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Directional Properties of the Dummy-Head in Measurement Techniques based on Binaural Evaluation

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Abstract

Dummy-heads are often used for standardized measurements where modeling of the average human head and torso is relevant and evaluation of results is made binaurally. They are used for noise measurements, in-situ testing of acoustical environments as well as for research in human spatial hearing and localization. As a measurement device, it has spectral, temporal and first of all, directional properties. These are characterized by the complex Head-Related Transfer Functions (HRTF) describing the directional dependent filtering of the ears. These properties can be evaluated through measurements using accurate settings of sound source directions, long-term averaging and increased spatial resolution. Monaural HRTFs of a Brüel & Kjær manikin were measured in the anechoic chamber and they were evaluated spectrally by focusing on directional properties, spectral distortions, effect of the head-shadow area and symmetries in measurement data.

Introduction

Dummy-heads (also called Head and Torso Simulators) are standardized measurement devices. They try to model the average human head and body in its geometry, size and shape. On the other hand, material, stiffness of the body and skin, as well as extra "accessories" such as hair or clothing are seldom applied. The artificial pinna is the most important part of a manikin. Nevertheless, there are very large individual differences among human beings; we can not find two identical shaped and sized pinna, head or nose. Therefore, an averaged model that tries to fit for everybody will have also limited acceptability. Dummy-heads have measurement microphones (usually 1/4 or 1/2 inch condenser microphones) implemented in the "ear simulator". Former technique used microphones at the eardrums and this needed the simulation of eardrum impedance, transmission and acoustical properties of the ear canal. Newest techniques use microphones placed at the blocked entrance of the ear canal or may offer both methods. The latest has been proved to be satisfactory [1-4]. Blocked ear canal entrance measurements are suited for spatial hearing researches or for measurement of transfer functions of headphones. On the other hand, devices such as in-ear-headphones or noise protection ear-plugs can not be tested.

Dummy-heads are very well suited for long-term measurements using noise excitation, averaging and standardized evaluation. Transfer functions of headphones, binaural evaluation of noise radiation, acoustical properties and sound pressure levels in interiors of vehicles can be determined and the device is applicable in all fields where binaural hearing and in-situ testing of human factors are relevant (see Fig.1 and Fig.2).

Another important approach is human spatial hearing research. First of all, localization related questions and virtual audio simulation [5-13]. In this case, the dummy-head is used to measure the transfer functions of the ears (monaural or binaural) and this set of directional filters are used for simulation of virtual sound sources in virtual acoustic environments. This technique also includes headphone equalization during playback. It is well known that transfer functions from dummy-head measurements are inferior to those that have been measured on "random real humans" or individually [6, 14-16]. All these leads to conclude that dummy-heads are better suited for measurements mentioned above as for human spatial hearing research.

Evaluation of the dummy-head, as a measurement device, is an important approach. Plotting transfer functions and calculated directional characteristics measured accurately deliver information about practical use and applications they are suited for [17]. This evaluation is made based on the spectral properties, which means, exhaustive evaluation of the measured directional dependent transfer functions.

Fig.1. Different types of dummy-heads inside of a car [18].

Fig.2. The Brüel & Kjær Head and Torso Simulator Type 4128 in an anechoic chamber.

The Head-Related Transfer Functions (HRTFs) describe the transmission from a given point in the free-field to the eardrums. This filtering effect is responsible for basic localization cues during human spatial hearing [1, 7, 19-21]. Measurements can be done on real human heads by placing small microphones on the eardrum or at the entrance of the ear-canal. Such measurements deliver individual results but human subjects are not very well suited for long-term measurements. Furthermore, repeatability and reproduction of the results are hard to realize.

Instead of real humans dummy-head measurement systems are suited for long-term acoustical and noise measurements having the advantageous property of standardized and repeatable measurements. For investigating the role of the HRTFs an exhaustive investigation was made using a dummy-head for recording the HRTFs in one-degree spatial resolution horizontally and in 5 degrees resolution vertically [22].

This paper analyzes the monaural (left ear condition) HRTFs of a dummy-head focusing on the repeatability property in frequency and space. After presenting the setup and definitions, the spectral representation of measured transfer functions and the variations of the peak-valley structure using the "naked" torso in the horizontal plane are presented. Evaluation of directional information, symmetries in measured data and the role of the head-shadow area are discussed.

Measurement Setup

The measurement setup includes the Brüel & Kjær Head and Torso Simulator Type 4128 placed on a turntable in the anechoic room (Fig.2) [23]. The turntable is controlled by a computer in 1 degree steps. Accuracy and repeatability was deeply investigated in order to create a measurement system suited for long-term accurate measurements [25, 25]. Changes of 1 dB in the measured transfer functions can be evaluated. Pseudo random white noise signal was used as stimuli and results were collected for both ears simultaneously.

The measured data was accumulated, averaged and after applying the FFT the magnitude of the transfer functions were plotted as function of frequency. The HRTFs were calculated as usual (Eqn.1):

$$HRTF = \frac{P_1(j\omega)}{P_2(j\omega)} \qquad (1)$$

where P_1 is the sound pressure at the eardrum and P_2 is the sound pressure in the origin of the head-related coordinate system (Fig.3) using the same signal excitation and sound source, but recorded with a unidirectional microphone [7].

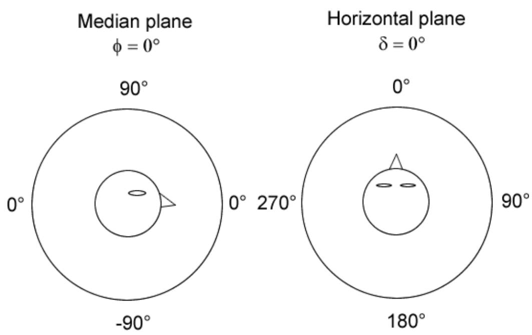


Fig.3. The head-related coordinate system.

The analysis uses the following definition of the free-field HRTF Difference (HRTFD). It is defined as a quotient of HRTFs from the same direction but under modified conditions (Eqn.2):

$$HRTFD = \frac{HRTF_{C1}}{HRTF_{C2}} \qquad (2)$$

where C_2 identifies the reference and C_1 the modified condition. We plot the 20log/HRTFD/ magnitude response as the function of frequency or as 2D polar histogram as function of frequency and azimuth [25-27]. With simple words: an HRTFD is the difference between re-measured HRTFs from the same direction. They are well suited for investigating the repeatability-property of the measurement system as well. Similar method was used by *Freeland et al.* in [28]. They define the Interpositional Transfer Functions (IPTF) as $HRTF_1/HRTF_2$, where $HRTF_1$ is the initial as long $HRTF_2$ is another measured direction. They use this quotient for interpolating missing HRTFs, extended by interaural time delays.

This simple method is often neglected although it is very useful tool for spectral evaluation of transfer functions in repeated measurements.

The complex quotient refers to subtraction of two logarithmic magnitude responses. This difference gives us the deviation in dB between two HRTFs. For analyzing the HRTFDs we do not need individual recordings on real human heads because the dividing will eliminate the individual differences. Due to the symmetry of the dummy-head, only results for one ear will be presented.

