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Psychophysical tuning curves for very low centre frequencies

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ABSTRACT

Noise with energy in the low-frequency range (i.e. below 200 Hz) is known to produce problems with annoyance and represents an environmental problem (Leventhall, 2004). Attempts to understand and predict problems produced by low-frequency noise require information about human frequency selectivity in the low-frequency range. However, there are few data on frequency selectivity for centre frequencies below 100 Hz. To estimate the characteristics of auditory tuning for very low frequencies, in this study psychophysical tuning curves (PTCs) were obtained for tonal and narrow-band noise maskers at centre frequencies (CFs) of 31.5, 40, 50, 63, and 80 Hz. For the tonal maskers, pairs of tones designed to produce modulation-detection-interference (MDI) were added to the masker, as a way to evaluate and reduce the effects of beats. For each subject, an equal-loudness-level contour was also obtained using closely spaced frequencies. This was used as a rough estimate of the shape of the individual middle-ear transfer function (METF) in the frequency range below 100 Hz. Preliminary results obtained using 9 subjects are described. Sharp tips were observed for some of the PTCs derived with the tonal maskers, probably reflecting the influence of beats. Addition of the MDI tones produced more regular and broad tips for cases where beating was evident. The PTCs obtained with the noise maskers were generally more regular around their tips. For both masker types, the overall shapes of the PTCs were broad, indicating that frequency selectivity at very low frequencies is relatively poor. Also, the PTCs were generally asymmetrical, with steeper lower skirts than upper skirts, an effect that became more pronounced as the CF was decreased. For the CFs of 31.5 and 40 Hz, the tips of the tuning curve did not occur at the CF, but at a higher frequency. The overall shapes of the tuning curves, and the degree to which tuning was affected at the lowest CFs, appear to be influenced by the shape of the (estimated) METF.

INTRODUCTION

Noise with energy in the low-frequency range (e.g. below 200 Hz) is known to produce problems with annoyance and represents an environmental problem (Leventhall, 2004). While for simple sinusoidal signals, their audibility and loudness can be predicted by the use of threshold curves and equal loudness contours (ISO 226, 2003), environmental noises are often complex signals. In order to understand how these signals excite the hearing organ, and to model and understand human sound perception of low frequencies, the characteristics of auditory tuning are required (Moore et al., 1997). However, few results exist that describe the characteristics of frequency selectivity in this range. Jurado and Moore (2010) have obtained estimates of the bandwidth and shape of the auditory filter for several CFs down to 50 Hz, using the notched-noise method. Their results indicate that, while the bandwidth of the auditory filter at low CFs is wider relative to CF than at higher CFs, there is a decrease in equivalent rectangular bandwidth (ERB) at least down to a CF of 80 Hz. At 50 Hz, they found a further worsening of tuning that made the ERB increase at this CF. This worsening in tuning occurred mainly because the derived filter shapes had very shallow upper skirts. For CFs below 100 Hz, the lower filter skirts were sharper than the upper skirts, a clear reversal of the asymmetry often observed at high CFs. The asymmetry at low CFs was attributed to the attenuation produced by the middle-ear highpass filter (as observed in the physiological estimates of Cheatham and Dallos (2001)). The middle-ear transfer function (METF) is assumed to become steeper in slope below about 50 Hz, because it includes the shunt effect of the helicotrema (Marquardt et al., 2007, Marquardt and Hensel, 2008). This slope was found largely to determine the lower skirt of the auditory filter as the CF approached 50 Hz. Jurado et al. (2010), calculated auditory filter shapes by assuming that the auditory filters were preceded by METFs as estimated by Marquardt and Pedersen (2010), from distortion product isomodulation techniques. These METFs have a small resonance feature that forms a transition region separating two distinct slope regions (see e.g. Marquardt and Pedersen (2010)). The results suggested that the irregular resonance feature in the METFs could also affect the tips (i.e. maximum gain point) of tuning curves for very low CFs; the shape around the tip could be altered and the tip could be shifted so that it was not at the CF, but typically at a higher frequency.

In the present work, psychophysical tuning curves (PTCs) were obtained for CFs below 100 Hz, in order to obtain a direct and detailed description of frequency selectivity within this range. The CFs used were 31.5, 40, 50, 63, and 80 Hz.

Both tonal and narrow-band noise maskers were used to mask sinusoidal signals at those CFs.

When tonal maskers are used, beats between the signal and masker can provide a powerful detection cue (Wegel and Lane, 1924, Egan and Hake, 1950, Greenwood, 1971). To reduce the influence of beat detection on the results, conditions were included where pairs of beating tones were added to the main masker, to reduce the influence of beats via the phenomenon of modulation detection interference (MDI) (Yost and Sheft, 1989, Bacon and Moore, 1993). The influence of the METF on tuning was also studied, by estimating its shape from equal-loudness-level contours (ELCs) measured using closely spaced frequencies in the range below 160 Hz. Additional aims were to quantify the extent of individual differences and to identify the CF of the "bottom" auditory filter, the one with the lowest CF. The results were expected to contribute to general understanding of frequency selectivity at very low frequencies and therefore to help in characterizing human perception of low-frequency noise.

