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Factors affecting psychophysical tuning curves for hearing-impaired subjects with high-frequency dead regions

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Abstract

A dead region (DR) is a region of the cochlea where there are no functioning inner hair cells and/or neurons. DRs can be detected using the threshold-equalizing-noise (TEN) test, but psychophysical tuning curves (PTCs) are sometimes used to give a more precise estimate of the edge frequency of a DR; a shifted tip of the PTC indicates a DR. We show here that the shapes of PTCs for hearing-impaired subjects can be influenced by the detection of beats and simple difference tones (SDTs). As a result, PTCs can have tips at f_s, even when f_s falls in a DR. PTCs were measured for subjects with mild to moderate low-frequency and severe high-frequency hearing loss using sinusoidal and narrowband noise maskers (80-, 160-, 320-Hz wide): (1) in quiet; (2) in the presence of additional lowpass filtered noise (LF noise) designed to mask SDTs; (3) in the presence of a pair of low-frequency tones designed to interfere with the detection of beats (MDI tones). In condition (1), the PTCs were often W-shaped, with a sharp tip at f_s. This occurred less for the wider noise bandwidths. For subjects with good low-frequency hearing, the LF noise often reduced or eliminated the tip at f_s, suggesting that this tip was partly caused by detection of SDTs. For the sinusoidal and 80-Hz wide noise maskers, the addition of the MDI tones reduced the masker level required for threshold for masker frequencies adjacent to f_s, for nearly all subjects, suggesting a strong influence of beat detection. To minimize the influence of beats, we recommend using noise maskers with a bandwidth of 160 or (preferably) 320 Hz. In cases of near-normal hearing at low frequencies, we recommend using an additional LF noise to mask SDTs.
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Keywords: Psychophysical tuning curve; Dead region; Beats; Combination tone

1. Introduction

A dead region (DR) is a region of the cochlea with no functioning inner hair cells (IHCs) and/or neurons. Its extent can be defined in terms of the characteristic frequencies (CFs) of the IHCs and/or neurons immediately adjacent to the DR (Moore and Glasberg, 1997; Moore, 2001; Moore et al., 2001). In a DR no transduction occurs and no information is transmitted to the brain about the vibration of the basilar membrane. However, a tone with a frequency falling in a DR may be detected via off-place or off-frequency listening – i.e., via a place (or auditory filter) with a CF different from the frequency of the tone (Johnson-Davies and Patterson, 1979). This phenomenon has been used to detect and define DRs.

Abbreviations: CDT, cubic difference tone; CF, characteristic frequency; DR, dead region; ERB_N, equivalent rectangular bandwidth of auditory filter for normally hearing people; f_s, signal frequency; HL, hearing level; IHC, inner hair cell; LF, lowpass filtered; MDI, modulation detection interference; PTC, psychophysical tuning curve; SDT, simple difference tone; SL, sensation level; SPL, sound pressure level; TEN, threshold equalizing noise

