Methods for binaural recording and reproduction

Hammershøi, Dorte; Møller, Henrik

Published in:
Acustica United with Acta Acustica

Publication date:
2002

ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 88 (2002) 303–311

Methods for Binaural Recording and Reproduction

Dorte Hammershøi, Henrik Møller
Department of Acoustics, Aalborg University, Fredrik Bajers Vej 7 B4, DK-9220 Aalborg Ø, Denmark, dh@acoustics.dk

Summary
The term binaural technique is used as a headline for methods for sound recording, synthesis and reproduction, where the sound pressure signals recorded (or synthesized) are the eardrum signals of the listener, and where successful reproduction is achieved, if these are truely reproduced in the ears of the listener. This paper shortly summarizes the main results of a series of investigations that are the current basis for the utilization of the binaural technique at Aalborg University and possibly elsewhere, including investigations on sound transmission in the ear canal, measurements of HRTFs (head-related transfer functions), calibration of headphones and localization experiments in real life and with binaural recordings from real heads and artificial heads.

PACS no. 43.64.Ha, 43.66.Qp, 43.66.Yw

1. Introduction

The fundamental idea of binaural technique is based on the fact that we create our auditory impression on the basis of only two inputs, namely the sound pressures at our two eardrums. If these are recorded–literally–in the ears of the listener, and reproduced exactly when played back, then the original listening experience is obtained.

Binaural signals may also be synthesized by computer provided that the sound transmission from the source to the listener's ears has been thoroughly mapped–in principle–for all possible placements of the sound source. It can then be controlled by the computer where the listener will hear the sound, and sound sources can be placed at any place spatially. This technique is obvious for virtual reality applications, but many other applications exist.

The present paper introduces methods that can be used for proper recording (or synthesis) and reproduction of binaural signals of human origin. The body of research, which is summarized in the present paper, is described in detail in a number of publications (for references see the subsequent text), and partly compiled in (Hammershøi [1]). For a thorough review of spatial hearing, please see Blauert [2] and for a detailed introduction to the fundamentals of binaural technique, please see Møller [3].

2. Recording site

One objective has been to find out whether recordings can be made at other places in the ear than at the eardrum and still contain the same directional information that reaches the eardrum. This will be the case for any place from which the further transmission to the eardrum is unique and independent of direction (and distance) to the sound source. The directional dependence of the sound transmission within the ear canal has been studied experimentally in several investigations.

Wiener and Ross [4] measured the sound at the eardrum, at the entrance of the ear canal, and at the midpoint between entrance and eardrum, for 3 directions of sound incidence in the horizontal plane (azimuths 0°, 45° and 90°). 6-12 subjects were reported as participants in the study. It was found that for the frequency range considered (up to 8 kHz), the sound transmission to the eardrum from the entrance of the ear canal was independent of direction.

Shaw [5], [6], [7] verified this for a single replication of an ear. For 11 directions of sound incidence, he measured sound at the eardrum, at three points at the ear canal entrance plane, and at 12 points outside the ear canal. As expected, the transmission to the eardrum depended on direction for all of the points outside the ear canal. For the center point at the entrance, Shaw concluded that the sound transmission to the eardrum was independent of direction up to a frequency of 14 kHz. For each of the two other ear canal entrance points the transmission was independent of direction up to a slightly lower frequency. Shaw gave the explanation that transverse modes do exist at the entrance, but they are not transmitted to the eardrum.

Mehrgardt [9] and Mehrgardt and Mellert [10] measured sound at the eardrum and at a number of points along the ear canal, stopping at 2 mm inside the ear canal. Three subjects participated, and 10 directions of sound incidence in the horizontal plane were included. It was concluded that for the point 2 mm inside the ear canal, there was no

Received 30 August 2001, revised 22 February 2002, accepted 15 April 2002.

