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Acoustics of Open Fittings

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The use of so-called "open fittings" instead of individual ear shells has become very popular in hearing aid fitting, in particular because open fittings avoid the occlusion effect, but also because they are more comfortable, easier to manufacture, and cosmetically preferred. On the other hand however, there are acoustical issues with open fittings, including the mixture of direct and amplified sound, a poor low-frequency performance, an increased risk of feedback and a supposedly less reproducible position of the sound delivering device (tubing or speaker) in the ear canal, which in turn may result in a greater variability of acoustic parameters such as RECD and REOG. The two latter issues are addressed here in a study with 20 subjects, for individual shell and a number of open fittings, comprising closed and open domes of different diameters with tubings as well as with ear canal receivers. It was observed that in comparison to individual shell fittings, the open fittings did not exhibit a higher variability of RECD and REOG, but up to 15dB (closed domes) to 25dB (open domes) lower feedback thresholds.

1 Introduction

The use of so-called "open fittings" instead of individual ear shells has become very popular in hearing aid fitting, in particular because open fittings avoid the occlusion effect, but also because they are more comfortable, easier to manufacture, and cosmetically preferred. On the other hand however, there are acoustical issues with open fittings, including the mixture of direct and amplified sound, a poor low-frequency performance, an increased risk of feedback and a supposedly less reproducible position of the sound delivering device (tubing or speaker) in the ear canal, which in turn may result in a greater variability of acoustic parameters such as RECD and REOG. The two latter issues are addressed here in a study with 20 subjects, for individual shell and a number of open fittings, comprising closed and open domes of different diameters with tubings as well as with ear canal receivers.

2 Material and Methods

2.1 Fittings Considered in this Study

In this study, 3 Phonak behind-the-ear (BTE) hearing instruments were used together with a number of different tubings and so-called "domes", i.e. small ear pieces, see fig. 1. Depending on how many different tubings could be used on a particular subject, up to 32 different fittings per subject were investigated in this study, summarized in table 1. All fittings were administered onto the subjects by the same fitter (the second author).

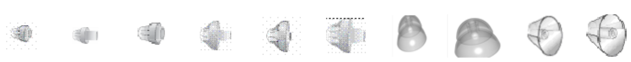

Figure 1: Domes used in this study. From left to right: small and long 5 mm-dome, small and long 7 mm-dome, small and long 10 mm-dome, 11 mm-dome, 13.5 mm-dome, small and long closed dome.

2.2 Subjects

Twenty subjects (13 male, 7 female, 25–74 years old) participated in this study. Individual silicone impressions of each subject's left ear were taken at the subject's first visit. These impressions were used to manufacture individual ear shells and to classify the subjects according to the geometry of the ear canal slice right after the first bend, see fig. 2: The two main diagonals of the elliptical ear canal cross section were taken to be the parameters characterizing the subject's ear canal geometry. Four groups of subjects were classified based on these two parameters: large circular, large slit, small circular and small slit, see fig. 2.

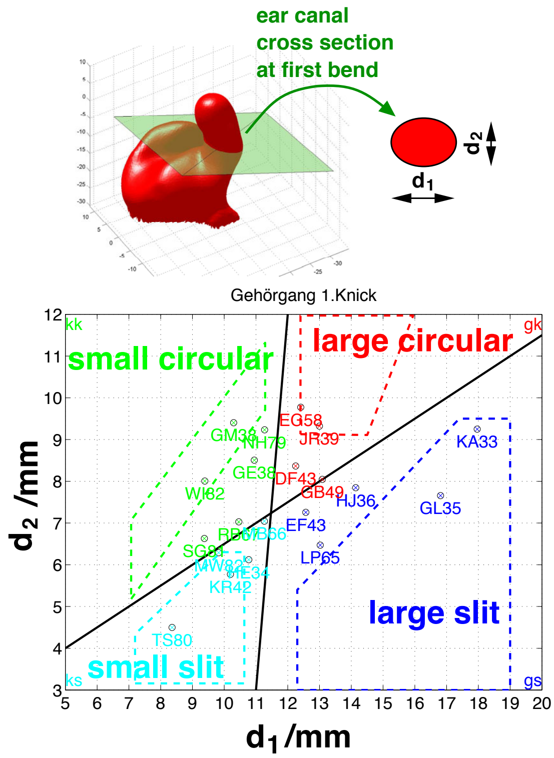

Figure 2: Classification of subjects according to ear canal geometry. The two main diagonals of the elliptical cross section of the ear canal just after the first bend were taken as parameters characterizing the subject's ear canal geometry.