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There are two methods that have been widely used to diagnose DRs. One involves measuring the masked threshold of a sinusoid in threshold-equalizing noise (TEN) (Moore et al., 2000; Moore, 2001, 2002, 2003). The original version of the TEN test is designed to produce almost equal masked thresholds (in dB SPL) over a wide frequency range (250–10,000 Hz), for normally hearing listeners and for listeners with hearing impairment but without any DR. The noise level is specified in terms of the level in a one-ERB_N wide band around 1000 Hz (from 935 to 1065 Hz), where ERB_N stands for the average value of the equivalent rectangular bandwidth of the auditory filter at moderate sound levels for young listeners with no known hearing defect. The "normal" detection threshold is approximately equal to the TEN level specified in this way. For listeners with cochlear impairment, but without any DR at the signal frequency, the masked thresholds in the TEN are typically only 2–3 dB higher than for normally hearing listeners (Glasberg and Moore, 1986; Moore et al., 2000). However, when the signal frequency falls in a DR, the signal is detected at a place in the cochlea that is tuned away from the place producing maximum vibration. At this remote place, the signal is very effectively masked by the TEN. Hence, the masked threshold is usually considerably higher than normal. On the basis of a study comparing the results of the TEN test with measurements of PTCs (described below), Moore et al. (2000) proposed the following criteria for positive diagnosis of a DR: if the threshold in the TEN is 10 dB or more above the TEN level/ERB_N, and the TEN produces at least 10 dB of masking, this is taken as indicating a DR at the signal frequency (f_s). In a more recent version of the test, called the TEN(HL) test, the noise is designed to produce equal masked thresholds in dB HL, over the more restricted frequency range 500–4000 Hz (Moore et al., 2004). The TEN(HL) has a smaller bandwidth than the TEN(SPL), which reduces the loudness of the TEN(HL). Also, the TEN(HL) was synthesized so as to have a very low peak factor (ratio of peak to root-mean-square value). The lower loudness and lower peak factor allow testing at higher levels for the TEN(HL) than for the TEN(SPL), which can be useful when subjects with severe or profound hearing loss are being tested.

The second method of diagnosing DRs involves measuring psychophysical tuning curves (PTCs) (Chistovich, 1957; Small, 1959). For normally hearing subjects, the tip of the PTC (i.e., the frequency at which the masker level is lowest) always lies close to f_s (Kluk and Moore, 2004; Moore, 1978; Vogten, 1974). When the tip of the PTC is shifted away from f_s, this indicates that the signal is detected by IHCs with a CF different from f_s (via off-place listening) (Florentine and Houtsma, 1983; Huss and Moore, 2003; Moore et al., 1998, 2000; Moore and Alcántara, 2001; Thornton and Abbas, 1980; Turner et al., 1983). The masker frequency at the tip of the PTC is assumed to reflect the boundary or edge frequency of the DR. Hence, the clinical use of PTCs requires that they should reflect frequency selectivity at the frequency/place where the signal is detected. However, the shapes of PTCs around their tips may be affected by a variety of factors not connected with frequency selectivity per se. This paper examines the influence of two of these factors for subjects with DRs.

PTCs in the audiology clinic are usually measured using simultaneous masking. This means that the signal and the masker interact with each other. One consequence of this interaction is the generation of combination tones (Goldstein, 1967; Greenwood, 1971; Plomp, 1965; Smoorenburg, 1972a,b). The strongest of the combination tones is the cubic-difference tone (CDT) $2f_1 - f_2$, which reflects the inherent nonlinearity in the cochlea and is dependent on the 'active mechanism'. The audibility of this CDT is reduced for low levels of the primary tones (the signal and the masker) (Greenwood, 1971; Kluk and Moore, 2004; Smoorenburg, 1972a,b). Hence, as shown by Kluk and Moore (2004), CDTs do not influence the shapes of PTCs for normally hearing people when the signal has a low sensation level (SL). Also, CDTs are usually not audible for people with cochlear hearing loss (Leshowitz and Lindstrom, 1977; Smoorenburg, 1972b). Hence, it is also unlikely that CDTs influence the shapes of PTCs for hearing-impaired subjects when the SL of the signal is low (Alcántara and Moore, 2002).

For relatively high primary tone levels, the simple difference tone (SDT) $f_2 - f_1$ can be perceived (Plomp, 1965). The SDT may arise partly from distortion produced in the middle ear (Helmholtz, 1863). SDTs can influence PTCs for hearing-impaired subjects when the primary tone frequencies (the frequency of the signal and the masker) fall in a region of substantial hearing loss and/or a DR, but the SDT frequency falls in a region of near-normal hearing (Alcántara and Moore, 2002). The SDT would be expected to provide a salient detection cue when three conditions are satisfied: (1) The level of the primaries (the masker and the signal in the case of a PTC) should be above about 60 dB SPL (Plomp, 1965); (2) The absolute threshold of the subject should be reasonably low in the frequency region of the SDT; (3) The frequency of the SDT should not be too low, as the sensitivity of the cochlea decreases at very low frequencies, even for normally hearing subjects (Cheatham and Dallos, 2001; Moore et al., 1997). Hence, SDT detection would be expected to play a role mainly when the primaries fall in a region of severe hearing loss and the SDT falls in a region with relatively good hearing. Because of the decreased sensitivity of the cochlea at very low frequencies, SDT detection might lead to a tip of the PTC at f_s even when f_s falls in a DR, since the SDT would not be detectable for very small frequency differences between the masker and signal, but would be detectable for larger differences.

