Sound transmission to and within the human ear canal

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Sound transmission to the eardrum from various points in the external ear was measured by means of probe microphone technique. Twelve human subjects participated, and three directions of sound incidence were included. For the major part of the audio frequency range the transmission to the eardrum proved independent of direction from points at the centerline of the ear canal, including the entrance (open or blocked). The results further suggested that the region with independent transmission extends some millimeters outside the entrance plane. The transmission from the free field to the eardrum was divided into a directional-dependent part and two directional-independent parts: (1) the transmission from the free field to the blocked entrance, (2) a pressure division between the radiation impedance and the ear-canal input impedance, and (3) the transmission along the ear canal. All parts of the transmission were seen to be highly individual. The first part was shown to be uncorrelated with any of the other parts, whereas mutual dependence of parts (2) and (3) resulted in a smaller variation in the combined transmission than for the parts in separate. The standard deviation between subjects for head-related transfer functions (HRTFs) measured at the eardrum, the open entrance, and the blocked entrance was studied, and the lowest values were found for the blocked-entrance HRTFs. It is concluded, that the blocked entrance is the most suitable point for measurements of HRTFs and for binaural recordings, since sound at this point includes the complete spatial information, and in addition to that the minimum amount of individual information.

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INTRODUCTION

Knowledge about the sound transmission to the eardrum is essential in various areas of acoustics. It is of interest in the context of computation of the resulting eardrum sound pressure, when a human is exposed to a certain sound field, for instance a diffuse field, or a free field with sound incidence from a certain direction. It is likewise of interest, when sound is produced by means of transducers mounted close to the ear, such as Hi-Fi or audiometric headphones. The eardrum sound pressure is also of interest for the evaluation of hearing protectors.

Whatever the sound source is, an important part of the transmission to the eardrum is the propagation within the ear canal. When a human is exposed to a sound field, then—from a certain point in the ear canal—the further sound propagation toward the eardrum will be independent of the direction of sound incidence. An important property of sound at that point is that complete spatial information is present, and consequently the point is suitable for binaural recordings.

It was the aim of the present investigation to determine the physical position of the point, from which the sound propagates independently of direction, and furthermore to gain insight into the transfer functions involved in the sound propagation. The investigation served as a background study for various investigations on binaural technique,[1–11] and it was first presented in Ref. 12. Yet the investigation is relevant for many others, and it is now brought about for a wider audience.

A. Theory

The human ear canal is about 8 mm in diameter and about 25 mm long. The canal bends slightly, and the cross-sectional area varies along the canal. The canal is terminated by the eardrum, which is angled with respect to the canal with the upper part inclined toward the canal entrance. The eardrum is not completely stiff or otherwise simply described with respect to its impedance.

Some idea of the sound distribution and the transmission to the eardrum can be obtained, if the ear canal is approximated by a tube. For frequencies at which the wavelength is much larger than any dimension of the canal, the same sound pressure exists at all points within it. The largest dimension is the length, which is equal to one wavelength at approximately 14 kHz. Thus an equal sound-pressure distribution is expected up to a fraction hereof, say a few kilohertz.

For frequencies where the wavelength is much larger than the diameter only, the sound pressure varies along the canal, but is constant across it. The diameter corresponds to one wavelength at approximately 43 kHz, so an equal cross-sectional sound pressure is expected up to fraction hereof, say about 10 kHz. For high frequencies nonplanar propagation can exist, and the lower limit can be calculated to 25 kHz for the current diameter (Kinsler *et al.*,[13] p. 222).

The sound transmission along the ear canal is independent of direction in either of the above-mentioned frequency ranges, since only one mode of propagation, the longitudinal mode, is present. If the sound in the human ear canal is comparable to that of a tube, then a frequency range and a physical portion of the ear canal extending from the eardrum exist, for which the sound propagation is independent of direction.

The sound field outside the ear canal is complicated due to diffractions around pinna, head and torso, and no simple prediction of the sound field can be made. In general, it is expected that the sound transmission to the eardrum from any point outside the ear canal is dependent on the direction of the incoming sound wave.

More extensive model studies of the sound transmission in the external ear exist (e.g., Refs. 14–24), but neither has aimed at evaluating a possible directional dependence.

B. Previous investigations

Wiener and Ross[25] measured the sound at the eardrum, at the entrance of the ear canal, and at the midpoint between entrance and eardrum, for three directions of sound incidence in the horizontal plane (azimuths 0°, 45°, and 90°). Six to 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[26,27] verified this for a single replication of an ear. For eleven 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. He concluded that the sound transmission to the eardrum from the center point at the entrance was independent of direction up to 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. (References 26 and 27 are the original publications, whereas Ref. 28 is a more accessible publication presenting most of the same material.)

Mehrgardt[29] and Mehrgardt and Mellert[30] 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 ten directions of sound incidence in the horizontal plane were included. It was concluded that—up to 6 kHz—there was no directional dependence in the transmission to the eardrum from the point 2 mm inside the ear canal. Deviations seen for higher frequencies were reported 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.*[31] 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 four points, of which three 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.

On this background it seems liable that the transmission to the eardrum from the entrance of the ear canal is directional independent for the major part of the audio frequency range. This means that the entrance of the ear canal can be used as recording point for sound containing complete spatial information. Nevertheless, most measurements and recordings have been made some millimeters inside the ear canal (e.g., Refs. 16, 17, 31–44) or even close to the eardrum (e.g., Refs. 45–54).

There are of course many factors to take into account in the choice of measurement point, but several authors seem to question the ear canal entrance as a suitable point. This concern initiated the present investigation.

It was further an objective to study the transfer functions involved in the sound propagation along the ear canal, and several investigations have dealt with this. These are referenced and compared with the results of the present investigation in the discussion (Secs. IV D and E).

C. Goal of investigation

The investigation has two goals and is consequently divided into two experiments. Experiment 1 serves to determine the point within the ear, from which the sound—within a certain frequency range—propagates to the eardrum independently of direction. This knowledge is used in experiment 2, where the transmission is split up into directional-dependent and directional-independent parts. Each part is examined, and especially variations between subjects are considered.

I. EXPERIMENT 1: METHOD

Measurements were carried out on the left ear of subjects sitting in an anechoic chamber, with sound produced by loudspeakers placed in front, at the left side and behind the subject. Impulse responses were measured with maximum length sequence (MLS) technique, for the transmission from the voltage at the input of the power amplifier to the output of the measuring microphone, placed to measure the sound at various points in the ear. Pressure transfer functions were obtained through Fourier transformation of the measured impulse responses, followed by appropriate divisions.

A. Subjects

Twelve subjects in the age range of 20 to 31 years participated, 5 females and 7 males. None of the subjects had reported ear abnormalities that might affect the middle ear function, and all had normal hearing.

B. Free-field setup

The measurements were carried out in an anechoic chamber with a free space between the wedges of 6.2 m (length) by 5.0 m (width) by 5.8 m (height). Three ball loudspeakers (diameter 15.5 cm, diaphragm diameter 7.5 cm) were placed at a distance of 2 m from the subjects, one in front, one behind and one at the left side of the subject. An

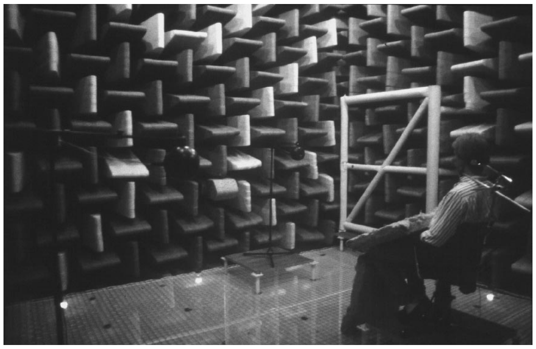

FIG. 1. Free-field setup in the anechoic chamber.

FIG. 2. Placement of the probe microphone and the flexible tube.

example of the free-field response of a loudspeaker is given in the time and the frequency domains as Fig. 7 in Ref. 1.

The subject was placed in a hairdresser's chair with a small support to prevent head movements. The chair was adjusted to a height comfortable for the subject, and the three loudspeakers were adjusted to the height of the subject's left ear. Damping material was placed to cover the subject's knees, since pilot experiments had shown that subjects tended to move their knees slightly during a measuring session. Such movements would cause differences in the transfer functions measured, which were erroneous for the investigation. By means of a small racket the microphone housing was fixed along the neck of the subject. A photo of the free-field setup is shown in Fig. 1.

C. Microphone

A Brüel & Kjær 4182 probe microphone was used for all measurements. An approximately 7-cm flexible silicone tube (inner diameter 0.76 mm, outer diameter 1.65 mm) was attached to the microphone. The sensitivity of the microphone was approximately 3 mV/Pa, gradually declining to −15 dB at 20 kHz. The response of the microphone was in general rather smooth without standing wave patterns as sometimes seen for probe microphones. The manufacturer had obtained this by continuing the measuring tube 1.5 m within the microphone housing, so that the tube acted like an endless transmission line.

The acoustical impedance of the probe was approximately 10^9 Ns m^{-5}, which at 500 Hz corresponds to the impedance of a 0.05-cm^3 volume. At higher frequencies the corresponding volume decreases, and the loading of the ear canal by the tube was therefore considered negligible in the frequency range of interest.

The frequency response of the probe microphone can be seen as Fig. 4 in Ref. 1.

D. Measurement points

Measurements were made close to the eardrum and at various other points in the ear. The measurements points were

(1) 1–2 mm from the eardrum
(2) 12 mm within the ear canal*
(3) 6 mm within the ear canal
(4) at the entrance to the ear canal
(5) 6 mm outside the ear canal*
(6) at the caudal cavum conchae*
(7) at the posterior cavum conchae*
(8) 3–4 cm outside the ear canal*

Measurements at the points marked with an asterisk were only made for 4 of the 12 subjects.

Placement of the probe tip was carried out by a medical doctor. The length of the ear canal had been measured initially by means of the flexible tube. Marks were made on the tube to assure correct placement within the ear. Then the subject was seated in the chair in the anechoic chamber, and the microphone was mounted.

At first the microphone housing and the racket holding it, were fixated in a position close to the subjects neck, where it would cause the least possible disturbance of the sound field. The placement is shown in Fig. 2. Following that, the tube tip was placed at the eardrum, and measurements for each of the three directions were taken. Then the flexible tube was pulled out successively to the other measurement points without changing anything else in the setup.

For the points inside the ear canal and for the point 6 mm outside, the tube tip was placed on the centerline of the canal. This was not trivial to assure for the points within the ear canal, and the accuracy of the radial position was estimated to 1–2 mm, and 2–3 mm for the eardrum position. For points outside the ear canal a soft knot was sometimes made on the tube, or a small piece of medical tape was used to arrange the tube tip at the correct position. A new piece of tube was used for each subject.

