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4pEAa7. Using inter-individual standard deviation of hearing thresholds as a criterion to compare methods aimed at quantifying the acoustic input to the human auditory system in occluded ear scenarios

Matthias Blau*, Tobias Sankowsky-Rothe, Simon Köhler and Jan-Henning Schmidt

*Corresponding author’s address: Institut für Hörtechnik und Audiologie, Jade Hochschule Wilhelmshaven/Oldenburg/Elsfleth, Ofener Str. 16/19, Oldenburg, 26121, Niedersachsen, Germany, matthias.blau@jade-hs.de

Occluded ear scenarios are found in many applications, e.g. hearing aids or insert ear phones. Unfortunately, the correct quantification of the acoustic input delivered to the auditory system in such a scenario is complicated by the individual character of our outer ear anatomy. For instance, one can easily observe inter-individual differences in ear drum pressure level of up to 30dB at 10kHz with one and the same sound source. We may thus ask: 1.) Is the sensitivity of our auditory system at threshold adapted to our outer ear anatomy? and 2.) what is the best method to quantify the acoustic input? We propose using the inter-individual standard deviation of hearing thresholds as a means to answer these questions: The quantity that is best suited to describe the input to the auditory system should result in the lowest inter-individual standard deviation of thresholds. Preliminary results based on tests with custom ear shells and with foam ear plugs show that up to 6kHz, there are no significant differences between the methods tested, whereas in the 7-10kHz frequency range, individual estimates of the sound pressure at the ear drum yield a significantly lower inter-individual standard deviation than the ear simulator pressure.

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INTRODUCTION

Occluded ear scenarios are found in many applications, e.g. hearing aids or insert ear phones. Unfortunately, the correct quantification of the acoustic input delivered to the auditory system in such a scenario is complicated by the individual character of our outer ear anatomy. For instance, one can easily observe inter-individual differences in ear drum pressure level of up to 30dB at 10kHz with one and the same sound source [1].

What happens with these large inter-individual differences? Do they result in equivalent or even larger differences in perceived hearing thresholds? Or alternatively, is the auditory system adapted to our outer ear anatomy, such that it compensates for the sound transfer within the individual ear canal? In either case, what is the best method (among the ones currently available) to quantify the acoustic input for an individual subject?

Most of the research reported in the literature has focused on this last question. Typically, researchers proposing methods to quantify the acoustic input argue that their respective methods don't suffer from the quarter-wavelength minimum problem encountered when measuring the sound pressure in the ear canal [2, 3, 4]. While it is certainly good to get rid of the $\lambda/4$ dip, this merely tells us that our measurement may be less prone to errors and thus perhaps more reliable but it does not tell much about the validity of the measurement, i.e. about what we are actually sensitive to.

For instance, one check that was proposed by Neely and Gorga [2] is to make sure that the quantity in question would not give different results for different insertion depths of the sound source. This led those authors to claim that sound intensity in the ear canal would be a better reference quantity than sound pressure for OAE measurements. Unfortunately, this doesn’t answer the question “what do we hear?” either. Ultimately, the requirement of being independent of insertion depth would favor quantities that are independent of the individual ear acoustics, such as the ear simulator pressure or the voltage applied to the sound source.

As another example, methods predicting the sound pressure at the ear drum are often assessed by comparing the predictions to direct measurements with probe tube microphones. However, at higher frequencies the reliability (let alone the validity) of probe tube measurements becomes questionable. The problem is usually quantified by numerical simulations of the sound field in front of the ear drum. Unfortunately, these simulations are rather cumbersome, with the result that only single case studies exist. For instance, Hudde/Schmidt [5] observed level differences of more than 20 dB (!) at 8 kHz, while Roeske et al. [6] obtained only about 4 dB at the same frequency. Thus, for the time being, one may trust probe tube measurements up to somewhere between 4...8 kHz, but rather not at higher frequencies. Incidentally, this is exactly the frequency range where the individual ear canal acoustics starts to produce large inter-individual differences, see also fig. 7 in the discussion.

As a consequence, we have to look for something else, and take perception into account as well. This is of course complicated because all we know about perception depends in turn on a known strength of the acoustic input. In order to break this vicious circle, the only way to go is to trust statistics.