In order to achieve a wide spread of the two parameters, a total of about 300 ear shells from the database of patients in Oldenburg's "Haus des Hörens" and 10 shells from a previous study were examined, out of which the subjects for this study were recruted.

Written consent to participate in the study was obtained from each of the subjects prior to the experiments. All experimental procedures were approved by the Oldenburg University Ethics Committee.

2.3 Measurement Methods

All real-ear measurements were done in the Oldenburg University anechoic room. Subjects were seated in a chair at 1.5 m distance from a loudspeaker (Fostex 6301B), see fig. 3. The ear canal sound pressure was captured using an ER-7C probe microphone (Etymotic Research, Elk Grove Village IL, USA) attached to an ear hook, see fig. 3. The probe microphone tip was positioned at a distance of 3 mm from the subject's ear drum.

	μSavia Art 100 dSZ				μSavia Art CRT dSZ	μPower V 300 dAZ
tubing	slim tubes			standard tube + hook (HE9 680)	ear canal receiver (Knowles FK 200)	ear canal receiver (Sonio 31015A)
	smaller	ideal length	larger	ideal length		
domes	closed dome S open dome 5/7/10 mm S	closed dome S/L open dome 5/7/10 mm S/L	closed dome L open dome 5/7/10 mm L	closed shell vented (2 mm) shell "fit&go" (w/wo cerumen protection)	closed dome S/L open dome 5/7/10 mm S/L	(closed) dome 11/13.5 mm

Table 1: Summary of fittings investigated in this study. S and L stand for short or long domes, respectively.

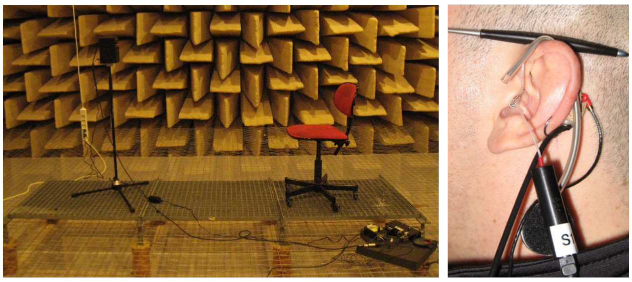

Figure 3: Measurement set-up. **Left:** loudspeaker and subject's seat in the anechoic room. **Right:** Subject ear with hearing instrument and probe microphone.

For the real-ear-occluded-gain (REOG) and the real-ear-unaided-gain (REUG) measurements, the probe microphone was calibrated by reference to the sound pressure measured with the probe microphone at the position of the subject's head (when the subject was absent). For the real-ear-to-coupler-difference (RECD) measurements, the probe microphone was calibrated by reference to the sound pressure measured by the probe microphone in a modified (in order to enable probe tube microphone measurements and the use of slim tubes and external receivers) 2-cc coupler (GRAS Sound &Vibration, Holte, Denmark). The coupler reference measurements were done with the largest (63 mm) slim tube for slim tube configurations, with a 25 mm standard tube for standard tube configurations and with custom-made adaptors for canal receiver configurations.

All measurements were carried out as 2-channel transfer function measurements of the probe microphone sound pressure with respect to the loudspeaker (REUG, REOG) or hearing instrument receiver (RECD) driving voltages, using a RME Hammerfall DSP Multiface audio interface (RME Intelligent Audio Solutions, Heimhausen, Germany) together with a customized version of the PureMeasurement collection of patches [1] for the PureData software [1].

For the REUG and REOG measurements, a white noise test signal was delivered by the loudspeaker, whereas for the RECD measurements, a pink noise test signal was delivered by the hearing instrument receiver.

