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Individual differences in low-frequency noise perception

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ABSTRACT

Standards on hearing like threshold and equal-loudness-level contours show the normal hearing sensitivity at low frequencies as smooth curves. However, recent non-invasive measurements of the forward middle-ear transfer function (FMETF) reveal a resonance feature seen as a dip and a peak in the FMETF where the slope changes approx. 6 dB/octave (around 40-65 Hz depending on person). The change in slope is attributed to the shunting effect of the helicotrema. A preliminary study has been carried out in order to see if this resonance feature measured objectively is also found in perceptual data. The FMETF and an equal-loudness contour (ELC) were measured for five subjects with a fine frequency resolution from 20 Hz to 100 Hz. For two subjects a clear resonance feature was seen in the ELC, but it was not evident in the data for the remaining subjects. This means that some people have a narrow frequency range where they are more sensitive and a narrow range where they are less sensitive compared to the standards. Since the frequency range is subject dependent this could explain why some people are annoyed by a low-frequency sound that is not audible to other people.

1. INTRODUCTION

Much of the environmental noise is of low-frequency nature, so knowledge about the human hearing at low frequencies is important in order to prevent adverse effects of the noise. Here, acknowledging that existing individual differences in sensitivity is of great importance in order to understand how people might react to a given noise. The standard deviation in hearing thresholds at low frequencies are in the order of 5 dB[1], but differences related to age are quite low[1] compared to what is seen at higher frequencies..

From standardized data like the hearing threshold in ISO 389:2005[2] and equal-loudness-level contours in ISO 226:2003[3] it can be seen that the sensitivity of the hearing becomes lower towards lower frequencies, and appears to follow a smooth monotonic curve. These standards are based on average data, and one might assume that a random normal hearing person would have curves similar in shape to these. However, recent non-invasive measurements of the transfer function from the pressure at the ear canal to the pressure difference across the basilar membrane (BM), also called the forward middle-ear transfer function (FMETF), reveal a resonance feature

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seen as a dip (near 45 Hz) and a peak (near 60 Hz) in connection with a slope increase by approx. 6 dB/octave for frequencies below the resonance feature[4]. The change in the slope of the FMETF is attributed to the shunting effect of the *helicotrema* as much of the pressure at the very lowest frequencies is equalized through this opening between the *scala vestibuli* and the *scala tympani* at the *apical end* of the cochlea.

If this prominent resonance feature is part of a normal hearing function, then it could be assumed that individual persons have a narrow frequency range where their sensitivity is higher and another where it is lower than expected from the standard hearing curves ISO 389-7:2005[2] and ISO 226:2003[3].

In order to investigate if the resonance feature found in the FMETF is affecting the sensitivity and thereby the perception of low-frequency sound, FMETFs and ELC of individual subjects are measured and compared

2. METHODS

A. FMETF Measurements

Below a certain stimulus frequency, the travelling wave reaches the apical end of the cochlea and the differential pressure across the basilar membrane (BM) is shunted by the helicotrema. This does not only prevent BM displacement to static pressure changes, but can also alter the hearing sensitivity to low-frequency sounds. An objective measure of this effect can be seen in the forward middle-ear transfer-function (FMETF).

The non-invasive measurement of the shape of the FMETF has been described in detail by Marquardt et al.[4], although the hardware has slightly changed since. The principle will be only briefly summarized here. Inverted FMETFs were obtained experimentally by adjusting the level of a tonal low-frequency stimulus so as to evoke constant BM displacement amplitude, independent of its frequency. Constant BM displacement was monitored by simultaneously measuring distortion product oto-acoustic emissions (DPOAEs), which were suppressed periodically with the frequency of the BM displacement.

