The effect of the helicotrema on low-frequency loudness perceptiona)

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Below approximately 40 Hz, the cochlear travelling wave reaches the apex, and differential pressure is shunted through the helicotrema, reducing hearing sensitivity. Just above this corner frequency, a resonance feature is often observed in objectively measured middle-ear-transfer functions (METFs). This study inquires whether overall and fine structure characteristics of the METF are also perceptually evident. Equal-loudness-level contours (ELCs) were measured between 20 and 160 Hz for 14 subjects in a purpose-built test chamber. In addition, the inverse shapes of their METFs were obtained by adjusting the intensity of a low-frequency suppressor tone to maintain an equal suppression depth of otoacoustic emissions for various suppressor tone frequencies (20–250 Hz). For 11 subjects, the METFs showed a resonance. Six of them had coinciding features in both ears, and also in their ELC. For two subjects only the right-ear METF was obtainable, and in one case it was consistent with the ELC. One other subject showed a consistent lack of the feature in their ELC and in both METFs. Although three subjects displayed clear inconsistencies between both measures, the similarity between inverse METF and ELC for most subjects shows that the helicotrema has a marked impact on low-frequency sound perception.
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I. INTRODUCTION

There is a growing awareness of the specific role of the low-frequency (LF) components in environmental noise. Sources of LF-noise are common, e.g., ventilation and air conditioning systems, machinery, aircraft, transformers, and wind turbines (e.g., see Fidell *et al.*, 2002; Møller and Pedersen, 2010; Di *et al.*, 2015) and have been found to produce annoyance (Waye *et al.*, 2001; Kaczmarskaa and Łuczakb, 2007; Pedersen *et al.*, 2008). The issue has become sufficiently troublesome for there to be government funded research into it (for example, in the UK: see DEFRA funded report by Leventhall *et al.*, 2003; in Germany: see Umweltbundesamt report by Krahé *et al.*, 2014). LF-noise is almost impossible to shield against, is often very intrusive, and can have a serious effect on the quality of life on those affected by it (for reviews, see Berglund *et al.*, 1996; Leventhall *et al.*, 2003; Leventhall, 2004, 2009; Salt and Hullar, 2010). Characterization and a functional understanding of the perception of LF-sounds are important for the assessment of, and the search for possible solutions to problems caused by LF-noise.

The helicotrema—a small passage that connects the scala tympani and the scala vestibuli at the apex of the cochlea—determines ultimately the lower frequency end of cochlear sensitivity. It prevents not only the displacement of the cochlear partition in response to changes in static pressure, but limits hearing sensitivity to LF-sounds: at frequencies so low that the cochlear travelling wave reaches the apex, differential pressure across the cochlear partition is shunted through the helicotrema. Other factors, reducing sensitivity toward LFs are the middle ear, whose stiffness-dominated impedance increases below its resonance (Aibara *et al.*, 2001; Nakajima *et al.*, 2009), and the inner hair cell's transduction process, which shows proportionality to the basilar membrane (BM) velocity rather than displacement (Dallos *et al.*, 1972; Russel and Sellick, 1978; Nuttall *et al.*, 1981), both causing effectively a high-pass filter, each with a slope of 6 dB/octave (Cheatham and Dallos, 2001).

Dallos (1970) demonstrated that the shunt impedance of the helicotrema shapes the middle-ear-transfer function (METF) in a species-specific manner (the METF is defined in this context as the frequency-dependent ratio between the differential pressure across the BM and the pressure in the ear canal). While in some species the oscillatory perilymph movement through the helicotrema is impeded by inertia (indicated by a 12 dB/octave slope in the METF), in others it is impeded by viscous friction, so that the slope of the METF remains 6 dB/octave at lower frequencies, as it is within the existence region of the resistive travelling wave. Despite this variation, the data of all species tested show a distinct non-monotonic resonance feature just above the frequency below which the shunting starts (approximately 100–150 Hz). Similar physiological studies of the transfer of LF-sound into the cochlea

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have been performed in animals, e.g., by Dancer and Franke (1980), Nedzelnitsky (1980), Ruggero *et al.* (1986), Magnan *et al.* (1999), Voss and Shera (2004), and in temporal bone preparations from human cadavers, e.g., by Merchant *et al.* (1996), Aibara *et al.* (2001), Puria (2003), and Nakajima *et al.* (2009).

Marquardt *et al.* (2007) described a technique, based on the suppression of distortion product otoacoustic emissions (DPOAE), that allowed the non-invasive assessment of the shape of the METF up to 500 Hz in humans. Their results from guinea pigs were in good agreement with the previously published METF data (e.g., Dallos, 1970; Dancer and Franke, 1980). The human curves followed roughly the equal-loudness contour (ELC) at 80-phon (ISO, 2003). However, whilst these standardized isophon curves indicate a smooth monotonic increase of sensitivity with tone frequency, the typical shape of METFs exhibited a transition region between about 40 and 90 Hz, below which there is a sharp increase in slope by 6 dB/octave. This transition region was commonly characterized by a non-monotonic resonance feature, similar to that observed, e.g., in the four species studied by Dallos (1970). Since its spectral location is approximately an octave lower than in these laboratory animals, the shunting by the helicotrema in humans appears to become fully effective below approximately 40 Hz. This cutoff frequency roughly agrees with the center frequency of the lowest auditory filter estimated psychoacoustically by Jurado *et al.* (2011); the authors suggest further that the steep high-pass flank of this filter is caused by the helicotrema shunt. It is thus reasonable to consider it as inherent part of cochlear tuning at very low frequencies. Above approximately 80 Hz, the travelling wave terminates before reaching the helicotrema and so the latter appears to have no influence on cochlear tuning (Jurado and Moore, 2010).

Recently, Marquardt and Hensel (2013) showed that a simple lumped-element model of the apical cochlea can account for the physiologically observed METFs from both animals and humans, including the often observed non-monotonic resonance feature. The abruptly increasing slope below the resonance was explained by the shunt impedance of the helicotrema. Hensel *et al.* (2007) extended the human METF measurements to the infrasound range, and showed that inertia dominates the METF down to at least 6 Hz.

The present study addresses the question whether the irregular shape of the METF affects loudness perception. Models predict loudness by incorporating a series of sound-processing stages, which include fixed filters representing the acoustical transfer from the sound field to the eardrum (effectively flat below 500 Hz), through the middle-ear (6 dB/octave high pass below 500 Hz), followed by the calculation of an excitation pattern that describes the mechanical response along the BM (see Moore, 2014, for a review). The assumed METF used in the loudness models by Moore and co-workers is broadly consistent with the characteristics described above, except that their function curves smoothly (e.g., see Moore *et al.*, 1997; Glasberg and Moore, 2006). Its LF roll-off helps to replicate the increasing slope of the isophon curves toward low frequencies (ISO, 2003). It is, however, not clear whether also the sharp slope transition, or even the non-monotonic step region, evident in many measured METFs, will affect loudness because these might be only present at the specific measurement location of the METF, whereas loudness is predicted from the entire area under the BM excitation pattern (Chen *et al.*, 2011).