The frequency resolution of the measured transfer functions was about 2 Hz (32000 Hz/16384), all further analyses of REUG, REOG and RECD were however carried out in frequency bands with mid frequencies of 160, 320, 480, 640, 800, 960, 1120, 1280, 1520, 1840, 2160, 2480, 2880, 3360, 3920, 4640, 5520, 6560, 7840, and 9440 Hz, respectively.

Feedback thresholds were measured using Phonak's iPFG fitting software (version 1.6.0.13642).

2.4 Statistical Analysis

In the analyses presented here, fittings were classified according to the following 8 classes: (individual) closed shell, (individual) vented shell, slim tubes with open domes, slim tubes with closed domes, "fit&go", "CRT" instrument with open domes, "CRT" instrument with closed domes, and the "Power" instrument. As all fitting classes were measured on the same subjects, a repeated measures approach was necessary, which was, for each frequency band, implemented as a linear mixed effects model with one random factor on the subjects. For example, the RECD of the ith subject was modeled as

$$\begin{aligned} \mathbf{RECD}_i &= \mathbf{X}\boldsymbol{\beta} + b_i + \boldsymbol{\varepsilon}_i, \qquad i = 1, \ldots, 20, \\ b_i &\sim \mathcal{N}(0, \sigma^2_{\text{subj}}), \qquad \boldsymbol{\varepsilon}_i \sim \mathcal{N}(\mathbf{0}, \sigma^2_{\text{resid}}\mathbf{I}), \end{aligned} \tag{1}$$

where $\mathbf{X}$ is a model matrix which was parametrized using so-called treatment contrasts (meaning that the RECD for a reference situation of e.g. fitting class is estimated as intercept $\boldsymbol{\beta}(1)$, and differences to this reference situation are estimated as fixed effects $\boldsymbol{\beta}(2\ldots)$) and b_i is the random subject effect (of which the standard deviation σ_{subj} is estimated), see [2]. All statistical computations were done in R [2].

[1] http://puredata.info/

[2] http://www.r-project.org/

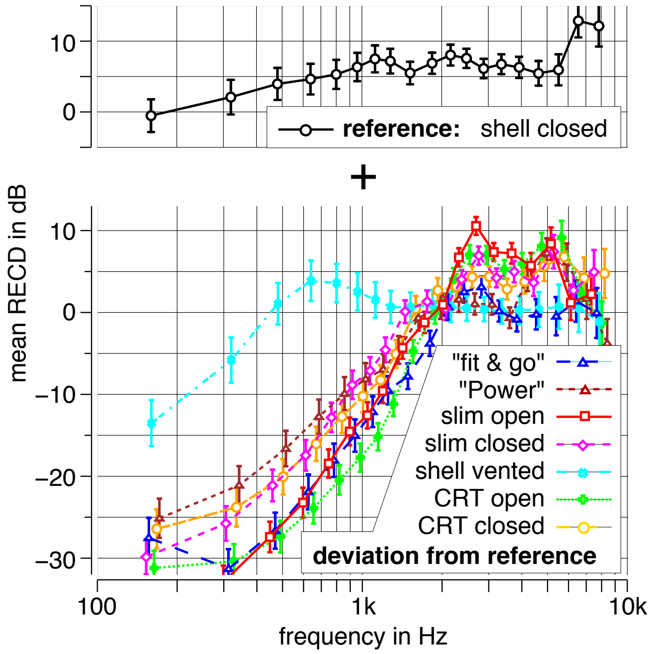

Figure 4: Mean RECD values (including approximate 95% confidence intervals) for different classes of fittings, according to eq. 1 (with fitting class as fixed effect and subject as random effect).

3 RECD

In a first step, RECD values were, for each frequency band, modeled according to eq. 1, with the fitting class (see sec. 2.4) as fixed predictor and one random subject effect.

The results are shown in fig. 4. It is seen that for closed individual shells the mean RECD values are higher than 0 dB for practically all frequency bands, with a more or less frequency-independent average of about 6…7 dB in the frequency range from 1 kHz to 6 kHz, which is in good agreement with [3].