The method is based on the assumption that a constant DPOAE suppression depth indicates a constant BM displacement (independent of the suppressor frequency). Because the BM displacement is monitored at a location that is far basal from the characteristic place of the suppressor tone, the BM displacement caused by this tone is stiffness-controlled, and therefore proportional to the pressure difference across the BM. Consequently, the FMETF measured here is defined as the ratio between this pressure difference and the pressure in the ear canal. The illustrated raw data represent the inverse of the FMETF. (Nevertheless, they are in the text referred to as FMETF.) The absolute level of the suppressor tone necessary to achieve a certain DPOAE suppression is dependent of both suppression depth and DPOAE primary parameters. It has been shown previously, however, that the shape of the FMETF, which is of interest here, is independent of suppression depth and DPOAE primary parameters[4] (for individual DPOAE primary parameter, and suppression depth see Table 1).

DPOAE were measured with an Etymotics ER-10C probe. The high-pass cut-off frequency of its microphone amplifier was increased to 1 kHz in order to avoid overloading the AD converter of the multi-channel sound card (MOTU UltraLite) with the comparatively intense suppressor tone. This tone was produced by a DT48 earphone (Beyerdynamic) that was directly driven by the headphone amplifier of the soundcard. The earphone output was delivered to the probe’s ear plug via a narrow silicone tube (300 mm in length, ~0.5 mm in diameter), constituting an acoustic low-pass filter that prevents accidental sound delivery above 100 phon (given the maximum voltage of the headphone amplifier). Stimulus waveforms and DPOAE signal analysis was computed by custom-made Matlab software running under Windows XP. After displaying the 2f1-f2 suppression pattern of a 20-s long recording, the suppressor tone level for the next 20-s recording could be adjusted by the experimenter. This was repeated until the desired DPOAE suppression was achieved (typically 3 or 4 repetitions). Suppression levels for the following suppressor tone frequencies have been obtained in ascending order: 20, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 90, 100, 125, and 250 Hz.

Table 1: Individual DPOAE primary parameters and chosen DPOAE suppression depth. Out of the 18 combinations tested in each ear, the primary parameters given here resulted in the largest unsuppressed 2f1-f2 DPOAE. These parameters were subsequently used during the measurement of this ear's FMETF. The measurement involved the low-frequency suppression the 2f1-f2 DPOAE by a constant, but arbitrarily chosen amount (given in column "Suppress.").

Subject, ear	f1 [Hz]	f2 [Hz]	l1 [dB SPL]	l2 [dB SPL]	2f1-f2 [dB SPL]	Suppress. [dB]
A, left	2095	2515	62	50	16	11
A, right	1610	1915	65	50	14	4
B, left	2060	2515	65	50	3	13
B, right	1580	1915	62	50	2	10
C, left	1845	2215	62	50	1	11
C, right	1830	2215	65	50	6	11
D, left	2060	2515	65	50	3	5
D, right	1815	2215	62	50	7	7
E, left	2080	2515	62	50	6	11
E, right	2080	2515	62	50	8	13

B. Threshold measurements

The pure-tone low-frequency hearing thresholds were measured using a slightly modified version of the standard ascending method[5]. The modification consists of having level steps of -7.5 dB rather than -10 dB after each ascend, a modification that was proposed by Lydolf et al.[6] in order to give interlaced presentation levels, and thus a higher resolution of the psychometric function. Each of the frequencies 20, 50, 100 and 250 Hz was measured once except for 100 Hz, where a second measurement tested for repeatability. Their mean value at 100 Hz was then used to determine the level of the subsequent equal-loudness contour measurements. Pilot measurements on subject A were more extensive with repeated measurements at the same frequencies as the FMETF measurements (see section A) except for the frequencies 35 and 90 Hz.

C. Equal-loudness contour measurements

For each subject a complete equal-loudness-contour (ELC), having the same frequency resolution than the FMETF, was obtained within a day, but consisted usually of two separate sessions. The results of four of such measurements, spread over several days, were averaged. A two-alternative forced-choice maximum-likelihood procedure was applied as described by Møller and Andresen[7]. The tone durations for both threshold and equal-loudness determinations were 1 second plus linear fade in/out ramps of 250 ms each. For each subject the reference tone was a 100 Hz tone at a level of 20 dB above the individual hearing threshold. Pilot measurements on subject A were more extensive using levels of 10, 20, 40 and 60 dB above the threshold.