E. Measuring setup

All measurements were made with the general-purpose measuring system known as MLSSA (maximum length sequence system analyzer, by DRA Laboratories). A thorough review of the MLS measuring technique is given by Rife and Vanderkooy.[55]

A 4095-point maximum length sequence at 50 kHz (with a duration of 81.9 ms) was used. The stimulus was fed into a power amplifier, from which the output signal could be switched to either of the three loudspeakers in the anechoic chamber. The loudspeaker voltage was 1.87 V_{rms} resulting in a free-field sound pressure of 75 dB (A-weighted) at the subject's position, a level that was assumed not to activate the middle ear tensors.

The microphone signal was amplified by a Brüel & Kjær 2607 measuring amplifier, and converted by the 12-bit A/D converter on the MLSSA board. Each impulse response was calculated from the average of 16 recordings (pre-averaging).

F. Data processing

Results of the measurements were impulse responses for the transmission from the input to the power amplifier to the output of the measuring amplifier. Data were postprocessed in MATLAB (The MathWorks Inc.).

A frequency-domain representation of the transmission was obtained by a 256-points Fourier transform (rectangular window) of the segment between 5.12 and 9.00 ms of the impulse response (samples 256–450 and zero padded up to sample 511). The segment included the entire response, and excluded reflections from floor etc.

The sound transmission to the eardrum from a certain point was found as the transfer function measured at the eardrum divided by the transfer function measured at the point in concern.

II. EXPERIMENT 1: RESULTS AND DISCUSSION

At first, an example of the sound transmission to the eardrum from all measurement points is presented for a single subject (Sec. II A). The transmission from the entrance of the ear canal is presented for all 12 subjects in Sec. II B. Section II C presents the transmission from the point 6 mm outside the ear canal for the four subjects, for which the measurements are available. Mean values for the transmission to the eardrum from the three points: (1) 6 mm inside the ear canal, (2) at the entrance, and (3) 6 mm outside are given in Sec. II D.

Rather than looking at the exact transmissions, it is possible to compute some statistics in order to evaluate directional dependence. This is presented in Sec. II E. Similar statistics have been reported by other investigators, and their data are compared with ours in Sec. II F.

A. Transmission from all points, one subject

The transmission to the eardrum from all measurement points for a single subject is shown in Fig. 3.

For all measurement points it is clearly seen that the sound transmission is frequency dependent. At low frequencies the transmission approaches 0 dB, an observation that is in agreement with our expectation of a uniform sound field in this frequency range. Above 2 kHz, peaks as high as 20 dB appear at different frequencies for the various measurement points. The peaks are recognized to be due to standing-wave patterns of a transmission line, with the peaks decreasing in frequency with increasing distance to the eardrum.

The main observation, though, is the alikeness of the curves for the three directions for a given measurement point. Except for narrow peaks and notches, concordance in the entire audio range seems to exist for the points in the ear canal, at the entrance, and 6 mm outside. For the points in the concha, agreement between the curves is seen up to 4

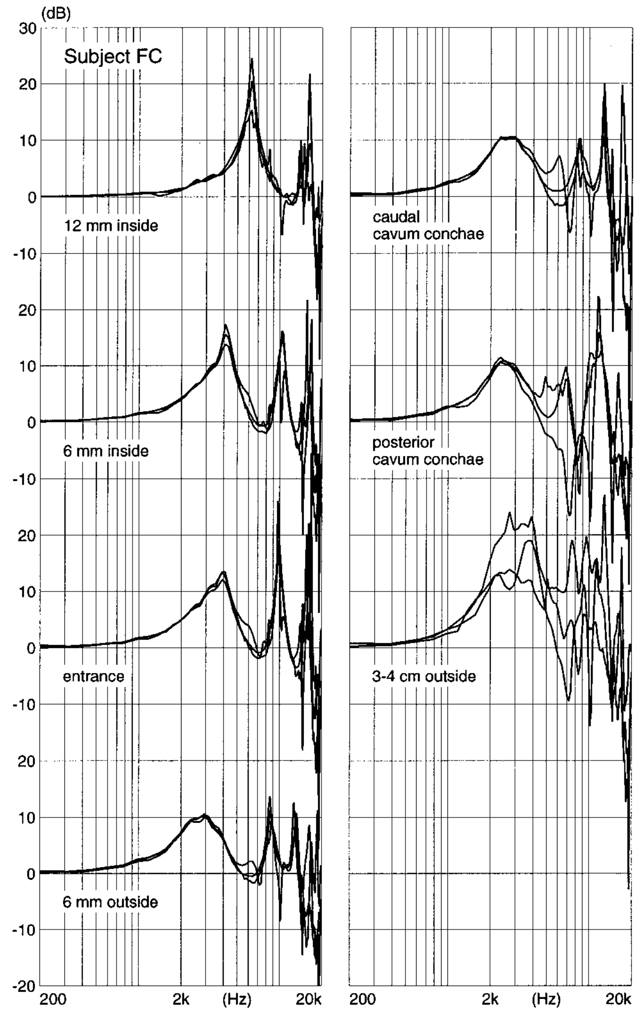

FIG. 3. Sound transmission to the eardrum from distal points in the external ear for the left ear of subject FC. Measurements for the three directions are overlaid in each frame.

kHz only, whereas for the point 3–4 cm outside the ear canal agreement is seen only up to slightly below 2 kHz.

These observations imply that the transmission to the eardrum from any point between the eardrum and the point 6 mm outside the ear canal can be considered directional independent. This observation for a single subject holds in general. The transmission considered most interesting—that is from the entrance of the ear canal—is presented for all 12 subjects in the following section.

B. Transmission from entrance, 12 subjects

Figure 4 shows the sound transmission to the eardrum from the entrance of the ear canal for the 12 subjects.

The most immediate observation is that the variation from subject to subject is rather high. Most structures are seen for all subjects, but in different appearances. The first peak occurs at frequencies between 3.0 and 5.5 kHz, with subjects ML and AH as the two extremes. The presence of individual differences has the consequence that for a certain frequency the transmission differs as much as 20 dB between subjects. The characteristics of some of the structures of the transfer function also vary, with some subjects having espe-

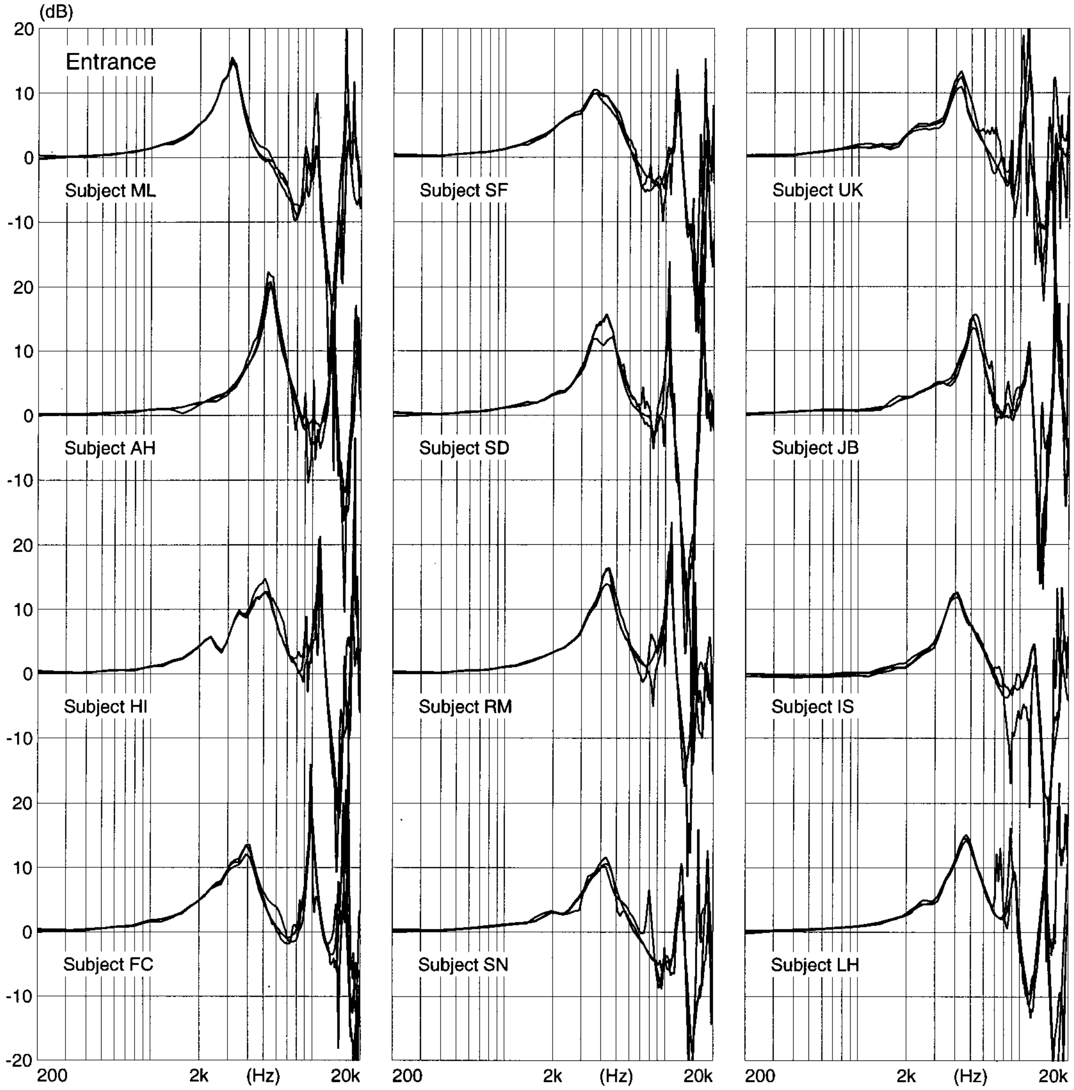

FIG. 4. Sound transmission to the eardrum from the entrance of the ear canal for the left ear of 12 subjects. Measurements for the three directions are overlaid in each frame.

cially deep notches (e.g., subject SD), and some having additional fluctuations between 2 and 5 kHz (especially subject HI).

Another observation is that the data do not tend to support the simple model of the ear canal. If the ear canal could be modeled by a tube with a hard termination, the first and the second peak in the amplitude response would occur at frequencies in a ratio 3:1, which they don't (e.g., a ratio of 13.5 kHz:5.3 kHz for subject AH, a ratio of 10 kHz:4 kHz for subject FC, a ratio of 11 kHz:4.3 kHz for subject RM).