In the frequency range up to about 1.5 kHz, all other fittings have lower RECDs than the closed individual shell (except for the Helmholtz resonance produced by the vented shell at around 600…700 Hz). This can be explained by the sound leaking through vents and more or less open domes. It appears from fig. 4 that there are 3 degrees of leakage, namely (a) the vented shell, (b) the closed domes and (c) the open domes. Surprisingly, the so-called "closed" domes exhibit substantially more leakage than the vented shell, whereas the difference between closed and open domes is less pronounced.

Above about 2 kHz, the vented shell (and above 3 kHz the "fit&go" fitting as well) is not significantly different from the individual closed shell, whereas all other (except the "Power" instrument) fittings have a significantly higher RECD compared to the closed individual shell. The "Power" instrument behaves like the individual shell in the frequency range from 1.5 kHz…3.5 kHz, and like the other canal receiver instruments above 4 kHz.

In a second step, the total model errors were compared for the different fitting classes, in order to get an idea of how well individual RECDs might be predicted. This was done by setting up models of the form presented in eq. 1, for each fitting class and each frequency, with all significant predictors as fixed effects and one random subject effect. This allowed the estimation of the inter-individual standard deviation σ_{subj} and the residual standard error σ_{resid}. As the random effect and the residuals are assumed to be independent normal variables, the total model error was formed by summing their (estimated) variances. For the individual shell fittings, there was only one observation per subject, such that an ordinary linear model (without random effects) was fitted. Similarly, for the "fit&go" and the canal receiver fittings, ordinary models without random effects were fitted due to numerical difficulties. In these cases, the total variability is thus accounted for by the residual standard error only.

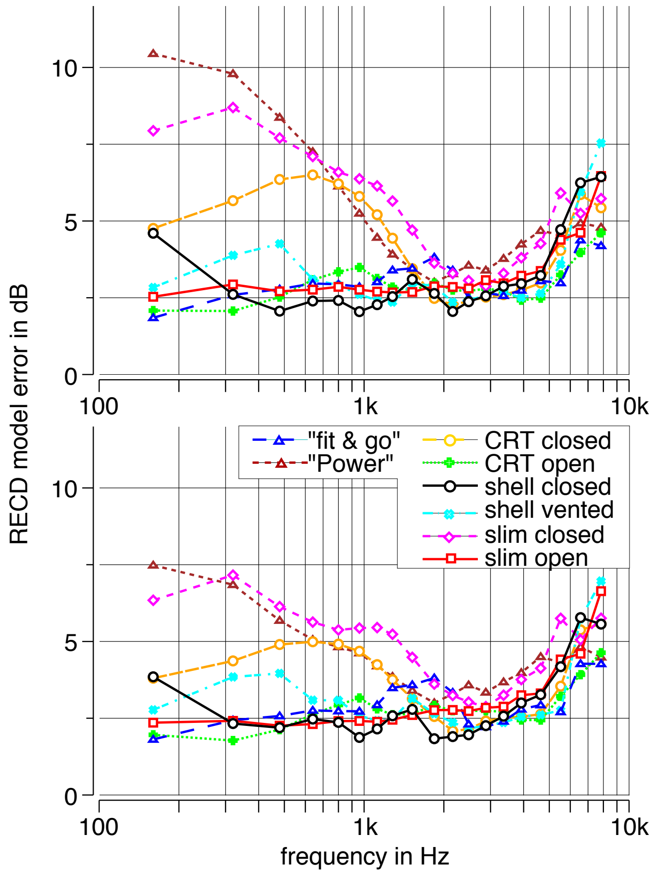

Figure 5: RECD model total error $\sqrt{\sigma^2_{\text{subj}} + \sigma^2_{\text{resid}}}$ for different classes of fittings. **Top:** For each fitting class, an individual model (eq. 1) was fitted (with all significant fixed predictors as fixed effects and subject as random effect). For the individual shell fittings, the "fit&go" fitting and the canal receiver fittings, an ordinary linear model (no random effects) was fitted. **Bottom:** The ear canal cross section (as defined in sec. 2.2) is considered as additional predictor.

The results are shown in fig. 5. One notes that the anticipated higher variability of open fittings (compared to individual shells) does *not* show up for frequencies above about 2 kHz. Only at frequencies below about 1 kHz will fittings with closed domes exhibit a higher variability, which can be explained by the uncertain tightness of fit for these fittings.