METHODOLOGY

Experiment 1: PTCs derived with tonal maskers

A PTC is the level of a narrowband masker required to mask a signal that is fixed in frequency and level, plotted as a function of masker frequency, f_m. The signal was a sinusoid with frequency f_s presented at a fixed level of 15 dB sensation level (SL). The maskers were sinusoids. In order to describe the tip as well as the overall shape of the PTCs, the values of the relative separation, $\Delta = (f_m - f_s)/f_s$, between f_m and f_s depended on f_s. To define the tip, finer spacing was used around f_s. A total of 9 values were used for each f_s. These were: –0.6, –0.4, –0.2, 0, 0.2, 0.4, 1.2, 2.2, and 3 for 31.5 Hz; –0.6, –0.5, –0.4, –0.2, 0, 0.2, 0.4, 1.2, and 2.2 for 40 Hz; –0.6, –0.5, –0.4, –0.2, 0, 0.2, 0.4, 0.8, 1.6 for 50 and 63 Hz, and –0.6, –0.5, –0.4, –0.2, 0, 0.2, 0.4, 0.8, and 1.2 for 80 Hz.

Signals were 1.2 sec long, including 0.2 sec linear ramps at start and end. The masker had the same length and ramp characteristics as the signal. The masker and signal were gated synchronously.

Experiment 2: PTCs derived with tonal maskers and MDI tones

In order to study the influence of beats on the PTCs, "MDI tones" were added to the stimuli. These tones consisted of a fixed and a variable frequency tone; the frequency of the fixed tone was $2.2f_S$, except for f_s = 80 Hz where it was $2f_s$. The variable frequency tone had the same value of Δ relative to the fixed tone as for the masker and signal. For example, if the masker had a frequency of 30 (or 70) Hz, and the signal had a frequency of 50 Hz, the fixed MDI tone had a frequency of 110 Hz and the variable MDI tone had a frequency of 90 (or 130) Hz.

For the first two subjects tested, the MDI tones were included for Δ = –0.4, –0.2, 0.2, and 0.4. However, this appeared not to cover enough of the tip of the PTC, particularly for the lowest signal frequencies. Therefore, for the rest of the subjects, a value of Δ of 1.2, was included for f_s = 31.5 and 40 Hz, and a value of Δ of 0.8 was included for f_s = 50 and 63 Hz.

The level of the MDI tones was set so that they were salient enough to provide effective interference with beat detection, while avoiding levels that might be high enough to directly mask the signal. The appropriate level was found after initial tests, for each subject at each f_s. The level varied from 8 to 18 dB above the ISO 226 (2003) absolute threshold levels for the frequencies of the MDI tones.

The MDI tones were gated synchronously with the signal and masker, the time configuration of all signals being the same as for experiment 1.

Experiment 3: PTCs derived with narrowband-noise maskers

Narrow-band noise with a bandwidth of $0.5\times f_s$ was used as a masker. This bandwidth was chosen to be wide enough to reduce the influence of beats as a cue (Kluk and Moore, 2004, Alcántara et al., 2000, Moore et al., 1998), while being narrow enough that it did not limit the measured frequency selectivity. The values of Δ used were based on the centre frequency of the signal and were the same as for experiment 1, with the exception that the largest value was Δ = 1.2 instead of 1.6 for f_s = 63 Hz.

The noise maskers were created by filtering a wideband white noise signal with a 200th order Chebyshev type II digital IIR bandpass filter. The slopes of the filter were effectively infinite.

Noise bursts were 1.3 sec long, including 0.2 sec linear ramps at the start and end. They were taken randomly from a 39-second noise buffer. In each 3-alternative sequence, the same randomly chosen burst was used. Tone signals were 1.2 sec long with 0.2 sec ramps at start and end. The tone signal started 50 ms after the noise started, and ended 50 ms before it ended.

Threshold procedure

A 3-alternative forced-choice task with a 3-up 1-down adaptive procedure was used to estimate the 79% point on the psychometric function (Levitt, 1971), for all three experiments. The silent interval between the three stimuli in a trial was 400 ms. Feedback was provided after each response. The procedure started with a simple 1-up 1-down rule for the first four presentations in order to rapidly approach the region of masked threshold. At the beginning, the masker started at a relatively low level, so that the signal was clearly audible. This level depended on f_s and on Δ, and was selected after pilot tests. The stepsize started at 8 dB, was decreased to 4 dB after 2 reversals, and was decreased to 2 dB after 2 further reversals, where it remained.

A total of 12 reversals was obtained and the masked threshold was estimated as the average of the levels at the last 8. Two threshold estimates were obtained. If the difference between them was more than 3 dB, a third estimate was obtained. All estimates were averaged. Absolute thresholds were obtained in a similar manner (but with a 3-down 1-up procedure).