Evaluation of HRTFs in the Horizontal Plane

Movement of the Sound Source in the Most Sensitive Region

In this section we analyze the horizontal plane HRTF-set recorded in a resolution of 1 degree [29]. Due to the median plane symmetry the analysis is made only for one ear. We search for typical changes in the peak-valley structure both in frequency and magnitude by azimuthal movements of the sound source.

In the region 0°-30° there is a constant increase of the overall HRTF level up to 3-5 dB independently from the frequency (Fig.4). Furthermore, the peak at 9 kHz increases by 7-9 dB. Other deviations of the nearby HRTFs are limited under 1 dB except between 2-10 kHz where this limit is 2 dB.

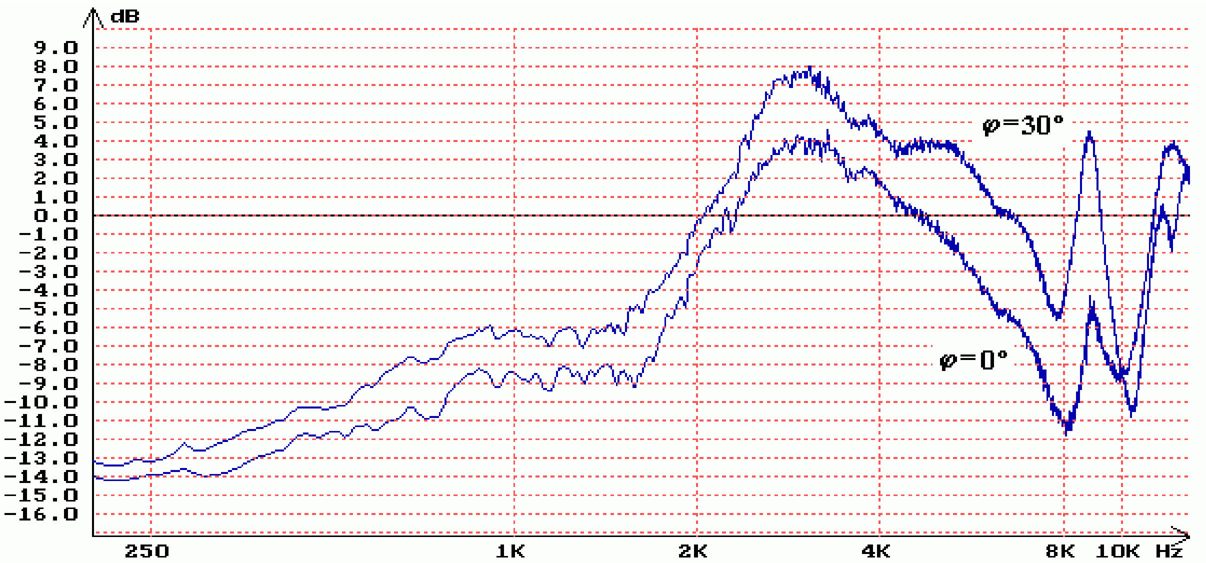


Fig.4. Horizontal plane HRTFs from the directions φ=0° and φ=30°. The overall signal level increased without significant changes of the peak-valley structure. The peak at 9 kHz increased about 9 dB.

The signal level reached at 30° remains constant until 80°. The plotted HRTFs are very similar. This is very interesting because this would assume low spatial discrimination in this region. The IPTFs defined and calculated in [28] also support this and assume similarities during HRTF interpolation. The positive-going edges are very thin; the changing of the azimuth is only noticeable on the height or deepness of a peak or valley (Fig.5). Only the changes in the domain between 7-8 kHz are not limited under 1 dB. Some increase of the peaks and valleys at 8, 10 and 12 kHz is also noticeable. Minimal changes (1-1,5 dB) within repeated measurements and asymmetrical spectral variations of the HRTFs about the interaural axis were also found by *Carlile and Pralong* supporting our observations [30-31]. They show the so called minimum audible field (MAF) sensitivity function, which describes the minimum detectable pressure level, determined at the position of the subject’s head for a free-field stimulus in the median plane. This is also defined as a binaural measure of sensitivity for a free-field sound but it can be applied to the monaural HRTFs. It seems there is a marginal increase in sensitivity under binaural listening conditions.

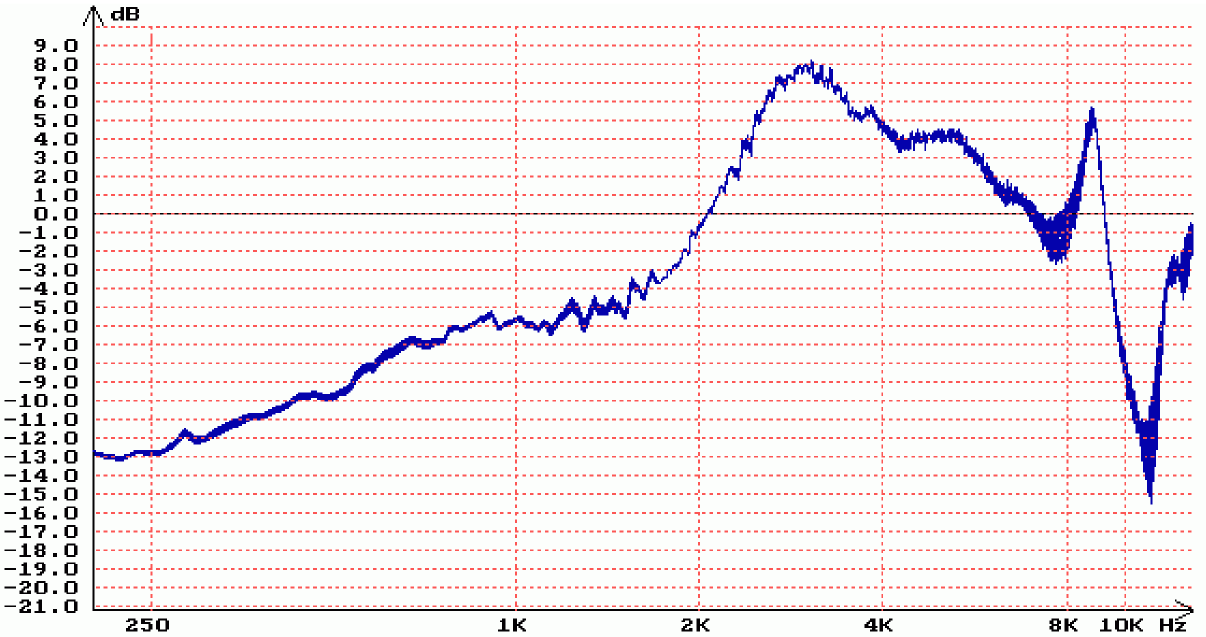


Fig.5. Typical changes in the peak-valley structure of the HRTFs in the horizontal plane. Ten figures are plotted between 40 and 50 degree in 1° resolution.

Between 70°-110° the most important peak at 3 kHz and the valley at 4 kHz is falling down by 4 and 9 dB on aggregate respectively. The height of the peaks and valleys is changing significantly, up to 5-7 dB (Fig.6).