Except for peaks and notches so narrow that they are assumed nonessential in this context, the similarity between the three directions (in Fig. 4) is again obvious. Deviations of a few decibels between 3.5 and 4.5 kHz are seen for subject SD, and for slightly higher frequencies for subjects IS and LH. These differences are nonsystematic, and they are altogether much smaller than the differences between directions for the total transmission from the free field. Examples of the latter transmissions are shown in Sec. IV A. For more information on this topic, *head-related transfer functions*, see for instance Møller *et al.*[1]

C. Transmission from 6 mm outside, four subjects

For most purposes it is sufficient to know that sound including full directional information can be recorded at the entrance to the ear canal, but according to Fig. 3 also the point 6 mm outside seems applicable. The sound transmission to the eardrum from this point is shown in Fig. 5 for the four subjects, for whom measurements were made.

Just as for the transmission from the entrance, the transmission from this point varies between subjects, but for a given subject the transmission is quite alike for the three directions. It would therefore be reasonable to believe that, in general, the transmission to the eardrum is independent of direction already from the point 6 mm outside the ear canal.

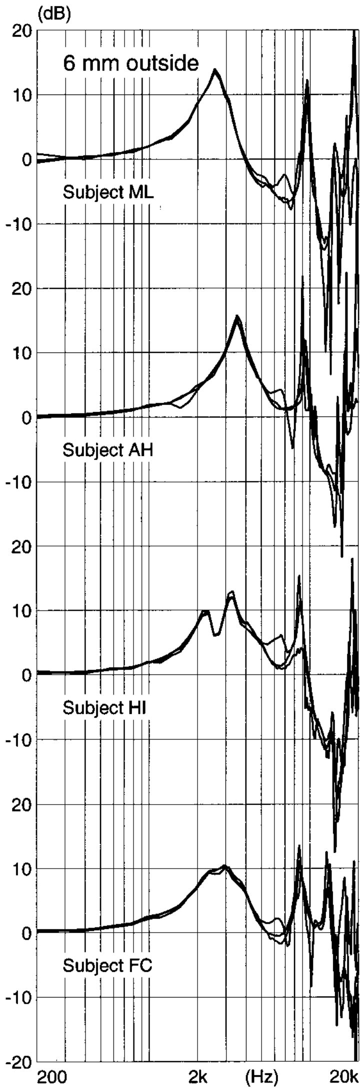

FIG. 5. Sound transmission to the eardrum from 6 mm outside the entrance of the ear canal for left ear of all four subjects. Measurements for the three directions are overlaid in each frame.

D. Mean values of transmission, three points

The sound transmissions to the eardrum from 6 mm inside, at the entrance, and 6 mm outside, averaged across subjects for each direction, are shown in Fig. 6.

The mean values do in general display the same peaks and dips as those for the single subjects. Especially at higher frequencies, though, the amplitude and width are smeared out, because of the inter-individual differences. Not unexpected, the mean curves for the three directions display great similarity because of the directional independence for the individual transmissions as observed earlier.

The transmission to the eardrum from the entrance constitutes one of the parts that the transmission from the free field to the eardrum is divided into in experiment 2.

E. Directional spread, all points

The visual comparison between transmission curves showed great similarity for the three directions, valid for individuals (Secs. II A to B) as well as for averages across subjects (Sec. II D). A similar approach was made by Wiener and Ross,[25] and by Shaw[26] (for an ear replica). They only observed negligible differences between directions, and they made the same conclusions as we have done.

The qualitative inspection of the transmissions in the previous sections can be supplemented by a quantitative analysis. For this purpose the *directional spread* is introduced as 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 calculation is done in decibels frequency by frequency for each subject, and subsequently averaged across subjects. The directional spreads are shown for all measurement points in Fig. 7.

It is immediately apparent that for the points in the ear canal, at the entrance, and 6 mm outside, the directional spreads are approximately equal, and much lower than for the remaining points. For the former points the directional spreads are close to 0 dB at low frequencies, and they only exceed a couple of decibels for frequencies above 12–14 kHz. We therefore conclude that the transmission to the eardrum from either of these points is only insignificantly influenced by direction for frequencies below 12–14 kHz. The fact that the spreads for the points in the ear canal, at the entrance, and 6 mm outside are alike, indicates that the directional information is no better included in points millimeters inside the ear canal than at the entrance.

For the points in the concha the directional spreads exceed a couple of decibels for frequencies above 5–6 kHz, and for the point 3–4 cm outside the same happens above approximately 2 kHz. We therefore conclude that significant directional dependence is present in the transmission to the eardrum from these points for frequencies above 5–6 kHz and 2 kHz, respectively.

All conclusions from the directional spread confirm the observations made from the visual inspection of the transmissions in Secs. II A–D.

Figure 7 also shows the experimental spread (estimated from repetition measurements, see the Appendix). For the points in the ear canal, at the entrance, and 6 mm outside the directional spreads and the experimental spreads are in the same order of magnitude, and it is therefore quite likely that the true directional spreads are even lower than shown.

The experimental spreads for the points in the ear canal, at the entrance, and 6 mm outside are alike, whereas the experimental spreads for the points in the concha and 3–4 cm outside are somewhat higher. This is quite natural, since the transmissions for the latter points depend on the external sound field, and these transmissions are therefore influenced by exact head orientation, placement of microphone housing etc. Consequently, differences in the physical setup increase the experimental error for these points, and not for the points in the ear canal, at the entrance, and 6 mm outside. For the point 3–4 cm outside the experimental error is further affected by the rather poor definition of position (no special effort was made to obtain the same position in the repetition measurements).

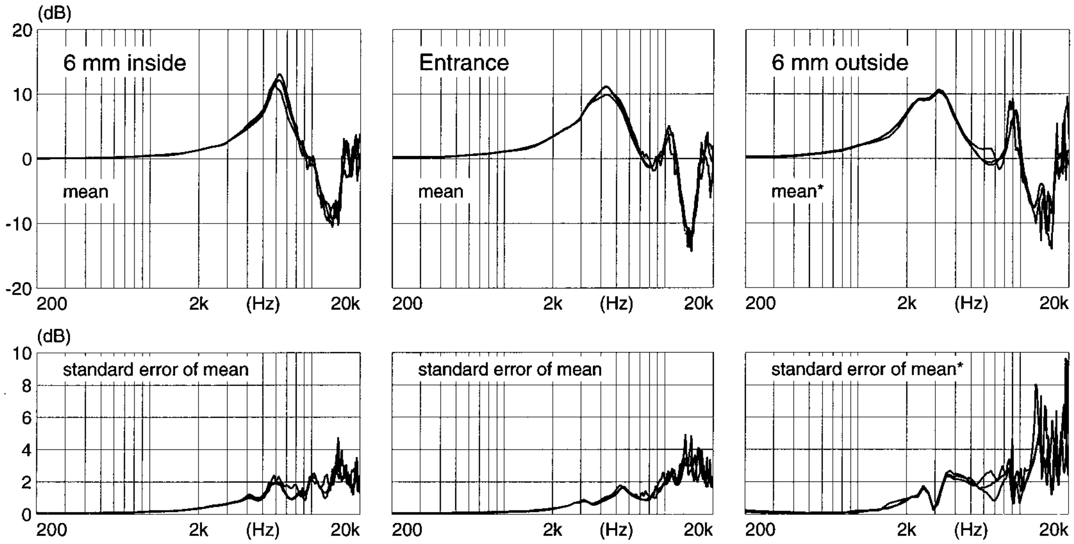

FIG. 6. Mean values and standard deviations across subjects for the sound transmission to the eardrum from 6 mm inside the ear canal, and from the entrance for 12 subjects, and from 6 mm outside for four subjects (marked by asterisks). Data for the three directions are overlaid.

F. Directional spread, previous investigations

Directional spreads are available from Wiener and Ross[25] (computed by us), and from Middlebrooks *et al.*[31] Mehrgardt and Mellert[30] reported ranges of transfer functions for the directions investigated, and Shaw[27] gave—in frequency intervals—boundaries for the ranges. Details on the number of subjects and directions were reported in the Introduction, subsection B (the ranges reported by Mehrgardt and Mellert are for a single subject, though).

Data from the investigations mentioned, are compared with directional spreads of the present investigation in Fig. 8 (minor deviations exist in the exact position of the measurement points, as reported in the text of Fig. 8).

The directional spreads (Wiener and Ross, Middlebrooks *et al.*, and the present investigation), show the same pattern, which is (1) low values for frequencies below 12–14 kHz for the points in the ear canal and at the entrance, and (2) low values up 5–6 kHz for the point in the concha.

The data by Middlebrooks *et al.* are somewhat lower for the points in the ear canal and at the entrance. This is quite natural, since they have reduced the experimental spread by using two microphones placed in the ear of the subject at the same time, and by having a smaller distance between the microphones. Our own data (Sec. II E) suggest that in the ear canal and at the entrance, the computed directional spreads display experimental spreads rather than true directional spreads.

The ranges given by Shaw tend to be higher than the directional spreads, which is quite natural, because ranges are inherently larger than spreads. An inspection of his individual curves (Ref. 26, reported for the measurement at the entrance only) suggests a directional spread of the same size as those of the present investigation.

The ranges reported by Mehrgardt and Mellert are in the extremity of what could be expected from the other investigations, even when appropriate concern is given to the fact that they are ranges and not spreads. As reported in the Introduction, part B, 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 remain to be explained.

G. Summary

In summary, we conclude that for the major part of the audio frequency range (up to 12–14 kHz) the transmission toward the eardrum is independent of direction at least from the ear canal entrance. The degree of accuracy, to which this has been proven, decreases with increasing frequency. Our own results suggest that this is caused by an increase in experimental error, rather than an actual directional dependence, and the transmission may be independent of direction even in a wider frequency range.

III. EXPERIMENT 2: METHOD

A theoretical tool, previously described by Møller,[56] is introduced. The model splits the transmission into directional-dependent and directional-independent parts. The dividing point used in the following, is the point at the ear canal entrance, but any other point, from which the sound propagates independent of direction toward the eardrum, could in principle be used.

A. Model of sound transmission

The complete sound transmission to the eardrum can be modeled as shown in Fig. 9.

The complete sound field outside the ear canal—whatever the source—is described by a Thévenin equivalent, consisting of the open-circuit sound pressure P_2, and a generator impedance. In the free field the generator impedance is identical to the radiation impedance, $Z_{\mathrm{radiation}}$, as seen from the entrance of the ear canal looking out into the free field.