With this in mind, a review of LF-psychoacoustical data by Møller and Pedersen (2004) did not reveal any convincing behavioral homologue to the typically observed step region in the METF, neither in the hearing threshold, nor in ELC data. Whilst an irregularity, or an increased variance can occasionally be seen in the expected frequency region (e.g., Frost, 1987; Watanabe and Møller, 1990), many data have insufficient frequency resolution. Furthermore, the frequency of the resonance might vary individually so that the process of averaging over many subjects might have led to a cancelation of this feature in most studies. Since the published behavioral data were not entirely conclusive, Marquardt and Pedersen (2010) set out to measure ELC and METF shapes of five subjects, and compare their features on an individual basis. The METF shapes of all five subjects showed similar non-monotonic irregularities as those reported by Marquardt *et al.* (2007). Nevertheless, the ELC of only 2 out the 5 subjects exhibited non-monotonic irregularities that matched those in their METF. The ELCs of two further subjects exhibited rather abrupt slope-transitions at spectral locations that coincided with the dip of their METF irregularity.

Nonetheless, the preliminary study by Marquardt and Pedersen (2010) suggested a link between the irregularly shaped METF and the judgment of loudness at least for some subjects. The observed inter-subject variability and occasional inconsistency between METF and ELC, however, calls for a more comprehensive study. In this study, both measurements were performed in a larger subject group with the aim to study their covariance and individual variability in greater depth.

II. METHODS

A. Measurement of the shape of the METF

The procedure applied to obtain the shape of the METF has been described in detail by Marquardt *et al.* (2007). Its principle will be only briefly summarized here. METFs were obtained experimentally by adjusting the level of a LF-tone, so as to evoke constant BM displacement amplitude, for tone frequencies of 20, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 90, 100, 125, and 250 Hz. Constant BM displacement was monitored by simultaneously measuring the $2f_1$-f_2 distortion product otoacoustic emission (DPOAE), which was suppressed periodically with the frequency of the BM displacement (i.e., twice per LF-tone cycle). The method is based on the assumption that, independent of the suppressor frequency, a constant DPOAE suppression depth indicates a constant BM displacement magnitude (Bian *et al.*, 2002). Knowing that the DPOAE is generated near the characteristic places of the primary tones, the monitoring of the BM displacement in response to the LF-suppressor tone takes place at a location where such displacement is impeded by the BM's stiffness. Consequently, the monitored BM displacement is proportional to the pressure difference across the BM. Note that the obtained iso-suppression curve, like the behavioral ELC data, is obtained as an iso-output function, and represents therefore the inverse shape of the METF (i.e., 1/METF). In the following text, the measured functions are therefore referred to as inverse METF (iMETF). Marquardt *et al.* (2007) have previously shown that the METF shape, which is of interest here, is unaffected by the chosen DPOAE suppression depth and the parameters of the primary tones. For each individual ear, 27 primary tone combinations were tested in a short series of 5-s recordings immediately prior to the iMETF measurement. To maximize signal-to-noise ratio, the combination that produced the highest $2f_1$-f_2 level was then chosen for the iMETF measurement. In each series, the primary-tone frequencies varied between 1.8 and 2.8 kHz, with ratios close to 1.2. The level of f_2 was set at 50 dB sound pressure level (SPL), and the level of f_1 was varied between 62 and 68 dB SPL. For individual DPOAE levels, suppression depths, and suppressor tone levels at 20 Hz, see Table I.

DPOAEs 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 of the AD converter of the multi-channel sound card (MOTU UltraLite) by the comparatively intense LF-suppressor tone. This tone was produced by a Beyerdynamic DT-48 earphone, which was directly driven by the headphone amplifier of the soundcard. The earphone output was delivered into the ear canal via a custom-made adaptor to a narrow silicone tube (200 mm in length, ∼0.5 mm of inner diameter), which was fed tightly through the pierced ear plug of the ER-10C probe. Such thin delivery tube constitutes an acoustic low-pass filter that prevented accidental sound delivery above 100-phon (given the maximum possible voltage of the headphone amplifier). Stimulus waveforms and DPOAE signal analysis was performed using custom-made software. After displaying two cycles of the $2f_1$-f_2 suppression pattern (i.e., the time course of the DPOAE magnitude), averaged over a 20-s long recording, the suppressor tone level for the next 20-s recording could be adjusted by the experimenter to achieve the desired suppression depth. This required typically three or four attempts per suppressor frequency. Measurements of both ears were obtained in a single session usually lasting less than 1.5 h, including probe fit checks, the primary tone parameter optimizations per ear, and a short break when changing between ears.

B. Equal-loudness-level contours

In addition to the iMETFs, equal-loudness-level contours were also obtained for all subjects, using a 50-Hz reference tone. The measured frequencies were identical to those used to determine the iMETFs, except that the uppermost frequency was reduced from 250 to 160 Hz in order to stay within the controllable frequency range of the apparatus. Measurements were carried out in a chamber (0.8 m × 1.4 m × 0.9 m), purpose-built for the playback of LF signals under a pressure field condition. Each side wall contained four Seas 33 F-WKA 13-in. loudspeakers driven by a Crown Studio Reference I (1160 W) power amplifier. Up to approximately 60 Hz, the cabin provided an effective pressure field in its entire volume. Before the experiments commenced, calibrated measurements ensured a flat transfer function within the range of possible head positions (±3 dB up to 160 Hz), and inaudibility of external sounds caused by activity in the building. In order to ensure inaudibility of harmonic distortion, medium level ELCs of approximately 40 phon were obtained. The validation measurements of the apparatus are described in detail in Jurado *et al.* (2011).