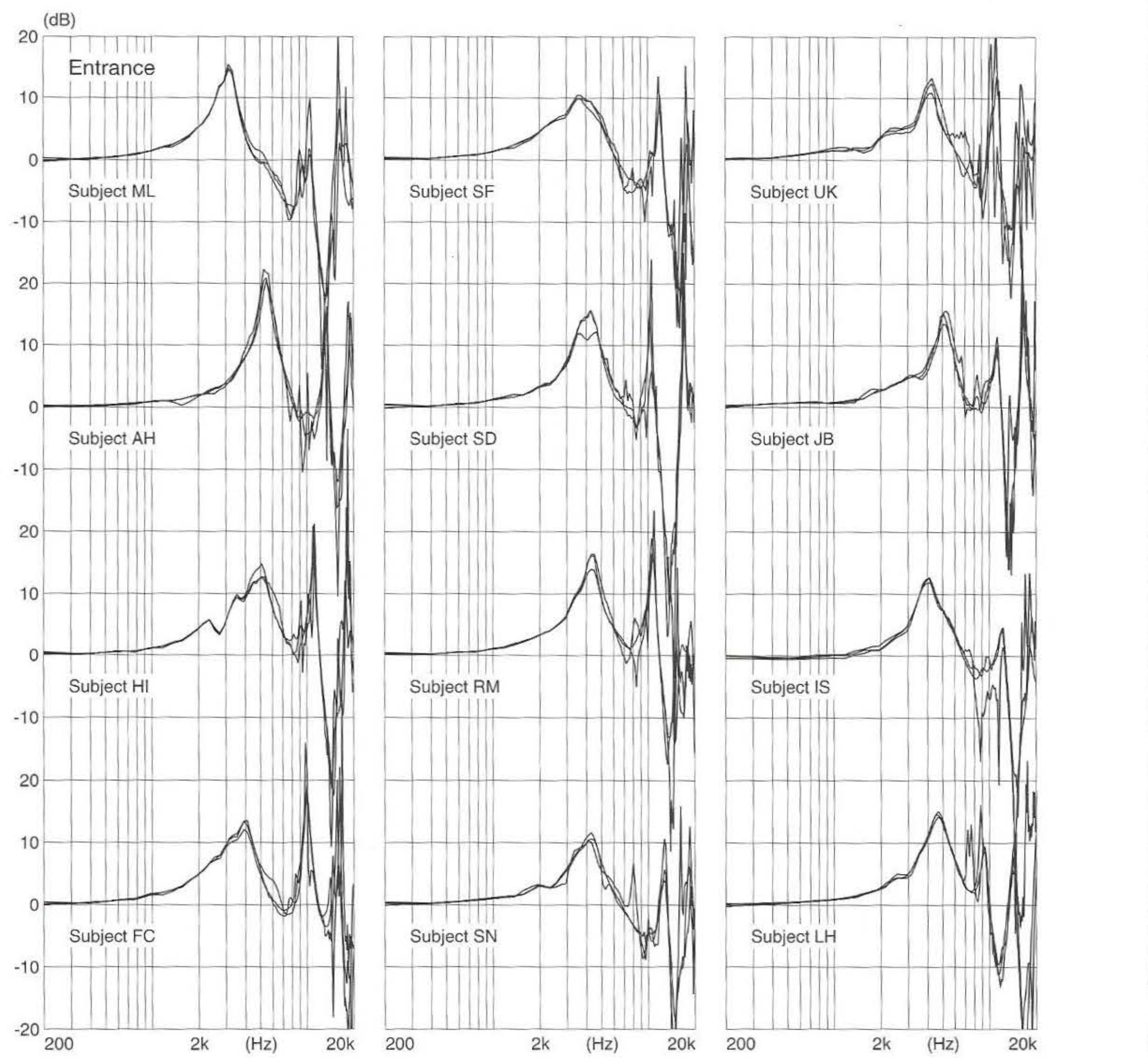

Figure 1. Sound transmission to the eardrum from the entrance of the ear canal for the left ear of 12 subjects (from Hammershøi and Møller [8]). Measurements for three directions in the horizontal plane (azimuths 0°, 90° and 180°) are overlaid in each frame.

directional dependence in the transmission to the eardrum up to 6 kHz. At higher frequencies they reported deviations between directions, but these were said to be due to a low sound pressure at the entrance to the ear canal, resulting in inaccuracy in the computed transfer functions. The authors did not include a point at the ear canal entrance plane, since for this plane "significant dependence of the transfer function on the direction of the external sound field was found for frequencies higher than 10 kHz". Data for this dependence were not published.

Middlebrooks *et al.* [11] measured with two microphones positioned in the ear at the same time. One subject participated, and 356 directions were included. They measured the transfer functions to a point 10 mm inside the ear canal from 4 points, of which 3 were outside the ear canal, and one was at the entrance. They also measured the transmission to a point 14 mm inside the ear canal from a point 5 mm inside. It was found that for the frequency range concerned (up to 16 kHz) the transmission was independent of direction of sound incidence in each of the two cases 5 to 14 mm and 0 to 10 mm inside the ear canal.

Extensive model studies of the sound transmission in the external ear also exist (e. g. [12], [13], [14], [15], [2], [16], [17], [18], [19], [20], [21], [22], and more recently [23], [24], [25]) but neither has aimed at evaluating a possible directional dependence.

In our own study (Hammershøi and Møller [8]) the transmission to the eardrum from several points in the external ear was measured for 12 subjects and three directions in the horizontal plane (azimuths 0°, 90° and 180°). We concluded that for the major part of the audio frequency range (up to 12-14 kHz) the transmission towards the eardrum is virtually independent of direction from points at the centerline of the canal at least from the ear canal entrance, and possibly even up to 6 mm outside the canal (see Figures 1 and 2).

We further showed theoretically [3] and experimentally [8] that blocking the ear canal has no impact on the directional sensitivity in the transmission to the eardrum, an observation that also Shaw [6] made (without showing the actual transmission). Note that this transmission–from blocked entrance to eardrum–does not exist in real life, because the two sound pressures do not exist at the same time.

A comparison of statistical measures of directionality from the investigations mentioned was also made in Hammershøi and Møller [8]. The directional spread is the standard deviation between directions of the transmission to the eardrum from a distal point in the ear. A low directional spread thus represents directional independence, while a high directional spread reflects a directional dependence. The directional spreads (Wiener and Ross [4], Middlebrooks *et al.* [11], and Hammershøi and Møller [8]), (see Figure 2) show the same pattern, which is 1) low values (directional independence) for frequencies below 12–14 kHz for the points in the ear canal and at the entrance, and 2) low values (directional independence) up to 5-6 kHz for the point in the concha.

The ranges given by Shaw [6] (still in Figure 2) are higher than the directional spreads. This is to be expected, because ranges are inherently larger than spreads, and an inspection of Shaw's individual curves (reported for the measurement at the entrance only, Shaw [5]), suggests a directional spread similar to those of the present investigation.

The ranges reported by Mehrgardt and Mellert [10] are in the upper range of what could be expected from the other four investigations. As mentioned earlier the authors themselves reported that the results for higher frequencies were inaccurate. Therefore, they were only able to conclude that the transmission was independent of direction up to 6 kHz. Still, for the lower frequencies the high magnitude of their ranges remains to be explained.

Results of Hammershøi and Møller [8] (not reprinted here) further suggest that in the ear canal and at the entrance, their computed directional spreads display experimental spreads rather than true directional spreads. The even lower directional spreads by Middlebrooks *et al.* [11] support this, as they have reduced the experimental spread by using two microphones placed in the ear of the subject at the same time.

On this background it seems liable to conclude that the transmission to the eardrum from the entrance of the ear canal is virtually directional independent for the major part of the audio frequency range.

The authors are aware that it is a common opinion that a such conclusion is only valid for points that are at least a few millimeters inside the ear canal. However, the experimental data show that the small differences that do exist between directions do not decrease when going some millimeters into the canal, thus the conclusion is equally valid at the entrance and a few millimeters inside.