Experiment 4: Equal-loudness-level contour

An equal-loudness-level contour was obtained for every subject for frequencies between 20 and 160 Hz. This was done in order to obtain a rough estimate of the shape of the subject's METF. The reference signal had a frequency of 50 Hz and a fixed level of 40 dB SL. Comparison tones were used with frequencies of 20, 30, 35, 40, 45, 55, 60, 65, 70, 75, 80, 90, 100, 125, and 160 Hz. Their duration and ramp characteristics were the same as for the signals used in experiment 1.

Loudness balance procedure

A 1-up, 1-down, adaptive loudness balance procedure was used to estimate the 50 % point on the psychometric function, corresponding to equal loudness. A 2-alternative task was used. The reference (fixed-level) tone and comparison tones were presented in random order. Two interleaved tracks were used. The procedure randomly selected one of the two tracks when choosing the level of the next presentation. For a given comparison tone, the level of one track started 10 dB below the 40 phon standardized ISO equal loudness level (ISO 226, 2003), and the other track started 10 dB above it (the ISO curve was interpolated to obtain values at all frequencies). 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, avoiding initial levels that were too high. These starting levels were found to be adequate after pilot testing; typically the listener's point of subjective equality lay between these extremes.

The stepsize started at 8 dB, was decreased to 4 dB after 2 reversals, and was decreased to 2 dB after 2 further reversals, where it remained. For each track, 10 reversals were obtained and the point of subjective equality (PSE) was obtained from the average level at the last 6. For a given run, one PSE was determined, corresponding to the average PSE of the two tracks. Two runs were performed, and the PSE was estimated from the average PSE for the two runs. If the two PSE estimates differed by more than 3 dB, a third run was performed and all three PSE estimates were averaged.

Subjects

Five subjects, 3 male and 2 female, participated in experiments 1 and 2. Four subjects, 2 male and 2 female, participated in experiment 3. Some subjects were tested with both masker types, as indicated in the results section. All 9 subjects participated in experiment 4. All subjects had normal hearing and ages between 22 and 37 years.

Apparatus

A cabin specially designed for playback of low-frequency signals under pressure field conditions was used. The cabin had dimensions of 0.8 × 1.4 × 0.9 m (~1 m^3). It had four loudspeakers in each side wall, positioned behind covering panels. The listener sat facing the door, with the ears at 90° relative to the side walls. The cabin provides a perfect pressure field up to about 61 Hz. However, deviations in space are small up to higher frequencies (below ±3 dB up to about 150 Hz).

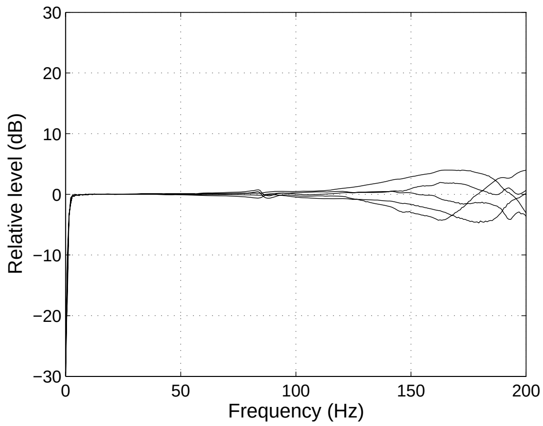

Figure 1: Differences between the average response (i.e. assumed response) and the responses at each of 5 listening position points.

A listener's position was defined by 5 points covering a region where it was expected that the listener's ears and centre of the head would be located. Calibration was done by filtering all stimuli with a digital filter representing the inverse room magnitude response, obtained after averaging the magnitude responses measured at the 5 positions. When performing the task, all listeners were instructed to find a comfortable position, without leaning to the sides, and to avoid moving much within blocks of measurements. Figure 1 shows the differences between the assumed response (0 dB reference), and the response at the 5 positions, as a function of frequency.

One-third octave background noise sound pressure levels were measured in the cabin. Equivalent levels were obtained in 4 min 10 sec intervals and for worst-case scenarios, when activity was expected nearby in the building. The levels were measured with a low-noise microphone (B&K 4179, noise floor −5.5 dBA) using a 01 dB Harmonie system frequency analyzer. A worst case scenario example is shown in figure 2.

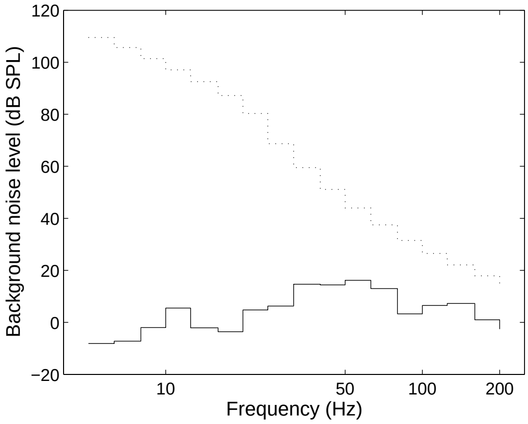

Figure 2: One-third octave background noise levels in the listening cabin (solid lines). The ISO 226-2003 (2003) absolute threshold levels are plotted as dotted lines.

As illustrated, all noise levels in the low-frequency range are well below the hearing threshold. The overall background noise level in the cabin was 21 dB SPL (~0 dBA) over the frequency range 5-20,000 Hz.