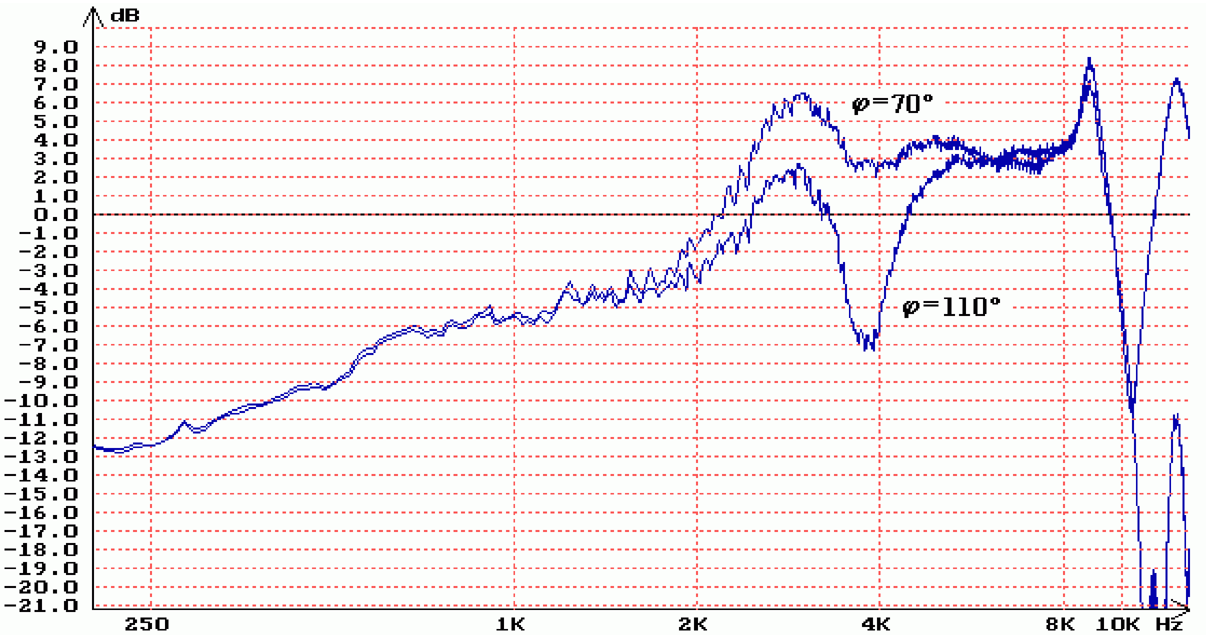


Fig.6. Horizontal plane HRTFs from the directions φ=70° and φ=110°. The valley at 4 kHz decreased about 9 dB.

The effect of the pinna at 11 kHz between 70°-90° is discussed in [25]. The HRTFs are almost identical during repeated measurements, except between 11 and 12 kHz, where a small frequency shift of about 25-30 Hz appears causing large differences (up to 15 dB) in the quotient of the magnitude responses.

Decrease of the overall signal level at the middle frequency components is conspicuous between 90°-140°. At 4 kHz this can reach 20 dB (Fig.7). The signal level increases again between 140°-180°. This area can be influenced very much by affecting the acoustical environment near the head. From the direction "back" we have a median plane source, where no interaural level differences appear.

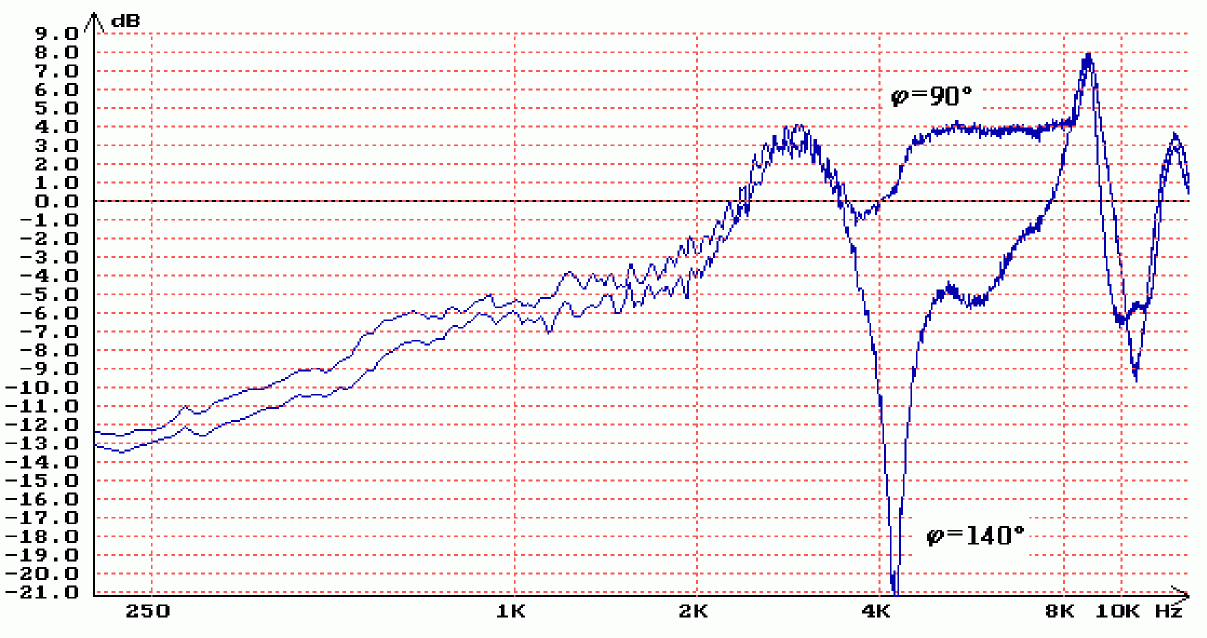
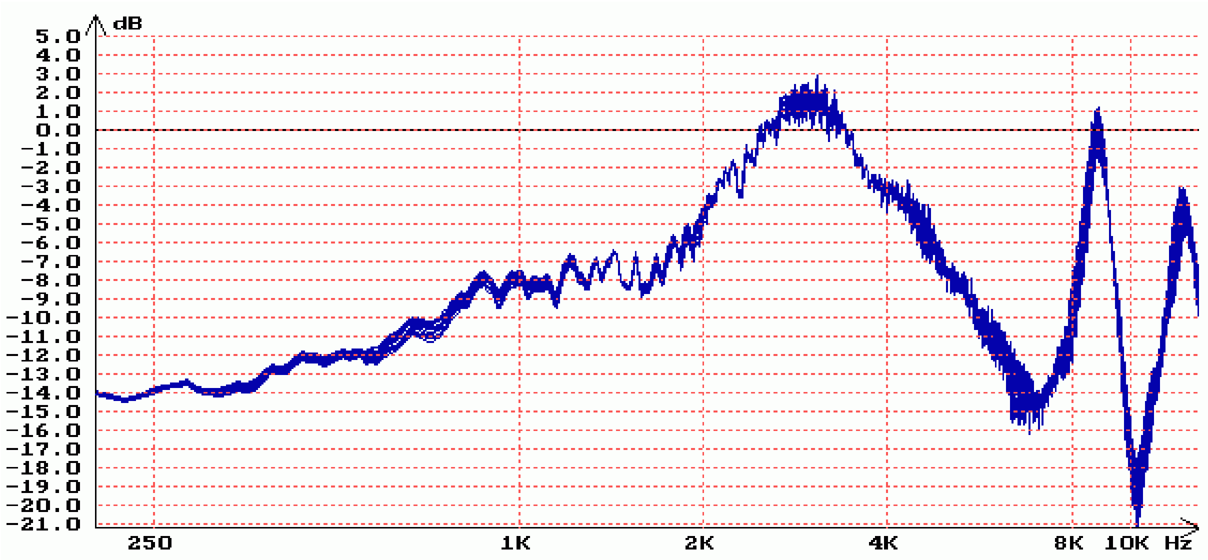