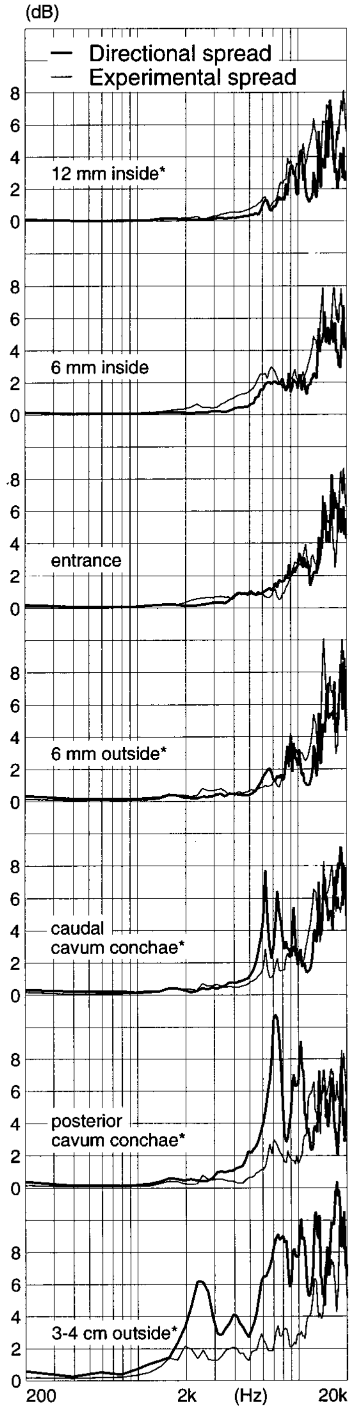

FIG. 7. Directional spreads computed as the standard deviations between directions of the transmission to the eardrum from distal points in the ear. The calculations are made in decibels frequency by frequency for each subject, and subsequently averaged across the 12 subjects, or—whenever marked with an asterisk—four subjects. Experimental spreads (estimated from repeated measurement series as described in the Appendix) are shown with thin lines.

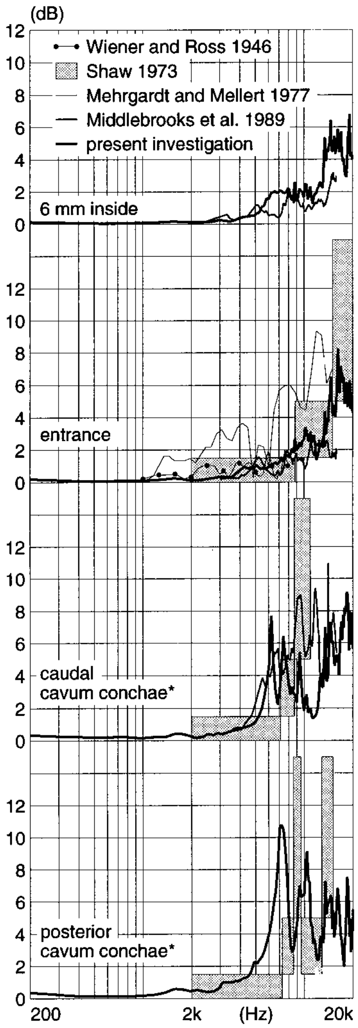

FIG. 8. Directional spreads of transmissions to the eardrum (Wiener and Ross[25] computed by us, Middlebrooks *et al.*,[31] and this investigation), ranges of transfer functions for the directions investigated (Mehrgardt and Mellert[30]), and boundaries for ranges (Shaw[27]). The exact position of the points from the literature deviate from those of the present investigation as described in the following. Shaw's ''caudal cavum conchae'' point is in the lower region of the conchae (denoted ''B5'' in his figure), whereas our point was at the dip in the edge of pinna. His ''posterior cavum conchae'' point (denoted ''C'') was slightly further from the rear of conchae than our point. The ''entrance'' data by Mehrgardt and Mellert are for the transmission from a point 2 mm inside the ear canal. The ''6 mm inside'' data by Middlebrooks *et al.* refer to the transmission from 5 mm to 14 mm inside, their ''entrance'' data are for the transmission from 0 mm to 10 mm inside, and their ''caudal cavum conchae'' data refer to the transmission from a point ''outside the ear canal, on the floor of the cavum conchae'' to 14 mm inside, whereas the point used in this investigation was at the dip in the edge of pinna.

P_2 does not exist during normal listening conditions, but if the ear canal is blocked, for instance by an earplug, P_2 can be found just outside the earplug.

P_4 denotes the sound pressure at the eardrum, and P_3 denotes the sound pressure at the entrance of the ear canal. The ear canal is modeled by a two-port, which is loaded by the eardrum impedance Z_{eardrum}. The input impedance to the two-port (as seen from the entrance of the canal), is denoted $Z_{\text{ear canal}}$.

When the model is used to describe the transmission in the free field, yet another definition is needed, namely P_1, which is the reference sound pressure found at the position corresponding to the center of the subject's head (subject absent).

The total sound transmission from the free field to the eardrum can be described by the ratio between the sound

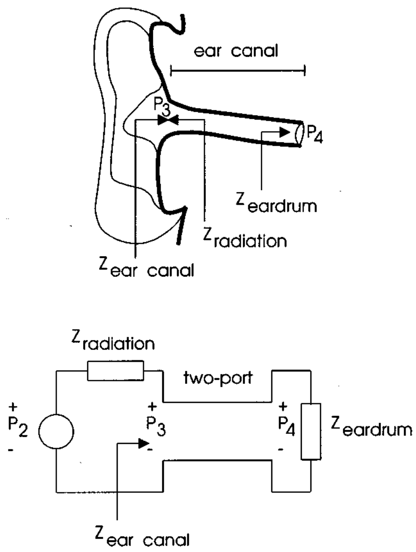

FIG. 9. Model of the free-field sound transmission to the human external ear. Upper part is a sketch of the anatomy and lower part is an analogue model.

pressure at the eardrum and the reference sound pressure (P_4/P_1). Using the model, the transmission can be split up into a directional-dependent part and two directional-independent parts:

$$\frac{P_4}{P_1}\ (\text{direction}) = \frac{P_2}{P_1}\ (\text{direction}) \cdot \frac{P_3}{P_2} \cdot \frac{P_4}{P_3}. \quad (1)$$

P_4/P_3 is the sound transmission along the ear canal, and P_3/P_2 is a pressure division at the entrance of the ear canal between $Z_{\text{ear canal}}$ and $Z_{\text{radiation}}$:

$$\frac{P_3}{P_2} = \frac{Z_{\text{ear canal}}}{Z_{\text{radiation}} + Z_{\text{ear canal}}}. \quad (2)$$

Both P_4/P_3 and P_3/P_2 are independent of direction of sound incidence. P_2/P_1 represents the directional-dependent part.

B. Data acquisition

Subjects, setup and instrumentation were the same as in experiment 1, and all measurements were made at the same occasion. After the measurements already reported for experiment 1, the ear canal was blocked by an EAR earplug, and the tube tip was left resting on the outside of the earplug, for measurement of P_2. P_1 was also measured by the probe microphone.

IV. EXPERIMENT 2: RESULTS AND DISCUSSION

Section IV A presents the division into transmission elements for a single subject. According to the model, the transmission from the entrance of the blocked ear canal to the eardrum is independent of direction, a fact that is supported by results shown in Sec. IV B.

Transmission elements for more subjects are shown in Sec. IV C. Comparisons with previous studies are given in Sec. IV D (single subjects) and in Sec. IV E (mean values).

A. Transmission elements, single subject

In Eq. (1) the complete transmission from the free-field sound pressure (without subject) to eardrum sound pressure was divided into 3 parts. For a single subject the division is shown for the three directions of sound incidence in Fig. 10. The example is characteristic for all 12 subjects.

It is (as expected) evident that the transmission from the free field to the blocked entrance (P_2/P_1) depends on direction. The three curves each have distinct features, and the differences are much larger than the differences seen in Sec. II. The pressure division (P_3/P_2) and the transmission along the ear canal (P_4/P_3) are independent of direction.

No further analysis of the directional-dependent features of P_2/P_1 is given here. It is not the aim of the investigation, and the racket and the microphone housing are likely to have had some influence on these transfer functions. However, Sec. II deals with the inter-individual variation of the free-field transmission to the ear. For additional studies on such functions—*head-related transfer functions*—carried out in our laboratory for more subjects and more directions, the reader is referred to Møller *et al.*[1]

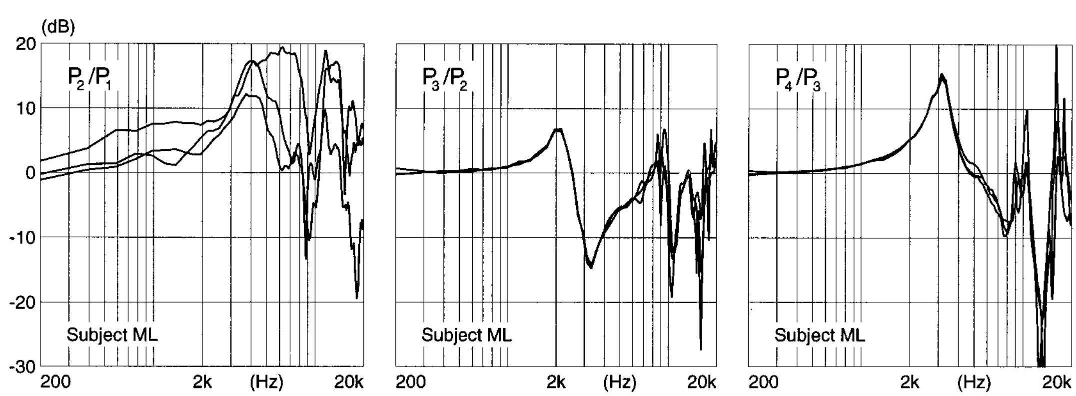

FIG. 10. Free-field sound transmission to the eardrum split up in consecutive parts for subject ML. Measurements for the three directions are overlaid in each frame.

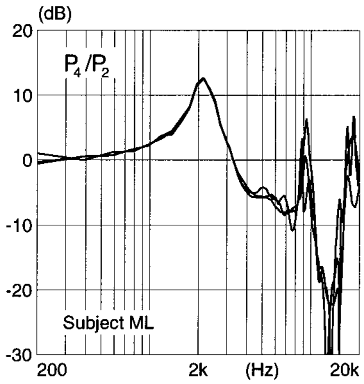

FIG. 11. Sound transmission to the eardrum from the entrance of the blocked ear canal for subject ML. Measurements for the three directions are overlaid.

The pressure division is approximately 0 dB for frequencies up to 1 kHz, which means that $Z_{\text{radiation}}$ is small compared to $Z_{\text{ear canal}}$ for this frequency range [see Eq. (2)]. For higher frequencies large fluctuations below and above 0 dB are seen, indicating that the two impedances are in the same order of magnitude, but unequal. In most cases, peaks in P_4/P_3 occur at the same frequencies as notches in P_3/P_2 and vice versa. This indicates an inter-dependence between the two parts.

B. Directional dependence, blocked entrance

The transmission to the eardrum from the blocked entrance is shown for a single subject in Fig. 11. As expected, this transmission is independent of direction. For completeness, the directional spread and experimental spread have also been computed, and they are shown in Fig. 12. Both spreads for this transmission are in the same size as those of the transmission from points within the ear canal, at the entrance, and 6 mm outside, as reported in Sec. II E.

On this background we do not hesitate in concluding that the directional independence observed for points in the open ear canal, is also valid for the blocked entrance.