Harmonic distortion was measured at 1/3-octave intervals using sinusoids with frequencies between 5 and 100 Hz, and at a level of 130 dB SPL. This level is much higher than the levels actually used in the experiment. In all cases, the 2nd, 3rd and 4th harmonics had levels at least 30, 40, and 50 dB, respectively, below that of the fundamental (typically by more than 10 dB). Since the levels used in the experiment were typically at least 30 dB below 130 dB SPL, harmonic distortion levels were much lower than the levels described above. Thus, it seems likely that harmonic distortion in the acoustic signals was not audible.

Signals were sent through the ADAT optical outputs of an RME DIGI 96 PC soundcard to an RME ADI-8 D/A converter, using a sample rate of 48 kHz and 24-bit resolution. The 8 loudspeakers were driven by a Crown Studio Reference I (1160 W) power amplifier. The same apparatus was used in all experiments.

RESULTS

Experiments 1 and 2

Figures 3 and 4 show the individual PTCs obtained using the tonal maskers for f_s between 31.5 and 80 Hz (circles and solid lines). The overall shapes of the PTCs were broad, reflecting poor frequency selectivity at these low frequencies. For the f_s = 50 Hz and 80 Hz, sharp tips and irregularities around the tips occurred in many cases, which may reflect the influence of beats. However, even for f_s = 31.5 Hz, some irregularities occurred around f_s (see the results for subjects ESB and KW), which may also indicate the influence of beats. For f_s above 50 Hz, the tips of the PTCs were usually close to f_s. This was not the case for f_s = 31.5 and 40 Hz, where the tips of the PTCs were always above f_s. For f_s = 50 Hz, the tips of the PTCs were located at 50, 50, 60, 70, and 90 Hz, for subjects JP, ESB, JE, MS, and KW, respectively. Overall, the masked threshold levels typically increased with decreasing f_s, possibly as a consequence of the general increase in absolute thresholds with decreasing frequency. The PTCs became increasingly asymmetrical as f_s decreased, with steeper lower skirts than upper skirts. There were clear individual differences. For example, for subject KW, the upper skirt was very shallow for f_s from 31.5 to 50 Hz, while subject MS had relatively steep upper skirts.

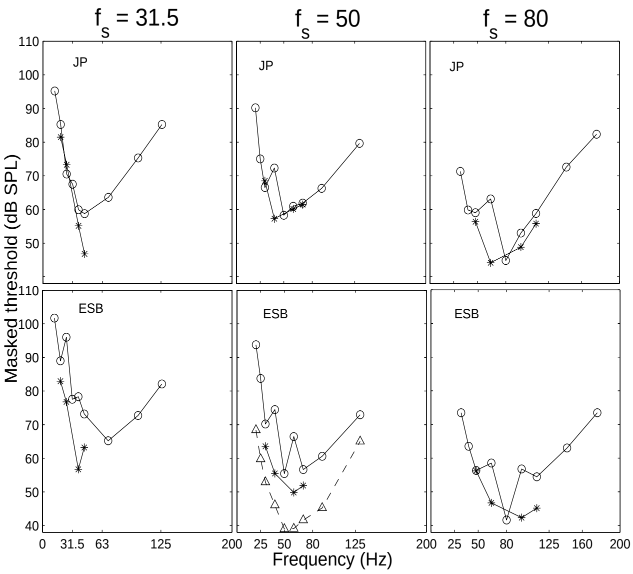

Figure 3: PTCs for CFs in the low frequency range, obtained using sinusoidal maskers without (circles and solid lines) and with (asterisks and solid lines) MDI tones. Capital letters in the upper left corners are the subject's initials. Triangles and dashed lines show a PTC obtained with the noise masker, which is further described in the next section.

The results obtained in the presence of the MDI tones are shown by asterisks and solid lines. Masked thresholds were typically lower when the MDI tones were present. This suggests that beats played a significant role in detection of the signal for masker frequencies close to the signal frequency. However, lower masker levels might also occur if the MDI tones produce a large enough output from the auditory filter centred near f_s. The effect produced by the MDI tones typically decreased for higher values of Δ. For f_s = 50 Hz and above, in most cases a more regular and broader tip occurred when the MDI tones were present than when they were absent. For f_s = 31.5 and 40 Hz, where the tip of the PTC typically lay above f_s, addition of the MDI tones did not affect this trend. It should be noted that while the MDI tones seem to have been effective in reducing the use of beats as a cue, the presence of the MDI tones generally made the task more difficult. Furthermore, the possibility cannot be ruled out that the MDI tones had a direct masking effect on the signal in some cases. The origin of the PTCs with sharp tips in the presence of the MDI tones, such as that for subject MS for f_s = 50 Hz, is not clear. They may reflect individual differences in the depth of the "internal" beats produced by the MDI tones as the value of Δ was varied.

The main trends of the changes in frequency selectivity with f_s found in experiments 1 and 2 are consistent with those derived from notched-noise masking data (for CFs down to 50 Hz) by Jurado and Moore (2010).