Just before each ELC measurement, absolute thresholds for a 50-Hz sinusoid were obtained with a three-alternative forced-choice (3AFC) task with a three-down one-up

TABLE I. Parameter values of the measured iMETF (for each ear), binaural 50-Hz absolute thresholds (50-Hz Th.), step frequencies (f_s) and root-mean-squared deviations (RMSD) between each subject's ELC and binaurally combined iMETF (after vertical alignment). For each ear the unsuppressed DPOAE level (L_{dp}) is shown, together with the 20-Hz suppressor tone level ($L_{Sup.20\,Hz}$) required to suppress the DPOAE by an amount shown as dp_{sup}. In the RMSD calculation, subscript "noTurn" considers the binaurally combined but uncompensated iMETFs; "compens." indicates that compensation for the dB-difference between the 40- and 70-phon ELCs from ISO (2003) was applied to the combined iMETFs; while "40-phon" and "50-phon" consider the fit of individual ELCs to the 40- and 50-phon curves from ISO (2003), respectively. No data are shown where no reliable measure could be obtained.

Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Left ear														
L_{dp} (dB SPL)	0.3	14.3	1.9	4.1	16	7.6	4.7	8.3	7.5	7.2	5.6	9.3	11.5	11.9
dp_{sup} (dB)	12	4	7	4	10	8	—	4	6	7	6	3	11	—
$L_{Sup.20\,Hz}$ (dB SPL)	113	114	113	114	113	113	—	110	114	117	118	116	111	—
Right ear														
L_{dp} (dB SPL)	6.3	13.8	2	4.5	14.1	4.6	8.6	10.4	9	8.4	7.5	5.4	14.5	8.5
dp_{sup} (dB)	10	4	10	6	5	8	3	6	4	5	7	4	10	5
$L_{Sup.20\,Hz}$ (dB SPL)	112	115	113	114	106	113	118	115	118	117	115	117	113	116
50-Hz Th. (dB SPL)	35.1	38.4	29.4	44.6	32.8	47.3	43.8	38.2	39.1	46.2	37.8	46.6	34.3	36.1
f_s — iMETF (Hz)	59.9	61.8	54.5	52.6	50.5	50.4	38.9	39.9	52.5	54.6	57.8	56.9	—	—
f_s — ELC (Hz)	61.6	59.2	54.6	56.0	52.7	49.2	38.1	43.3	40.6	51.9	56.7	57.7	39.3	—
$RMSD_{noTurn}$ (dB)	2.8	2.9	4.1	2.6	2.1	1.5	3.3	4.8	2.2	1.5	3.5	3.8	2.5	5.5
$RMSD_{compens.}$ (dB)	1.4	1.7	2.5	1.7	1.4	1.8	2.4	3.0	3.3	2.4	2.4	2.6	3.2	3.9
$RMSD_{40\text{-}phon}$ (dB)	3.2	2.4	2.3	3.7	3.6	4.8	3.2	2.2	5.5	4.6	3.3	3.0	5.2	2.0
$RMSD_{50\text{-}phon}$ (dB)	2.8	2.0	1.9	3.2	3.0	4.1	2.7	2.6	4.9	4.0	3.0	2.7	4.6	2.1

adaptive procedure, averaged over two repeats. This was done so that the 50-Hz reference stimulus could be individually set to 40 dB SL during the subsequent ELC experiment. The stimuli were 1.2 s long, including 0.2 s linear on- and offset ramps. Their timing was indicated by illuminating the response button corresponding to each interval. The inter-interval gaps were 400 ms. Feedback was provided after each response by illuminating the correct button. The procedure started at 15 dB hearing level (HL) with a simple one-down one-up rule for the first four presentations in order to rapidly approach the region of detection threshold. The initial step size of 8 dB was decreased to 4 dB and later to 2 dB, each after two reversals. The procedure terminated after further eight reversals and threshold was obtained by averaging these eight reversal levels.

Equal loudness was adjusted using a 2AFC task with a one-up one-down adaptive loudness balance procedure. Stimulus timing and inter-stimulus interval were identical to the threshold measurements. The 50-Hz reference tone (fixed at 40 dB SL) and the comparison tone were presented in random order, and the subject was asked to press the button associated with the louder stimulus interval. Two interleaved tracks were used. The procedure randomly selected one of the two tracks. For a given comparison tone, the level of one track started 10 dB below the 40-phon standardized ISO equal-loudness level (ISO, 2003), and the other track started 10 dB above it. This was done except when the frequency of the comparison tone was 20 Hz, in which case the tracks started at ±5 dB from the 40-phon level. These starting levels were found to be adequate after pilot testing. The initial step size of 8 dB was decreased to 4 dB and latter to 2 dB, each after two reversals. Each track terminated after six further reversals and the PSE was estimated by averaging these six reversal levels. For a given run, one PSE was determined, corresponding to the average PSE of the two interleaved tracks. Two runs were performed, and the PSE was estimated by averaging the PSEs obtained in the two runs. If the PSEs of the two runs differed by more than 3 dB, a third run was performed and all three PSE estimates were averaged. The sequential order of the comparison tones tested (ranging from 20 to 160 Hz) was randomized. Breaks took place regularly after every second run (roughly every 5 to 8 min) to keep the subjects alert. The psychoacoustical measurements were obtained in a single session, lasting about 2.5 hours in total, including breaks. Except for subjects 1, 3, and 5 (see below), ELC measurements were carried out within one month of measuring their iMETFs.

C. Data analysis

In order to allow an individual comparison of the monaural iMETFs with the binaurally obtained ELC, left- and right-ear iMETFs were combined to obtain a single representative curve for each subject by applying the binaural loudness summation model proposed by Sivonen and Ellermeier (2006), which is based on binaural power summation. Because only the shape of the iMETF mattered, and therefore the left- and right-ear iMETF were not necessarily measured with equal suppressor tone intensities, they had to be vertically aligned prior to power summation. The root-mean-squared (RMS, in dB) difference was minimized by vertically shifting the individual curves using the Levenberg-Marquardt algorithm (Marquardt, 1963). The suppression pattern caused by the 250-Hz suppressor often deviated from the typical shape, consequently the DPOAE suppression depth was sometimes difficult to estimate reliably. Therefore, the alignment was based on data points between 20 and 125 Hz.

Also for the calculation of standard deviations (SDs) among individual iMETFs and ELCs, each individual curve was first vertically aligned to match its respective average curve using the same method as for the alignment of the iMETFs, so as to compensate for individual overall-level differences.[1]

In order to define the approximate frequency location of the typically observed step in the individual curves, these were fitted between 20 and 70 Hz by a 4th-order polynomial. The step frequency, f_s, was then determined as being the spectral location of the maximum of the 1st derivative.

D. Subjects

A group of 14 subjects, 10 male and 4 female, participated in both the iMETF and ELC experiments. A standard audiometry, using the ascending method (ISO, 1989), indicated that subjects had normal hearing thresholds in both ears (20 dB HL or better) for frequencies between 125 and 4000 Hz. Their hearing threshold for the reference signal in the ELC experiment (50 Hz) was also found to be normal (threshold was obtained with the method described in point B above). Subjects had no history of hearing disorders or special aversion to LF-noise. No tympanometry was performed, since the required equipment was not available.[2] Subjects 1, 3, and 5 had already participated in the preliminary study by Marquardt and Pedersen (2010) as subjects C, B, and A, respectively. Their iMETF data were re-used,[3] but their psychophysical measurements were repeated with the current method.