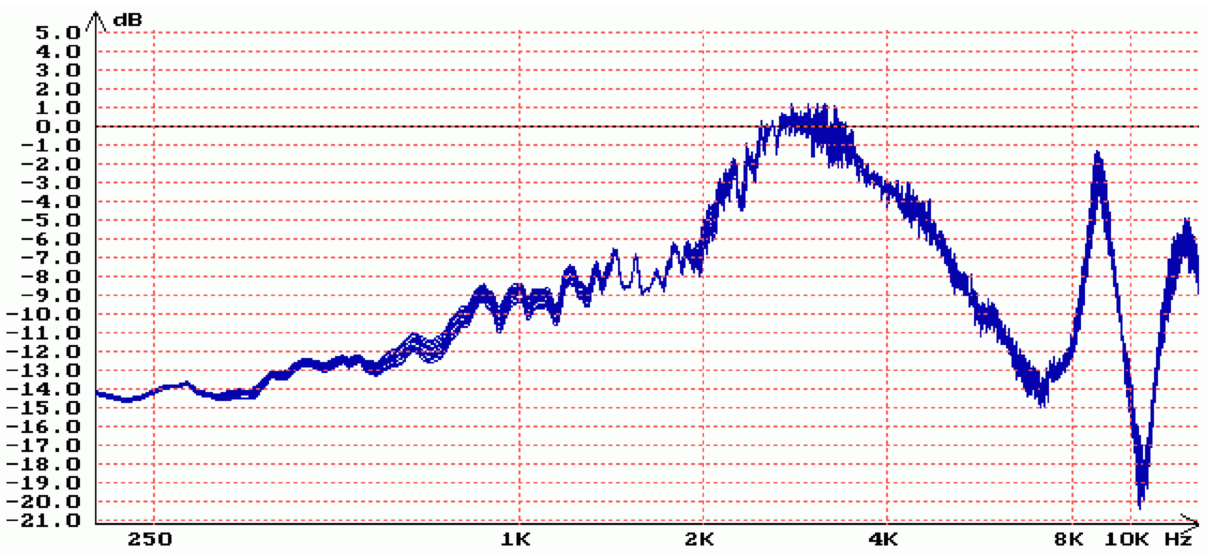
Fig.7. Horizontal plane HRTFs from the directions φ=90° and φ=140°. Only the domain between 4-8 kHz changes significantly.

Symmetry and the Head-shadow Area

The HRTFs have a ±20° symmetry to the direction back (180 degrees). An interesting result is that the same ±20° symmetry is visible at the frontal direction (Fig.8-9).

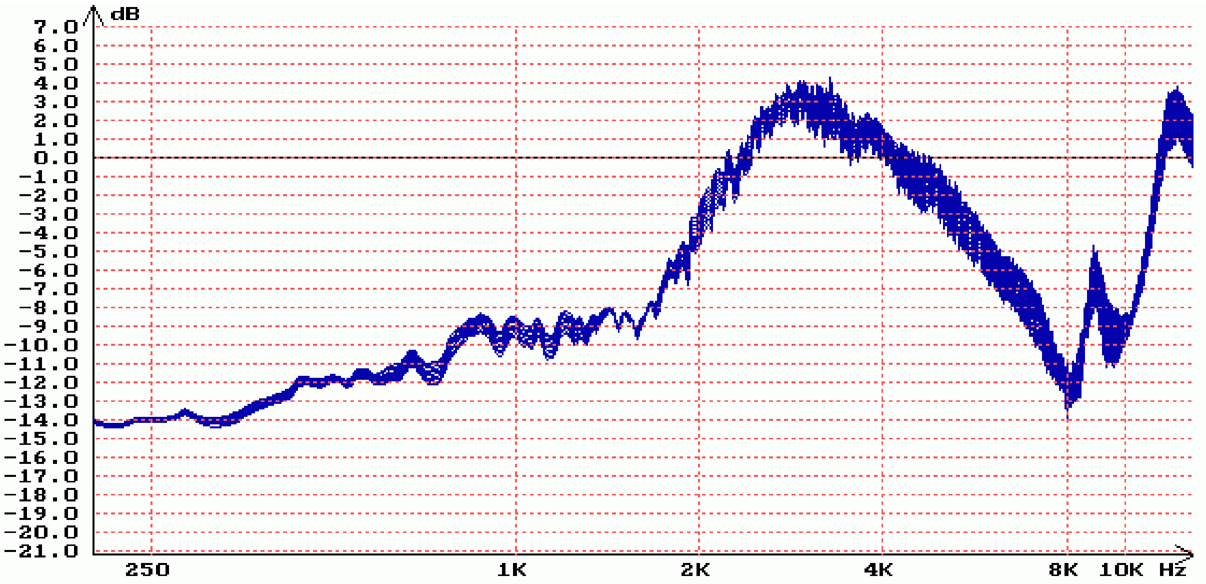


(a)

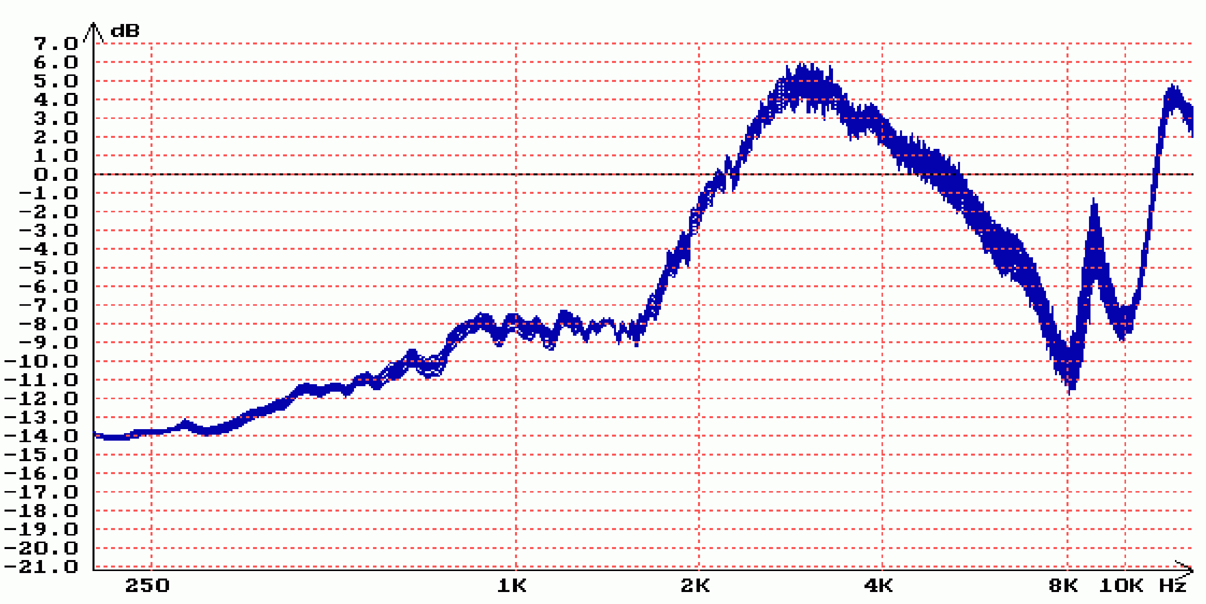


(b)

Fig.8. Two figures show ten plotted HRTFs in 1° resolution in the horizontal plane for comparison (a) φ=170°-179°, (b) φ=180°-189°. Note the median plane symmetry to the φ=180°-axe in the local maximum area of the monaural sensitivity. The HRTFs in figure (a) „look like" those from figure (b). Compare with Fig.9.