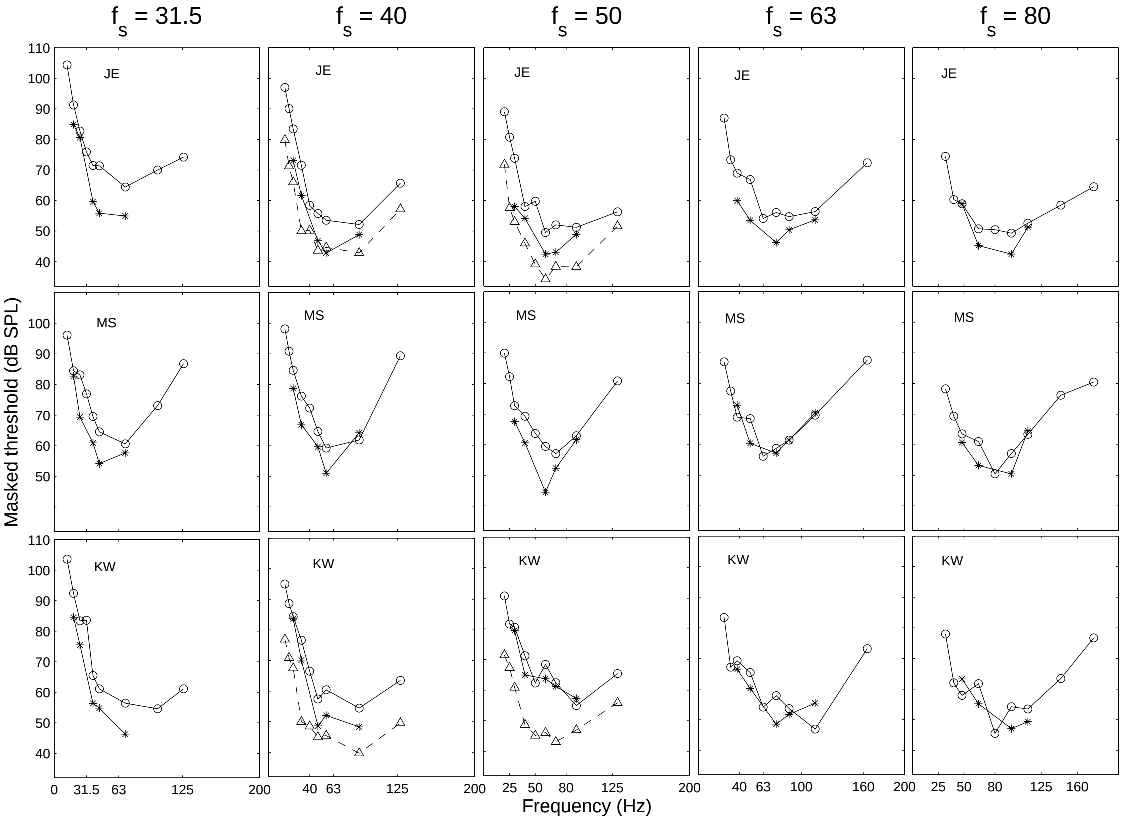

Figure 4: As figure 3, but for f_s spaced at one-third octave intervals between 31.5 and 80 Hz.

Experiment 3

Figure 5 shows the PTCs obtained using the noise maskers for f_s between 31.5 and 80 Hz. For all PTCs obtained with this masker type, the spectral density level of the band of noise (i.e. level in dB/Hz) is plotted on the *y*-axis. These PTCs have more regular tips than those obtained using the tonal maskers (without MDI tones), suggesting that beats probably did not provide a strong detection cue. Even though the masker bandwidth was proportional to f_s, the PTCs typically broadened as f_s decreased. This reflects the worsening of frequency selectivity with decreasing CF. As was the case for the PTCs obtained using the tonal maskers, the PTCs for f_s = 31.5 and 40 Hz had tips that fell above f_s. For higher f_s, the tips of the PTCs fell close to f_s. For f_s = 50 Hz, the tips of the PTCs were located at 70, 50, 70, and 60 Hz for subjects SR, FK, VD, and JM, respectively. In addition, the PTCs were asymmetrical, the lower skirts becoming increasingly steep relative to the upper skirts as f_s decreased. There were clear individual differences. For example, for subject SR the upper skirt of the PTC for f_s = 31.5 Hz was very shallow, only starting to increase for the highest masker frequency used, while for JM the upper skirt started increasing for frequencies much closer to f_s.

The general trends were similar across experiments 1, 2 and 3. Indeed, for subjects for whom data were obtained for both tonal and narrowband noise maskers, the shapes of the PTCs show good general agreement. As expected, the masker level required to mask the signal was lower for the narrowband noise maskers than for the tone maskers, as, at a given density level, the noise maskers will produce larger outputs from the auditory filters. In addition, the inherent fluctuations in the noise maskers introduce level uncertainty and make beats less effective as a detection cue. The main trends are also consistent with those derived from notched-noise masking data (for CFs down to 50 Hz) by Jurado and Moore (2010).