A second consequence of the interaction of the signal and masker is the generation of beats (Ehmer, 1959; Wegel and Lane, 1924). Beats become harder to detect as the beat rate increases above 125 Hz, although they can still be detected for rates up to about 1000 Hz (Kohlrausch et al., 2000; Moore and Glasberg, 2001; Riesz, 1928). Beats can provide a salient detection cue. Hence, the masker level required to mask the signal is greater then would be the case if beats were not audible. Beats do not occur when the signal and masker frequencies are equal. This can result in a sharp local tip in the PTC at f_s (Kluk and Moore, 2004).

Several studies have shown a good correspondence between PTC and TEN-test results (Huss and Moore, 2003; Huss, 2004; Moore et al., 2000; Moore, 2001, 2002). One study (Summers et al., 2003) showed discrepancies between the results of the TEN test and PTCs; in several cases, the TEN-test results suggested a DR at f_s, but the PTC showed a tip at f_s. However, in several of these cases, the PTC showed more than one tip, so the PTC was W-shaped. Moore (2004) suggested that the discrepancy between the TEN-test results and the PTCs occurred because the PTCs were influenced by detection of beats and/or SDTs.

W-shaped PTCs had been reported earlier by Hoekstra and Ritsma (1977). They measured PTCs using a sinusoidal masker for 20 hearing-impaired subjects using a Békésy-up-down procedure with a sinusoidal probe presented at a level of 5–10 dB SL. They found that, for hearing losses of more than 40 dB, a dramatic alteration in the form of the PTCs sometimes occurred; the PTCs become W-shaped. They did not offer any clear explanation for this effect, although a role for beat detection was proposed. Also, Leshowitz and Lindstrom (1977) measured PTCs using a low-SL signal and a sinusoidal masker for subjects with steeply sloping hearing losses. They reported that the PTC could be W-shaped when f_s was located in the frequency region of elevated absolute threshold. They suggested that this might be due to the detection of combination tones in the region below the frequency of the masker.

Moore and Alcántara (2001) used an 80-Hz wide noise masker and also obtained W-shaped PTCs for two out of five subjects with sensorineural hearing loss who were suspected of having DRs. These subjects had high-frequency hearing loss, and the PTCs had one tip at f_s and a second tip a few hundred Hertz below f_s. Moore and Alcántara suggested that the exact frequency at the tip of the PTC could be influenced by beat detection when the masker frequency was within a few hundred Hertz of f_s, which complicated the interpretation and use of PTCs as a diagnostic tool for DRs.

In the present paper, we show that both beat detection and SDT detection can lead to W-shaped PTCs and can lead to a tip of the PTC at f_s even when there is a DR at f_s. The methods used in our paper resemble those used in an earlier paper in which we studied the effect of beats and combination products on the shapes of PTCs for normally hearing people (Kluk and Moore, 2004). In that study, PTCs were measured for 1- and 4-kHz sinusoidal signals using as maskers a sinusoidal tone and 80-, 160-, and 320-Hz wide bands of noise. The PTCs obtained using the sinusoidal masker showed distinct irregularities, particularly for masker frequencies close to f_s. The PTCs determined for the noise maskers were more regular. The broader the masker, the more regular were the shapes of the PTCs. This strongly suggested that beat detection was at least partly responsible for the irregularities.