The transmission to the eardrum from the blocked entrance has previously been reported by Shaw.[26,27] The ranges between directions reported in Ref. 27 were almost identical to those for the open entrance (Fig. 8, second row). In Sec. II E we argued that these ranges correspond to directional spreads of the same size as those of the present investigation. (Without showing the actual transmission, Shaw observed earlier that the transmission from the blocked entrance was directional independent up to 12 kHz.[57])

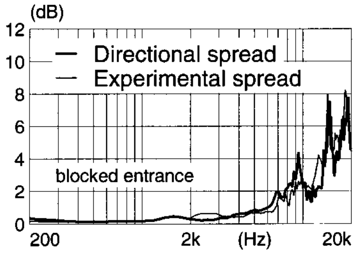

FIG. 12. Directional spread and experimental spread for transmission to the eardrum from the blocked entrance (based on data for 12 subjects). The directional spreads for the other transmissions to the eardrum were shown in Fig. 7.

In the further analysis of the directional independent transmission elements (P_4/P_3, P_3/P_2, and P_4/P_2), an average (in decibels) of the almost identical data for the three directions of sound incidence is used.

C. Transmission elements, 12 subjects

Figure 13 shows the directional independent transmission elements for 12 subjects. Upper row shows transmission elements for individual subjects. Although they vary much from subject to subject, the same structures can be identified.

Second and third row, respectively, show the mean value computed in decibels frequency by frequency and the corresponding standard deviation. The lowest standard deviation is seen for P_4/P_2. Although the transmission P_4/P_2 is the product of P_4/P_3 and P_3/P_2, the standard deviation is lower than if computed from the added variances (shown with a thin line on the same figure). This suggests a high correlation between P_4/P_3 and P_3/P_2. Correlation between transmission elements is further discussed in Sec. V D.

In general, the mean values display the same characteristics as the individual curves, although the peaks and notches are wider and reduced in size. This is due to the fact that the individual peaks and notches are placed at slightly different frequencies, thus the averaging blurs the structures. Alternative mean curves, obtained by averaging characteristic points in both frequency and level, are shown in the fourth row, and labeled *structural mean*.

The structural means are believed to better represent a typical subject. The transmission from the open entrance to the eardrum displays two peaks, one rather wide around 4 kHz (14 dB high), and one narrow around 12 kHz (11 dB high). A notch is also seen around 14 kHz. The two peaks are recognized in the pressure division as corresponding notches, and they are therefore not present in the transmission from the blocked entrance to the eardrum. The latter displays a wide main peak around 2.5 kHz, and the notch around 14 kHz.

It is not within the scope of this investigation to develop a circuit model that explains the measured transfer functions. It is, though, worth mentioning that a simple transmission line, rigidly terminated, is insufficient, since that would result in a ratio of 3 between the frequency of the two peaks in P_4/P_3. Furthermore, it would be tempting to suggest that the notch in P_4/P_3 and P_4/P_2 is due to an unintended distance to the eardrum during measurements of P_4. However, a distance in the order 6 mm (one fourth of a wavelength) would be required, and we believe that complicated structures of the eardrum impedance (and geometry) interact.

The term ear canal resonance is sometimes used, when the transmission to the eardrum is described. It is quite evident that several resonances are involved in the transmission, and the term is ambiguous. Even when only the structures at the lowest frequencies are considered, the term might ad-

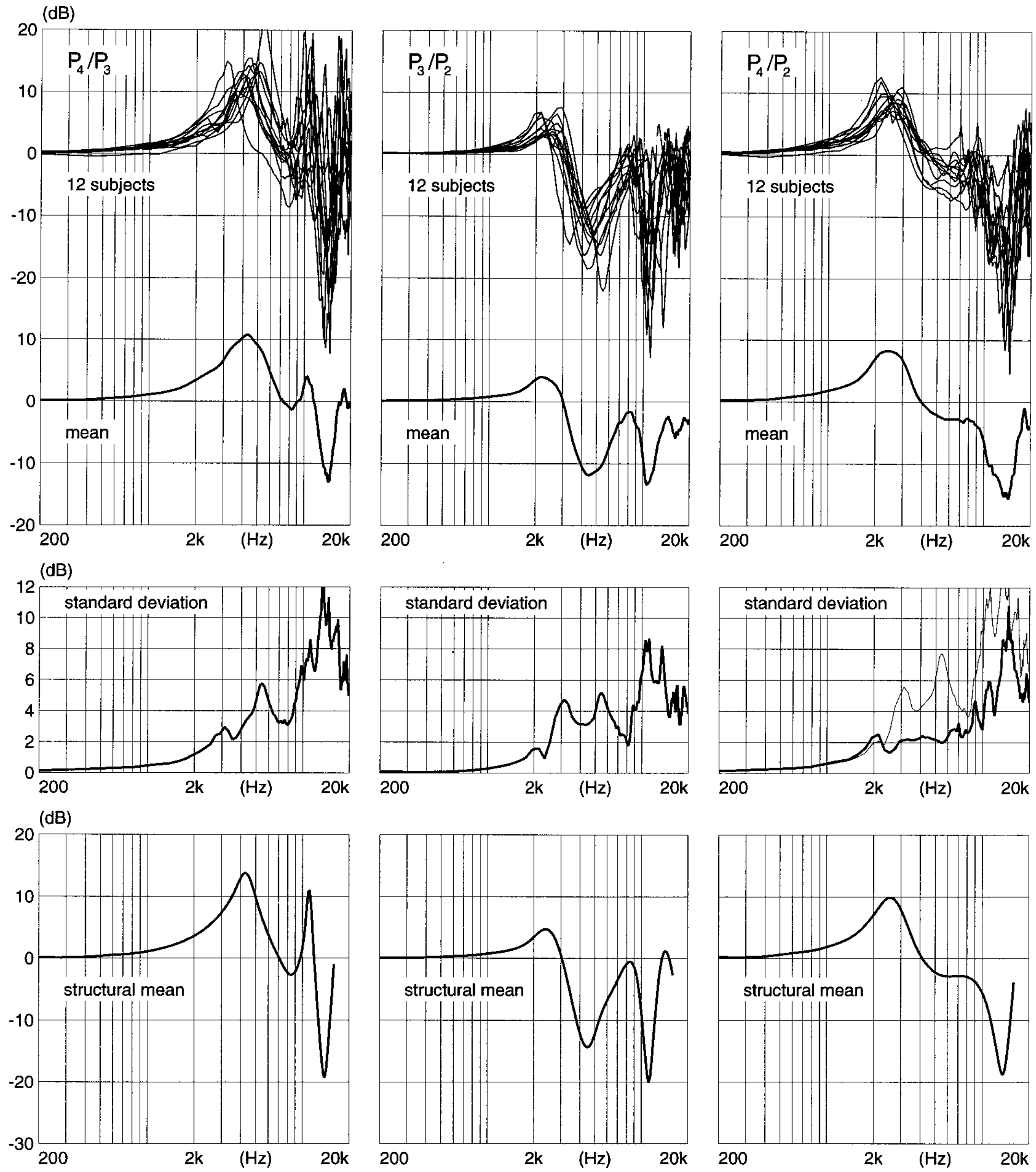

FIG. 13. Directionally independent parts of the sound transmission. Mean values and standard deviations are computed in decibels frequency by frequency. The thin curve in the frame with the standard deviation of P_4/P_2 is a computation of the same, assuming P_4/P_3 and P_3/P_2 uncorrelated. The structural means are obtained by averaging characteristic points, both in frequency and level.

dress the peak in P_4/P_3 (at 4 kHz) as well as the peak in P_4/P_2 (at 2.5 kHz).

D. Previous studies, single subjects

The literature presents only few data on the transmission elements for single subjects. Data on P_4/P_3 and P_4/P_2 for one ear replica are available from Shaw,[26] and data on P_4/P_3 for three subjects from Mehrgardt and Mellert.[30] Data on P_3/P_2 for a single subject can be calculated from data given by Sank.[58] These are shown in Fig. 14.

Shaw's data display characteristics that are very similar to those of our data. Although the actual levels are somewhat different from our typical data, there is excellent agreement with single subject data from our investigation (for P_4/P_3 compare for instance with subject RM in Fig. 4).

The general structure of the data by Mehrgardt and Mellert is also in good agreement with data of this investigation, but their data fluctuate unexpectedly around 1–2 kHz. Furthermore, the data for Mehrgardt and Mellert's three subjects seem more alike than the ones seen in this investigation.

The pressure division that we have computed from P_3 and P_2 data given by Sank,[58] matches in general poorly with our data. Sank used a $\frac{1}{4}$-in. microphone placed at the caudal cavum conchae, so his data represent approximate P_3 and P_2 data only. However, the difference in position is considered insignificant up to 5–6 kHz, and we believe that the devia-

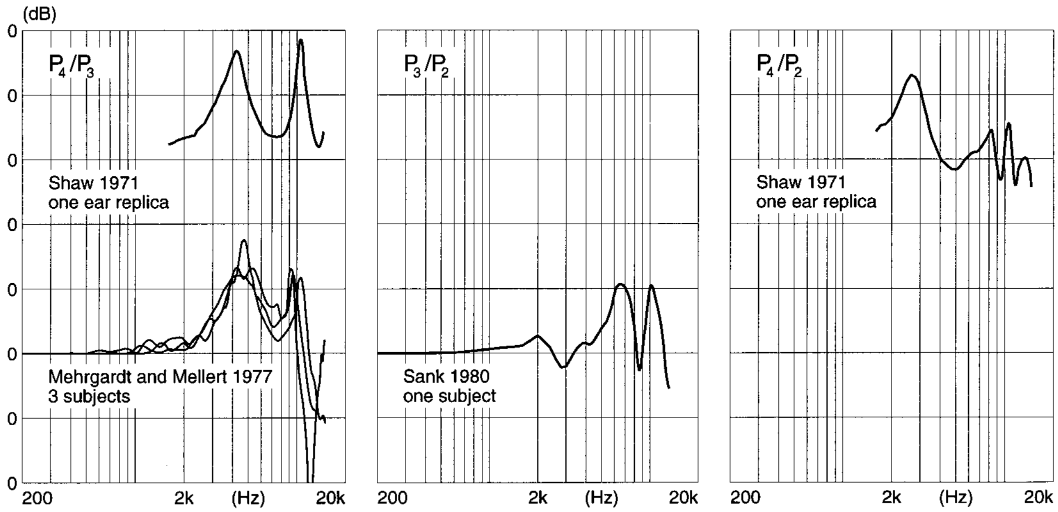

FIG. 14. Single subject measurements from the literature (Shaw,[26] Mehrgardt and Mellert,[30] and Sank[58]). From Shaw's data representing eleven directions, and being nearly identical, we have estimated typical curves. The original data by Sank were P_3 and P_2 measurements, and we have computed the ratio.

tions are only partly explained by differences in microphone techniques.

