "normal". The advantage of the "hard" motor adjustment is that the engine is more fuel efficient. The disadvantage, of course is that it produces more noise. In psychoacoustic experiments it was assessed whether the acoustic disadvantage of the fuel efficient “hard” motor adjustment can be reduced by absorptive measures. In one part of the study, frequencies from 1 kHz to 5 kHz where attenuated by 3 to 15dB in 3dB steps. In the other series of experiments, the whole spectrum was attenuated by 3 to 15 dB again in 3 dB steps. The data displayed in figure 6 show the ranking of sound quality by circles (medians and inter-quartiles) as well as physical measurements of loudness (crosses).

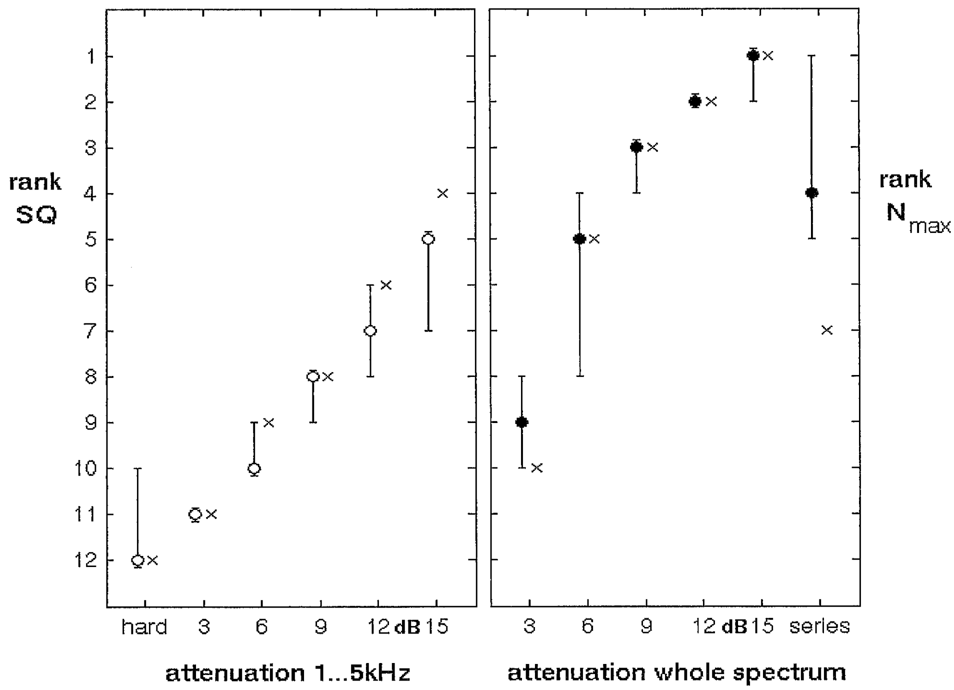

Fig. 6. Improvement of the sound quality of a diesel motor with "hard" motor adjustment by simulated absorptive measures. Circles: subjective sound quality estimates, crosses: physical measurement of loudness. (Patsouras et al. [17])

The results displayed in figure 6 clearly show that the motor with "hard" motor adjustment gets the poorest sound quality ranking (rank 12). On the other hand, the motor with the "normal" motor adjustment as used in series vehicles attains rank 4 in sound quality. Even better ranks (1 to 3) are obtained when the whole spectrum of the "hard" motor sound is attenuated by 9 to 15 dB.

The results depicted in figure 6 suggest that even when the sound of a hard motor adjustment is attenuated in the frequency range of 1 to 5 kHz by as much as 15 dB, the sound quality of a "normal" motor adjustment as in a series vehicle is not achieved. Rather the whole spectrum of the motor sound for hard motor adjustment would have to be attenuated by about 7.5 dB to attain the sound quality of a present day series vehicle. Although it will not at all be easy, it seems quite worthwhile for engineers to take this challenge, because of the fuel efficency of the motor with hard motor adjustment.