To reduce the detectability of beats produced by the interaction of the signal and masker, Kluk and Moore (2004) added to the main masker a pair of low-frequency tones, called "modulation detection interference (MDI) tones". These introduced beats at the same rate as produced by the interaction of the signal and main masker. The MDI tones reduced the threshold level of the sinusoidal masker by up to 20 dB for frequencies within 300 Hz of f_s, confirming a strong role of beat detection. A similar but smaller effect was found when an 80-Hz wide noise masker was used. Adding a lowpass filtered (LF) noise to the sinusoidal or narrowband noise masker did not affect the low-frequency sides of the PTCs, suggesting that there was no influence of combination products. Kluk and Moore suggested that, in order to achieve a PTC whose shape around the tip is minimally affected by beats, one should use a noise masker with a bandwidth approximately equal to the bandwidth of the auditory filter for which the PTC is measured.

The aim of the current paper was to investigate the effect of detection of beats and SDTs on the shapes of PTCs for hearing-impaired subjects, especially subjects with DRs. This issue is important if PTCs are to be used for diagnosing DRs and defining their limits. A further aim was to clarify the extent to which the use of a noise masker reduces the use of beats as a cue, and to assess the noise bandwidth required to minimize the use of beats as a cue.

2. Experiment 1: Diagnosing DRs using "traditional" methods

In an initial experiment we used two "traditional" methods to select subjects with DRs, the TEN test and measurement of PTCs. The PTCs were measured using an 80-Hz wide band of noise as a masker, as this bandwidth has often been used previously to determine PTCs for subjects with DRs (Moore et al., 2000; Moore and Alcántara, 2001).

2.1. Subjects

Six hearing-impaired subjects with severe high-frequency hearing loss took part in the experiment. The absolute thresholds of the ears tested are given in Table 1. The table also shows the ages of the subjects. The hearing losses were diagnosed as being sensorineural, based on normal results of tympanometry and lack of an air-bone gap. Subject PJ became ill part way through the experiment and so some of the data are incomplete for him. Two subjects (MD and PM) had almost normal low-frequency hearing, two subjects (PJ and MW) had slightly worse hearing at low frequencies, and two subjects had moderate or severe low-frequency hearing loss (NC and RL).

All subjects were tested using only one ear. Some of them had previous experience of psychoacoustical masking experiments. The subjects received practice until their performance appeared to be stable. No systematic changes in performance occurred during the course of the experiment. All subjects were paid for their services. This work was approved by the Cambridge Research Ethics Committee.

2.2. Procedure

The TEN test was carried out as described by Moore et al. (2000), using a procedure similar to manual audiometry, except that masked thresholds were measured using a 2-dB final step size, as recommended by Moore et al. (2004). The TEN test was conducted using a Philips compact disk player, model CD 753, connected to a Grason-Stadler GSI 16 audiometer fitted with Telephonics THD-50P earphones. Both the TEN and the signal were replayed from CD. All subjects were tested using the earlier version of the TEN test, which is now referred to as the TEN(SPL) test (Moore et al., 2000). In addition, one subject (MW) was tested using the newer TEN(HL) test (Moore et al., 2004) (see http://hearing.psychol.cam.ac.uk/dead/dead.html). The criteria for diagnosing a dead region were as recommended by Moore et al. (2000, 2004): if, for a specific f_s, the threshold in the TEN was 10 dB or more above the TEN level/ERB_N, and the TEN produced at least 10 dB of masking, this was taken as an indication of a DR at f_s.