In the present study, we propose using the inter-individual standard deviation of hearing thresholds as a means to answer the questions outlined above: The quantity that is best suited to describe the input to the auditory system should result in the lowest inter-individual standard deviation of thresholds. In particular, if the sensitivity of the auditory system at threshold was adapted to our outer ear anatomy, then non-individual quantities such as the ear simulator pressure should result in lower inter-individual standard deviations of thresholds than individual quantities.

While the inter-individual standard deviation at threshold can be applied to quite different quantities such as the voltage at the sound source, sound intensity and forward going components of the sound pressure in the ear canal, to name a few, we focus on the sound pressure here. More specifically, we compare
FIGURE 1: Devices used for sound delivery to the subjects' ears. Left: custom ear shell, right: foam plug.

- the sound pressure generated in an ear simulator (ear simulator pressure, SimP), and
- the sound pressure at the individual ear drum (ear drum pressure, DrumP).

The latter is usually not measured directly, but estimated from simpler measurements. Here, we consider methods based on the measured acoustic impedance at the entrance of the residual ear canal; see also the companion papers [7, 8].

MATERIAL AND METHODS

As a basis for this research, hearing thresholds and acoustic input impedances were measured in human subjects.

Two series of measurements have been completed. In one of them, custom ear shells were used to deliver sound to the subjects' ears, see left picture in fig. 1. The measurements took place between November 2010 and March 2011, and some results have been published in [9] (in German only). In the other one, ordinary yellow foam ear plugs were used, see right picture in fig. 1. These measurements were performed between September 2011 and June 2012.

Both custom ear shells and foam plugs were fitted with silicone tubes in order to provide microphone and receiver ports, see fig. 1. These tubes were respectively connected to a wideband hearing aid receiver (Knowles type TWFK-23991, Knowles Electronic Holdings, Inc., Itasca, IL, USA) and to an ER-7C microphone (Etymotic Research, Elk Grove Village, IL, USA).

Subjects

Nineteen subjects were recruited for the ear shell study, and 31 subjects for the foam plug study. All subjects were students with previous experience in audiometric testing.

Subjects with more than 20 dB hearing loss at any audiometric test frequency were excluded from the study prior to the actual experiments (1 subject in the ear shell study, 2 subjects in the foam plug study). In addition, subjects with unusual ear canal impedances (i.e. with no clear quarter wavelength dip) were excluded from the study (2 subjects in the ear shell study, 4 subjects in the foam plug study). Thus, in total 16 subjects (7 female, 9 male, 19 to 32 years old) finally participated in the ear shell study and 24 subjects (13 female, 11 male, 20 to 25 years old) in the foam plug study.

All experimental procedures were approved by the University of Oldenburg ethics committee.

Measurement of Hearing Thresholds

Hearing thresholds were measured using the Békésy tracking method with pulsed tones of logarithmically increasing frequency (4 octaves, from 707 Hz to 11314 Hz). Each pulse consisted
FIGURE 2: Illustration of the procedure to extract the interpolated hearing threshold. Only frequencies between 1 kHz and 10 kHz were considered in the subsequent analysis.

of an “on” phase of 200 ms, preceded and followed by linear ramps of 60 dB per 120 ms, and was repeated every 448 ms. With the frequency of the test tone increasing at 1 octave per minute, this resulted in 134 pulses per octave. During the “on” phase and the ramps, the frequency of the test tone was kept constant. The level changed at a rate of 2.5 dB/s.

Stimuli were generated and controlled digitally using a custom patch within the Pure Data software package [10]. The sound was delivered to the subjects’ ears via a DA converter (RME Multiface, RME Intelligent Audio Solutions, Heinhausen, Germany) and an electronic attenuator (TDT type HB 7, Tucker-Davis Technologies, Alachua, FL, USA), to which the receiver-shell/foam plug devices shown in fig. 1 were connected.

The presentation level was calibrated such that, at 0 dB HL, it would generate the corresponding RETSPL values of ISO 389-2 (up to 4 kHz) and the minimum audible pressure level values at the ear drum of [11] (above 4 kHz) in a model of an IEC-711 ear simulator, driven by our model of the source. The ear simulator model was in turn adapted from [12], the source model from pressure measurements at the end of hard-walled tubes of varying length (method a taken from [13], see there for details of the source models).