At this point it is important to note that the conclusion of directional-independent transmission in the ear canal does not in any way conflict with the possibility of having transverse modes in the canal; it does not rely on an assumption

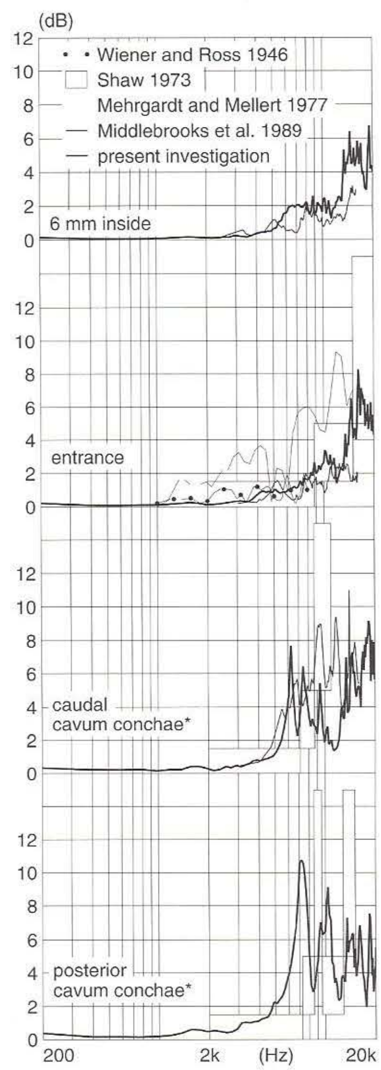

Figure 2. Directional spreads of transmissions to the eardrum (from Hammershøi and Møller [8]). The directional spread, i.e. the standard deviation between directions of the transmission to the eardrum from a distal point in the ear. The calculation is done in decibels frequency by frequency for each subject, and subsequently averaged across subjects. The data shown from Mehrgardt and Mellert [10] (here shown in the "entrance" frame, but measured 2 mm inside) are ranges for transfer functions, and the data from Shaw are boundaries for ranges, and these data are thus inherently larger than the directional spreads.

of lack of transverse modes, nor does it imply that such modes would not be excited. It is simply demonstrated by experimental data from 5 laboratories.

There is hardly any doubt that the complicated structures of the pinna geometry will result in the excitation of transverse modes, and that these will depend on direction. However, the transverse modes will be attenuated along the ear canal and reach an–apparently–insignificant level before they reach the eardrum. Likewise, the slanting of the eardrum and the eardrum's non-piston-like behavior will introduce transverse modes that propagate in the other direction and similarly reach an insignificant level before

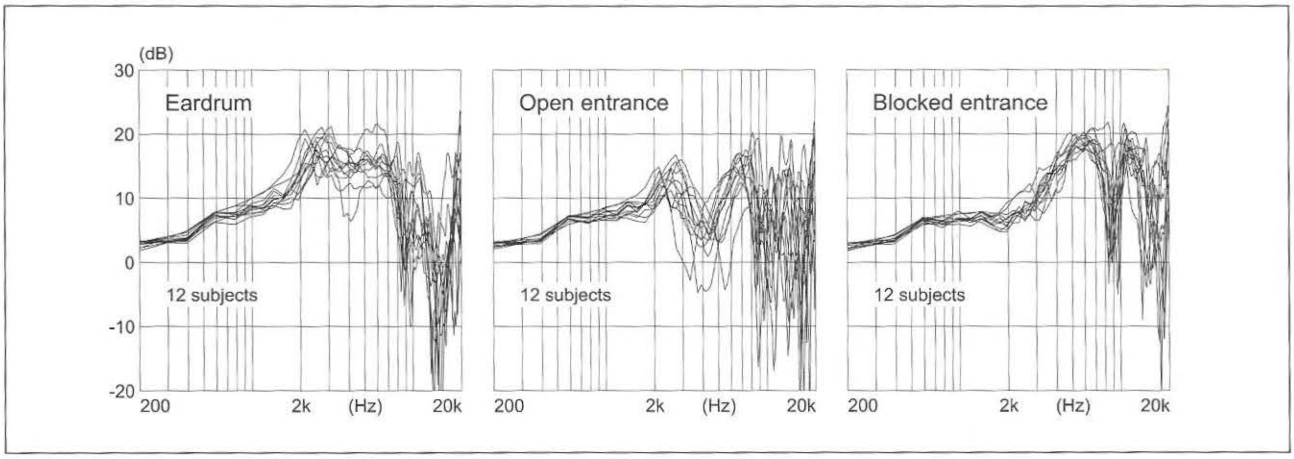

Figure 3. Head-related transfer functions measured at the eardrum, at the open entrance, and at the blocked entrance, sound from the left side (from Hammershøi and Møller [8]).

the entrance. The lack of directional dependence in the experimental data is believed to be due to the fact that the measurement points are at the centerline of the ear canal, where the transverse modes that are relevant for the audio frequency range exhibit minimum pressure. Thus possible transverse modes excited at the entrance are not measured with the microphone technique used. This explanation is supported by Shaw's data [6], where some dependence of direction is seen at high audio frequencies for non-center points at the ear-canal entrance (not reprinted here).

Since the transverse modes are not transmitted to the eardrum, the centerline measurements (or recordings) give a true representation of the input to the hearing. Most likely, a microphone of which the diaphragm covers the whole ear-canal area would also pick up a minimum of the transverse modes at the entrance and thus serve the purpose equally well.

In summary, it is concluded that the entrance of the ear canal can be used as a recording site for sound containing complete spatial information, and as the "error" made by not recording at the eardrum is not related to the spatial properties, it can be accounted for by traditional equalization.

The possibly most attractive result of this part of the study is that binaural recordings may also be made at the entrance of the ear canal, even if the canal is closed by, for instance, an earplug. This is a very practical solution because the recording microphone may be built into or even constitute the blockage. The investigation (see Hammershøi and Møller [8]) further shows that recordings made in this way will be less influenced by individual characteristics from the person it came from, and it will thus be of more general applicability. Examples of HRTFs measured at 12 persons and at three positions in the ear canal are given in Figure 3.

3. Reproduction

It has also been investigated whether the correct reproduction of the eardrum signals may in fact be obtained when subsequently played back. Previous investigations on headphone transfer functions were studied, but transfer functions of headphones are seldomly measured on human subjects. One reason for this is the practical difficulties associated with measurements in the ear canal.