D. Subjects

Ten subjects (8 male, 2 female, aged 22 – 40) were recruited and initially tested for high levels of the 2f1-f2 DPAOE. In search for optimum stimulus conditions, three f2-tones were tested (1915 Hz, 2215 Hz, and 2515 Hz; l2 = 50 dB SPL) in combination with various parameter settings for the other primary tone (f1 and l1; 18 combinations in total). When the 2f1-f2 component exceeded 0 dB SPL in any of these, the FMETF of this ear was obtained immediately, using the best combination found, without replacement of the DPOAE probe. As known from previous experiments, a minimum 2f1 f2 level of 0 dB SPL is required for a sufficient signal-to-noise ratio to reliably apply the FMETFs analysis. Seven of the ten subjects fulfilled this criterion. For two of these seven subjects, the FMETF could not be obtained because their DPOAE was not sufficiently suppressible by even a 90-phon low-frequency suppressor, the loudest tones approved by the UCL Ethics commission for this study. Where the FMETF could be measured in one ear, they could usually also be obtained in the other ear, so that altogether ten FMETFs have been obtained (five subjects, both ears). ELC from these five subjects have then been obtained within three month of their FMETF measurements,

E. Experimental setup for threshold and equal-loudness measurements

A special low-frequency test facility[8] was used for the threshold and ELC measurements. The signal to each of 40 the loudspeakers mounted in two walls is individually filtered (digitally pre-computed) in a manner that avoids standing waves within the test room so that a large homogeneous sound field in its centre is created (frequency range 2-350 Hz). The facility is equipped with a ventilation system that gives sufficient airflow for continuous occupation of the room, while still maintaining a background noise level lower than 10 dB below the normal hearing threshold[2] for each 1/3-octave frequency band. A Pentium 4 3.2 GHz PC runs the psychophysical protocols and controls the output of two RME 9652 Hammerfall soundcards connected via optical cables to five eight-channel Swissonic 24-bit 48 kHz D/A-converters. The D/A converters are connected to eight six-channel Rotel RB-976 MK II power amplifiers (modified for lower noise and frequency range) that drive the forty 13-inch Seas 33F-WKA woofers.

3. RESULTS

Individual measurements of FMETF and threshold and equal-loudness contours on subject A can be seen in Figure 1. Figure 2 and Figure 3 shows the individual measurements on subject B, C and D, E respectively. Note that the vertical position of the FMETF cannot be compared across ears because it is largely influenced by the DPOAE primary parameter and the chosen suppression depth.

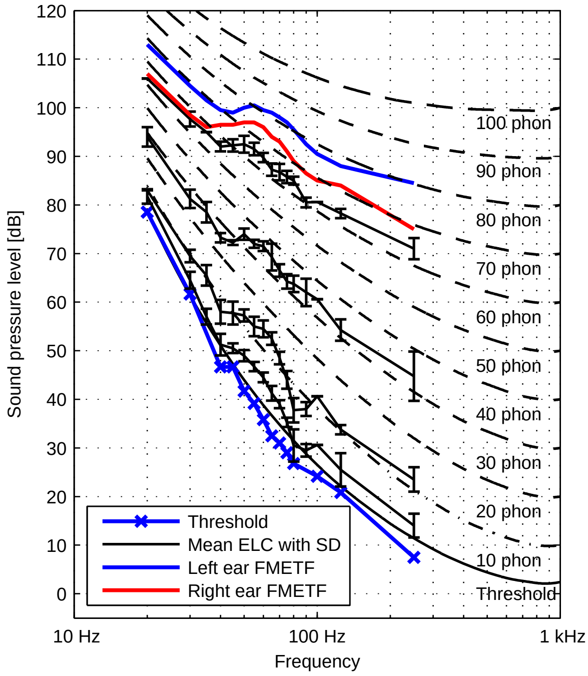

Figure 1: Individual FMETF, threshold and mean ELC with error bars for ± one standard deviation for subject A plotted with the standard equal-loudness-level contours[3].