Experiment 4

The equal loudness level contours obtained for the 9 subjects (solid lines) and the mean across subjects (dashed line) are shown in figure 6. The curves appear to have three regions: (1) A region above 100 Hz with a shallow slope; (2) A transition region, more irregular in shape (covering a range from about 40 to 100 Hz in the mean data); and (3) A steep region below about 40 Hz. For the mean data, the slopes in regions 1 and 3 were about −10 dB/oct and −25 dB/oct, respectively. The three regions are in qualitative agreement with objective measures of the METF reported by Marquardt and Pedersen (2010). However, the slopes observed in the ELCs are much steeper than the slopes of the METF reported by Marquardt and Pedersen. Inner hair cell velocity dependence (Cheatham and Dallos, 2001), may account for some of the differences.

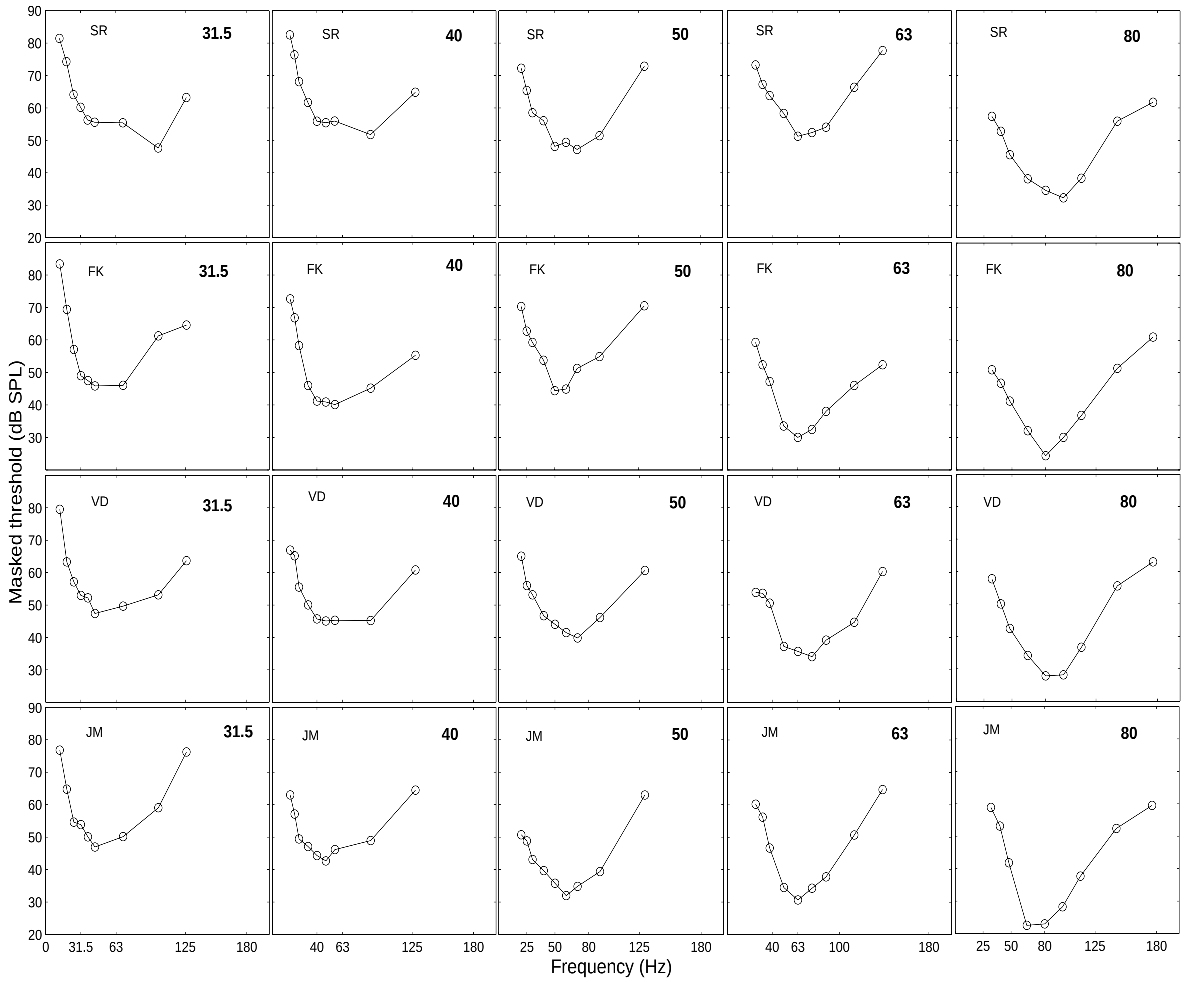

Figure 5: As figure 4, but for narrow-band noise maskers. The circles indicate the centre frequency of the band of noise. The signal frequency (same for each column) is indicated in the upper-right corner of each panel.