Another reason is the fact that for reproduction of traditional recordings, the headphone is supposed to simulate the entire transmission in a traditional set-up, including the loudspeaker response and the transmission through the room to the listener's ear canal. This transmission is rather complex, and headphones are normally evaluated through loudness comparisons between sound emitted by the headphone under test and sound emitted by a loudspeaker in specified surroundings [27], [28]. The sound field created by the combination of the loudspeaker and the room is called the reference field. The comparison may also be made between a reference headphone and the headphone under test [29].

Even when measurements are made in the ear canal, results are normally given as the deviation between the sound obtained from the headphone and from the reference sound field [30], [31], [32]. Measurements in the ear canals of human subjects and aiming at a predetermined design goal–corresponding to the transmission from the reference sound field–have been suggested by a few authors [33], [34], [35].

Although measurements on human ears are reported in the literature (e.g. [33], [34], [36], [37]), a comparison is not possible. Not only have different methods been used, but the headphones are often unidentified. The following conclusions are therefore based on our own investigation (Møller *et al.* [26]).

Møller *et al.* [26] investigated headphone performance on human ears with the aim of using the headphones for reproduction of binaural recordings made at the blocked ear canal entrance. The correct reproduction can be obtained by insertion of (for instance) an electronic equalizer, which corrects for the non-flat frequency response of the headphone.

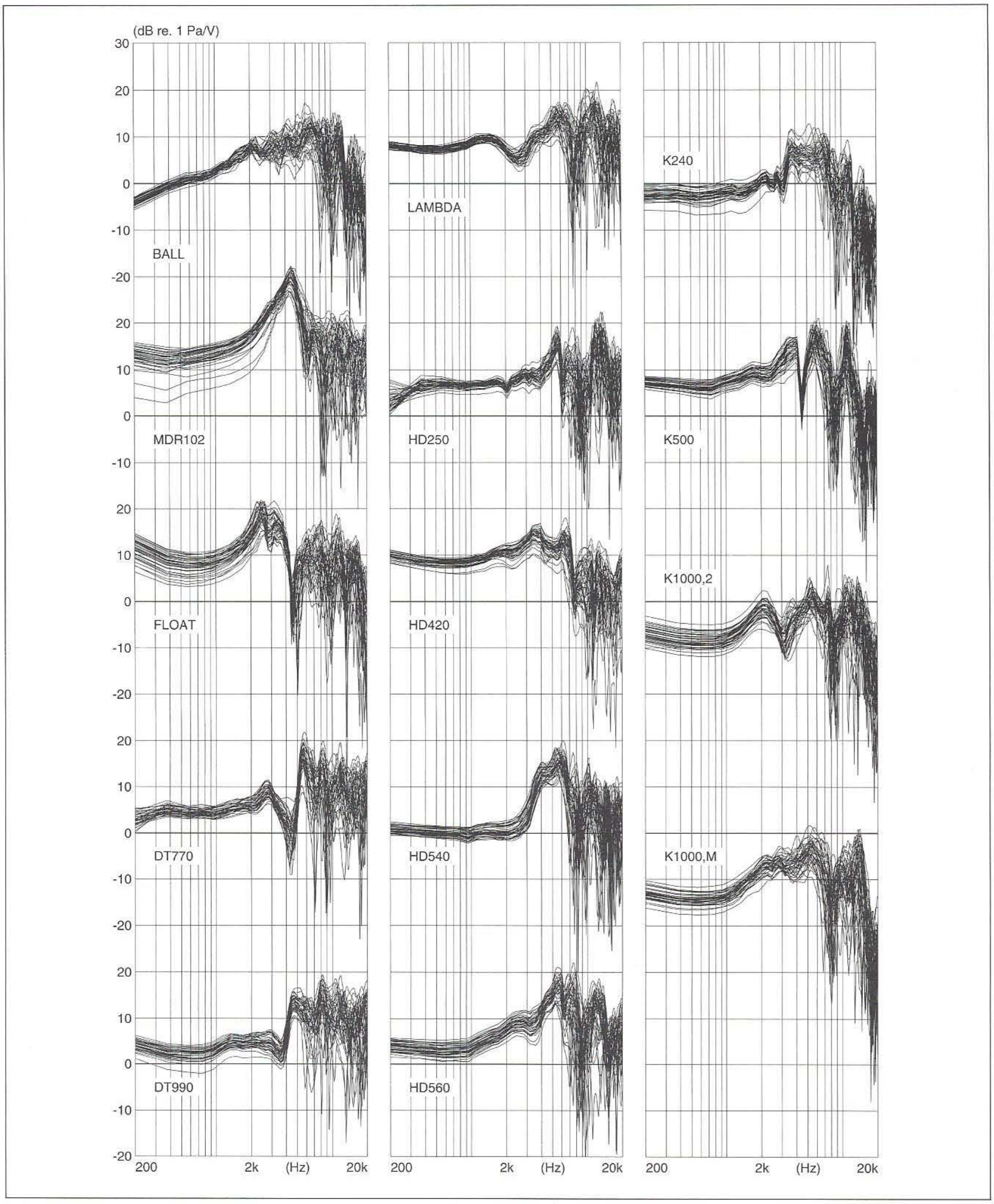

Figure 4. Headphone transfer functions for 14 headphones measured at the blocked ear canal entrance of 40 human subjects (from Møller et al. [26]). The headphones included (from top left down and right) close-mounted loudspeakers (BALL), Sony MDR-102, Jekclin float model two, Beyerdynamic DT 770 Professional, Beyerdynamic DT 990 Professional, STAX SR Lambda professional, Sennheiser HD 250 linear, Sennheiser HD 420 SL, Sennheiser HD 540 reference, Sennheiser HD 560 ovation, AKG Acoustics K 240 DF, AKG Acoustics K 500, AKG Acoustics K 1000 (see [26] for details).