Thirdly, the foregoing analysis was repeated, but this time with the ear canal cross section class (as defined in sec. 2.2) as an additional predictor, see bottom part of fig. 5. It is seen that this simple factor mainly acts on the

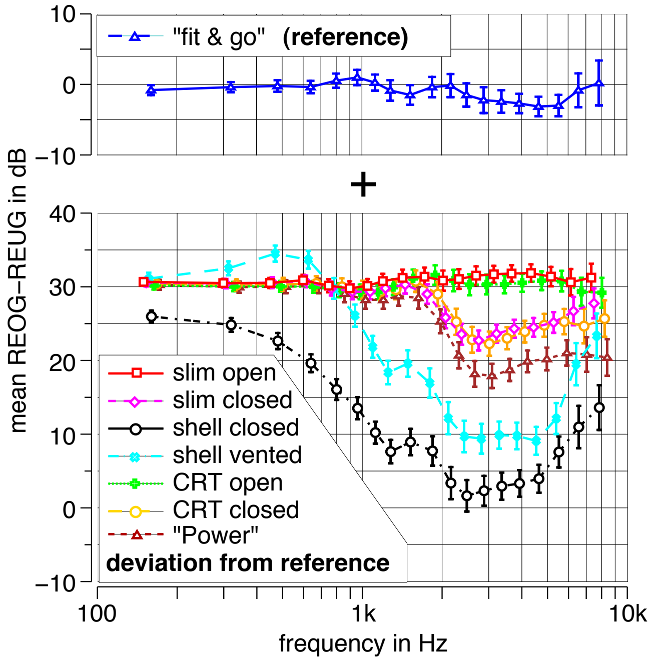

Figure 6: Mean values (including approximate 95% confidence intervals) of (REOG-REUG) for different classes of fittings, according to eq. 1 (with the fitting class as fixed effect and subject as random effect).

low-frequency range (up to 1 kHz) where its consideration substantially lowers the variability for the fittings with closed domes. Still, they exhibit a higher variability compared to the other fittings in this frequency range.

4 REOG

REOGs are presented here not directly, but as REOG-REUG, which tells how much the fittings attenuate the sound transfer from outside the head to the ear drum in comparison to the open ear condition.

In fig. 6, mean values of this metric are shown, again in a form resulting from the parametrization of the statistical model (eq. 1) with treatment contrasts. This time, the "fit&go" fitting was used as reference, as it does not have a dome and is thus suspected to have the least potential to alter the sound transfer to the ear drum. In fact, the results for this fitting are around 0 dB at most frequencies, except in the 1.5…5 kHz range where an attenuation of up to 3 dB is obtained. Fittings with open domes perform similar to the "fit&go" fitting, whereas fittings with closed domes show about 5 dB and the "Power" instrument about 10 dB more attenuation in the 2…10 kHz range. As expected, individual shells give a higher attenuation of about 20 dB (2…5 kHz) with respect to the "fit&go" fitting for the vented shell and even more for the closed shell.

Again, model errors were compared for the different fitting classes, see fig. 7. One first notes that in the low-frequency range, the individual shell fitting gives the highest variability (simply because it is the only fitting that provides sound attenuation at all in this frequency range). This variability can be decreased by considering the ear canal cross section as an additional predictor.

In the 2…5 kHz frequency range, the "Power" instrument gives the highest variability, followed by the other closed domes, the individual shell, and the open domes. The variability of the closed domes fittings in this frequency region decreases if the ear canal cross section is considered as predictor as well.

