The importance of binaural hearing for noise validation[1]

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In a project that has been funded by the German Ministery of Research and Technology (BMFT) fundamental questions of noise validation have been addressed by an interdisciplinary research consortium. The aim of the project was to provide knowledge that will lead to a new, binaural and aurally-adequate measurement technique which can especially be used for the validation of the effects of noise for levels below the legislative limit of 85 dB(A) at workshop places. The investigations have proven that the spatial distribution of sounds has an influence on physiological responses of humans exposed to noise, and that psychoacoustic parameters, e.g., loudness, depend on the direction of sound incidence. In consequence an aurally-adequate measurement technique has to consider binaural processing. A binaural model that could be used for this task is presented.

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1 Introduction

The results presented in this paper are mainly based on a project which has been funded by the Federal Ministery of Research and Technology (BMFT) under the A&T program (Work and Technique). The title of the project was “Development of a measurement technique for the physiological valuation of the effects of noise taking into account psychoacoustic properties of the human auditory system”[1]. The research team consists of the industrial coordinator Head acoustics (Dr. Genuit), the institute of Working Medicine of Düsseldorf University (Prof. Jansen), the institute of Physics of Oldenburg University (Prof. Mellert), and the institute of Acoustics of Bochum University (Prof. Blauert).

The project addressed several fundamental questions of noise validation. Physiological investigations have been performed in order to prove whether there really is a need for a binaural measurement technique for noise validation, opposing physiological responses of subjects exposed to noises that have been recorded using either a conventional one-microphone equipment or a dummy head. Psychoacoustic experiments aimed at determining the dependency of loudness perception on the direction of incidence of sound sources, thus forming a first approach towards the definition of binaural loudness. A computer model of binaural interaction was used to analyse the spatial distribution of sound fields, a tool which will be necessary to implement a binaural noise measurement device. The results of the respective investigations are described in more detail in the following chapters.

2 Motivation

The measurement technique that is conventionally used for the validation of the effects of noise differs in some important aspects from the way humans perceive and evaluate sounds. The following differences can be stated:

- due to the shapes of ears, head and shoulders the outer ears form *directional filters*. This means that the transfer function that can be measured between a sound source and the eardrum depends on the position of the sound source. The conventional technique uses a unidirectional microphone and is thus not able to consider these effects.
- the human auditory system makes use of two input signals, supplied from the left and right ear, which are combined in the auditory pathway. This *binaural processing* offers a lot of advantages, e.g., *spatial hearing* and *binaural selectivity.* The conventional technique uses only one microphone.
- auditory sensations are characterised by *psychoacoustic properties* like *loudness*, *sharpness* and *roughness*, and do not only depend on the sound pressure level.

Regarding these differences it becomes obvious that the conventional technique can not generally be used to validate the effects of noise. If we consider for example a complex sound situation, in which several noises are emitted from different positions, the conventional technique will perform a simple summation of the sound pressure levels of all signals. In contrast to that the human auditory system performs a selective analysis of the underlying situation, separating the sources from each other and assigning to them their own respective perceptual

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attributes. Thus the resulting validation is not performed on the physical sum of the signals, but as a combination of the evaluation of each individual signal. Up to today it has not been proven to what extend this selective process influences the effects of noise on humans, that is, to what extend a validation with conventional measurement techniques differs from the validation humans perform. To do so, physiological responses have to be measured, extended and supported by psychoacoustic experiments. Further research on the topic of modeling binaural interaction is used as a direct preparation for the implementation of an advanced binaural measurement tool.

3 Physiological Responses

Physiological responses of male and healthy subjects have been measured at Düsseldorf University in three series of experiments, involving 48, 8 and 15 subjects, respectively (SCHWARZE et al., 1991; NOTBOHM et al., 1992). The subjects were exposed to noises in a sound-proof chamber via headphones. Fingerpulse amplitude (FPA), skin conductance response (SCR), heart frequency (HF) and electro-myogram of m. frontalis (EMG) were recorded continuously.