Ideally the headphone correction filters are determined from measurements with the headphone as the physical source, and with the same microphone position as during the recording. The correct recording and reproduction is

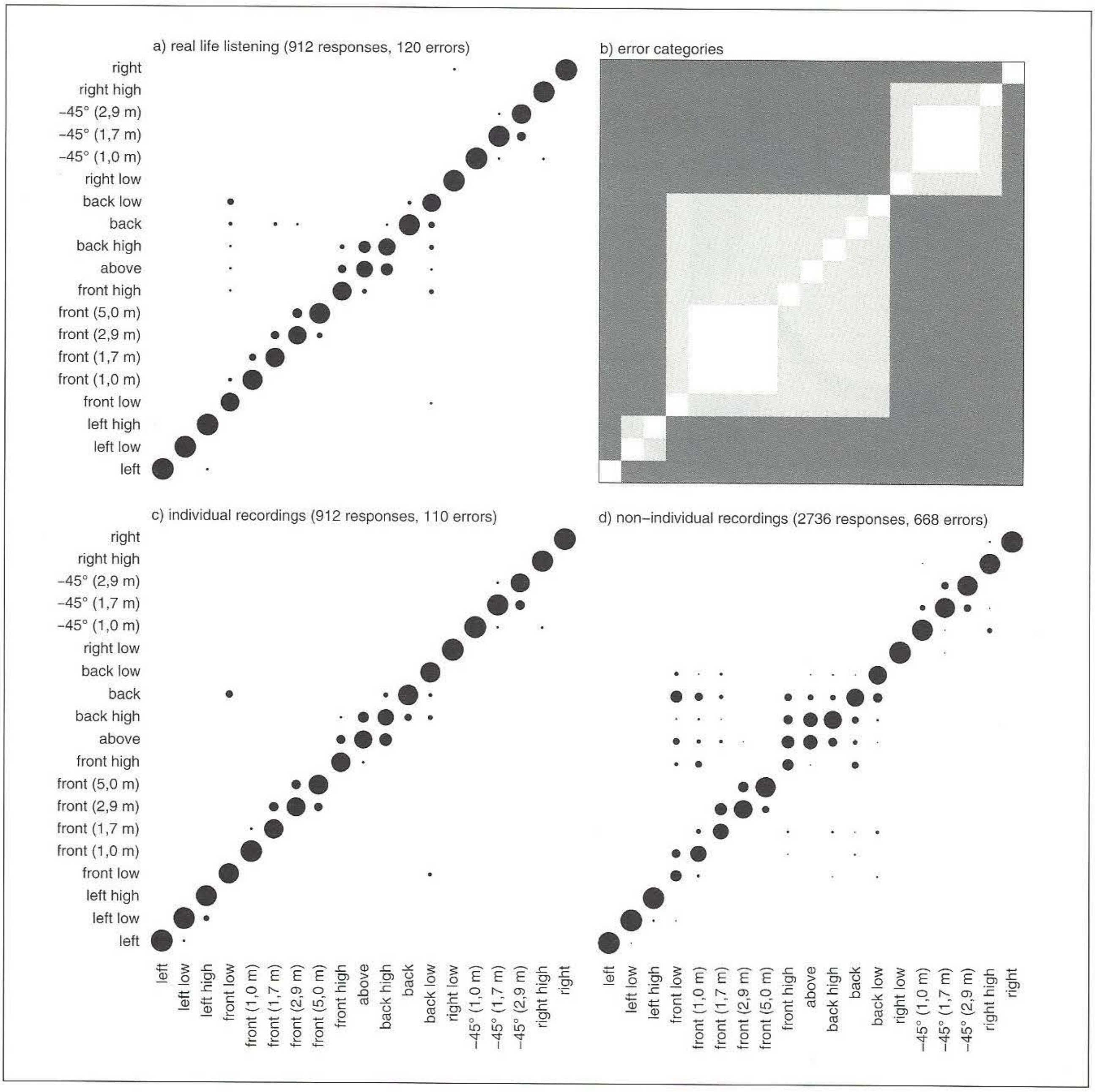

Figure 5. Stimulus response matrices for the localization experiments (from Møller *et al.* [38], graphics from [1]). The area of each circle is proportional to the number of responses it holds. a) shows responses for the real life situation, c) for reproduction of individual binaural recordings, and d) for reproduction of non-individual recordings. b) is a sketch of error categories; light grey shading is wrong judgement of distance, medium grey shading is confusion of sources of equal ITDs, and dark grey shading are the remaining errors. The same kinds of errors are made in the experiments. It is typically sources at different distances or other sources providing equal ITDs that are confused. Significance tests (Fisher-Irwin test on hypergeometrical distributions, e.g. Ross [39]) reveal that the difference in number of errors in each category between real life listening and reproduction of individual recordings is insignificant. Tests also show that there are significantly more errors in the error category holding confusions of sources of equal ITDs with non-individual recordings than in real life or with individual recordings.

thus obtained with absolutely no unpleasant measurements at the eardrum.

In principle, with a headphone applied to the ear the impedance relations at the ear canal entrance will differ from the impedance relations with the ear in the free air, but measurements on many subjects and headphones show that this can typically be ignored [26]. In the same investigation it was concluded that none of the specific headphones investigated was expected to perform well without proper equalization (see Figure 4).

To keep the record straight it is noted that it is no error that the headphones don't display flat frequency responses, as they are in fact designed to reach other ideals. A direct comparison of the average headphone transfer function to the presumed ideals (Figure 14, in [26]), do however reveal that the agreement is not generally succesfull.