(a)



(b)

Fig.9. Two figures show ten plotted HRTFs in 1° resolution in the horizontal plane for comparison (a) φ=350°-359°, (b) φ=0°-9°. Note the median plane symmetry to the φ=0°-axe in the binaural sensitivity domain. The HRTFs in figure (a) „look like” those from figure (b). Compare with Fig.8.

The head-shadow causes level decrease and random effects in the HRTFs [7-9]. Beyond 200° the overall signal level decreases ca. 2 dB/10°. The minimum of the sensitivity of the hearing system is between 250°-260° (Fig.10). In the head-shadow area the signal level and the overall SNR is low. Random incidence from reflections and diffractions around the head as well as high level of noise make measurement results noisy and variable in this region. Repeated measurements even from the same direction followed by one after another result in deviations up to 15 dB above 2 kHz. The domain between 340-360 degrees is comparable with 0-20° (Fig.9).

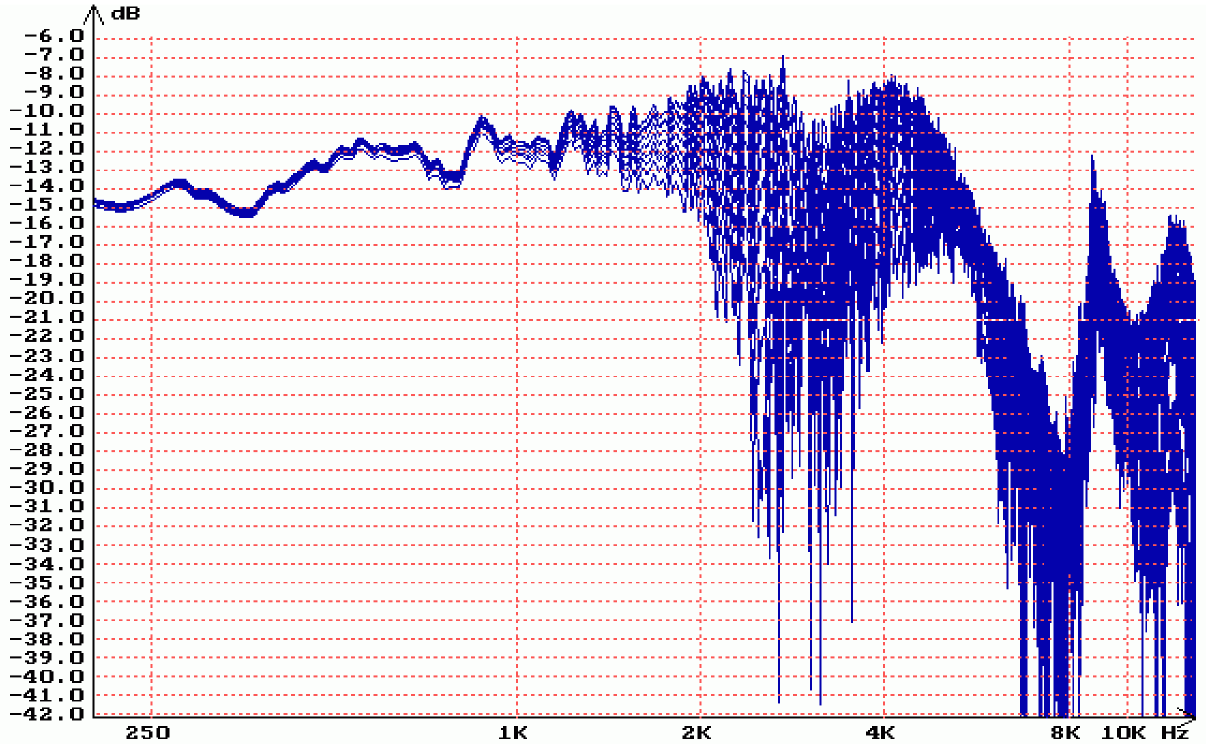


Fig.10. Minimum of the monaural sensitivity in the head-shadow area. Ten HRTFs (a) are plotted between φ=250° and φ=260° in 1 degree resolution. The components above 2 kHz are too variable to allow evaluation of high frequency directional information, but there is no difference below 1600 Hz.

Evaluation of the dummy-head was made in the horizontal plane using the "bare" torso, because this measurement setup is the most important and widely used. Results were already presented about the effect of hair, clothing and the environment near the head [25-27]. For further analysis the sensitivity domains of the hearing system as well as the properties of measurements in the head-shadow area can be determined based on the measurement results and plots.

Sensitivity Regions

Sensitivity of the hearing system and of the ears can be defined as we do it with antennas. There are spatial domains, characterized by the directional filtering and represented by polar diagrams, from where reception is the best or the worst. The most sensitive regions as well as the head-shadow area can be determined in frequency and space [32].

The Sensitivity Domains

The section earlier showed the monaural HRTFs of the dummy-head. We could conclude that

- spatial domains, where the overall signal level of the HRTFs is high, is where the localization blur is small. This can be simply explained by the high SNR [33],
- domains, where HRTFs can be re-measured with high accuracy the spatial separation capability of the ears is good,
- the head-shadow area decreases the localization performance because high frequency evaluation (above about 1600 Hz) is not possible with the shadowed ear.

These results are based on high accuracy HRTF measurements. It has to be mentioned that binaural evaluation in real life is made by two ears simultaneously.

An engineer can handle the ears as ordinary antennas. Antennas have directional filtering, with other words, directional dependent sensitivity. The most important is the pinna, followed by the size and geometry of the head and body. Figure 11 shows the role of the pinna filtering effect at frontal incidence. Two HRTFs were measured with and without the artificial pinna of the head and torso simulator. The sound collecting effect at 3 kHz and above 8 kHz is clear. Average differences between the spectra of the torso below 3 kHz with and without pinna of 0,86 dB was reported in [34]. Our measurement did not show differences less than 0,5 dB.