E. Previous studies, mean values for P_4/P_3

Mean values for the transmission from the open entrance to the eardrum, are available from Wiener[59] (based on data from Wiener and Ross[25]), Yamaguchi and Sushi,[60] Jahn,[46] Djupesland and Zwislocki[61] (median values, though), Shaw[62] (based on data from Wiener and Ross, Djupesland and Zwislocki, and Shaw[26]), later tabulated by Shaw and Vaillancourt,[63] Mehrgardt and Mellert[30] (computed by us), and Hellstrom and Axelsson.[52] Although minor deviations exist in the exact position of the measurement point at the entrance and—given the different experimental procedures—possibly also at the eardrum, we compare these data with ours. The mean values are shown in the left column of Fig. 15, while the middle column shows standard deviations whenever available. The standard deviation shown for Djupesland and Zwislocki has been derived from reported interquartile ranges, by assuming a normal distribution with an interquartile range equal to the average of the two ranges reported.

Good agreement is seen with data by Wiener and Ross, Djupesland and Zwislocki, and Shaw. Up to 8 kHz good agreement is also seen with the data from Hellstrom and Axelsson. Taking the span in time, the low number of subjects involved, and the wide range in instrumentation into account, it is remarkable that so similar results can be obtained.

Structures comparable to those of our data, are seen in the data of Yamaguchi and Sushi, and of Jahn, although at somewhat lower frequencies. This suggests that their measurement points may have been slightly outside the entrance, as also argued by Shaw.[62] The large standard deviation reported by Yamaguchi and Sushi, combined with the fluctuating nature of the mean curve, suggests a large experimental error.

Also the mean value by Mehrgardt and Mellert displays the same characteristics as our results, but the level differs somewhat. The mean value is based on three subjects only, and as mentioned in Sec. IV D the individual curves are much alike, a fact that is also reflected in their lower standard deviation. Mehrgardt and Mellert concluded that ''*(...) the transfer function of the ear canal corresponds to that portion, which (...) changes only little between different subjects*.''

We believe that the similarity between the three subjects by Mehrgardt and Mellert was coincidental, and that the standard deviations reflected in the studies by Wiener and Ross, Djupesland and Zwislocki, and by us, more truly represent the population.

Djupesland and Zwislocki have attempted to describe a typical subject by averaging after adjusting the frequency scale for individuals in a way that brings the first main peaks to match. The mean shown by Mehrgardt and Mellert is not identical to the computed mean of their individual subjects, and we assume that some process was used to likewise obtain a more typical curve. These two attempts are shown together with our structural mean in the right column of Fig. 15. Neither of the two differ much from the mean values of the investigations in concern, nor do they look more like our structural mean.

F. Summary

We conclude that the free-field transmission to the eardrum can be divided into three parts, (1) the transmission from free field to the blocked entrance, (2) a pressure division between the radiation impedance and the input impedance of the ear canal, and (3) the transmission along the ear canal. The latter two parts are directional independent, and have structures that vary in frequency and level between subjects. The two parts are correlated, and the combined transmission therefore varies less between subjects than either of the two.

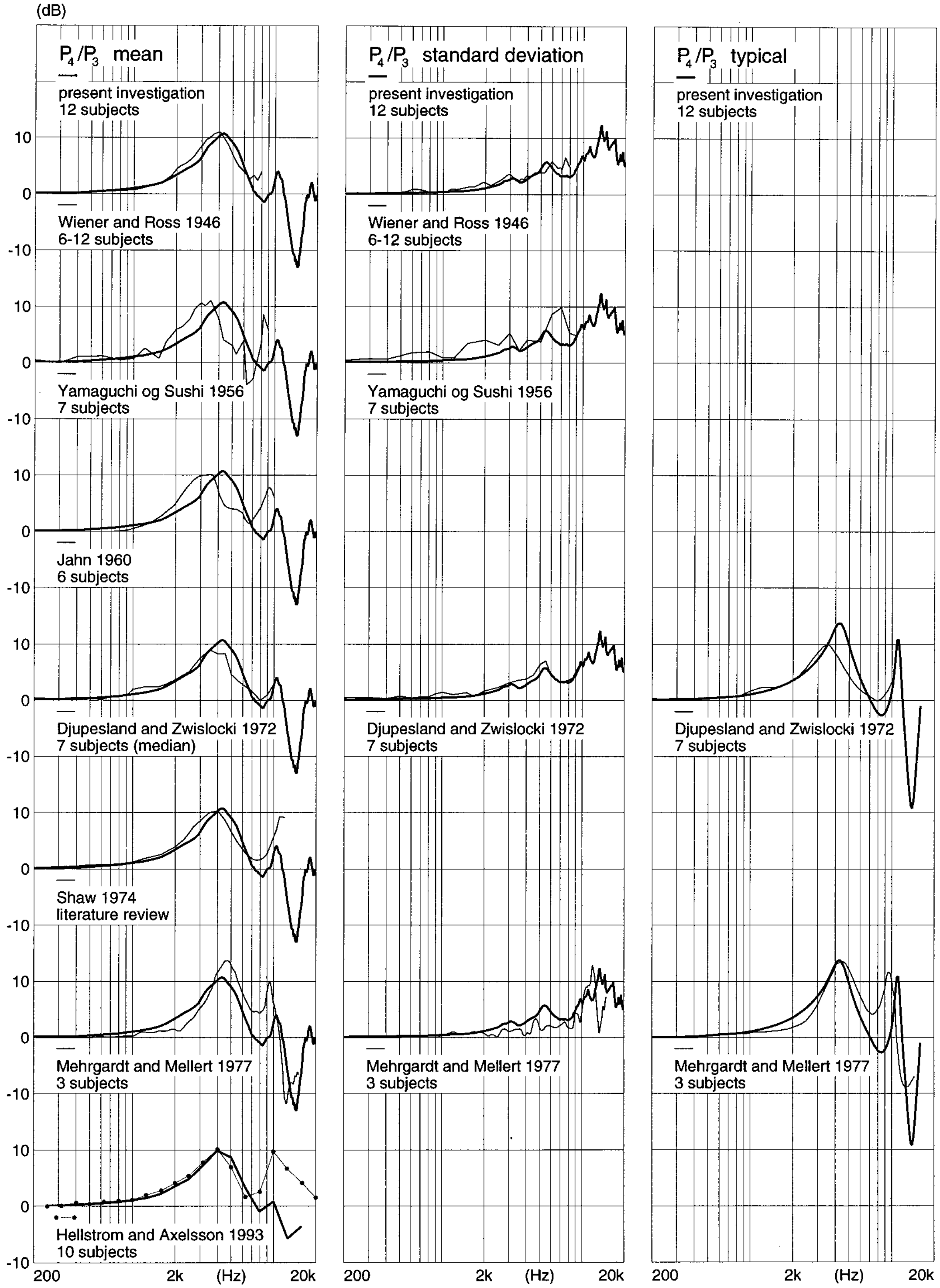

FIG. 15. P_4/P_3 means and standard deviations from the literature: Wiener and Ross,[25] (the mean value taken from Wiener[59]), Yamaguchi and Sushi,[60] Jahn[46,64] (determined in diffuse field), Djupesland and Zwislocki[61] (mean shown in the left column is the reported median values, standard deviation computed from interquartile ranges by us, the typical mean is their reported ''average (...) after normalization''). Shaw[62] (data taken from Shaw and Vaillancourt[63]), Mehrgardt and Mellert[30] (mean and standard deviation computed by us, the typical shown in the right column is their reported ''mean''), and Hellstrom and Axelsson[52] (third octave measurements, data from the present investigation have been computed as such for comparison. Measurements from a point 22 mm distant from the eardrum, being the entrance for the subjects with the shortest ear canals, while a few millimeters inside for others).

Typical curves for the pressure division, the transmission along the ear canal, and the combined transmission from blocked entrance to eardrum, have been derived by averaging characteristic points in both frequency and level.

V. HEAD-RELATED TRANSFER FUNCTIONS, VARIATION BETWEEN SUBJECTS

From the two experiments reported, we have concluded that the sound transmission to the eardrum is independent of

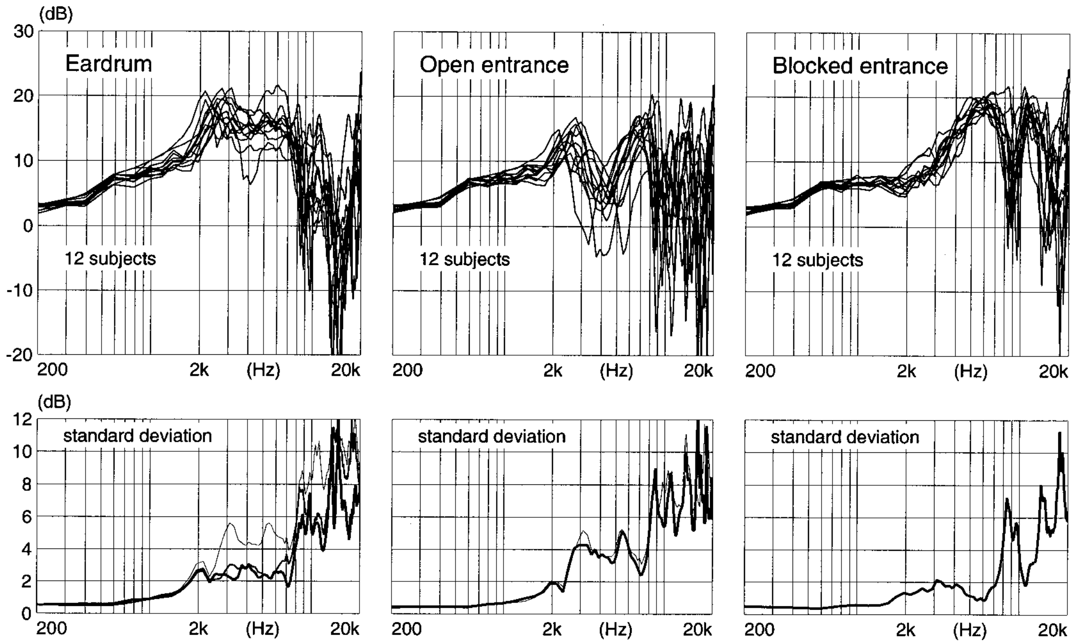

FIG. 16. Head-related transfer functions measured at the eardrum, at the open entrance, and at the blocked entrance, sound from the left side. Standard deviations (thick line) computed in decibels frequency by frequency. The thin line for the standard deviation of the open-entrance HRTF is computed assuming P_2/P_1 and P_3/P_2 uncorrelated. The thin line for the standard deviation of the eardrum HRTF is computed assuming P_3/P_1 and P_4/P_3 uncorrelated, whereas the medium line is computed assuming P_2/P_1 and P_4/P_2 uncorrelated.

direction for points within the ear canal, at the entrance, and possibly up to 6 mm outside. Also the transmission from the blocked entrance was independent of direction. Thus the sound at all these points include the complete spatial information provided the listener. Consequently any of the points may be used as recording point for binaural signals, or in characterization of the directional-dependent sound transmission to the ear.