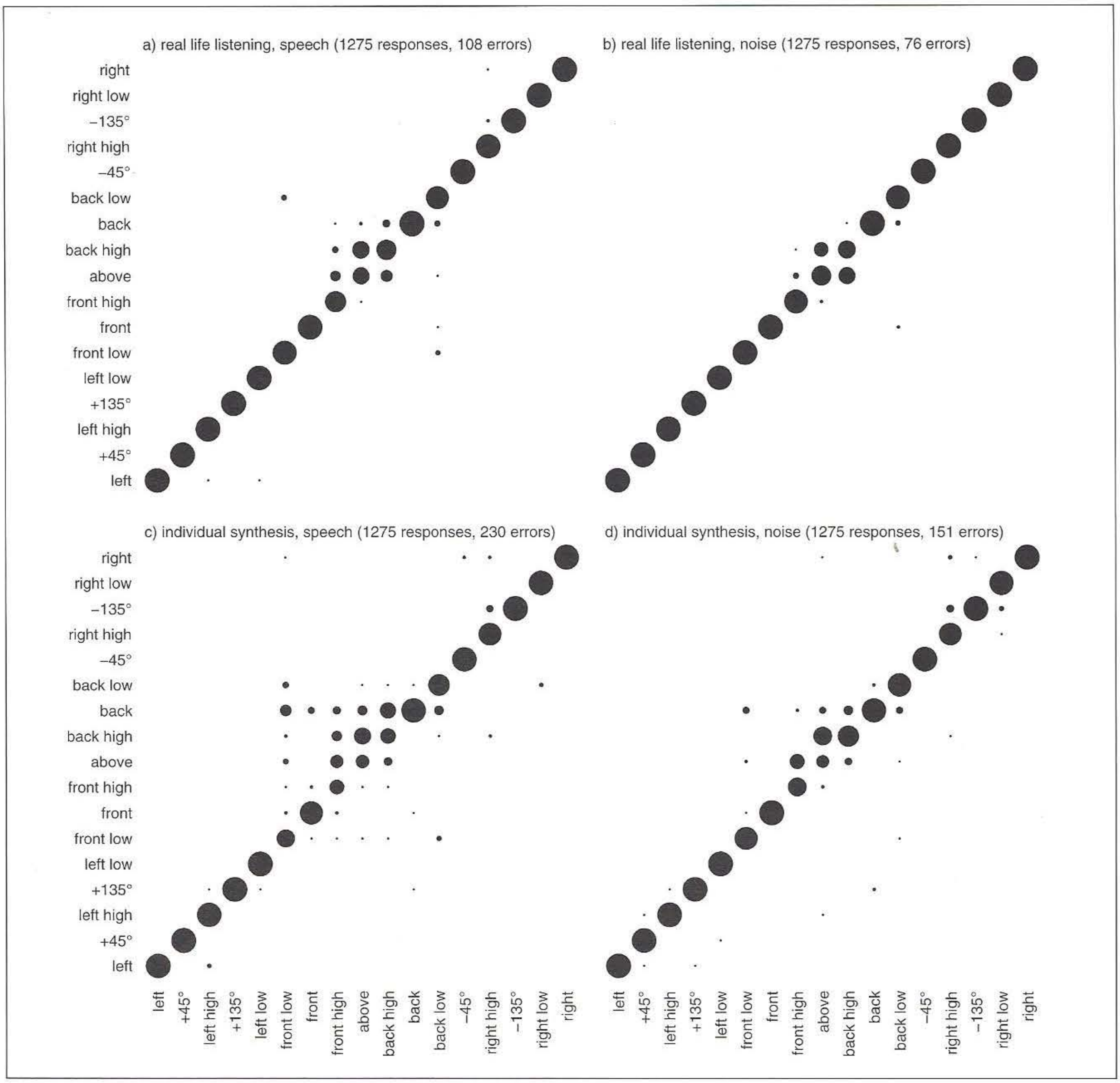

Figure 6. Stimulus response matrices for real life listening and individual binaural synthesis (from Hammershøi and Sandvad [40], graphics from [1]). The area of each circle is proportional to the number of responses it holds. The directions are organized "cone-wise" so that sources providing similar ITDs are next to each other. Degrees denote azimuths, whereas 'high' and 'low' denotes elevations at 45° up and down respectively. From left; the first cone consist of the source at 'left' only, second cone consist of sources at '+45°', 'left high', '+135°' and 'left low', the third cone consists of sources in the median plane, etc. It can be seen that the subjects identify the source direction quite well, and that errors are primarily due to confusion of the sources 'front high', 'above', and 'back high'. Significance tests (Fisher-Irwin test on hypergeometrical distributions, e.g. Ross [39]) reveal that the difference in the number of errors between real life listening and simulation is significant for both stimuli. The difference in the number of errors between speech and noise is significant in both listening conditions.

4. Performance

It has further been investigated whether ideal binaural signals (recordings from the listener's own ears) do indeed provide the true, authentic auditory experience, especially with respect to the spatial experience of the sound sources' positions. With regard to our own experiments (Møller *et al.* [38]), it turned out that a listening panel in fact localized the sound sources' original positions equally well with the reproduction as in the corresponding experiments in the real setup (see Figure 5). These experiments thus 1) show that true reproduction can in fact be obtained, and 2) they support the above argumentation that recordings may indeed be made at the entrance of the blocked ear canal.

It has further been an objective to see if this can also be reached if ideal binaural signals are synthesized by a computer. The general conclusion from reviewing previous investigations of free-field simulation and free-field listening [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56] is that the localization performance is more or less degraded with synthesized signals. This accounts for our own experiments with individual binaural synthesis as well [40], however, the (re)production obtained was surprisingly convincing (see Figure 6, and [1] and [40]). For instance with a wideband stimulus a sound source at the front was never mistaken, a fact which contradicts the myth that binaural synthesis can not produce a convincing experience of sound from the front (Figure 6, lower right panel).

Finally, it has been an objective to see if binaural signals, which are recorded in the ears of 'other' subjects, i.e. non-individual recordings, can also provide the true reproduction, or if the anatomical differences subjects inbetween impair the reproduction of an authentic, spatial experience. The general conclusion is that more localization errors occur with non-individual recordings. The extra errors occur mainly as confusions between directions with the same arrival time difference between left and right ear (same interaural time difference, ITD). It should be noted that the listeners' judgement of the distance to the sound source was almost the same with non-individual recordings, which contradicts the myth that non-individual binaural recordings should give a sensation of the sound being within the head (see Figure 5, and [38] and [57] for statistics).