The crosses displayed in figure 6 indicate the ranking of the physically measured maximum loudness N_{max} produced by each sound. As a rule there is good agreement between the sound quality ranking and the ranking of the maximum loudness. However, for an attenuation between 1 and 5 kHz of 15 dB sound quality attains only a rank of 5 while the ranking of maximum loudness attains the rank 4. On the contrary, for the series motor, the ranking in loudness attains only rank 7 whereas the sound quality attains rank 4. This means that loudness alone can not always predict sound quality ratings. In spite of its larger loudness (rank 7) the sound quality of the motor of the series vehicle is ranked better (rank 4). This is presumably due to the "natural" familiar sound. A similar argument holds true for the hard motor attenuated by 15dB in the frequency range 1 to 5 kHz. Although the loudness is significantly reduced (rank 4) the sound quality is ranked lower (rank 5), presumably because the resulting stimulus sounds quite unnatural.

The data displayed in figure 7 enable a comparison of annoyance ratings of car sounds in psychoacoustic experiments (dots) versus data calculated from physical measurements according to the formula given in section 3.5 (crosses). Sounds range from coasting with motor off (16) to racing start (12); details are given in Zwicker and Fastl[5].

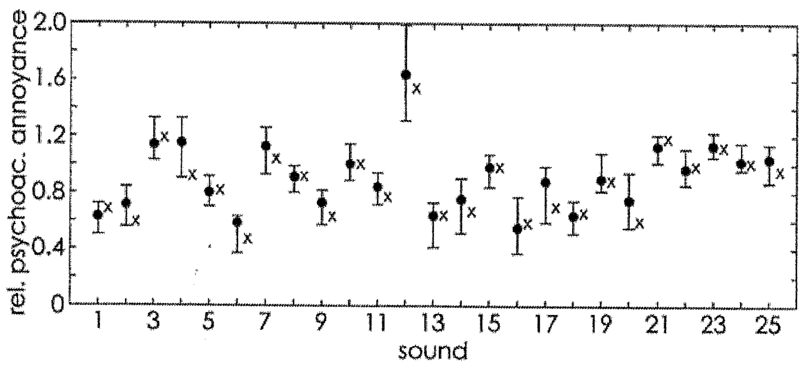

Fig. 7. Psychoacoustic annoyance of car sounds. Subjective (dots) versus physical (crosses) evaluation. (Zwicker and Fastl[5])

Usually there is good agreement between subjective and physical annoyance evaluation, i.e. the physical measurements (crosses) are within the interquartiles of the subjective evaluations.

5 MEANING OF SOUND

When evaluating sound quality the meaning of a sound 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. [18]) 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 of dangerous or unpleasant.
In order to overcome such problems a procedure has been proposed (Fastl[19]) which largely removes the information about the sound source from a stimulus. A block-diagram displayed in figure 8 illustrates the correlated procedure. From an original noise, e.g. train noise, a spectral analysis is performed by an FTT algorithm. The Fourier-time transform FTT (Terhardt[20]) 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 the sound is re-synthesized by inverse FTT. In this way a sound with the same spectral and temporal envelope and hence the same loudness-time function is created from which, however the information about the sound source is removed.

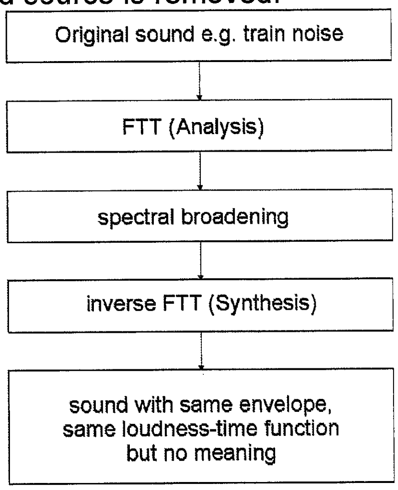

Fig. 8. Block diagram illustrating the procedure to remove the information about the sound source from a stimulus (Fastl[19]

With the procedure outlined in figure 8 from many signals important in daily life the information about the sound source can be removed. However, some signals like for example FTT-processed speech sounds still have great similarity to the original sound source.