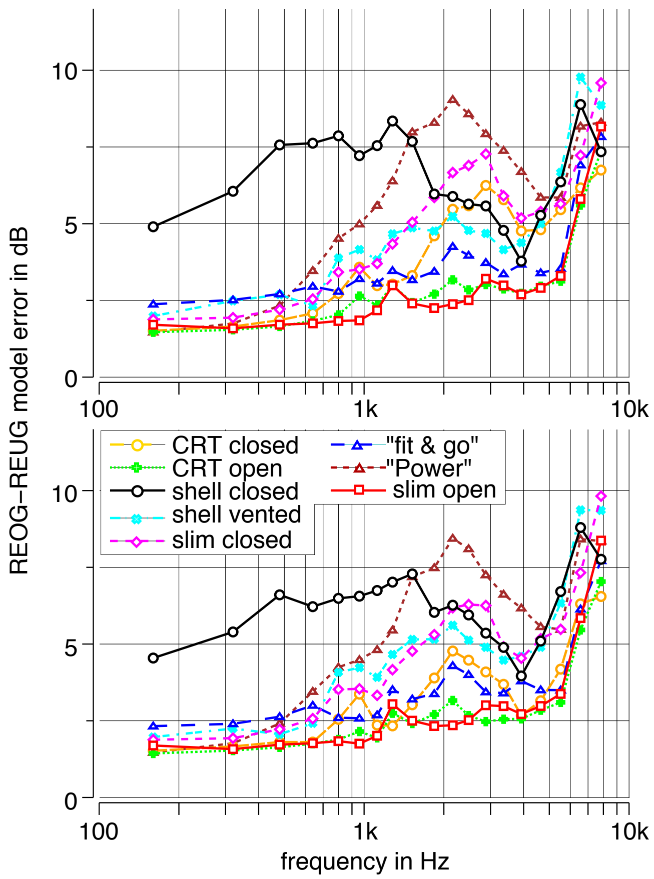

Figure 7: (REOG-REUG) model total error $\sqrt{\sigma^2_{\text{subj}} + \sigma^2_{\text{resid}}}$ for different classes of fittings. **Top:** For each fitting class, an individual model (eq. 1) was fitted (with all significant fixed predictors as fixed effects and subject as random effect). For the individual shell fittings, the "fit&go" fitting and the canal receiver fittings, an ordinary linear model (no random effects) was fitted. **Bottom:** The ear canal cross section (as defined in sec. 2.2) is considered as additional predictor.

5 Feedback Thresholds

The susceptibility of the different fittings to feedback was measured using the standard procedure implemented in the iPFG fitting software. For each frequency band, the maximum amount of amplification before feedback occurs was measured.

As a general feature across fitting classes, feedback did not occur at low frequencies, as the maximum output levels of the hearing instruments were not sufficient to induce feedback in this frequency range. The respective frequency bands are thus not shown in the diagrams presented below. Also, the highest 3 frequency bands were not actually measured but estimated from the values at other frequencies, and are therefore ignored as well.

In fig. 8, the mean feedback threshold is shown together with approximate 95%-confidence intervals, with reference to the individual closed shell (again based on

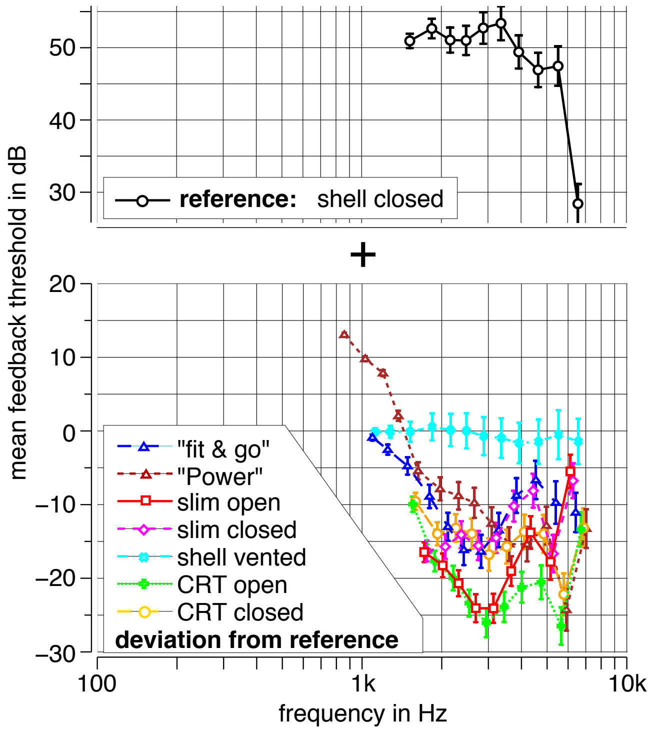

Figure 8: Mean values (including approximate 95% confidence intervals) of feedback thresholds for different classes of fittings, according to eq. 1. Frequency bands where no feedback occured are not shown.

model 1). Whereas the vented shells do not significantly depart from the closed shells, one has substantially lower (up to 15 dB) feedback thresholds for closed domes and the "fit&go" fittings, and up to 25 dB lower thresholds for fittings with open domes.