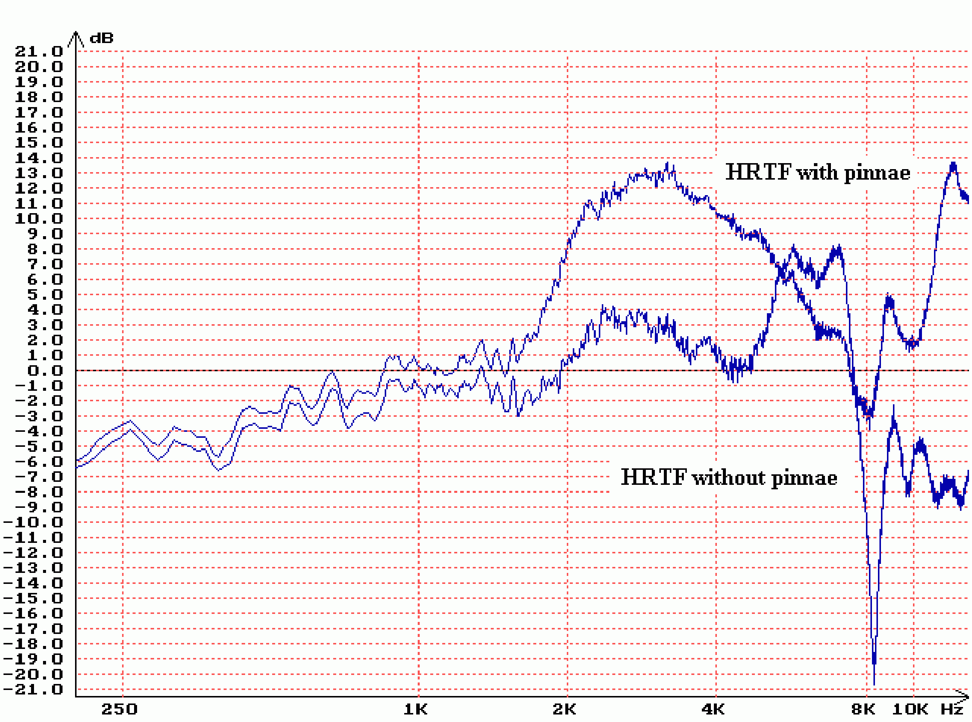


Fig.11. Effect of the pinna at frontal incidence. Both HRTFs contain the effects of the torso and the head. The reflecting and amplifying effect of the pinna is clearly visible at the main resonance frequencies of 3, 9 and 11 kHz.

The most sensitive spatial area is in the frontal direction ±20°. In this domain both ears' HRTFs are very helpful for evaluating directional information in the entire frequency range. This area seams to be smaller than the stereo-area of the eyes. Based on the overall signal level (the highest SNR) provided by the HRTFs, the direction 45° seems to be the most sensitive direction. This has to be in connection with the placement of the pinna on the head (Fig.12).

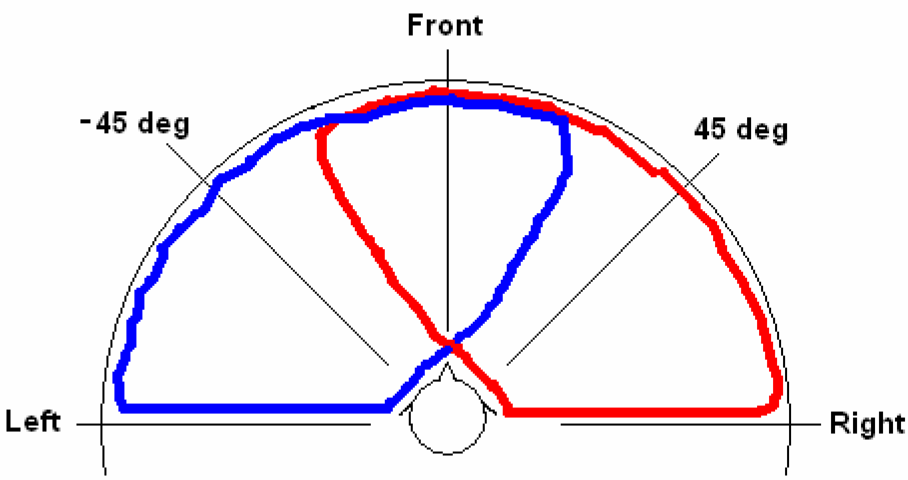


Fig.12. Footprints of the ears representing the monaural sensitivity regions based on the HRTF analysis of the dummy-head.

Our measurement shows that this kind of “monaural sensitivity region” can be recognized significantly only between elevations of -10° to +30°. Above +30° the shadowing effect of the head disappears. A *local* monaural sensitivity domain can be identified ±20° around the direction “back”. Superior localization acuity for rear locations compared with lateral locations was also reported in [35]. This is not general, but it could be due to the local increase of the monaural sensitivity near to the median plane.

The binaural sensitivity domain can be defined as the overlapping area of the two monaural sensitivity regions. This assumes that the interaural and complex auditory sensitivity is not based only on the monaural sensitivity of the HRTFs. Humans try to face the sound sources for the best localization and use the interaural differences and the binaural fusion. In the median plane no interaural differences appear and only the HTRF should deliver all localization cues. In real-life situations head movements are very useful and important to find the sound source. If they are not present, front-back confusion and poor localization performance appear.

Similarly, if we can find the most sensitive regions for one ear, we will find the spatial domain where the sensitivity and the possibility of extracting directional information is the worst. This minimum is at ca. 250°-260° in the head-shadow area. Local minimum at –90° in the Interaural Level Differences was also found and modeled by a rigid sphere [36, 37].

Frequency Limits in the lateral-contralateral Evaluation

There are different domains in the frequency partitioned by “cut-off” frequencies during the evaluation of sound source information.

The limit at 1500-1600 Hz is well known from the literature [1, 7, 37-39]. The HRTF has five major resonant points: 3, 5, 9, 11 and 13 kHz but there are large individual differences. The high frequency components are responsible for the localization: the sensation is more correlated with the real source direction if the signal has components above 5 kHz. Above 1600 Hz the lateralization is made based on the envelope, below 1600 Hz it is based on Interaural Time Delays (ITD) [30]. Interaural Level Differences (ILD) are present from 20 Hz-20 kHz but they become important above 500 Hz. Monaural spectral features of the pinna appear above 3-3,5 kHz, primarily for elevation cues [34]. Low frequency elevation cues are not due to the pinna but to the torso below 3 kHz [40]. We can support these observations, as we did not observe any effects or deviations below 1600 Hz in the HRTFDs.

Shadowing effects cause random incidence. This means, the HRTFs of the contralateral ear vary too rapidly and randomly to evaluate and to allow decoding high frequency information and the SNR is decreased in contrast to the lateral side. Our test with the torso wearing a baseball cap supports the finding that shadowing and diffraction effects are responsible for the large high frequency deviations in the HRTFs. The frequency, from where these effects will be effective, depends on the azimuth, elevation and the environment near the head as well. The variations of this “cut-off frequency” are shown on Fig.13 as function of azimuth. This averaged result is calculated from –10° up to +60° elevation for all measurements with the bare and dressed torso. The lowest value of 3 kHz is in the area of the minimum monaural sensitivity supporting the findings in [33, 34, 41].

Although this frequency limit depends on azimuth we can define a stationary value around 3500 Hz. Near to this frequency limit changes and differences in the re-measured HRTFs appear both at the closer and at the contralateral ear. In the shadowed area only some low frequency components will be affected at 1600, 1800, 2200 and 2500 Hz. The so called “bright spots” were found by *Shaw* e.g. at 1,9 and 2,4 kHz [8, 41]. On the other hand, the closer ear will be affected at high frequencies: 9, 11, 4-5 kHz, and only seldom below 3 kHz. Special is the 8 kHz component where the most significant differences appear.