The first series of experiments addressed the question whether a difference in the physiological response of subjects exposed to noise can be observed comparing the following two conditions:

1. signals are recorded with one unidirectional microphone and are presented diotically via headphones. This corres-ponds to the conventional measurement technique.
2. signals are recorded with a dummy head and are presented dichotically via headphones.

Therefore, the results can prove whether the physiological responses depend on binaural processing, and whether this binaural processing has to be considered for the validation of noise.

Three different noises have been recorded at workshop places of wood- and metal-processing industries (circular saw, hacksaw and engine construction), supplemented by pink noise as a control stimulus. All signals have been adjusted to the same level of 83 dB(A). This level has been chosen because german legislative has fixed a maximum level of 85 dB(A) at workshop places.

Fig. 1 shows an example for the results, the skin conductance response to hacksaw noise (averaged values for intervals of 5 s), Fig. 2 shows the fingerpulse amplitude. The responses to the dummy head recordings are significantly higher than to the conventional recordings. This is consistent for all stimuli, but more prominent for the industrial noises. The results prove that binaural processing plays a role with regard to the physiological responses of humans exposed to noise.

The subsequent series of experiments were intended to identify the most prominent parameters that determine the difference between conventional and binaural measurement techniques with regard to their influence on physiological responses. It is obvious that the major difference is the spatial distribution of sounds which can be reproduced from dummy head recordings, but not from conventional recordings. Therefore, the second experiment addressed the question which influence the spatial distribution of sound sources has on physiological responses. To do so, the following situations have been compared:

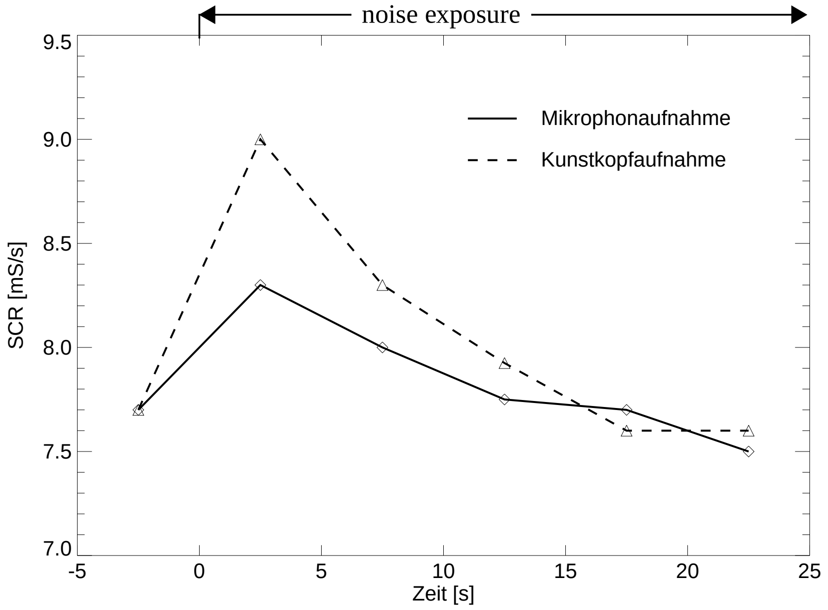

Fig. 1 Skin conductance response (SCR) to hacksaw noise recorded either with one unidirectional microphone (solid line) or a dummy head (broken line).