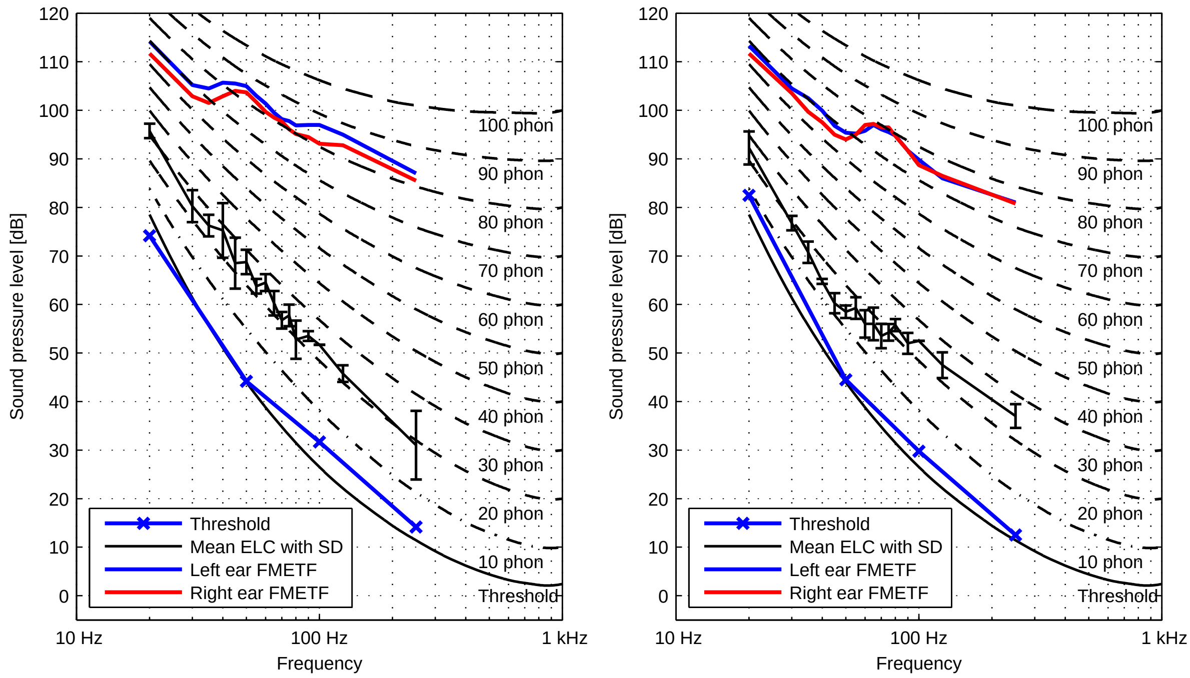

Figure 2: Individual FMETF, threshold and mean ELC with error bars for subject B and C plotted with the standard equal-loudness-level contours[3].