This evaluation uses the HRTFDs as a tool for representing the repeatability-property. If we re-measure the HRTFs from the same direction without any changes, then we divide them and plot the difference, it has to be a flat (0 dB) line. This is true only in the monaural sensitivity where we can re-measure the HRTFs with an accuracy of less than 1 dB. As the sound source is moving on, this repeatability-property is getting worse and reaching the head-shadow area the re-measured HRTFs even from the same direction have differences more than 10 dB. We assume that this is the natural behaviour and property of the dummy-head (and the real human head as well) due to the shadowing effect of the pinna and head. Our former investigation supported this observation, because the visor of the baseball cap caused the same effect: the extension of the shadowed area [25-27]. Measured HRTFs from the direction “above” (90 degrees, over the head) are identical and can be measured and re-measured in 1 dB precision. In this case, turning of the head (turntable) is irrelevant for the measurement and all the HRTFs are the same. By practical application, this means, we will need less HRTFs and decreased resolution of measured HRTFs as the sound source is moving up inside the upper hemisphere. We may have a one degree spatial resolution in the horizontal plane (360 HRTFs), but we only need a single HRTF from above.

A dummy-head is a two-channel measurement equipment with special directional characteristics and with directional dependent SNR. The directional property is represented by a limited number of HRTFs. For a constant spatial resolution, we need more HRTFs in the horizontal plane as we need at higher elevations. The (monaural) SNR will decrease if the sound source is not in the most sensitive region.

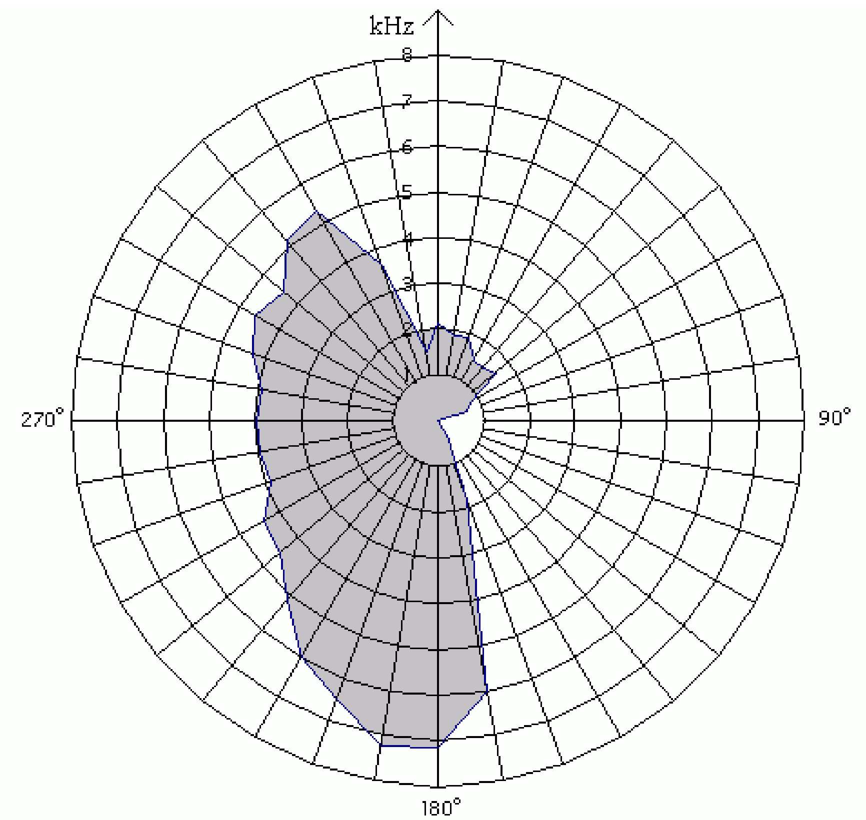


Fig.13. Frequency limit of the head-shadow area as the function of azimuth. Results are averaged over all measured and calculated HRTFDs. The lowest “cut-off frequency” of 3000-3500 Hz is at the minimum of the monaural sensitivity (250-290°).

Binaural Evaluation

Dummy-heads were evaluated already in listening tests [8-11]. The importance of the HRTFs was obvious during solving localization tasks. Our investigation related to spatial hearing in virtual acoustic fields does not include (yet) listening test with these HRTFs, only spectral analysis was made in the frequency domain. The HRTFDs confirm the important role of the interaural differences. If the source is in the monaural sensitivity region of one ear, the differences and changes due to the environment appear in the high frequency regions. At the same time, the HRTF of the contralateral ear will be influenced at lower frequencies and this result in an increased ILD. We do not find that frequency components vary in the way to decrease the ILD. Head and pinna reflections are responsible for detection and evaluation on the lateral side. The closer ear in the high frequency regions in the monaural sensitivity domain will evaluate the information encoded in the sound waves. The contralateral ear makes evaluation of some low frequency elements where no high frequency information is available (low-pass filtering). Shadowing-effects affect the localization: it causes random incidence, secondary sound paths, diffuse-like sound field and no primary wave front. Head shadow is the natural reason for that, but objects near the head can influence this phenomenon.

Summary

Dummy-heads are well suited for long-term, accurate and standardized measurements. A precisely controlled system allows setting and re-setting the spatial directions (sound source locations) to re-measure and to analyze recorded transfer functions easily. We investigated directional properties through accurate HRTF measurements.

Different spatial regions can be determined based on spectral properties, deviations and variations of the peaks and valleys in the HRTFs. Changing of the azimuth does not really influence the peak-valley structure in the frequency (no shifting) only the height of the peaks and valleys. This is important because objects near the head - such as a cap or hair - produce relevant shifting in the frequency and create new peaks and valleys.

By analyzing the monaural HRTFs of the dummy-head, we can determine the monaural sensitivity regions of the hearing system. We have found this to be symmetrical to the median plane (±20º) and the axe of 45 degrees as the most sensitive monaural direction. The extent of the monaural „antenna footprint" of the ear in the horizontal plane is from about -20 degrees to 90 degrees.

We have found the minimum of the monaural sensitivity of the hearing system on the contralateral side of the head, in the head-shadow area about 255 degrees. Furthermore, symmetries to the median plane both in frontal and in back directions are clearly visible within ±20 degrees. Due to the symmetry of the dummy-head, the same observation and conclusion can be drawn for the other ear as well. In real (binaural) listening situation these two regions overlap. If the ear is in the head-shadow area, only some low-frequency information can be evaluated.

Shadowing effects can be regarded as the worst effect: the HRTFs vary too rapidly to allow high-frequency recognition. Incoming sound waves suffer from diffraction, refraction and reflection effects due to the head that can cause random incidence. Furthermore, overall signal level and the SNR is low. All this proves that a dummy-head has different SNR depending of the direction of the sound source and this may limit spectral evaluation. The cut-off frequency of the head-shadow area varies from 3-6 kHz, although there seems to be a constant value of about 3500 Hz that separates the lateral-contralateral evaluation.