For the PTCs, masked thresholds were measured using a three-alternative, forced-choice (3AFC), three-down one-up procedure tracking the 79.4% point on the psychometric function (Levitt, 1971). The masker was presented in three observation intervals and the signal was gated synchronously with the masker in one of those intervals, chosen randomly from trial to trial. Observation intervals were marked by lights on the response box. The subject indicated, by pressing one of three buttons, the interval thought to contain the signal. Feedback was provided by lights on the response box. A run was started with the masker at a level about 20 dB below the expected threshold value, as determined in practice trials. After three successive correct responses the masker level was increased, while after a single incorrect response it was decreased. The initial step size was 5 dB. After four reversals, the step size was decreased to 2 dB and a further eight reversals were obtained. The threshold was estimated as the mean masker level at the last eight reversals. Initially, two threshold estimates were obtained for each condition. If the two estimates differed by more than 2 dB, at least one additional estimate was obtained and the two closest estimates were averaged. Typically, the standard error of the threshold estimate for a given masker frequency was less than 2 dB. Absolute thresholds for the sinusoidal signal were measured using a similar 3AFC procedure, as described by Kluk and Moore (2004).

2.3. Stimuli for measurement of PTCs

For each PTC, the signal frequency was fixed and the signal level was fixed at 10 dB SL. The frequency of the signal was chosen so as to fall close to or within a suspected DR. The masker was an 80-Hz wide band of noise. The three masker bursts each had a steady-state duration of 200 ms, and 10-ms raised-cosine rise/fall ramps. The inter-stimulus interval was 500 ms. The sig-

Table 1
Absolute thresholds of the test ears of the subjects, in dB SPL

Subject	Ear	Age	Frequency (kHz)									
			0.25	0.5	1.0	1.5	2.0	3.0	4.0	5.0	6.0	8.0
MD	R	67	35	20	25	25	40	65*	80*	85*	75*	90*
MW	R	65	45	61	70*	75*	104*	120*	116*	120*	120*	↑*
NC	L	80	60	40	55*	70*	90*	110*	120*	120*	120*	120*
PJ	L	74	40	30	50*	65*	75	75*	85*	90*	100*	115*
PM	R	60	36	20	14	16	24	92*	96*	92*	100*	100*
RL	L	91	90	75	60*	77*	70*	70	70*	75*	100*	115*

An asterisk indicates frequencies falling within the estimated DR. An arrow indicates that the absolute threshold was too high to be measured with the available equipment. The age of each subject (years) is also shown.

nal was gated synchronously with one of the masker bursts. The noise bands were generated by adding sinusoids spaced at 5-Hz intervals, with equal component amplitudes and phases drawn randomly from a uniform distribution in the range 0–360°. A new noise sample was calculated for every masker burst. The overall energy of the noise bands did not vary significantly from stimulus to stimulus. Masker levels are specified as overall levels. The spectral slopes were effectively infinite. The masker frequencies were chosen so as to define the PTC, and especially its tip, with reasonable accuracy. Typically, 15 masker center frequencies were used for each PTC. In cases of W-shaped PTCs, further investigations were undertaken, as described for later experiments.

The masker and signal were generated digitally, using a Tucker–Davis Technologies (TDT) System II, controlled by a PC, with a sampling rate of 25 kHz. Stimuli were converted to analog form using two channels of a digital-to-analog converter (TDT DD1), one for the signal and one for the masker. Programmable attenuators (TDT PA4) controlled the levels of the signal and masker. The signal and masker were mixed (TDT SM3), passed through two filters (Kemo VBF 8/04) in series (cut-off frequency 8 kHz, slope approximately 90 dB/octave/filter) and passed to a headphone buffer (TDT HB6), a final manual attenuator (Hatfield 2125) and one earpiece of a headphone (Sennheiser HD580). Sound levels are presented as estimated levels at the eardrum, based on calibration of the earphones using a KEMAR manikin (Moore et al., 1998). Subjects were tested in a double-walled sound-attenuated chamber.

2.4. Results

The top panels in Figs. 1 and 3 show masked thresholds in the TEN (open symbols) and absolute thresholds (filled squares) for the six hearing-impaired subjects. The symbols with up-pointing arrows indicate cases where the threshold was too high to be measured. The specific symbols used with the arrows indicate the lowest TEN level for which threshold could not be measured. The bottom panels in these figures show the PTCs for the same subjects. For clarity, symbols indicating the individual data points are omitted from the PTCs, and only lines connecting the individual points are shown. Filled symbols indicate the signal level and frequency. The up-pointing arrows indicate cases where the masked threshold was too high to be measured.