III. RESULTS AND DISCUSSION

The iMETFs of all 14 subjects could be obtained, although for subjects 7 and 14 from one ear only. The DPOAE in the left ears of subjects 7 and 14 could not be sufficiently suppressed by LF-tones below 90-phon [Marquardt and Pedersen (2010) also experienced a couple of such cases in their preliminary study]. Figure 1 shows an overview of all data obtained. Most iMETFs (thin lines, no marker) follow roughly the 80-phon curve. Individual curves commonly exhibit a step that separates two regions of different slopes (see below). The average iMETF (bold) also exhibits such step, a transition from the 70-phon curve below 40 Hz to the 80-phon curve above approximately 60 Hz. Consistent with the curved shape of the isophons, these frequency regions also differ in their slope. Amongst individual iMETFs, the mean slope was 12.9 dB/oct (SD = 2.3 dB/oct) below 35 Hz and 6.1 dB/oct (SD = 1.6 dB/oct) above 100 Hz. In contrast to the standardized isophons, this slope change occurs rather abruptly. Step frequencies of individual iMETFs are given in Table I; their mean value was 52.5 Hz, with SD = 7.1 Hz.

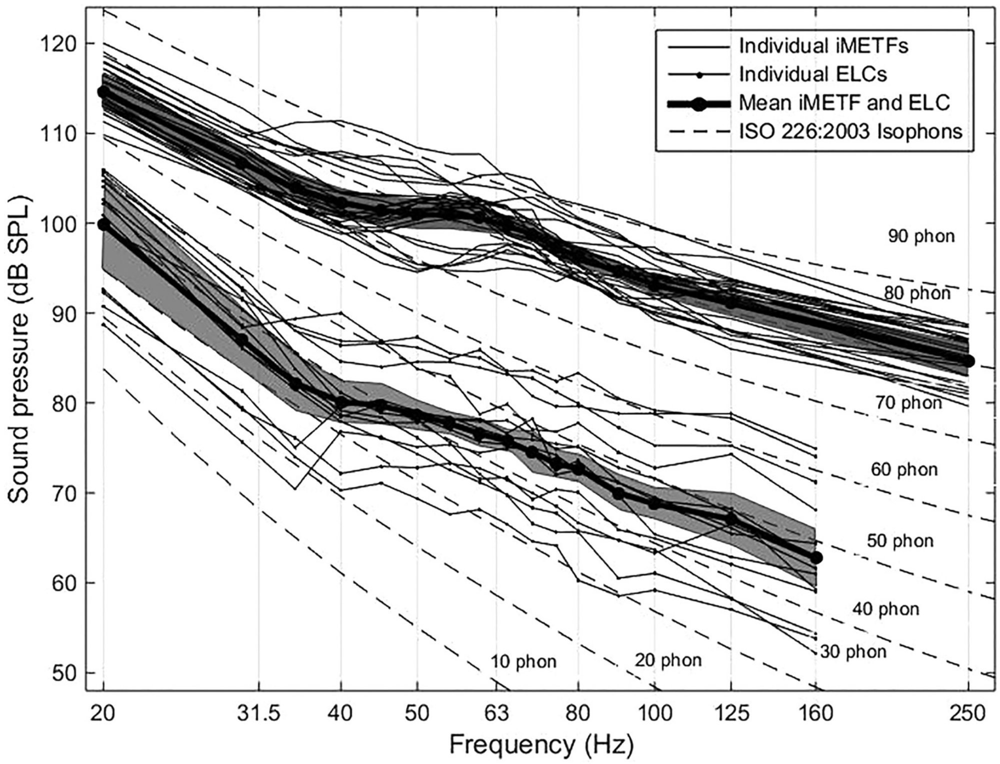

FIG. 1. Individual iMETFs and ELCs obtained for 14 subjects (thin solid lines without and with dot markers, respectively). The mean curves of iMETF and ELC are shown as thick solid lines with dots, and their SDs (after vertical alignment) are shown by the grey areas. For comparison, isophon curves (10- to 90-phon, indicated above each curve) from the ISO (2003) international standard are shown as dashed lines.

Suppressor level SDs, shown as grey areas in Fig. 1, tended to slightly increase below about 55 Hz and above 100 Hz, but never exceeded 2 dB.

While the iMETFs were obtained at levels between 60 and 90-phon, ELCs were obtained at lower stimulus levels. Individual ELCs (thin lines with dots) fell commonly between 20 - and 60-phon. This larger spread was in part a consequence of differences in the subject's detection threshold for the 50-Hz reference tone (29–47 dB SPL, mean 39.3 dB SPL; individual values are given in Table I). Like the majority of iMETFs, many of the individual ELCs contained the step feature. Its appearance in the average ELC (bold line with dots) is, however, rather subtle compared to that of the average iMETF. The average ELC follows roughly the 40-phon curve, although a marked transition from clearly below to well above this isophon is also evident here. A rather abrupt change in slope below about 40 Hz contrasts with the smoothness of the standardized ELCs (dashed lines). A more detailed discussion of the relation between the measured ELCs and ISO (2003) is given in Sec. IV C. Amongst individual ELCs, the mean slope was 22.1 dB/oct (SD = 3.7 dB/oct) between 20 and 35 Hz and 9.1 dB/oct (SD = 2.0 dB/oct) between 50 and 160 Hz. Step frequencies of individual ELCs are given in Table I; their mean value was 50.8 Hz, with SD = 8.0 Hz.

SDs in loudness level were significantly larger than suppressor level SDs ($t = -4.15$; $p < 0.001$). They increased markedly below the step (SD = 2.2; 3.2; 3.4; and 4.9 dB for 40, 35, 30, and 20 Hz, respectively). Factors thought to influence loudness level causing these larger SDs are discussed in Sec. IV B.

Figure 2 shows pairs of left- and right-ear iMETFs of each subject which were vertically aligned by minimizing the RMS difference. For clarity, curves of individual subjects are vertically offset (see Table I for the absolute sound pressure levels at 20 Hz for each individual curve). The iMETFs of the seven subjects with the most prominent resonance features in both ears (except subject 7, for which only the right-ear iMETF was measurable) are shown in the left panel, and ordered, top to bottom, by their step frequencies, which spread over approximately $\frac{2}{3}$ of an octave. The iMETFs of the subjects plotted in the right panel exhibit either no, or a less pronounced, step in either one (subjects 9, 10, and 11), or both (subjects 8, 12, and 13), of their ears. The right ear of subject 12 and 14 show rather unusual double peaks, which remain unexplained.