From the Békésy tracking, one obtains a frequency-dependent level curve which oscillates around the “true” threshold, see fig. 2 for an example. The threshold was determined from this curve by first computing the average level between two reversals and assigning this value to the average of the two reversal frequencies (crosses in fig. 2). Subsequently, these values were used in a cubic spline interpolation at 100 logarithmically spaced frequencies between 1 kHz and 10 kHz, see red curve in fig. 2.

**Estimation of the Sound Pressure at the Ear Drum**

In order to convert the interpolated hearing thresholds to equivalent drum pressure levels, the transfer function of the drum pressure, relative to the receiver voltage, is needed. These transfer functions were estimated using two-port models of the sound source and the ear canal (including leak and load impedances), derived from measured acoustic impedances at the entrance of the residual ear canals, as presented in the companion papers [7, 8]. The reader is referred to these papers for the details of the methods. Of the methods discussed in [8], method M4 (32-segment ear canal model, joint model for leak and drum from measured input impedance) was used. In addition, a manually tuned model of the ears was used, referred to as M10.
RESULTS

In fig. 3, the interpolated hearing thresholds are shown for both the ear shell and the foam plug configurations. For both configurations, the mean is within ±5 dB at all frequencies (except for the ear shells at around 1 kHz). One may notice a slight trend to positive hearing losses with the shell configurations at frequencies below about 6 kHz, and for the foam plug configurations at frequencies above about 6 kHz.

In fig. 4, the same data is expressed as equivalent simulator pressure levels, generated by the source models together with a two-port model of the IEC 711 ear simulator from [12]. The values obtained with the shell configurations match the estimate from [11] very well. With the foam plug configurations, one can observe slightly lower simulator pressure levels at threshold below about 4 kHz and slightly higher ones above about 5 kHz.

In fig. 5, the equivalent sound pressure levels at threshold are no longer based on ear simulator models, but rather on individual models of ear canal, leak and load impedance. Thus, we refer to drum pressure levels now.

In general, the spectrum of the mean drum pressure level at threshold remains more or less
the same across all methods and configurations. Also, the difference to the values from [11] rarely exceeds 5 dB.

Method M4 yields slightly higher drum pressure levels at threshold than the ones obtained with the ear simulator model (fig. 4). The mean results for M10 are, at least for the ear shell configurations, closer to the data from [11].

In fig. 6, we eventually turn to the analysis of the inter-individual standard deviation of the different quantities at threshold. Up to about 6 kHz (for the foam plug configurations) or 7 kHz (for the ear shell configurations), there is hardly any difference between the quantities considered here. It may however be noted that the inter-individual standard deviation of thresholds tends to be slightly higher for the foam plug configurations compared to the ear shell configurations.

Above 6...7 kHz, the picture becomes somewhat different for the ear shell versus the foam plug configurations. For the ear shell configurations, the inter-individual standard deviation of the simulator pressure level at threshold increases rapidly above 7 kHz, whereas for the foam plug configurations, this increase is much less pronounced. The individual drum pressure levels generally yield lower inter-individual standard deviations of thresholds at these frequencies (for the foam plug configurations, this is only true up to 8...9 kHz). This reduction of the standard deviation is statistically significant (Pitman's test [14] with \( p < 0.05 \)) for the drum levels predicted with M10 in the ear shell study between 7...10 kHz and for the drum levels predicted...
FIGURE 6: Inter-individual standard deviations of pressure levels at threshold. As a reference, the standard deviation of the simulator pressure levels at threshold is shown as a thick blue line. The standard deviations of the individual drum pressure levels at threshold are only shown as thick lines at frequencies where they are significantly (Pitman's test, \( p < 0.05 \)) different from the standard deviation of the simulator pressure levels at threshold. **Left:** ear shell study (N=16). **Right:** foam plug study (N=24).

with M4 in the foam plug study around 7 kHz.