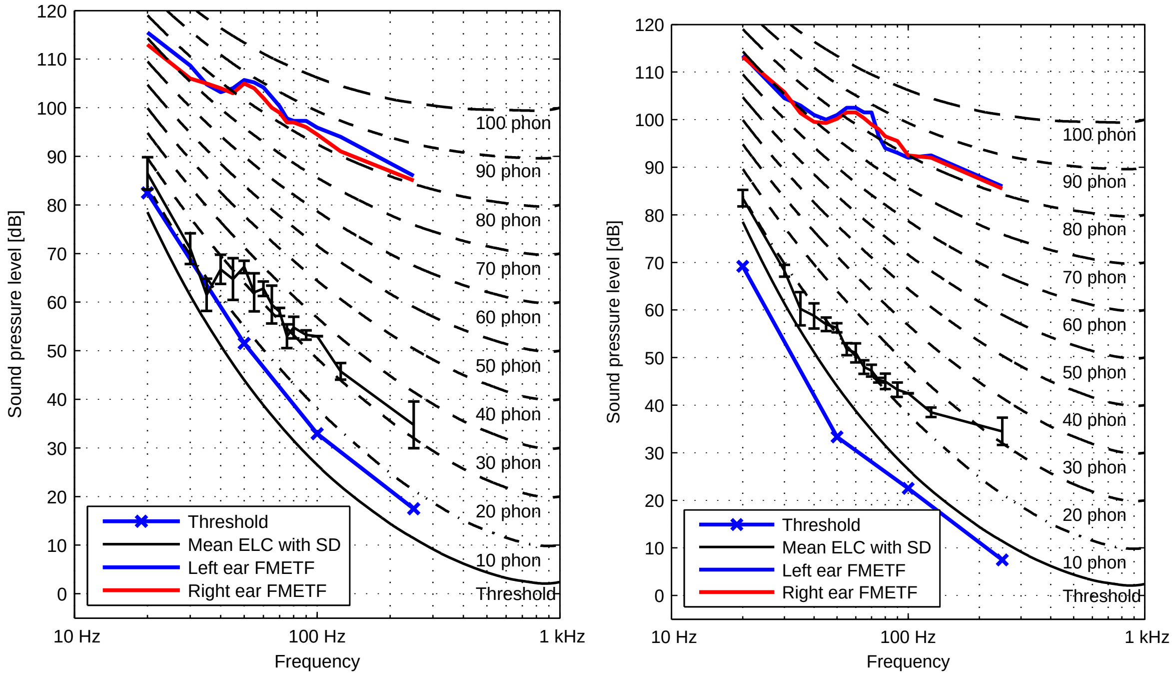

Figure 3: Individual FMETF, threshold and mean ELC with error bars for subject D and E plotted with the standard equal-loudness-level contours[3].

4. DISCUSSION

Out of an initial number of 10 subjects, only 7 subjects had sufficiently high distortion products for FMETF measurements, but for two of these subjects it was not possible to suppress the DPOAEs with the levels that were within the ethic limit set at 90 phon. We do not know if it would be possible to suppress the DPOAEs using even higher levels, or if these subjects have "insuppressible" DPOAEs. This means that only five subjects participated in the experiments. I.e. the subject group is selected on certain criteria, and caution must be taken in generalizing the findings.

The results show that all five subjects have a resonance feature in their measured FMETF, and even though the actual frequency range of this feature differs between subjects, they are quite similar between the two ears. The most extremes for these five subjects are subject B, who has the peak centered around 45 Hz, while subject C has the peak centered around 70 Hz. These differences can possibly be attributed to actual physical differences in the size and shape of the helicotremae between the two subjects. The guinea pig cochlea is an extreme example of a different anatomy, where the peak is found around 140 Hz[4].

The FMETF, as defined here, describes the gain between the pressure in the ear canal and the differential pressure across the BM as a function of frequency. Since the pressure across the BM drives the BM, which itself leads to the depolarization of the sensory cells, one would expect that any irregularities seen in the FMETF, especially such a narrow oscillation as observed here, would be also reflected in the neural output of the cochlea and show consequently an effect on auditory perception. It is therefore surprising that the resonance feature, visible in all FMETFs, is not consistently seen in the ELC data.

Only two subjects, A and D, have a feature in the equal-loudness contour similar in frequency to the resonance feature of their FMETF. This indicates that for these two subjects the FMETF is a good prediction for their actual perception. This does not seem to be the case for the three remaining subjects, B, C and E. One explanation could be that the hearing function for these subjects behave different at the levels where the equal-loudness contour were measured compared to at the relative high levels of the FMETF measurements. This would imply that the non-linear behavior of the cochlea somehow compensates for the resonance at lower levels. The fact that the FMETFs are measured monaurally and the ELCs are measured binaurally might also influence this comparison. However, the FMETF of left and right ear are so similar in shape that the influence should be minimal. From looking only at the slope of the equal-loudness contour it is quite evident, that the slope does change around the resonance feature in the FMETF for all subjects (for subject B the change in slope is quite small).