Marquardt and Pedersen (2010) reported a generally good match between the shape of left- and right-ear iMETFs in their five subjects. Although this was not uncommon also in the current study, there have been several exceptions, so that such across-ear symmetry cannot be generalized. Across-ear asymmetries are apparent in step frequency (subjects 2, 5, and 10), as well as in damping (subjects 2, 3, 9, 10, and 11).

As can be seen in Fig. 1, the ELCs in the 40-phon region were generally steeper than the iMETFs, which were obtained with suppressor tone levels close to 70 phon. This is consistent with the level-dependent slope of the

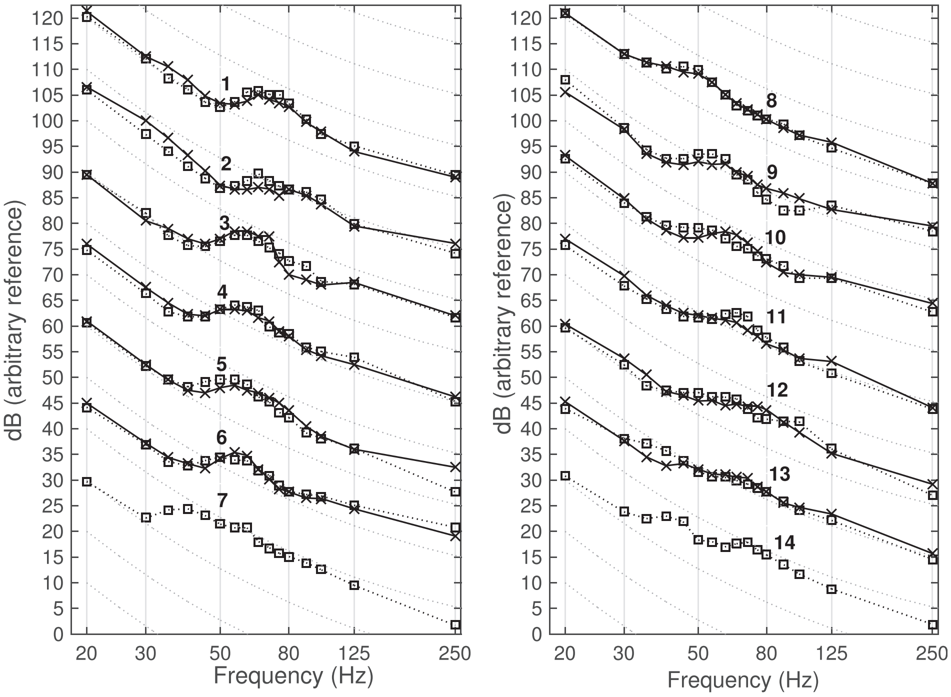

FIG. 2. Inverse middle ear transfer function (iMETF) shapes obtained for the left (solid lines with crosses) and right (dotted lines with squares) ears of each subject (1 to 14). Only the right ear could be measured for subjects 7 and 14. For clarity, individual curves are offset, so that the ordinate dB-scale is arbitrary (for actual dB SPL at 20 Hz, see Table I). Left and right iMETF of each subject have been aligned to minimize the RMS difference between both curves (exclusive of the 250 Hz values). The curvature of the horizontally oriented grid lines corresponds to the 80-phon curve in ISO (2003).

standardized ELCs in ISO (2003). To facilitate comparison with the binaurally obtained ELC, the left- and right-ear iMETF of each subject were combined into one curve (see Sec. II), and the slopes of the combined iMETFs were compensated by the slope difference between the 40- and 70-phon standardized ELCs.[4] Figure 3 shows these combined and compensated iMETFs (dotted lines with squares) together with the corresponding ELCs of the same subject (solid lines with asterisks). Both curves have been vertically aligned by minimizing their RMS difference (in dB) for frequencies between 20 and 125 Hz. As in the previous figure, data for each subject are offset (if desired, the reader may infer the absolute positions of the individual ELCs from the 50-Hz absolute threshold values given in Table I; the individual 50-Hz reference tones were 40 dB above these thresholds).

ELCs of most subjects were not smooth, but exhibited rather abrupt slope transitions, often in connection with a non-monotonic step, similar to those in their iMETF. With the exception of subjects 2 and to some extent 3, subjects with a pronounced step in the iMETF of both ears (left panel) also showed a frequency-matching step in their ELC. Although only the right-ear iMETF of subject 7 could be measured, its step shows reasonable similarity to that in their

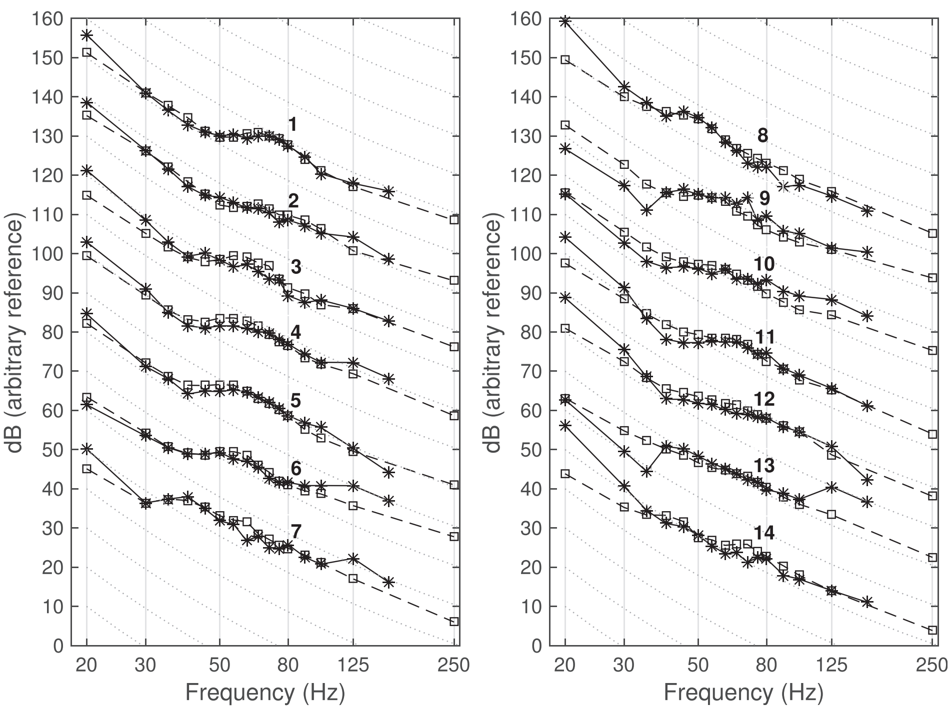

FIG. 3. ELCs (solid lines with asterisks) and iMETFs (combined from the left and right ears; dashed lines with squares) obtained for 14 subjects. Each iMETF was aligned to match the subject's ELC. The iMETFs have been compensated by the dB-difference between the 40- and 70-phon curves described in ISO (2003). The numbers above each curve are the subject's identifiers. The curvature of the horizontally oriented grid lines corresponds to the 40-phon curve in ISO (2003).