5. Artificial heads

The performance of existing artificial heads for binaural recordings has also been investigated (Møller *et al.* [58]) revealing unfortunate discrepancies to the use of human recording heads. Although the design goal for the dummies is to replicate the human in the recording situation, the results indicate that existing commercially available artificial heads do poorly in competition with humans (although several of the artificial heads fulfill current artificial head standards). A subsequent study (Minnaar *et al.* [59]) summarizes a series of similar experiments, including more recent developments of artificial heads. The results of these studies suggest that better artificial heads are obtained if the design is based on the geometry of a human, which is known to yield recordings that are well localized by a panel of listeners.

Acknowledgement

The study was carried out at the Department of Acoustics (earlier the Acoustics Laboratory) at Aalborg University, where all members of the staff have contributed to an inspiring atmosphere. In particular, our colleagues Peder Christian Frandsen, Michael Friis Sørensen, Clemen Boje Larsen (former Jensen) and Jesper Sandvad are thanked for their collaboration in different phases of the work. Financial support (for the original studies) from the Danish Technical Research Council, the European Commission, the Danmon Research Fund and the C. W. Obel's Fund is also acknowledged.

References

[1] D. Hammershøi: Binaural Technique – a method of true 3D sound reproduction. Dissertation. Department of Acoustics, Aalborg University, Fredrik Bajers Vej 7 B4, DK-9220 Aalborg Ø, Denmark, 1995.

[2] J. Blauert: Spatial hearing. The psychophysics of human sound localization. The MIT Press, Cambridge, Massachusetts, London, England, 1997.

[3] H. Møller: Fundamentals of binaural technology. Applied Acoustics **36** (1992) 171–218.

[4] F. M. Wiener, D. A. Ross: The pressure distribution in the auditory canal in a progressive sound field. J. Acoust. Soc. Am. **18** (1946) 401–408.

[5] E. A. G. Shaw: Acoustic response of external ear with progressive wave source. J. Acoust. Soc. Am. Suppl. **51** (1971) 150, manuscript from 82nd Meeting of the Acoust. Soc. Am., made available in personal communication.

[6] E. A. G. Shaw: Acoustic response of external ear replica at various angles of incidence. 86nd Meeting of the Acoustical Society of America (1973) 1–9.

[7] E. A. G. Shaw: External ear response and sound localization, Chapter 2, 30-41, in Gatehouse: Localization of Sound: Theory and applications. Amphora Press, Groton Conn., 1982.

[8] D. Hammershøi, H. Møller: Sound transmission to and within the ear canal. J. Acoust. Soc. Am. **100** (1996) 408–427.

[9] S. Mehrgardt: Die Übertragungsfunktion des menschlichen Aussenohres – Richtungsabhängigkeit und genauere Bestimmung durch komplexe Strukturmittellung. Fortschritte der Akustik, DAGA '75 (1975) 357–361.

[10] S. Mehrgardt, V. V. Mellert: Transformation characteristics of the external human ear. J. Acoust. Soc. Am. **61** (1977) 1567–1576.

[11] J. C. Middlebrooks, J. C. Makous, D. M. Green: Directional sensitivity of sound-pressure levels in the human ear canal. J. Acoust. Soc. Am. **86** (1989) 89–108.

[12] Y. Onchi: Mechanism of the middle ear. J. Acoust. Soc. Am. **33** (1961) 794–805.

[13] M. B. Gardner, M. S. Hawley: Network representation of the external ear. J. Acoust. Soc. Am. **52** (1972) 1620–1628.

[14] J. Blauert: Räumliches Hören. S. Hirzel Verlag, Stuttgart, Germany, 1974.

[15] J. Blauert: Spatial hearing. The psychophysics of human sound localization. The MIT Press, Cambridge, Massachusetts, London, England, 1983.

[16] S. Gilman, D. D. Dirks: Acoustics of ear canal measurement of eardrum SPL in simulators. J. Acoust. Soc. Am. **80** (1986) 783–793.

[17] R. D. Rabbitt: High frequency plane waves in the ear canal: Application of a simple asymptotic theory. J. Acoust. Soc. Am. **84** (1988) 2070–2080.

[18] R. D. Rabbitt, M. T. Friedrich: Ear canal cross-sectional distributions: Mathematical analysis and computation. J. Acoust. Soc. Am. **89** (1991) 2379–2390.

[19] K. N. Stevens, R. Berkovitz, G. J. Kidd, D. M. Green: Calibration of ear canals for audiometry at high frequencies. J. Acoust. Soc. Am. **81** (1987) 470–484.

[20] M. R. Stinson, E. A. G. Shaw, B. W. Lawton: Acoustical energy reflectance at the eardrum from measurements of pressure distribution in the human ear canal. J. Acoust. Soc. Am. **72** (1982) 766–773.

[21] M. R. Stinson: The spatial distribution of sound pressure within scaled replicas of the human ear canal. J. Acoust. Soc. Am. **78** (1985) 1596–1602.

[22] M. R. Stinson, B. W. Lawton: Specification of the geometry of the human ear canal for the prediction of sound-pressure level distribution. J. Acoust. Soc. Am. **85** (1989) 2492–2503.

[23] H. Hudde, A. Engel: Measuring and Modeling Basic Properties of the Human Middle Ear and Ear Canal. Part I: Model Structure and Measuring Techniques. ACUSTICA–acta acustica **84** (1998) 720–738.

[24] H. Hudde, A. Engel: Measuring and Modeling Basic Properties of the Human Middle Ear and Ear Canal. Part II: Ear Canal, Middle Ear Cavities, Eardrum, and Ossicles. ACUSTICA–acta acustica **84** (1998) 894–913.

[25] H. Hudde, A. Engel, A. Lodwig: Methods for estimating the sound pressure at the eardrum. J. Acoust. Soc. Am. **106** (1999) 1977–1992.

[26] H. Møller, D. Hammershøi, C. B. Jensen, M. F. Sørensen: Transfer characteristics of headphones measured on human ears. J. Audio Eng. Soc. **43** (1995) 203–217.