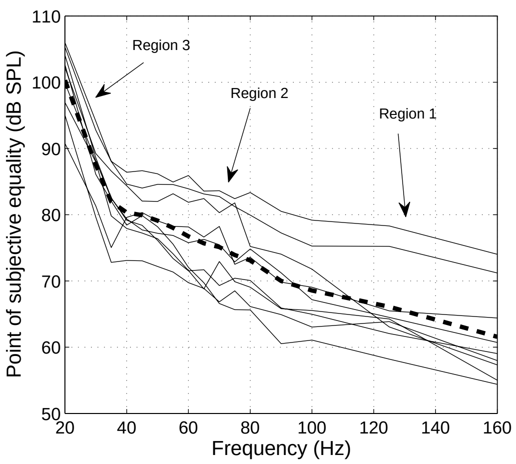

Figure 6: Individual (solid lines) and mean (dashed line) equal loudness level contours. The values at 50 Hz correspond to a level of 40 dB SL. The three regions observed are indicated by the arrows.

Marquardt et al. (2007) and Marquardt and Pedersen (2010) reported a mid region where there was typically an irregularity in the METF. Similar irregularities can be seen in the individual ELCs reported here, although the mean ELC is rather smooth, as the exact frequency where the irregularity occurred varied across subjects. The irregularity in the METF has been attributed to a cochlear resonance in the region where the helicotrema starts to be dominant (Marquardt and Hensel, 2008). Measures of the METF show similar individual differences to those reported here for the ELCs (Marquardt and Pedersen, 2010, Pedersen and Marquardt, 2009), suggesting that there may be a link between the two effects. Although the mean ELC was rather smooth, its shape is consistent with a mild resonance-transition region.

DISCUSSION

Tuning characteristics and their relation to the estimated trends in the METF

In this section the observed tuning characteristics are examined and discussed in terms of their relation to the shape of the ELC (and therefore to the estimated shape of the METF). For simplicity, only the mean masking data obtained using the narrowband noise maskers are considered in this preliminary analysis.

Figure 7 shows the mean PTCs obtained for CFs of 31.5, 40, 50, 63, and 80 Hz, together with the mean ELC for the corresponding subjects. To make the PTCs resemble filter characteristics, they (and the ELC) have been inverted and normalized by plotting the level at the tip at 0 dB. The mean PTCs have their tips (0 dB reference) at 44, 48, 60, 63, and 80 Hz, for the f_s = 31.5, 40, 50, 63, and 80 Hz, respectively. The shifted tips for the lowest values of f_s may indicate that there are no auditory filters tuned below about 50 Hz, as suggested by Moore et al. (1997). However, the steep slope of the METF may also lead to upward-shifted tips of the PTCs in this region (Jurado et al., 2010). The upper skirts of the PTCs are very flat for f_s = 31.5 and 40 Hz. This probably happens at least partly because, as the masker frequency is increased, the masker is attenuated less and less by the METF, so the PTC has a flatter high-frequency side than that of the auditory filter itself.

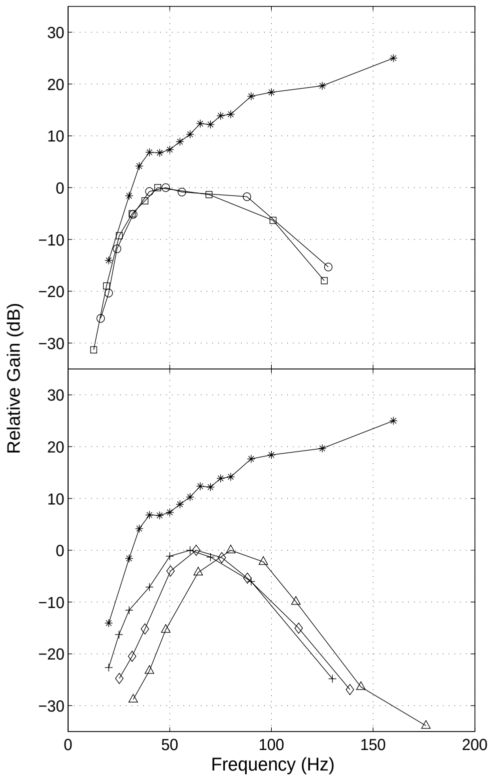

Figure 7: Mean PTCs inverted and normalized by the levels at their tips (solid lines) and ELC (inverted and at arbitrary reference, asterisks and solid line). The upper panel shows PTCs for f_s = 31.5 and 40 Hz (squares and circles, respectively) and the lower panel shows PTCs for f_s = 50, 63, and 80 Hz (crosses, diamonds, and triangles, respectively).

The lower skirts of the PTCS for the two lowest values of f_s are much steeper than the upper skirts (about 22 dB/oct and 20 dB/oct for f_s = 31.5 and 40 Hz, respectively) and their slopes are similar to the slope of the ELC. This is consistent with the idea that both the lower skirts of the PTCs and the ELC are determined largely by the shunt action of the helicotrema. In addition, the PTCs for f_s = 31.5 and 40 Hz are very close to each other, particularly on their low-frequency sides. This is consistent with the idea that the signals for both of these values of f_s were detected using the same auditory filter, a filter centred at the lowest (i.e. most apical) CF.