6 IMAGE OF BRAND NAMES

In addition to basic acoustic features like hearing sensations also the meaning of a sound or the image of a brand name may have an influence on sound quality evaluation. A well known typical example is that the (sound) quality of a car is judged on the basis of the sound produced by closing the door: if the door sound is "tinny" this suggests that the whole vehicle is cheap and not at all solid. On the contrary a full saturated sound of the closing of a car's door has a connotation of luxury. In a cooperation with colleagues from Osaka University Japan we studied the sound produced by closing of car doors with the method of semantic differential (Kuwano et al. [21]). The data obtained suggest that the car door sound of luxury sedans is governed by the adjectives deep, pleasant, heavy, dull, dark, powerful, calm, smooth, and pleasing. On the contrary adjectives related to the car door sound of an economy sedan are characterized as metallic, unpleasant, noisy, bright, shrill, rough, and unpleasing.
In addition we asked the subjects to guess the type of car and to give the corresponding brand name of the car. Figure 9 gives an example for the histogram of the brand names of cars associated with luxurious sedans from which the subjects thought that they had heard the sound of closing doors (Filippou et al. [22]).

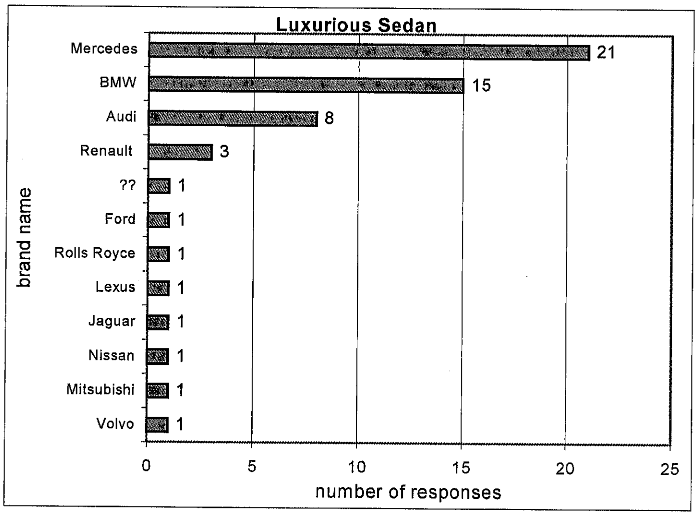

Fig. 9. Distribution of brand names associated with car door sounds of luxurious sedans.(Filippou et al. [22])

The twenty German subjects clearly related luxurious sedans to brand names like Mercedes, BMW or Audi. Interestingly, the ranking of car manufacturers by the German Automobile Association (ADAC) shows strong relations to the rating of the sounds of closing doors of cars. For example the brand name Mercedes, which is ranked first by the ADAC gets the highest rating in the category of luxurious cars. Obviously, the brand name of a car strongly triggers the expectations about the sounds produced by a closing door.

7 AUDIO VISUAL INTERACTIONS

Sound quality ratings can depend not only on acoustic stimuli but in addition on simultaneously presented visual inputs. The first example deals with the influence of an additional visual image on the sound quality rating of speech. In a concert hall speech was radiated from the stage and recorded at different positions in the hall. In a first experiment subjects just listened to the recorded speech and rated the speech quality. In another experiment in addition to the acoustic presentation of the speech sounds subjects where presented a picture showing the distance between the receiving point and the source on the stage of the concert hall. Figure 10 shows the schematic plan of the ground floor of a concert hall with indications of the sound source S and three positions 1 through 3 of the receiver. The sounds produced by the speaker S where recorded on DAT tape at the positions 1,2, or 3. In addition at these positions, photos where taken, showing the speaker on the stage and enabling to evaluate his distance from the receiving point.

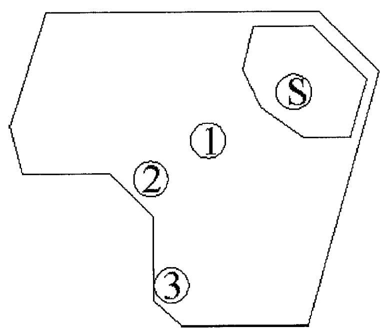

Fig. 10. Schematic plan of the ground floor of a concert hall with indications of the sound source S and three positions 1 through 3 of the receiver (Fastl[23])

Figure 11 gives the ratings of the speech quality for acoustic presentation alone (unfilled symbols) or with additional visual presentation (filled symbols).