[27] DIN 45 619: Part 1: Kopfhörer. Bestimmung des Freifeld-Übertragungsmaßes durch Lautstärkevergleich mit einer fortschreitenden Schallwelle. (Headphones: determination of the free-field sensitivity level by loudness comparison with a progressive sound wave). 1975.

[28] IEC 268-7: Sound system equipment. part 7: Headphones and headsets.

[29] DIN 45 619: Part 2: Kopfhörer: Bestimmung des Freifeld-Übertragungsmaßes durch Lautstärkevergleich mit einem Bezugs-Kopfhörer. (Headphones: determination of the free-field sensitivity level by loudness comparison with a reference headphone). 1975.

[30] G. Theile: On the standardization of the frequency response of high-quality studio headphones. J. Audio Eng. Soc. **34** (1986) 956–969.

[31] G. Spikofski: The diffuse-field probe transfer function of studio-quality headphones. EBU Review - Technical **229** (1988) 111–126.

[32] CCIR Rec. 708: Determination of the Electro-Acoustical Properties of Studio Monitor Headphones. vol. X, Part 1. International Telecommunication Union, Geneva, Switzerland, 1990.

[33] J. R. Sank: Improved real-ear tests for stereophones. J. Audio Eng. Soc. **28** (1980) 206–218.

[34] F. E. Toole: The acoustics and psychoacoustics of headphones. presented at the 2nd Audio Eng. Soc. Int. Conf., Anaheim, CA **preprint C1006** (1984).

[35] H. Møller, C. B. Jensen, D. Hammershøi, M. F. Sørensen: Design criteria for headphones. J. Audio Eng. Soc. **43** (1995) 219–232.

[36] M. D. Burkhard, E. L. R. Corliss: The response of earphones in ears and couplers. J. Acoust. Soc. Am. **26** (1954) 679–685.

[37] E. A. G. Shaw: Ear canal pressure generated by circumaural and supra-aural earphones. J. Acoust. Soc. Am. **39** (1966) 471–479.

[38] H. Møller, M. F. Sørensen, C. B. Jensen, D. Hammershøi: Binaural technique: Do we need individual recordings? J. Audio Eng. Soc. **44** (1996) 451–469.

[39] S. B. Ross: Introduction for probability and statistics for engineers and scientists. John Wiley & Sons, Inc., 1987.

[40] D. Hammershøi, J. Sandvad: Binaural auralization. Simulating free field conditions by headphones. Proc. 96th Audio Eng. Soc. Conv. **preprint 3863** (1994) 1–19.

[41] M. Morimoto, Y. Ando: On the simulation of sound localization. J. Acoust. Soc. Jpn. (E) **1** (1980) 167–174.

[42] E. M. Wenzel: Localization in virtual acoustic displays. Presence **1** (1992) 80–107.

[43] E. M. Wenzel, F. Wightman, D. Kistler, S. Foster: Acoustic origins of individual differences in sound localization behaviour. J. Acoust. Soc. Am. Suppl. **84** (1988) S79.

[44] F. Wightman, D. Kistler: Headphone Simulation of free-field listening. II: Psychophysical validation. J. Acoust. Soc. Am. **85** (1989) 868–878.

[45] E. M. Wenzel, F. L. Wightman, S. Foster: A virtual display for conveying three-dimensional acoustic information. proceedings for the Human Factors Society, 32. Annual Meeting (1988) 86–90.

[46] J. Kawaura, Y. Suzuki, F. Asano, T. Sone: Sound localization in headphone reproduction by simulating transfer functions from the sound source to the external ear. J. Acoust. Soc. Jpn. (E). **12** (1991) 203–216.

[47] J. Kawaura, Y. Suzuki, F. Asano, T. Sone: Sound localization in headphone reproduction by simulating transfer functions from the sound source to the external ear. J. Acoust. Soc. Jpn. (J). **45** (1989) 756–766.

[48] F. Asano, Y. Suzuki, T. Sone: Role of spectral cues in the median plane. J. Acoust. Soc. Am. **88** (1990) 159–168.

[49] D. Begault, E. M. Wenzel: Headphone localization of speech stimuli. proceedings for the Human Factors Society, 35. Annual Meeting (1991) 82–86.

[50] D. R. Begault: Perceptual effects of synthetic reverberation on three-dimensional audio systems. J. Audio Eng. Soc. **40** (1992) 895–904.

[51] E. M. Wenzel, M. Arruda, D. J. Kistler, F. L. Wightman: Localization using nonindividualized head-related transfer functions. J. Acoust. Soc. Am. **94** (1993) 111–123.

[52] E. M. Wenzel, M. Arruda, D. J. Kistler, F. L. Wightman: Localization using non-individualized acoustic display cues. ACM Conf. on Computer-Human Interaction (1991) 351–359.

[53] S. R. Oldfield, S. P. A. Parker: Acuity of sound localization: A topography of auditory space. I. Normal hearing conditions. Perception **13** (1984) 581–600.

[54] J. C. Makous, J. C. Middlebrooks: Two-dimensional sound localization by human listeners. J. Acoust. Soc. Am. **87** (1990) 2188–2200.

[55] S. H. Nielsen: Distance perception in hearing. Dissertation. Department of Acoustics, Aalborg University, Fredrik Bajers Vej 7 B4, DK-9220 Aalborg Ø, Denmark, 1991.

[56] S. H. Nielsen: Auditory distance perception in different rooms. J. Audio. Eng. Soc. **41** (1993) 755–770.

[57] H. Møller, C. B. Jensen, D. Hammershøi, M. F. Sørensen: Using a typical human subject for binaural recording. Proc. 100th Audio Eng. Soc. Conv. **preprint 4157** (1996) 1–10.

[58] H. Møller, D. Hammershøi, C. B. Jensen, M. F. Sørensen: Evaluation of artificial heads in listening tests. J. Audio Eng. Soc. **47** (1999) 83–100.

[59] P. Minnaar, S. K. Olesen, F. Christensen, H. Møller: Localization with binaural recordings from artificial and human heads. J. Audio Eng. Soc. **49** (2001) 323–336.