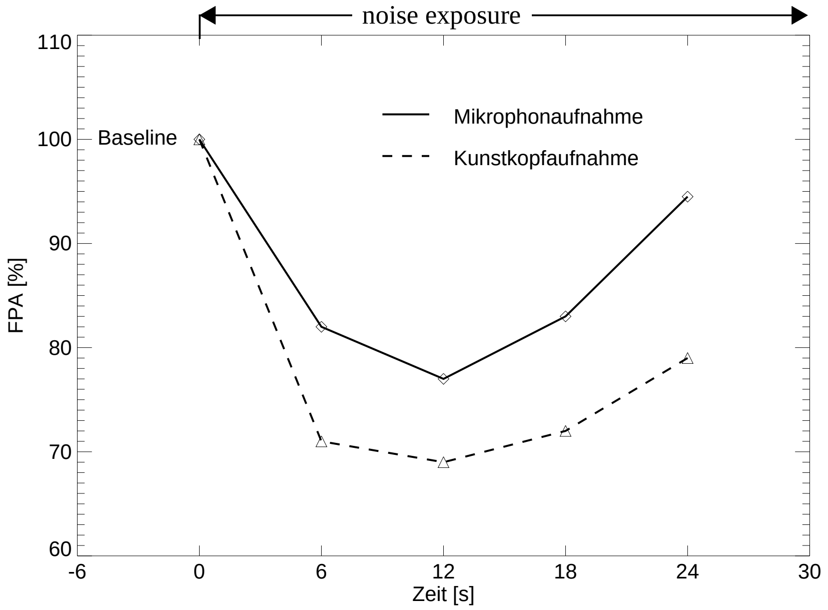

Fig. 2 Fingerpulse amplitude (FPA) for hacksaw noise recorded either with one unidirectional microphone (solid line) or a dummy head (broken line).

1. uni-directional situation: two sources are placed at the same position (azimuth 60^{o}),
2. multi-directional situation: the sources are placed at different positions (azimuths -40^{o} and 70^{o}).

The stimuli have been placed at the respective positions using a binaural mixing console.

This device convolves a one-channel input signal with the head-transfer functions of the left and right ear corresponding to the desired direction of incidence. It thus simulates a dummy head recording. The situations have been adjusted to a common level of 84 dB(A).

The results of the experiments with two industrial noises (a hacksaw and a coupling machine) show that the physiological responses are significantly stronger for the multi-directional than for the uni-directional presentation. The difference is very strong after the initial reaction (the first 30 s), when a re-regulation mechanism can be observed for the uni-directional situation. This re-regulation mechanism is delayed for the multi-directional situation, the baseline is not reached any more. The spatial distribution of sounds seems to have a significant influence on the strain that noises evoke.

In a third series of experiments two uncorrelated pink noises have been used as stimuli. The industrial noises that have been used so far carry information that may lead to specific associations of subjects to the signals which may result in amplified physiological responses. In addition to the uni- and multi-directional situation described above a third situation was investigated in which one noise moved from the left to the right and the other from the right to the left.

In this series a significant difference in the responses to the different situations was only observed for the fingerpulse amplitude. The results are depicted in Fig. 3. There is no difference in the initial response, but then the same behaviour regarding the re-regulation mechanism as in experiment 2 occurs: the baseline is only reached for the uni-directional situation, the re-regulation is delayed for the multi-directional and moving situations. The response to the moving situation is more intensive than to the multi-directional situation.

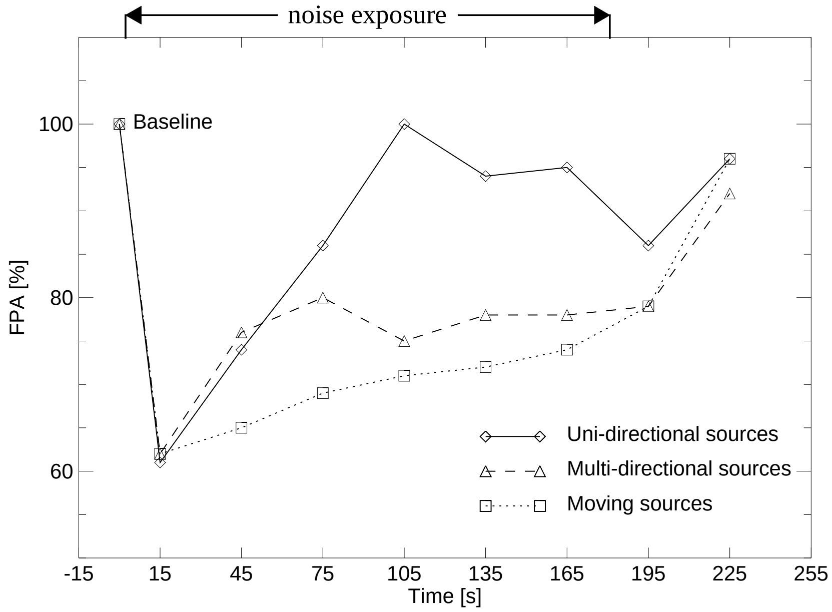

Fig. 3 Fingerpulse amplitude for uncorrelated pink noises. Uni-directional (solid line), multi-directional (broken line) and moving situations (dotted line).