The TEN-test results for subject PM (Fig. 1), suggest that a DR is present at high frequencies, starting between 2 and 3 kHz. The TEN-test criteria (masked threshold in the TEN 10 dB or more above the TEN level/ERB_N, and at least 10 dB of masking) are met at 3 kHz for the TEN levels of 70 and 80 dB/ERB_N. The PTC for f_s = 2.5 kHz shows two tips. One very sharp tip occurs at f_s, and a second broader tip occurs around 1 kHz. This makes the 2.5-kHz PTC difficult to interpret and indicates that further testing should be conducted.

Similarly, for subject PJ the TEN-test results suggest a DR between 1 and 2 kHz, then probably a small patch of surviving IHCs between 2 and 3 kHz, and again a DR above 3 kHz. The PTC obtained for the 1.5-kHz signal also suggests the presence of a DR at 1.5 kHz (the tip of the PTC is shifted downwards to 1 kHz) although there is a small second tip at f_s. The PTC for the 2-kHz signal has two distinct tips, one sharp tip at f_s and a second broader tip at 1 kHz. The minimum masker level occurs at f_s, which might be taken as indicating no DR at 2.5 kHz. However, the high masker level between 1.25 and 1.9 kHz could have been caused by the detection of beats or SDTs; this may explain the discrepancies between the TEN-test and PTC results.

The TEN-test results for MW show possible DRs at frequencies between 1 and 1.5 kHz and above 2 kHz. For f_s = 1.5 kHz, masked thresholds are elevated by 10 dB or more above the TEN level/ERB_N and above the absolute threshold. For f_s = 1 kHz, the masked threshold in the 70-dB TEN was elevated, while the threshold in 80-dB TEN did not show any elevation. This may indicate that the IHCs with CFs close to 1 kHz did not respond to medium-level stimuli but became active when the higher TEN level was used. For f_s = 2 kHz, the masked thresholds for TEN levels of 70 and 80 dB/ERB_N were equal to absolute threshold, which makes the results inconclusive. In this case a higher TEN level would be required for testing, but MW found it uncomfortably loud. Later, the new TEN(HL) test was used (Moore et al., 2004). Fig. 2 shows the results for the TEN(SPL) test (left panel) and the TEN(HL) test (right panel) for subject MW. It was possible to conduct the TEN(HL) test at a level of 90 dB/ERB_N. The masked threshold was shifted by 10 dB or more above the TEN level and above the absolute threshold for f_s = 1.5, 2 and 3 kHz (at 4 kHz the absolute threshold was too high to be measured), which confirmed the presence of a high-frequency DR starting between 1 and 1.5 kHz.

The PTCs for subject MW are shown in the bottom-right panel of Fig. 1. The tip of the PTC for f_s = 0.75 kHz is centered around f_s, suggesting no DR at this frequency. The tip of the PTC for f_s = 1 kHz is shifted downwards to 0.75 kHz, which indicates the presence of a DR at 1 kHz. The PTC for f_s = 1.25 kHz has two tips, one at f_s and a second broader one around 0.75 kHz. The minimum masker level is at f_s, which might be taken as indicating absence of a DR. However, the very high masker levels at threshold for masker frequencies between 0.75 and 1.2 kHz might have been caused by detection of beats and/or SDTs, which makes the results difficult to interpret. The tip of the PTC for f_s = 1.5 kHz is shifted downwards to about 0.75 kHz. Overall,