Both the generally shallow upper skirts and the large influence of the METF on frequency selectivity below the CF are consistent with the results of Jurado and Moore (2010) obtained using notched-noise maskers, although the lowest centre frequency used by them was 50 Hz. Most remarkably, all trends, the influence of the METF, the shifts in the tip of the PTCs, and the large flattening off of the upper skirts of the filters, agree with predictions derived by Jurado et al. (2010), based on calculations using real individual METFs. In that work, evidence was found that the irregular region in the METF, due to its own steep changes in slope, would affect the tuning of filters assumed to be centred within it. The closer the CF was to the start of the irregular region, the more affected (i.e. flattened) was the upper skirt. This is consistent with the present work, as the frequencies of 31.5 and 40 Hz are close to the point in the mean ELC below which the slope becomes steeper, which is at about 40 Hz.

To examine the characteristics of frequency selectivity after allowing for the effect of the estimated METF, the relative value of the METF was subtracted from the masker level at threshold. The results are shown in figure 8. As expected, steeper upper skirts were found, indicating that the shape of the METF, particularly within the irregularity region, may be responsible for the large flattening off of the upper skirts (especially for f_s = 31.5 and 40 Hz). In addition, the lower skirts were much flatter, although there was still some tuning for f_s down to about 40 Hz. Below 40 Hz, the METF appears to account for most of the measured frequency selectivity, as expected due to its increase in steepness. The tips of the PTCs were located very close to or at f_s for all f_s but 31.5 Hz (they were located at 44, 41, 50, 63, and 80 Hz for the f_s = 31.5, 40, 50, 63, and 80 Hz, respectively). This suggests that, although within the irregular region the tips of the auditory filters may be located close to f_s, the steepness in the METF results in upward shifts of the tips of the PTCs. This result strengthens the agreement with the work of Jurado et al. (2010), based on calculations perfomed using real individual METFs. Also, this analysis suggests that the bottom auditory filter may be located close to 40 Hz; note that the PTCs in figure 8 are almost identical for f_s = 31.5 Hz and f_s = 40 Hz.

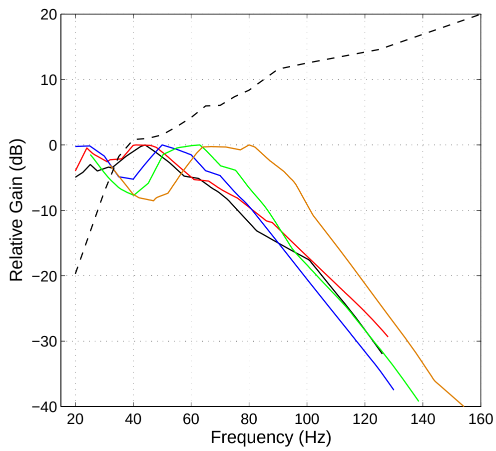

Figure 8: Mean PTCs obtained after allowing for the estimated METF (black, red, blue, green, and brown for f_s = 31.5, 40, 50, 63, and 80 Hz, respectively). The responses have been normalized by their maximum gains. The inverted ELC is plotted as a black-dashed line at an arbitrary reference for comparison purposes.

The ERBs of the PTCs were calculated using numerical integration. For comparison purposes, initially, calculations were performed for frequencies between $0.4f_s$, the lowest masker frequency common to all PTCs, and $2.2f_s$, the highest masker frequency common to all PTCs. The ERBs obtained in this manner were 30, 44, 34, 30, and 30 Hz for f_s = 31.5, 40, 50, 63, and 80 Hz, respectively. The sudden sharp decrease at 31.5 Hz appears to be an artifact due to the fact that even an upper frequency of $2.2f_S$ was not high enough to represent the true ERB. The ERBs obtained by integrating each PTC over the whole range of masker frequencies used are shown in table 1.

Table 1. ERB values obtained for each f_s

f_s	**31.5**	**40**	**50**	**63**	**80**
ERB (Hz)	**46**	**52**	**34**	**30**	**30**

These ERBs are both qualitatively and quantitatively in general agreement with those calculated from notched-noise masking data (Jurado and Moore, 2010) and with calculations performed using real METFs (Jurado et al., 2010).

CONCLUSIONS

The results show that for f_s below 100 Hz, the PTCs are broad, indicating that frequency selectivity at very low CFs is relatively poor (e.g., at 80 Hz the ERB is about 38% of the CF). The shapes of the PTCs are generally asymmetrical, with steeper lower skirts, this trend being more pronounced for the lowest f_s. The ERB appears to increase with decreasing CF below about 63 Hz. This effect occurred mainly because the PTCs for very low f_s have very shallow upper skirts. The irregular transition regions identified in the ELCs for individual subjects correspond qualitatively with trends observed in objective estimates of the shape of the METF (Marquardt and Pedersen, 2010). For f_s = 31.5 and 40 Hz, the PTCs had always their tips above the CF. Below f_s their lower skirts had slopes similar to those of the ELCs in that range, which are assumed to be determined by the shunting effect of the helicotrema. This suggests that the helicotrema itself (i.e. its shunting effect) forms part of the lowest (most apical) auditory filter.

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