ELC. While relatively smooth, subject 8 also displayed a non-monotonic irregularity in both iMETFs that matched their ELC fairly well. The pronounced resonance in the ELC of subject 11 is probably based on their right-ear iMETF (shown in Fig. 2), although, in the combined iMETF, the resonance appears less marked. Subject 12 showed a consistent lack of a non-monotonicity in left- and right-ear iMETF and their ELC. Subjects 2 and 10 also showed smooth ELCs, although their individual iMETFs had clearly visible steps (Fig. 2). However, a better match can be seen with their combined iMETF (Fig. 3), which is smoother due to across-ear differences in damping and step frequency.

Other subjects showed a clear inconsistency between the shapes of their ELC and iMETF: Subjects 9 and 13 had a sudden drop in their ELC below 40 Hz, which was not evident in their iMETF. The existence of such distinct dips only in the perceptual domain may indicate influences from other factors, such as a subjective hypersensitivity to specific low frequencies (however, these subjects did not report of any aversion to LF-sound). Previous results by Marquardt and Pedersen (2010) suggested that the occurrence of such dips in the ELCs may be level dependent (e.g., see Fig. 4, Sec. IV A). It is then possible that the feature disappears at the higher stimulus levels at which the iMETFs were obtained. Also, although both the ELC and iMETF of subject 14 show a hint of double resonance, these two curves show generally little resemblance to each other.

Unrelated to their iMETF, which are generally smooth in this frequency region, subjects 6, 7, and 13 showed a sudden increase in their ELC above 100 Hz. Again, it is possible that such features are reflected only in the ELC because they were measured at lower stimulus levels. At low levels and at around the same frequency region, Marquardt and Pedersen

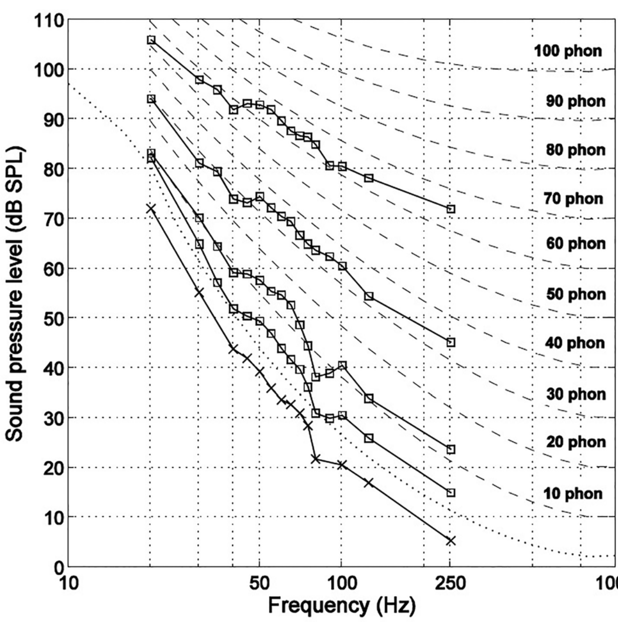

FIG. 4. ELCs (solid lines with squares) measured at different loudness levels for one subject reported by Marquardt and Pedersen (2010). The subject's detection thresholds are shown by the crosses. Dashed lines are the standardized isophons and the dotted line is the standardized detection threshold curve (ISO, 2003). Note that these data were obtained under artificial free-field conditions.

(2010) observed for one subject a similar irregularity in low-level ELCs (see example reproduced here in Fig. 4, and to be discussed further in Sec. IV A). But it is also possible that the LF chamber contributed to this effect, since above 60 Hz it does not provide a perfect pressure field in its entire volume and has slightly higher spatial uncertainties in sound pressure (for details see Jurado *et al.*, 2011). Nevertheless, a visual analysis indicates that, for the majority of subjects, there was a reasonable consistency between combined iMETF and ELC.

Like for the iMETFs, the step frequency in the individual ELCs ranged from about 38 to 60 Hz, and there was generally a good correspondence in step frequency between iMETF and ELC ($R^2 = 0.91$, $F = 94.3$, $p < 10^{-5}$; the analysis excluded subjects 9, 13, and 14).[5] For frequencies below the step, the steepness of both iMETFs and ELCs increased sharply, an indication of a perceptual effect of the helicotrema shunt.

As a further quantitative measure of the match between combined iMETFs and ELCs, the root-mean-squared deviation (RMSD) between both curves was calculated for each individual case, after the RMS vertical alignment. Values are given in Table I. As expected, the RMSD was generally lower when comparing the ELC with the compensated iMETF (mean = 2.4 dB) than with the uncompensated iMETF (mean = 3.1 dB); this difference was statistically significant ($t = 2.6$; $p = 0.02$).

When considering the average data in Fig. 1, comparison of the average ELC with the uncompensated average iMETF gave an RMSD of 2.5 dB (RMS aligned). The level compensation reduced the RMSD to 1.3 dB, an even better agreement than obtained for any individual. This indicates a relatively low residual variance in the average ELC, which was not explained by the compensated average iMETF.

Finally, we assess quantitatively whether the compensated-individual iMETFs predict the frequency dependence of loudness perception more accurately than the isophons in ISO (2003). Again, the individual ELCs were vertically offset to align (minimum RMS) with either the 40-phon curve, or the 50-phon curve. These two were chosen since these were the closest isophons to the average ELC (Fig. 1). These RMSD values, shown in the bottom two rows of Table I, were generally larger compared to the RMSDs between ELCs and compensated iMETFs. This difference was significant (40-phon: $t = 3.0$; $p = 0.01$; 50-phon: $t = 2.3$; $p = 0.04$). Also the average ELC, shown in Fig. 1, presents a higher similarity with the compensated average iMETF than with the isophons (RMSD of 1.3 dB compared with 2.8 and 2.3 dB for 40- and 50-phon, respectively).