Additional measurements of fingerpulse amplitudes have been performed at Oldenburg University. In experimental conditions that are similar to the series two and three described above subjects have been exposed to industrial noises via loudspeakers. The results agree with those found at Düsseldorf University.

The results of the investigations give evidence that the spatial distribution of noises has an influence on physiological responses. Therefore, binaural processing has to be considered for the validation of the effects of noise. To do so, further research is necessary to derive criteria for a validation procedure.

4 Psychoacoustic Investigations

It is well known that binaural hearing leads to a significant reduction of masking levels compared to monaural hearing. This can be quantified by means of the Binaural Masking Level Difference (BMLD). To measure the BMLD a masker is fixed at one position in space, and the masked signal moves around the head of the listener while the masking level is measured as a function of the azimuth. The BMLD is then calculated as the difference between the levels measured in monaural listening and binaural listening.

In a first series of psychoacoustic experiments performed at Oldenburg University masking and loudness perception of sinusoidal signals in different masking or comparison sound fields (pink noise) have been investigated. The following masking or comparison sound fields with equal sound pressure level at the position of the listener have been used in an anechoic chamber:

1. plane sound field (one loudspeaker active),
2. uni-coherent sound field (6 loudspeakers surrounding the listener and emitting identical signals),
3. diffuse sound field (6 loudspeakers surrounding the listener and emitting uncorrelated signals).

The sinusoidal test signal has always been emitted by one of the 6 loudspeakers. First, the masking level of the test signal has been measured in the three masking fields. Then, subjects were asked to adjust equal loudness for the test tone and the comparison sound field. The results show that the masking levels and sound pressure levels of equal loudness depend on the type of masking or comparison sound field, respectively. Differences between the sound fields of up to 12 dB can be observed.

The results show that masking and loudness perception depend on the spatial distribution of the sound field. Therefore, binaural loudness perception was investigated in more detail in a second series of psychoacoustic experiments. The task of the subjects was to adjust the following signals to equal loudness:

- the reference stimuli was a diffuse sound field, generated by 6 loudspeakers which emitted uncorrelated pink noise and surrounded the subject (75.4 and 85.3 dB(A))
- the test stimuli was pink noise emitted from one of the 6 loudspeakers.

The stimuli were presented alternatingly for intervals of 2 s, separated by pauses of 500 ms. The sound pressure level of the test stimulus at equal loudness was measured as a function of sound incidence. The results of experiments with 8 subjects are depicted in Fig. 4 on the left side. The results show that the sound pressure level for equal loudness differs from the sound pressure level of the diffuse reference sound for up to 3 dB(A). The backward direction shows

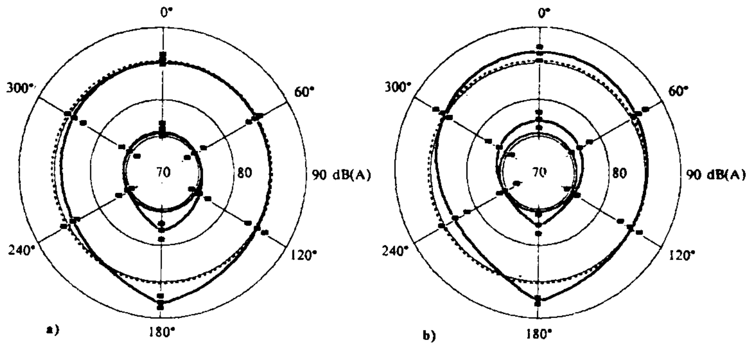

Fig. 4 Curves of equal loudness in dB(A) for pink noise as a function of sound incidence. Reference: diffuse sound field of 75.4 dB(A) (solid line) or 85.3 dB(A) (dotted line). Left: result of test in the real sound field. Right: result of dummy head recording/ headphone representation.

the lowest sensitivity with regard to loudness perception, whereas the directions of ±60° show the highest sensitivity. The frontal direction is similar to the diffuse reference.