From experiment 2 it was learned that all transmission elements are influenced by individual variations, and recordings at a given point will therefore be unique for each subject. The literature repeatedly suggest that individual binaural recordings are essential for good localization in the reproduction situation. However, we observed that the transmission elements are not equally influenced by individual variations, and we also noted a high degree of mutual dependence of the elements. We therefore suggest that a recording point may be found, to which the transmission from the free field shows minimal individual variation. A recording made at such a point in the ears of an arbitrary subject is thus more likely to resemble the recording that could be made in any listener's own ears.

The transmission from the free field to a point in the ear is described by the head-related transfer function (HRTF), defined as

$$\text{HRTF(direction)} = \frac{\text{sound pressure in the ear}}{\text{reference sound pressure}}\text{(direction)}. \tag{3}$$

The reference sound pressure corresponds to the pressure denoted P_1 in the preceding part of this article. In the following, variations across subjects in HRTFs for either of three points (at the eardrum, at the open entrance, and at the blocked entrance) are studied.

A. Three measurement points, single direction

Figure 16 shows HRTFs for 12 subjects, measured at the three points for a single direction. The general structure of the three transfer functions differ from one another, which is not unexpected recalling how the transfer functions from point to point look (Figs. 10 and 13).

The eardrum HRTFs rise slowly from 0 dB to approximately 10 dB at 1.5 kHz. Below this frequency only minimal variation is seen between subjects. A plateau is seen between 2 and 8 kHz, although some inter-individual variation exists. At higher frequencies there is a group of notches at 8–10 kHz, and one at 14–16 kHz.

The open-entrance HRTFs have broad peaks at 2–3 kHz, succeeded by broad notches at 3–5 kHz, both highly individual in frequency and level. Any pattern above 8 kHz is hardly identifiable.

The blocked-entrance HRTFs have broad peaks at 4–6 kHz, which are almost identical for the subjects. They are followed by deep notches around 8–10 kHz, and although they look very much the same for all subjects, the exact frequencies, at which they occur, differ slightly. Rather unsystematic peaks and notches are seen above 14 kHz.

The standard deviations between subjects for the three free-field transfer functions (given by the thick lines in the lower row of Fig. 16) reflect the observations just mentioned.

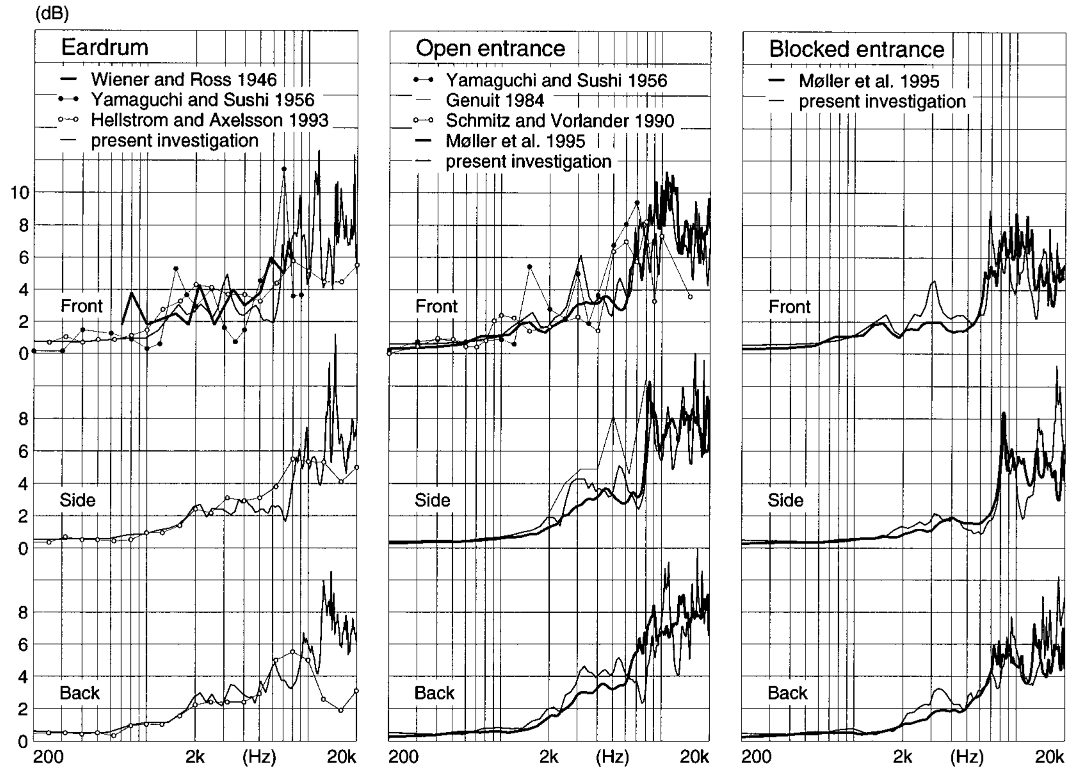

FIG. 17. Standard deviations between subjects for head-related transfer functions from the literature: Wiener and Ross[25] (6–12 subjects), Yamaguchi and Sushi[60] (7 subjects), Genuit[39] (measured 4 mm inside the ear canal, 6 subjects, computed by us), Schmitz and Vorländer[41] (measured 4–5 mm inside the ear canal, 10 subjects, computed by us), Hellstrom and Axelsson[52] (measured in third octave, 19 subjects), Møller *et al.*[1] (40 subjects, made available), present investigation (12 subjects).

The standard deviation is low up to 2 kHz for all three points. For the frequency range 2–8 kHz the blocked-entrance HRTF has the lowest standard deviation, while the open entrance has the highest. All points show high standard deviations above 14 kHz. The thinner lines in the figure will be discussed in Sec. V D.

B. Three measurement points, single directions, and previous studies

Standard deviations for single directions are available from Wiener and Ross[25] (6–12 subjects), Yamaguchi and Sushi[60] (7 subjects), Genuit[39] (computed by us, 6 subjects), Schmitz and Vorländer[41] (computed by us, 10 subjects), and Hellstrom and Axelsson[52] (19 subjects). Two sets of data from our laboratory are presented, the one from the present study, and one from a later study (Møller *et al.*,[1] 40 subjects). Genuit, and Schmitz and Vorländer measured 4–5 mm inside the ear canal, a fact that is considered unimportant in the comparison of inter-individual variations. Unlike for the other investigations, Hellstrom and Axelsson's made the measurements in third octave bands, a fact that should be remembered, when data are compared.

The data are presented in Fig. 17, with eardrum HRTFs, open-entrance HRTFs, and blocked entrance HRTFs, arranged columnwise. Data from three directions are presented in three rows.

In general, the standard deviations obtained in the various investigations compare well, although the data by Yamaguchi and Sushi do seem to differ somewhat from the others. Wiener and Ross have a slightly higher standard deviation at lower frequencies, which is likely to be caused by a larger experimental error (which is dominant in this frequency range). Data by Genuit are in general a little higher. Hellstrom and Axelsson obtain lower values for frequencies above 10 kHz, which may be due to the third-octave measurement technique that levels out the narrow and individual notches in this frequency range.

Comparison across the different measuring points suggest that the standard deviation is lowest for the blocked entrance.

C. Three measurement points, full sphere, and previous studies

A more representative illustration of the difference between the three measurement points is given in Fig. 18, where only data comprising more directions and many subjects are included. Data from the present investigation are averaged across three directions (left column), and data by Møller *et al.*[1] averaged across 97 directions (middle col-

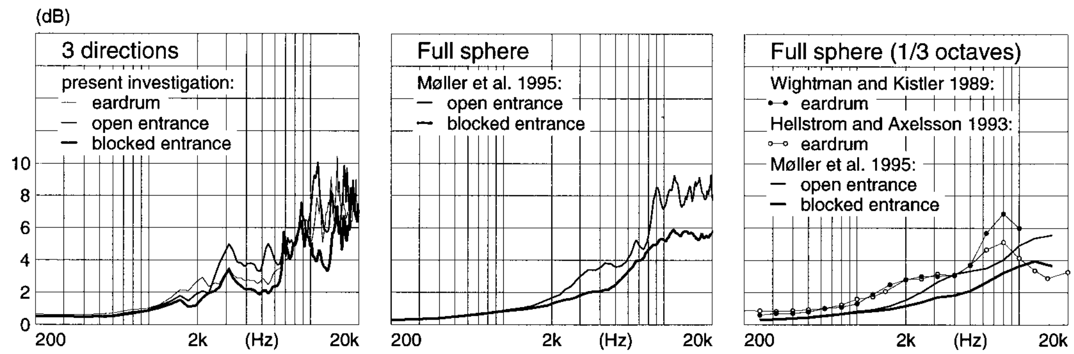

FIG. 18. Standard deviations for head-related transfer functions averaged across several directions: Wightman and Kistler[49] (48 directions, 10 subjects), Hellstrom and Axelsson[52] (72 directions, 19 subjects, computed by us), Møller *et al.*[1] (97 directions, 40 subjects), and present investigation (3 directions, 12 subjects).

umn). The right column shows data in third octaves from Wightman and Kistler[49] (averaged across 48 directions, 10 subjects), Hellstrom and Axelsson[52] (averaged across 72 directions), and Møller *et al.*

A cross comparison shows that the blocked-entrance HRTFs have the lowest standard deviation of all. Comparisons based on our own data further suggest that the standard deviation for the eardrum HRTFs is a little larger than the standard deviation for the open-entrance HRTFs around 1–2.5 kHz, while the data for the open entrance is larger than the eardrum data around 2.5–7 kHz. The same ranking between eardrum HRTFs and open-entrance HRTFs is not found in the full-sphere third-octave data, since here the standard deviations for the eardrum HRTFs equal or exceed the standard deviation for the open entrance for most of the frequency range.

On this background it seems safe to conclude that the inter-individual variation in the blocked-entrance HRTFs is lower than that of the open entrance and the eardrum HRTFs. How the two last rank, is not obvious.

D. Three measurement points, correlations

The difference in standard deviations between the three types of HRTFs can be explained by mutual dependencies.

The open-entrance HRTF (P_3/P_1) is the product of the blocked-entrance HRTF (P_2/P_1) and the pressure division (P_3/P_2). If the latter two are uncorrelated, then the standard deviation computed from their added variances will equal the standard deviation of the former. The standard deviation computed this way is shown with a thin line in Fig. 16 (bottom middle column). This is almost identical to the true standard deviation (thick line), and we conclude that the blocked-entrance HRTF (P_2/P_1) is uncorrelated with the pressure division (P_3/P_2).