Considering the variability of the feedback thresholds (fig. 9), one notes a difference between the frequency ranges below 4 kHz and above 4 kHz. Below 4 kHz, the open fittings show a lower variability than the individual shell fittings, whereas above 4 kHz this behavior is reversed. The "Power" instrument gives the highest variability in all frequency bands.

6 Summary and Conclusions

It was observed that in comparison to individual shell fittings, open fittings did not exhibit a higher variability (in terms of the respective model standard error) of the acoustic parameters, in particular RECD and REOG, but also (up to 4 kHz) the feedback threshold.

On the other hand, open fittings gave up to 15dB (closed domes) to 25dB (open domes) lower feedback thresholds, compared to individual shell fittings.

Below about 1 kHz, the tightness of fit (or rather: the lack of) governs the acoustics. The variability of the acoustic parameters in this frequency range is decreased (i.e. a more precise prediction is possible) by considering a very simple classification of ear canal geometry.

It appears that circular domes are perhaps not the best choice, given the rather elliptical shape of ear canal cross sections.

Further research is needed in order to improve the precision of predictions of the acoustic parameters for individual subjects, in order to yield a better basis for fitting various kinds of hearing instruments.

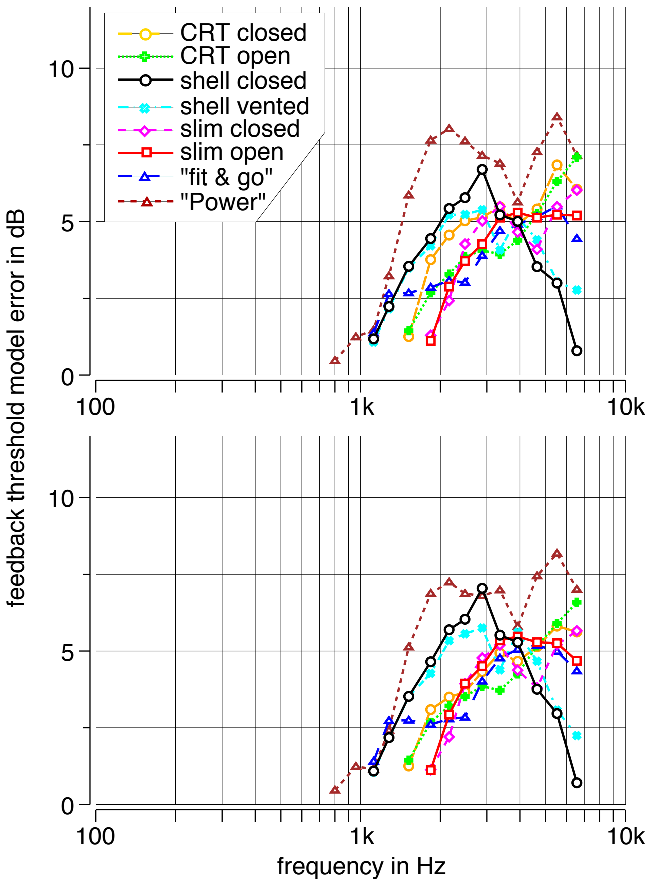

Figure 9: Feedback threshold model total error $\sqrt{\sigma^2_{\mathrm{subj}} + \sigma^2_{\mathrm{resid}}}$ for different classes of fittings. **Top:** For each fitting class, an individual model (eq. 1) was fitted (with all significant fixed predictors as fixed effects and subject as random effect). For the individual shell fittings, the "fit&go" fitting and the canal receiver fittings, an ordinary linear model (no random effects) was fitted. **Bottom:** The ear canal cross section (as defined in sec. 2.2) is considered as additional predictor.

Acknowledgements

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