A comprehensive measurement of the hearing threshold was only done for subject A, and surprisingly the threshold is not clearly influences by the FMETF resonance feature. For the ELCs obtained with a 100 Hz reference tone of 10 and 20 dB above threshold there is an 80-Hz dip. We should note here that this subject has occasionally a low-frequency tinnitus in his right ear that was audible before, during and after all measurements in the quiet test chamber (including the FMETF measurements). He describes its percept as fluctuating, like narrow-band noise, centered at approximately 80 Hz. This has probably affected the ELC measurements at 80 Hz at the soft levels. At the ELCs at higher levels the tinnitus was probably masked completely by the stimuli and therefore no effect is seen at these levels. None of the other subjects had low-frequency tinnitus.

In general, the individual ELC, measured here with high frequency resolution, show large deviations from the standardized curves of ISO 226. Based on previously published population averages that have been often obtained with lower frequency-resolution, the standard shows smooth featureless curves. Although a pronounced oscillation in the ELC can be regarded as an exception in our sample, the ELCs of all subjects show an offset, between their lower and higher frequency part. In other words, at frequencies below the slope transition, the ELC follows a lower iso-phon contour than at frequencies above it. The offset differs between individuals in magnitude and frequency, but is typically between five and ten phon, and happens at frequencies between 40–80 Hz. This offset is better seen in the FMETFs. Although these results need to be confirmed in a larger normal population first, they might impact on future revision of the standard ISO 226. Care must be taken not to obliterate the sensitivity steps in the ELC of the individual ears by averaging across the population because its frequency-location differs between individuals. One should keep in mind that the subjects in this study might not represent such normal population because they have been selected with regard to high DPAOE levels, and DPAOEs that can be modulated by low-frequency tones.

At the present stage it is known that the standard deviation on the threshold of normal hearing persons is in the order of 5 dB, which means that two normal hearing persons can easily have a general difference in threshold of 20 dB. The results from this preliminary study indicate that there are also individual differences in narrow frequency ranges where the sensitivity is lower and higher than the “general sensitivity”. Combined with the rapid growth of loudness with level at these frequencies this can help explain cases where a person is annoyed by a low-frequency sound that is soft or inaudible to other people[9]. The annoyed person could have the dip of the resonance feature at a prominent frequency of the noise, where the other person could have a peak. This can lead to a very significant difference in perceived loudness.

A question one might ask is why this resonance feature is not seen in the data that are the basis for the standardized equal-loudness-level contours[3]. One explanation could be that such data are usually measured with too large frequency steps to reveal the dip and peak of the resonance feature. Another explanation is that the frequency locations differ individually, and therefore they will “disappear” when averaged across many subjects (i.e., one subjects peak could be placed at another subjects dip).

5. CONCLUSIONS

A preliminary study comparing objectively measured FMETF with the actual perception for low frequency sounds has been carried out. Out of an initial group of 10 subjects, only 7 had distortion products large enough for measuring FMETF, but it was only possible to suppress the distortion products for five of these subjects. For these five subjects the FMETF was measured for each ear in the range 20-250 Hz, and a threshold and an equal loudness contour was measured in the same frequency range. All five subjects have a resonance feature in their FMETF, but there are differences in the actual frequency of the dip and peak of the resonance feature, with the peak varying between 45 Hz for one subject to 70 Hz for another subject. These differences can possibly be attributed to actual physical differences in the cochlea – for the same subject the left and right ear FMETF is similar. The slope of the measured equal-loudness contour changes in the frequency region of the resonance feature. But only two subjects had a clear resonance feature in their ELC. This implies that for these subjects the non-linear processing in the cochlea compensates for the resonance at lower levels. It seems that there are individual differences in perception that are not reflected in the standardized curves of equal-loudness-level contours in ISO 226. These individual differences are important to acknowledge as they might help explain why some people are annoyed by a low-frequency sound that is barely audible to other persons. Further research with more subjects is needed in order to generalize the findings.

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