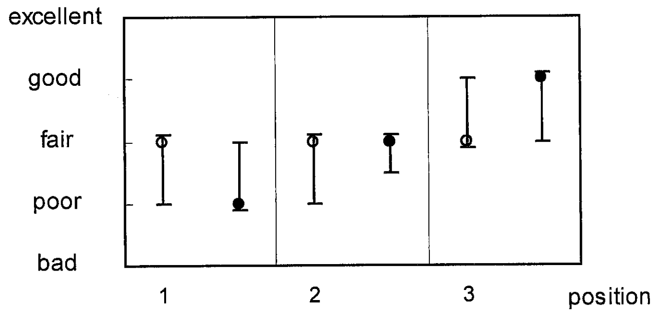

Fig. 11. Rating of speech quality in a concert hall at positions 1, 2, and 3 for acoustic presentation alone (unfilled symbols) or acoustic plus visual presentation (filled symbols).(Fastl[23])

The data displayed in figure 11 show that a visual image can have an influence on the rated sound quality of speech. At position 1, which is relatively close to the source, with the addition of the visual image the rating degrades from fair to poor (medians). This may be due to the effect that the visually perceived relatively small distance to the speaker calls for a better speech quality which is not degraded by reverberation as in a concert hall. Since the concert hall of course was designed for classic music with a reverberation time at mid-frequencies around 2 seconds, this reverberation is much too large for speech for which reverberation times below 1

second would be optimal (Cremer and Müller[24]). At position 2 there is no influence of the visual image on the rating of speech quality. Obviously the subjects think that for such a larger distance from the speaker the quality is fair. Most interesting is the rating at position 3: without visual information the speech quality is rated fair. However, with visual information the speech quality even is rated as good. Obviously, given the large distance between the speaker S and the receiving point 3 the subjects feel that for such an adverse situation the speech quality can be rated as being relatively good.
The last example deals with the influence of colour on the rating of the loudness of sound sources (Patsouras et al. [25]). Sounds of a passing train are presented either without visual input or with pictures of a train in different colour. Despite identical acoustic stimulus the train sound is perceived as being softest when the train is painted in a light green and 20% louder when the train is painted in red. The original painting of the train (a German ICE) is white with a red stripe. In this case also a relative loudness of 120 percent is reached. If the train-sound is heard without a visual input, it is perceived as somewhat softer than the presentation of sound plus original image and similar to a train painted in light blue. In summary then, the colour of a product can somewhat influence its loudness and hence its sound quality.

8 OUTLOOK

The application of psychoacoustic principles in sound engineering and sound quality design has become more and more accepted in the last decade or so. Despite a solid psychoacoustic basis (e.g. Zwicker[26]) some twenty years ago, applications of psychoacoustics in noise evaluation were rather exceptional (cf. Blauert[27]). In the meantime, the application of knowledge from psychoacoustics (e.g. Fastl[28]) or even from musical acoustics (e.g. Fastl[23]) in sound quality design is increasing. In a global market with many competing products of almost the same functionality, the noise produced can become an important feature. Moreover, frequently from the quality of the noise produced, inconsciously the quality of the whole product is rated. Therefore it is to be expected that the application of psychoacoustics in sound quality engineering still will increase in the future.

The author wishes to thank present and former members of his group Technische Akustik for their contributions to basics and applications of psychoacoustics. A large part of the research has been sponsored by the Deutsche Forschungsgemeinschaft

9 REFERENCES

1. Fastl H (2000) Sound Quality of Electric Razors - Effects of Loudness. In: Proc. inter-noise 2000, CD-ROM
2. Fastl H (2002) Psychoacustics and sound quality. In: Fortschritte der Akustik. DAGA, Dt. Gesellschaft für Akustik e. V., Oldenburg, pp 765-766
3. Kuwano S, Namba S, Schick A, Hoege H, Fastl H, Filippou T, Florentine M, Muesch H (2000) The timbre and annoyance of auditory warning signals in different countries. In: Proc. Internoise 2000, CD-ROM
4. Hellbrück J (1993) Hören. Hogrefe, Göttingen