**DISCUSSION**

The observation that the inter-individual standard deviation of hearing thresholds is reduced by referring the thresholds to estimates of the individual ear drum pressure level supports the hypothesis that the auditory system is *not* adapted to the individual transfer characteristics of our outer ears. If one thus assumes that the transfer characteristic of the outer ears is, at threshold, independent of the characteristics of the further stages in the auditory system, then the maximum possible reduction of the inter-individual variance of thresholds by referring to the individual drum pressure instead of the simulator pressure would be given by the inter-individual variance of the outer ear transfer characteristics in relation to that of the ear simulator. Because of the comparatively high source impedance in occluded ear scenarios, the transfer characteristics of the outer ear is given by its transfer impedance (i.e., the transfer function of the sound pressure at the ear drum, relative to the volume velocity at the entrance to the residual ear canal). In order to make an estimate of the maximum-possible reduction of the inter-individual variance, one must only relate the transfer impedance of the individual ears (estimated by the prediction methods considered here) to the transfer impedance of the ear simulator, obtained from a two-port model of the latter from [12]. This quantity is referred to as “RECD”, with the quotation marks indicating that it is not an RECD in the strict sense (because of the reference to an ear simulator instead of to a 2cc-coupler and because it is not directly measured).

In fig. 7, the observed reduction in variance by referring the thresholds to the ear drum pressure levels predicted by M10 instead of to the simulator pressure level is plotted alongside an estimate of the variance of the “RECD” (also based on M10). For comparison, the variance of the RECD, observed in a previous study (Blau et al. 2008 [15]), in which much care was taken to cover a wide anatomical range of ear canal cross sections, is also shown.

For the ear shell configurations, the estimated inter-individual variance of “RECDs” is close to the one observed in [15] up to about 5 kHz, but smaller at higher frequencies. For the foam plug configurations, the estimated inter-individual variance of “RECDs” is still smaller. This indicates that the subjects chosen in the ear canal study, and even more in the foam plug study, may have exhibited less anatomical variability than the subjects in [15]. It is speculative to
FIGURE 7: Estimated variance of the ratio of transfer impedances of the individual ears (estimated by M10) to the transfer impedance of an ear simulator, referred to as “RECD” (solid line), together with the observed reduction in the variance of hearing thresholds, if the latter were referred to individual drum pressure levels (predicted by M10) instead to simulator pressure levels (dashed line). Also shown is the variance of RECDs from Blau et al. 2008 [15] (crosses). **Left:** ear shell study (N=16), **right:** foam plug study (N=24).

predict what the results would have looked like with more anatomical variability, but there are chances that the observed reduction in inter-individual standard deviations of thresholds would become more pronounced.

Although the same trends were observed for shell and foam plug configurations, it is somewhat unsatisfactory that the reduction of inter-individual standard deviations of hearing thresholds is smaller in the foam plug configurations, and that the “best” method, resulting in the lowest inter-individual standard deviations, is M10 for the shell configurations whereas it is M4 for the foam plug configurations. Can these discrepancies be explained?

In fact, it turned out that the underlying assumption that the ear plug would occlude the ear as a hard wall is not justified: A measurement of the acoustic impedance of a foam plug squeezed into a cylindrical hard-walled tube of 7.5 mm diameter revealed that the foam plug impedance decreases from about 170 dB (re 1 Pa s/m^3) at 100 Hz to about 155 dB at 10 kHz, which means that it becomes lower than typical ear drum impedances above about 6 kHz. As a consequence, Q-factors of the λ/4 dip in the measured acoustic impedances at the entrance of the ear canals decreased from an average of about 9.2 in the ear shell study to an average of about 6.9 in the foam plug study. Thus, it appears that the models to predict the individual drum pressure levels suffered from not correctly taking into account this additional damping at the entrance of the residual ear canals in the foam plug study. It could therefore be worthwhile to supplement the models to predict the drum pressure in foam plug scenarios (e.g., OAE probes) with additional damping at the entrance of the ear canal.

**CONCLUSION**

In this research, we propose using the inter-individual standard deviation of hearing thresholds as a criterion to compare methods of quantifying the acoustic input to the human auditory system. While we only considered occluded ear scenarios in this work, the criterion can be (and in fact, has been) applied to open ear, headphone and loudspeaker scenarios as well.

It was shown that thresholds referring to estimates of the individual ear drum pressure resulted in lower inter-individual standard deviations than thresholds referring to ear simulator pressure at frequencies in the 7...10 kHz range. Thus, it is likely that the transfer characteristics of our outer ears is independent of the sensitivity of the succeeding stages of auditory processing.
It is hoped that this work will help to improve methods to predict the acoustic input to the human auditory system at high frequencies.

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