References

1. W. M. Hartmann, 'How we localize sound,' *Physics Today* 11, 24-29 (1999).
2. H. Møller, M. F. Sorensen, C. B. Jensen and D. Hammershøi, 'Binaural Technique: Do We Need Individual Recordings?,' *J. Audio Eng. Soc.* 44(6), 451-469 (1996).
3. J. C. Middlebrooks, 'Narrow-band sound localization related to external ear acoustics,' *J. Acoust. Soc. Am.* 92, 2607-2624 (1992).
4. H. Møller, 'Fundamentals of binaural technology,' Applied Acoustics 36, 171-218 (1992).
5. Gy. Wersényi, 'Localization in a HRTF-based Minimum-Audible-Angle Listening Test for GUIB Applications,' *Electronic Journal of „Technical Acoustics" (EJTA),* 2007(1), http://ejta.org/, 1-16 (2007).
6. P. Minnaar, S. K. Olesen, F. Christensen and H. Møller, 'Localization with Binaural Recordings from Artificial and Human Heads,' *J. Audio Eng. Soc.* 49(5), 323-336 (2001).
7. Jens Blauert, *Spatial Hearing*, The MIT Press, MA, (1983).
8. E. A. G. Shaw, 'Transformation of sound pressure level from the free-field to the eardrum in the horizontal plane,' *J. Acoust. Soc. Am.* 56(6), 1848-1861 (1974).

9. S. Mehrgart and V. Mellert, 'Transformation characteristics of the external human ear,' *J. Acoust. Soc. Am.* 61(6), 1567-1576 (1977).
10. D. Hammershøi and H. Møller, 'Free-field sound transmission to the external ear; a model and some measurement,' *DAGA'91, 473-476,* (1991).
11. H. Fisher and S. J. Freedman, 'The role of the pinna in auditory localization,' *J. Audiol. Research* 8, 15-26 (1968).
12. J. Blauert, 'Localization and the law of the first wavefront in the median plane,' *J. Acoust. Soc. Am.* 50, 466-470 (1971).
13. J. Blauert, Untersuchungen zum Richtungshören in der Medianebene bei fixiertem Kopf, Dissertation, Techn. Hochschule Aachen, (1969).
14. H. Møller, 'On the quality of artificial head recording systems,' *Proceedings INTER-NOISE 97, 1139-1142*, (1997).
15. P. Maijala, 'Better binaural recordings using the real human head,' *Proceedings INTER-NOISE 97, 1135-1138*, (1997).
16. H. Møller, D. Hammershøi, C. B. Jensen and M. F. Sorensen, 'Evaluation of artificial heads in listening tests,' *J. Acoust. Soc. Am.* 47(3), 83-100 (1999).
17. Gy. Wersényi, P. Tatai, 'Detection of reflections in free-field directional hearing by waveform analysis of accurate dummy-head HRTFs', *Proc. IEEE Instrumentation and Measurement Technology Conference, 606-609,* (2001).
18. F. Bozolli and A. Farina, 'Directivity balloons of real and artificial mouth simulators of measurement of the Speech Transmission Index,' *AES 115th Convention Paper Preprint*, New York, USA, (2003).
19. M. Morimoto and H. Aokata, 'Localization cues of sound sources in the upper hemisphere,' *J.A.S. of Japan* E 5, 165-173 (1984).
20. A. J. Watkins, 'Psychoacoustical aspects of synthetized vertical locale cues,' *J. Acoust. Soc. Am.* 63, 1152-1165 (1978).
21. R. A. Butler and K. Belendiuk, 'Spectral cues utilized in the localization of sound in the median sagittal plane,' *J. Acoust. Soc. Am*. 61, 1264-1269 (1977).
22. Gy. Wersényi, HRTFs in Human Localization: Measurement, Spectral Evaluation and Practical Use in Virtual Audio Environment, Dissertation, BTU Cottbus, (2002).
23. Brüel Kjaer Head and Torso Simulator Type 4128, Users Manual.
24. Gy. Wersényi and A. Illényi, 'Test Signal Generation and Accuracy of Turntable Control in a Dummy-Head Measurement System,' *J. Audio Eng. Soc*. 51(3), 150-155 (2003).
25. Gy. Wersényi and A. Illényi, 'Differences in Dummy-Head HRTFs Caused by the Acoustical Environment Near the Head,' *Electronic Journal of „Technical Acoustics" (EJTA),* 2005(1), http://ejta.org/, 1-15 (2005).
26. A. Illényi and Gy. Wersényi, 'Evaluation of HRTF data using the Head-Related Transfer Function Differences,' *Proceedings Forum Acusticum 2005, 2475-2479,* (2005).
27. A. Illényi and Gy. Wersényi, 'Environmental Influence on the fine Structure of Dummy-head HRTFs,' *Proceedings Forum Acusticum 2005, 2529-2534,* (2005).
28. F. P. Freeland, L. W. P. Biscainho and P. S. R. Diniz, 'Interpositional Transfer Function for 3D-Sound Generation,' *Audio Eng. Soc.* 52(9), 915-930 (2004).
29. Gy. Wersényi, 'Evaluation of dummy-head HRTFs in the horizontal plane based on the peak-valley structure in one-degree spatial resolution,' *Proc. INTER-NOISE 2006, 10 pages*
30. F. L. Wightman and D. J. Kistler, 'The dominant role of low-frequency interaural time differences in sound localization,' *J. Acoust. Soc. Am*. 91, 1648-1661 (1992).
31. S. Carlile and D. Pralong, 'The location-dependent nature of perceptually salient features of the human head-related transfer functions,' J. *Acoust. Soc. Am*. 95, 3445-3459 (1994).
32. Gy. Wersényi, 'Spatial and spectral properties of the dummy-head during measurements in the head-shadow area based on HRTF evaluation,' *Proc. INTER-NOISE 2006, 10 pages*, (2006).
33. C. I. Cheng and G. H. Wakefield, 'Introduction to Head-Related Transfer Functions (HRTFs): Representations of HRTFs in Time, Frequency, and Space,' *J. Audio Eng. Soc.* 49, 231-249 (2001).
34. V. R. Algazi, C. Avendano and R. O. Duda, 'Elevation localization and head-related transfer function analysis at low frequencies,' *J. Acoust. Soc. Am.* 109, 1100-1122 (2001).
35. S. E. Boehnke and D. P. Phillips, 'Azimuthal tuning of human perceptual channels for sound location,' *J. Acoust. Soc. Am*. 106(3), 1948-1956 (1999).
36. D. S. Brungart and W. M. Rabinowitz, 'Auditory localization of nearby sources. Head-related transfer functions,' *J. Acoust. Soc. Am*. 106(3), 1465-1479 (1999).

37. G. F. Kuhn, 'Model for the interaural time differences in the azimuthal plane,' *J. Acoust. Soc. Am.* 62, 157-167 (1977).
38. T. T. Sandel, D. C. Teas, W. E. Feddersen and L. A. Jeffress, 'Localization of sound from single and paired sources,' *J. Acoust. Soc. Am*. 27, 842-852 (1955).
39. W. Mills, 'On the minimum audible angle, 'J. Acoust. Soc. Am. 30, 237-246 (1958).
40. K. Genuit and H. J. Platte, 'Untersuchungen zur Realisation einer richtungsgetreuen Übertragung mit elektroakustischen Mitteln,' *DAGA'81, 629-632,* (1981).
41. E. A. G. Shaw, The external ear, in Handbook of Sensory Physiology 1, Auditory System, Anatomy Physiology Ear, Springer, New York, (1974).
42. F. E. Toole, 'In-head localization of acoustic images,' *J. Acoust. Soc. Am*. 48, 943-949 (1969).