5. Zwicker E, Fastl H (1999) Psychoacoustics. Facts and Models. 2nd edn, Springer, Heidelberg, New York
6. Zwicker E (1960) Ein Verfahren zur Berechnung der Lautstärke. Acustica 10, pp 304-308
7. Zwicker E, Fastl H (1983) A portable loudness-meter based on ISO 532 B. In: Proc. 11. ICA Paris, vol 8, pp 135-137
8. Zwicker E, Deuter K, Peisl W (1985) Loudness meters based on ISO 532 B with large dynamic range.In: Proc. inter-noise'85, vol II, pp 1119-1122
9. Chalupper J, Fastl H (2002) Dynamic loudness model. ACUSTICA/acta acustica 88, pp 378-386
10. Bismarck G.v. (1974) Sharpness as an attribute of the timbre of steady sounds. Acustica 30, pp 159-172
11. Terhardt E (1968) Über akustische Rauhigkeit und Schwankungsstärke. Acustica 20, pp 215-224
12. Fastl H (1982)Beschreibung dynamischer Hörempfindungen anhand von Mithörschwellen-Mustern. Hochschul-Verlag, Freiburg
13. Widmann U (1995) Subjektive Beurteilung der Lautheit und der Psychoakustischen Lästigkeit von PKW-Geräuschen. In: Fortschritte der Akustik, DAGA 95, Dt. Gesellschaft für Akustik e. V., Oldenburg, pp 875-878
14. Widmann U (1998) Aurally adequate evaluation of sounds. In: Fastl H, Scheuren J (eds) Proc. euro-noise 98. DEGA, Oldenburg, pp 29-46
15. Terhardt E (1984) Wohlklang und Lärm aus psychophysikalischer Sicht. In: Schick A, Walcher KP (eds) Ergebnisse des 3. Oldenburger Symposions zur Psychologischen Akustik. P. Lang AG, Bern, pp 403-409
16. Terhardt E, Stoll G (1981) Skalierung des Wohlklangs (der sensorischen Konsonanz) von 17 Umweltschallen und Untersuchung der beteiligten Hörparameter. Acustica 48, pp 247-253
17. Patsouras C, Fastl H, Patsouras D, Pfaffelhuber K (2002) How far is the sound quality of a diesel powered car away from that of a gasoline powered one? In: Proc. Forum Acusticum Sevilla 2002, NOI-07-018-IP, CD-ROM
18. Kuwano S, Namba S, Fastl H, Schick A (1997) Evaluation of the impression of danger signals – comparison between Japanese and German subjects. In: Schick A, Klatte M (eds) Contributions to Psychological Acoustics. BIS, Oldenburg, pp 115-128.
19. Fastl H (2001) Neutralizing the meaning of sound for sound quality evaluations. In: Proc.17th International Congress on Acoustics. Rome: CD ROM
20. Terhardt E, (1985) Fourier transformation of time signals: conceptual revision. Acustica 57, 242-256.
21. Kuwano S, Fastl H, Namba S, Nakamura S, Uchida H (2002) Subjective evaluation of car door sound. In: Proc. SQS Dearborn 2002. CD ROM
22. Filippou TG, Fastl H, Kuwano S, Namba S, Nakamura S, Uchida H (2003) Door sound and image of cars. In: Fortschritte der Akustik. DAGA 2003, Dt. Gesellschaft für Akustik e. V., Oldenburg
23. Fastl H (2002) Sound design of machines from a musical perspective. In: Proc. SQS Dearborn 2002, CD-ROM
24. Cremer L, Müller HA (1978) Die wissenschaftlichen Grundlagen der Raumakustik. Hirzel, Stuttgart
25. Patsouras Ch, Filippou TG, Fastl H (2002) Influences of color on the loudness judgement. In: Proc. Forum Acusticum Sevilla 2002, PSY-05-002-IP, CD-ROM
26. Zwicker E (1982) Psychoakustik. Hochschultext, Springer, Berlin
27. Blauert (1986) Cognitive and esthetic aspects of noise engineering. Proc. inter-noise 86 vol I, pp 5-14
28. Fastl H (1998) Psychoacoustics and Sound Quality Metrics. In: Davies P, Ebbitt G (eds) Proceedings of the Sound Quality Symposium. Ypsilanti Michigan, USA, pp 3-10