Likewise, the eardrum HRTF (P_4/P_1) is the product of the open-entrance HRTF (P_3/P_1) and the transmission along the ear canal (P_4/P_3). The standard deviation computed from the added variances is shown with the thin line in Fig. 16 (bottom left column). It is obviously higher than the true standard deviation (thick line), thus indicating a correlation between the open-entrance HRTF (P_3/P_1) and the transmission along the ear canal (P_4/P_3). This could be expected, since P_3/P_1 includes P_3/P_2, and this part has already been shown to be correlated with P_4/P_3 (see Sec. IV C).

Alternatively, the eardrum HRTF (P_4/P_1) can be regarded as the product of the blocked-entrance HRTF (P_2/P_1) and the transmission from the blocked entrance to the eardrum (P_4/P_2). The standard deviation computed from the added variances of these is shown with medium linewidth, and since it is almost identical to the true standard deviation, we conclude that the blocked-entrance HRTF (P_2/P_1) is uncorrelated with the transmission from the blocked entrance to the eardrum (P_4/P_2).

A similar calculation (not shown) has revealed that the blocked-entrance HRTF (P_2/P_1) and the transmission along the ear canal (P_4/P_3) are uncorrelated. We therefore conclude that the transmission from free field to blocked entrance is uncorrelated with any part of the remaining transmission. Furthermore, all above observations have been confirmed for the other two directions (not shown).

E. Summary

It is concluded that blocked-entrance head-related transfer functions have a lower standard deviation between subjects than open entrance and eardrum HRTFs. Our own results suggest that open-entrance HRTFs have the largest standard deviation between subjects.

The introduction of the blocked entrance has made it possible to divide the total transmission from the free field to the eardrum into (1) a directional-dependent part, and (2) a directional-independent part, in a way that renders the two parts uncorrelated.

VI. CONCLUSION

On background of our own measurements, and those reported earlier in the literature, we conclude that the sound transmission to the eardrum from the entrance of the ear canal can be considered independent of direction of sound incidence. This is the case for the open entrance as well as the blocked entrance. The transmission from points in the conchae is, in general, directional dependent. Our own results suggest, though, that the region with directional-independent transmission extends some millimeters outside the entrance plane.

Sound containing full spatial information can thus be recorded at any depth in the ear canal. This conclusion is supported in another study in our laboratory.[5] Individual binaural recordings made at the blocked entrance were reproduced through individually equalized headphones, and listening tests showed that the localization performance from the real life situation was truly reproduced.

The transmission to and within the ear canal is highly individual. The blocked entrance divides the transmission from the free field to the eardrum into two uncorrelated parts: (1) the transmission from the free field to the blocked entrance, and (2) the transmission from the blocked entrance to the eardrum. Only the former of these is directional dependent.

The directional-independent part can be further divided into two parts: (2a) the transmission from blocked entrance to open entrance, which is a pressure division between the radiation impedance and the ear-canal input impedance, and (2b) the transmission along the ear canal from the open entrance to the eardrum. Due to mutual dependence of the two parts, smaller variation between subjects is seen for the combined transmission than for any of the parts in separate.

It is obvious that the sound pressure at the eardrum is the physical input to our hearing. However, measurements at the eardrum of humans are difficult and potentially dangerous, and acousticians have from time to time tried to avoid these measurements, when quantifying sound exposures. On the basis of our investigations we dare give a few guidelines for various applications. Some of these are in accordance with current practice, some are not.

When aiming at knowledge about the actual sound pressure at the eardrum of a specific subject, no alternative to eardrum measurements exists. A lot of situations, though, only require comparison of the eardrum pressures in two situations. Except when a transducer or other elements are inserted directly in the ear canal, then—for a given subject—the transmission from the entrance is the same in the two situations. Consequently, exactly the same comparison can be made by using pressures measured at the entrance. Some examples involve a comparison between the exposure from two sound fields, such as a diffuse and a free field, free sound waves from two (or more) directions, or exposure in a given field with and without ear-muffs. Other examples are those where a transducer (headphone) is to replicate the exposure of a specific sound field (e.g., the calibration of Hi-Fi headphones to a diffuse or free field), or where the sound produced by a headphone is to be transferred to an equivalent free-field exposure (e.g., in assessing the risk of hearing damage from walkmen).

Whenever the pressure division is the same in the two situations, then also the transmission from the blocked entrance to the eardrum is the same. Consequently, the above mentioned comparison may be made between blocked entrance sound pressures. Identical pressure divisions only exist—in principle—when the radiation impedance is undisturbed, which requires that no object is mounted close to the ear. Although we believe that most headphones do affect the radiation impedance, we have (in another study[2]) seen that the effect of many traditional headphones is not so severe that it significantly alters the pressure division.

It is an interesting issue that measurements at the blocked entrance—whenever adequate from a pressure division point of view—provide information of more general validity than measurements at the open entrance. Due to the lower standard deviation, the blocked-entrance pressure is more likely to be representative of a population. Even the sound pressure at the eardrum of an individual can be more accurately estimated by (a) transferring individual blocked-entrance data to the eardrum with a typical (literature) transfer function, than by (b) transferring individual open-entrance data to the eardrum with a corresponding typical transfer function. The reason is that an open-entrance measurement contains individual characteristics that no typical transfer function can ever account for.

ACKNOWLEDGMENTS

The work presented in this paper was paid by the Danish Technical Research Council, and this support is acknowledged. Assistance in making the setups by Claus Vestergaard Skipper and constructive criticism from colleagues Michael Friis Sørensen and Clemen Boje Jensen is sincerely acknowledged. Medical doctor Peder Christian Frandsen from Aalborg Hospital is especially thanked for his collaborative attitude and his professional engagement in the placement of the probe tip in the ears of the subjects. Finally, our patient subjects who spent hours in our laboratory enduring these obnoxious measurements are truly acknowledged.

APPENDIX: VALIDITY OF RESULTS

There are many sources of errors in measurements of this kind, and one way to obtain an estimate of their magnitude is by comparing repeated measuring series. Repeated measuring series were conducted for most subjects, since a perfect monitoration of the measurements was considered impossible, as the desired transfer functions would not arise until after data processing using two transfer functions, not measured at the same time, and not necessarily existing at the same time. Only a few measurements were discarded in the succeeding data processing, though, and consequently valid data for repeated measuring series exist for most subjects.

Figure A1 shows repeated measurements of the directional-independent elements for six subjects. Placement of the subject (and microphone holder and probe tip) was redone in between the measurements. The general structure of the measurements are indeed similar and for most measurements, the transfer functions from time to time coincide.

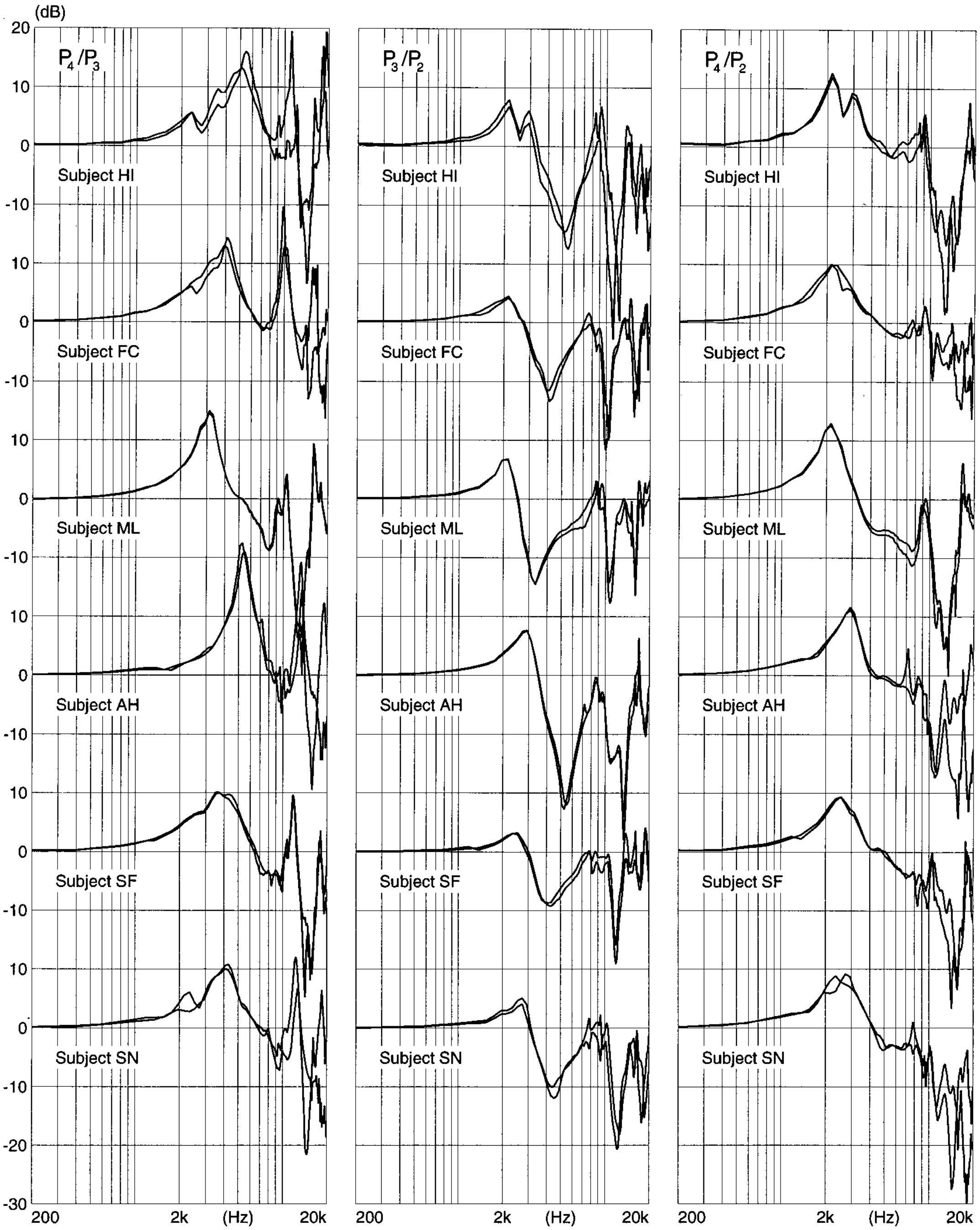

FIG. A1. Repeated measurements of the directional-independent transmission elements. Each curve is the mean of the three directions.

Differences in the general structure of the transfer functions are seen for frequencies above 12–15 kHz, see for instance subjects AH and SN.

The experimental spread discussed in Sec. II E and IV B, and shown in Fig. 7 and Fig. 12, has been computed as the standard deviation between the repetition measurements calculated in decibels frequency by frequency, subsequently averaged across directions, and finally averaged across subjects (for six subjects).

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