Overall, although clear discrepancies were observed in some individual cases, this quantitative analysis, as well as visual inspection, indicate that the shape of the compensated iMETF was generally a good predictor of the frequency dependence of loudness for the majority of subjects.

IV. GENERAL DISCUSSION

Overall, the comparison given above between 14 individual iMETFs and ELCs provides supportive evidence that the METF determines to a large extent the frequency dependence of loudness perception at frequencies below 100 Hz. It has to be borne in mind, however, that in some individual cases (e.g., subjects 9, 13, and 14) distinct discrepancies between iMETF and ELC have been observed, and therefore it should not be understood that the objectively measureable shape of the iMETF is *always* a good predictor of the ELC shape on an individual basis. There may be additional subjective effects (e.g., discomfort), which may influence the individual's loudness judgment, in particular, at frequencies below 40 Hz.

However, various measurement uncertainties were possibly also causes of such discrepancies. A methodological compromise in our study was that no monaural sound source for the behavioral ELC experiment was found that produced LF-tones without audible harmonics. Therefore, these measurements were taken binaurally in the available purpose-built pressure chamber. In contrast, the iMETF shapes are obtained separately for left and right ear, and had to be later combined for comparison with the binaural ELC. Because absolute iMETF magnitudes could not be measured non-invasively, there may be cases where they differ between left and right ear, and loudness might be dominated by the better ear. In such case, the approach taken of binaural power summation would be inappropriate. While the majority of subjects had symmetric iMETFs, and this issue was less critical, the ELC of subject 11 appears to be based entirely on their right iMETF. On the other hand, for three other subjects (2, 3, and 10) with discrepant left- and right-ear iMETF, the power combination approach helped in predicting the smoother step in their ELCs.

In the case of the ELCs, errors may also arise due to slight variations in SPL within the LF chamber (in particular $>$ 100 Hz), or as a result of variations in the subject's response criteria. In case of the iMETF measurements, the DPOAE suppression patterns deviated sometimes from the usual shape, especially for suppressor frequency $>$80 Hz. This made it in some cases difficult to estimate the suppression depth accurately and therefore to adjust the suppressor tone with confidence. Nevertheless, the generally favorable evidence of a strong influence of the METF on ELCs calls for a more-in-depth discussion of this relationship.

A. The influence of the METF on loudness perception

Since the definition of the METF, as used here, describes the gain between the pressure at the ear canal and the differential pressure across the BM (Dallos, 1970; Marquardt and Hensel, 2008, 2013), it not only considers the filtering of sound by the middle-ear, but also the high-pass effect of the helicotrema that shunts this differential pressure if the stimulation frequency is low enough for the travelling wave to reach it. Since it is the BM movement that leads to depolarization of the sensory cells, it is reasonable to expect that characteristics of the METF would be reflected in the neural output of the cochlea, and consequently affect perception. However, certain physiological factors possibly cause some differences between individual iMETF and ELC.

As mentioned earlier, an important difference between ELC and iMETF is that the latter is measured using DPOAE, which are generated more basally, near the characteristic places of the primary tones in the second cochlear turn (Gaskill and Brown, 1996), whereas the behaviorally obtained ELC is dominated by the large vibrations in response to LF-sound at the most compliant, apical, end. If the resonance involves the fluid mass in the helicotrema (Marquardt and Hensel, 2013), one would therefore expect it to be more pronounced in the ELC than in the iMETF. This was not generally observed, probably because the BM response shows little frequency tuning to LF-tones, which excite therefore almost the entire BM (e.g., see modelling by Schick, 1994) so that the resonance feature is evident even in METFs obtained from the 1st turn of animal cochleae (Dallos, 1970; Nedzelnitsky, 1980).

In addition to the METF, loudness perception depends further on activation of the auditory nerve. It is therefore affected by additional factors involving inner hair cell excitation and neural noise (Moore *et al.*, 1997; Cheatham and Dallos, 2001; Salt and Hullar, 2010). For example, the velocity sensitivity of the inner hair cells provides theoretically an extra 6 dB/octave high-pass filter prior to the auditory nerve excitation. In contrast, the DPOAE, used to derive the METF shape, are generated by the displacement-sensitive outer hair cells. This might be the explanation why the measured ELCs below the resonance region were still, on average, 5 dB/octave steeper than the already compensated iMETFs (especially noticeable in subjects 3, 7, 8, and 10–14).

The compensation of the iMETFs for the level dependence of isophons did considerably improve their agreement with the ELCs. The convergence of isophons below 500 Hz with decreasing frequency is well documented (Moore *et al.*, 1997; Suzuki and Takeshima, 2004), and is commonly explained by a lack of cochlear compression due to a gradual decrease in active amplification toward the apical end of the cochlea (Delgutte, 1990; Rhode and Cooper, 1996). Figure 4 shows an individual example reproduced from Marquardt and Pedersen (2010), where the ELCs of one subject were measured at different levels with a similar frequency resolution as in the present study. Whereas the range of suppressor levels suitable for our iMETF measuring technique are restricted to 70–90 phon, these multiple-level ELCs suggest that besides the expected changes in overall steepness, the qualitative features of the step region exist over a wide range of loudness levels.

B. Factors affecting SDs in loudness and suppressor levels

The significantly larger overall SDs amongst ELCs compared to those amongst iMETFs indicate a considerable involvement of subjective factors, such as variations in the response criterion related to difficulties in comparing tones of different perceptual qualities. Individual differences in LF-loudness perception tended to increase especially below 40 Hz, where stimuli lose tonality. Also the SDs in suppressor levels for the iMETF measurements increased slightly in this frequency region.

TABLE II. Single and two-factor linear regressions for the 20-Hz suppressor and loudness levels (Supp. L_{20Hz}, and Loud. L_{20Hz}, respectively). The dB/oct slope within 20–35 Hz and step frequency (f_s) have been used as factors. R^2 is the coefficient of determination. Significant linear relationships ($p < 0.05$) are indicated with asterisks. All correlations are positive. Note that the analysis includes all cases shown in Table I where step frequency could be reliably estimated.

Factor	f_s	Slope	Combination of both
Supp. L_{20Hz}			
R^2	0.36*	0.44*	0.50*
Loud. L_{20Hz}			
R^2	0.26	0.54*	0.61*

We suspected that the large variability at 20 Hz might relate to the slope between 20 and 35 Hz and the step frequency. We therefore performed linear regression analyses with these two curve parameters as single and combined factors. The results are shown in Table II. As expected, a positive correlation between both of these parameters and loudness/suppressor levels was found. For suppressor levels, both factors appear to contribute significantly, indicating that higher values lead to less sensitivity. On the other hand, the step frequency seems to impact significantly less on the loudness level and the slope appears here to be the dominant factor. This is clearly related to the higher SDs in slope observed amongst the ELCs compared to the iMETFs (Fig. 1), as differences in slope will have an increased impact on loudness level as frequency decreases.