In a variation of this experiment the sound was recorded with a dummy head and directly presented to subjects via headphones. Since the head-transfer functions of the dummy head may differ from those of the subject, differences in the results may be expected. The results are shown on the right side of Fig. 4. The general shape of the curve of equal loudness is similar to that depicted on the left, but some differences can be remarked. First, the sensitivity to the frontal direction is reduced, and the highest sensitivity now occurs for directions ±120°. This difference can be explained by the non-optimal equalisation of sounds, since differences in the HTFs may cause localisation inside of the head and front/back reversals.

The psychoacoustic investigations have proven that a tool for the prediction of loudness has to involve selective processing with regard to the direction of sound incidence. It can be assumed that this processing also has to be considered for the prediction of other psychoacoustic parameters, e.g., sharpness and roughness.

5 Modeling Binaural Hearing

The results of the physiological and psychoacoustic investigations can be interpreted in such a manner that a noise validation technique has to involve spatially selective processing. During the run of the project Bochum University investigated on the possibility to employ a model of the binaural human auditory system that is able to reproduce major aspects of sound localisation and binaural selectivity. The structure of the model as depicted in Fig. 5 has been proposed by Blauert (1983).

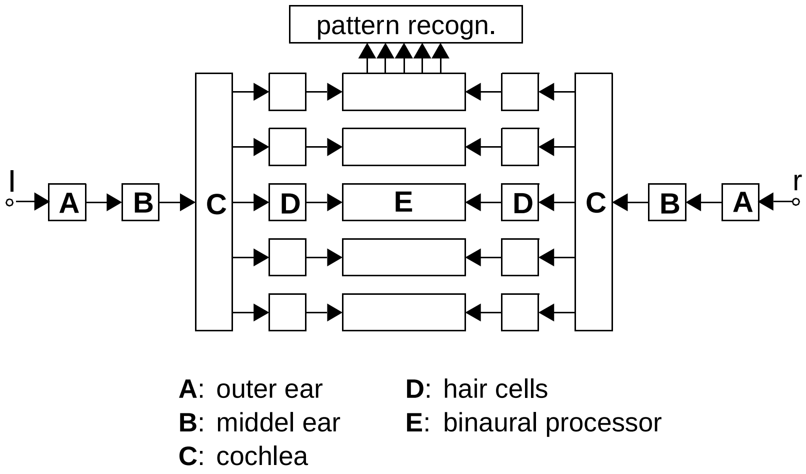

Fig. 5 Structure of the binaural model

The model that was used as a basis for the project has been developed by Lindemann (1986) and Gaik (1990, 1993). It is based on an interaural cross-correlation function that has been extended by powerful processing mechanisms. It shows the following features:

- the cross-correlation is performed in parallel on up to 24 bandfiltered signals corresponding to the bandwidths of critical bands as proposed by Zwicker and Feldtkeller (1967).
- it involves a *contralateral inhibition* mechanism.
- additional *monaural processors* consider pure monaural events.
- it can *adapt to* the interindividual characteristics of *head-transfer functions* in a supervised ‘learning’-phase.

The resulting model is able to reproduce influences of interaural differences in time (IDT) and intensity (IID) and, what is more important, of the combination of both. For details on the model please refer to the literature mentioned above.

The output of the model can be regarded as a simulation of neural excitations. Those neural excitations offer the decisive advantage that an additional dimension becomes available for the analysis - the spatial distribution. The task of the pattern recognition algorithm depicted in Fig. 5 is to analyse the neural excitations in such a manner that the position of hearing events can be predicted. Up to today, the prediction is restricted to the projection of the position into the frontal horizontal plane (azimuth). The pattern recognition algorithm includes the following processing (for details see Bodden, 1993):

- a correlation-azimuth transformation converts the correlation axis of the model to an axis that directly represents the azimuth. The transformation considers the interindividual differences of HTFs and can adapt to them in a supervised learning phase.
- a running average with a time constant of 100ms is used to smooth the patterns.
- information is combined across critical bands. The bands are weighted due to their general “reliability”.
- hearing events are formed using a selective decision mechanism.

An example for the result of the recognition algorithm is shown in Fig. 6. The predicted azimuth is shown as a function of time. The input signals were two alternating sound sources moving in opposite directions and crossing in front. The sources emitted uncorrelated noise bursts of a length of 350 ms, followed by a pause of 300 ms, so that they overlapped for periods of 50 ms. This example shows that even multiple moving sound sources can be traced by the algorithm.

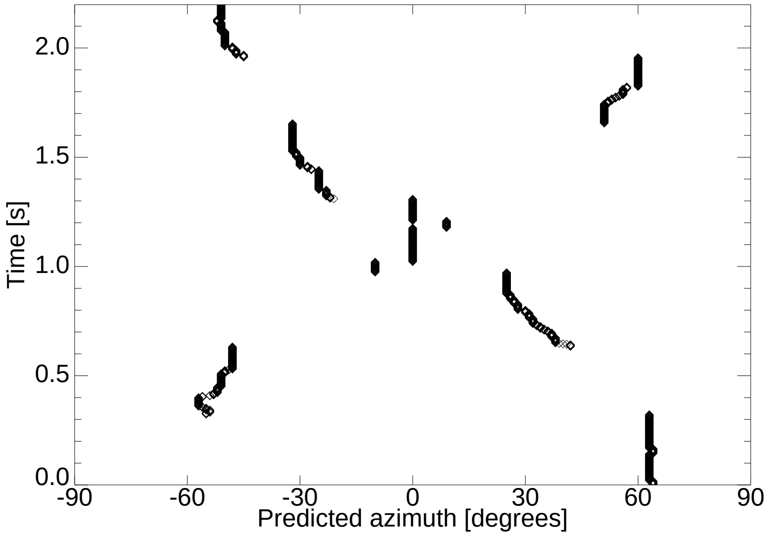

Fig. 6 Predicted azimuth of two alternating sound sources (uncorrelated noises) moving in opposite directions.

The results of the modeling research shows that the binaural model can be used to perform an analysis of the spatial distribution of the sound field. In a further extension of the model Bodden (1992, 1993) showed that it can be used as a basis for a Cocktail-Party-Processor, that is, for a system that is able to suppress interfering signals coming from different directions of incidence. Actual investigations of Bochum University aim at solving the problem of front-back discrimination and elevation perception (see Hartung et al., 1993), modeling the Precedence Effect (see Blauert, 1993), and explaining the role of neural adaptation mechanisms on localization (see Bodden and Meunier, 1993).

The experiments on loudness perception performed at Oldenburg University showed a difference between the answers of subjects that were either directly seated in the sound field or exposed to the same signals that have been recorded with a dummy head and played back via headphones (Fig. 4). Those differences are due to interindividual differences of the HTFs. This drawback of binaural technology can be avoided by the model since it can adapt to the HTFs used for sound recording, and therefore always performs the analysis for a correct set of HTFs.

6 Conclusions

The investigations described in this paper have proven that binaural processing has an influence on the physiological responses of humans exposed to noises even for levels that are below the limit of 85 dB(A). The spatial distribution of sound seems to be a parameter that influences physiological responses as well as characteristical perceptual attributes like loudness, sharpness and roughness.

A method for the validation of the effects of noise has to consider this binaural processing, and therefore has to employ a model of binaural interaction. The aim of the future research will be to

- extend the physiological investigations in order to find general rules for the validation of noises,
- extend the psychoacoustic investigations in order to find a definition for *binaural* loudness, roughness and sharpness,
- simplify the binaural model so that it can be implemented in real-time on common hardware platforms,
- develop a measurement device that considers all the above mentioned aspects, thus allowing *aurally-adequate measurements* (see Genuit, 1992),
- develop new norms that can be included in the standards and applied in legislation.

The new binaural noise validation technique is not intended to supersede the conventional technique, it is intended to extend it especially for situations in which people complain about the effects of noise in the range of levels under 85 dB(A).

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