C. Comparison of ELCs with standardized isophons

Isophons, as standardized in ISO (2003), describe smooth curves that monotonically decrease from 20 to 500 Hz. The ELCs (and iMETFs) described in this work generally deviate from these standardized isophons, in two ways: (1) their slope increased rather sharply below a commonly observed step region; (2) the measured ELCs generally do not follow a single isophon, but transit from one to another due to this step, which in more than half of the cases interrupts the monotonicity of their generally negative frequency dependence.

Apart from the preliminary work by Marquardt and Pedersen (2010), previous studies have shown only partial evidence supporting the existence of such a step region in the perceptual domain. Møller and Pedersen (2004) found that SDs in hearing threshold tend to increase in the frequency range 20–50 Hz. However, they did not report, or comment on, non-monotonic features in this frequency region, and focused on proposing hearing thresholds and ELCs for the infrasound range.

On the other hand, Frost (1987) found in one subject microstructures that show a distinct dip at 40 Hz in agreement with the present observations. However, no cases of a clear step region appear in Frost's data.

Watanabe and Møller (1990) obtained hearing thresholds in the frequency range 4–125 Hz, under a pressure field condition. Their absolute threshold curve is slightly irregular in the frequency region of the step. Also, a slight offset is evident, with the LF side approaching the 0-phon curve (ISO, 2003), while the high-frequency side sits between the 0- and 10-phon curves. However, all these features are clearly less pronounced than those observed in this study.

The individual variations in the resonance visible in our ELCs demand care when averaging across the population, so that it does not get obliterated. Despite this irregularity, the fact remains problematic that the measured ELCs tend to change consistently from one isophon curve to another. While this "offset" was about 10-phons for the mean ELC, for subjects 9 and 13 it reached up to 30-phons. This implies that the isophons may provide a wrong estimation of loudness by a factor of 2 to 8 sones at very low frequencies, for some subjects. The offset also indicates that the standardized curves underestimate the hearing sensitivity of most individuals below 40 Hz.

It seems evident that the use of A-weighted filters is inadequate at low frequencies, as has been suggested previously (Kjellberg *et al.*, 1984; Persson and Björkman, 1988; Leventhall, 2004, 2009). Such crude frequency compensation may lead to large errors in estimating loudness, which may partly explain the higher annoyance generally found for LF-noises compared to noises with higher spectral components of same A-weighted levels (Persson *et al.*, 1985, 1990).

Overall, our data suggests that, below 100 Hz, the shape of the ELC is not a smooth curve, as is generally assumed (e.g., see Fletcher and Munson, 1933; Robinson and Dadson, 1956; Takeshima *et al.*, 2003; Suzuki and Takeshima, 2004). The comparatively lower frequency resolution and the smoothing of individual irregularities due to averaging across many subjects are probable reasons why previous studies have not discovered the step region in their ELCs. Although more data need to be gathered, the consistent discrepancies with the standardized curves, found for all subjects and for our average ELC, might be considered in future revisions of ISO 226.

V. CONCLUSIONS

We have obtained and compared a set of individual ELCs and iMETFs measured with high spectral resolution in the LF range. These are our main conclusions from data of 14 subjects:

(1) The power of a LF-suppressor tone required for iso-suppression of DPOAEs presents a very similar frequency dependence as the power of such tone required to maintain equal loudness. This means that, as an across-subject average measure, the shape of the compensated iMETF is a good predictor of the frequency dependence of ELCs below 160 Hz.

(2) For some individuals, distinct discrepancies between iMETF and ELC have been observed, showing that the shape of the iMETF is not always a good predictor of individual ELCs. Although in agreement for the majority of subjects, the spectral location and detailed shape of the non-monotonic resonance feature in particular, were clearly inconsistent between both measurements in a few cases.

(3) The ELCs were generally steeper than the iMETFs. However, a better overall match between ELCs and

iMETFs was obtained after accounting for the difference in level at which the measurements were taken, in a manner consistent with the systematic slope variations present in standardized isophons.

(4) Below 40 Hz, the variability in loudness perception amongst subjects tends to markedly increase, while iMETFs do not show such a marked trend in this range. It is then possible that subjective factors are involved, which may introduce further variance when judging the loudness of unfamiliar sounds with low tonality.

(5) The average ELC obtained in this study fails to be adequately represented by isophon curves standardized in ISO (2003). Besides its sharp slope transition at 40 Hz, our average ELC followed about a 10-phon higher isophon curve above 65 Hz than below 35 Hz. This indicates that the hearing organ's sensitivity to very low frequencies might be underestimated by the standard.

(6) The observed characteristics of iMETFs and ELCs (besides their difference in steepness) are explained by the model of the apical cochlea proposed by Marquardt and Hensel (2013). It suggests that the helicotrema is a dominant factor in shaping and decreasing perceptual sensitivity to LF-sounds, with individual differences presumably arising from cochlear anatomical differences.

Future studies of LF-sound perception and detailed models of its mechanisms will be needed to fully understand how LF sensitivity relates to morphological variations in the apical cochlea. The methods used in this study might be applicable for the diagnosis of patients with unusual aversion to LF-sound.

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[1]Alignment was also done with versions sampled in higher resolution (cubic interpolation) at equally distant frequencies on a logarithmic scale to check if the denser measured frequency region (35–80 Hz) was dominating the RMS minimization. However, essentially the same results were obtained, therefore the applied analyses uses only the measured data points.

[2]It was assumed that any abnormal middle-ear function relevant for LF-sound transmission would also lead to an increase in 50-Hz hearing thresholds. However, Table I shows that all subjects had thresholds close to, or better than the threshold of ISO 226 (44 dB SPL @ 50 Hz).

[3]Repeated measurements of iMETF data of the second author's ears showed that iMETF were stable over a period more than a decade.

[4]The difference between the 40- and 70-phon curves was chosen for the compensation because below 40 Hz, where the slope difference between ELC and iMETF was largest, their average curves, respectively, follow (roughly) these two isophons (Fig. 1).

[5]Subjects 9 and 13 were excluded from the correlation analysis because the sudden drop in their ELC was considered not related to their iMETF; besides no reliable estimation of their step frequency could be obtained for the straight combined iMETF of subject 13. Subject 14 was also excluded because of the non-interpretable double peak in their data, which also prevented a reliable estimation of a single step frequency.

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