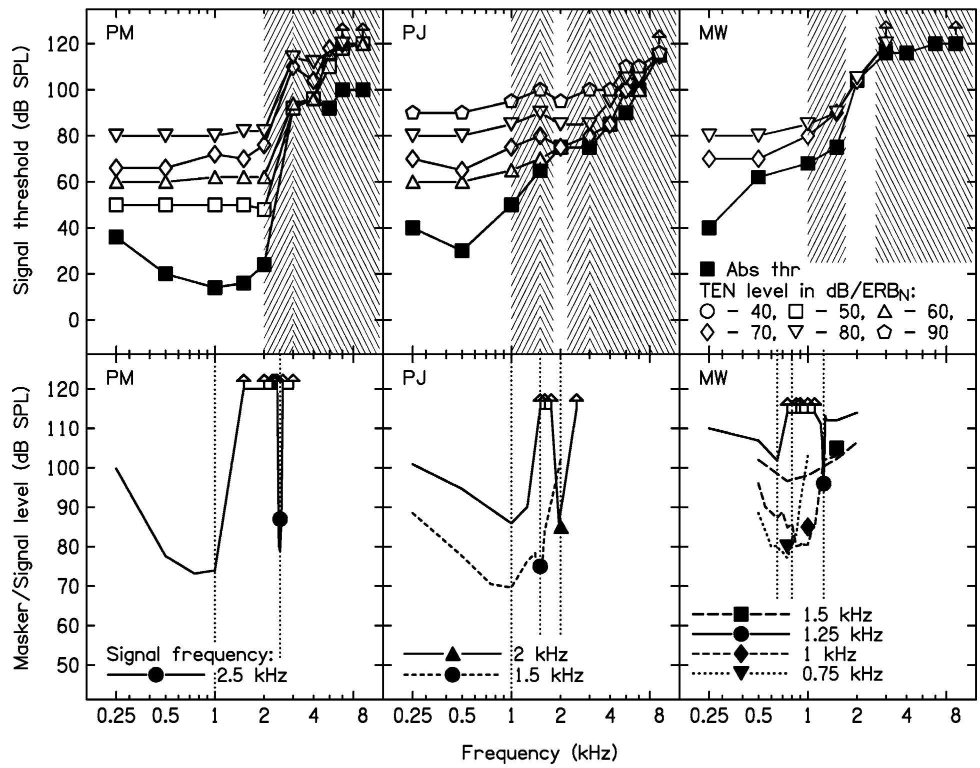

Fig. 1. Results for three subjects with moderately good low-frequency hearing and steeply sloping hearing loss at high frequencies. The top panels show absolute threshold (filled squares) and masked thresholds in the TEN (open symbols), plotted as a function of signal frequency, with the TEN level/ERB$_N$ as parameter. The shaded areas with upward sloping lines indicate the range of frequencies over which the edge frequency of a DR might be located (this covers the range between the highest frequency at which the TEN criteria were not met and the lowest frequency at which the criteria were met). The shaded areas with downward-sloping lines indicate the frequency region over which a DR is probably present. The symbols with up-pointing arrows indicate cases where the threshold was too high to be measured; the position of the symbol shows the lowest TEN level for which a threshold could not be measured. The bottom panels show PTCs determined using an 80-Hz wide noise masker. The level and frequency of each signal are indicated by a filled symbol. The corresponding PTC is indicated by specific line type, as indicated in the key. The up-pointing arrows indicate cases where the masked threshold was too high to be measured. When a single dotted vertical line is present, this indicates the tip frequency of the PTC. Multiple lines occur for PTCs with more than one tip.

the data suggest that MW has a high-frequency DR starting at about 0.75 kHz, but the irregularities in some of the PTCs make the results difficult to interpret. The origin of the irregularities is examined in more detail in Sections 3.2, 4.2 and 5.2.

The results of the TEN test for subject MD (Fig. 3) are inconclusive. The highest TEN level used (70 dB/ERB$_N$) did not produce any masking for frequencies of 4 kHz and above. It was not possible to use higher TEN levels, as the subject found them uncomfortably loud. The tip of the PTC for $f_s = 2$ kHz is at f_s, showing no DR at 2 kHz. However, the tip of the PTC for $f_s = 3$ kHz (inverted triangle) is shifted downwards to about 2.5 kHz, which suggests the presence of a DR at frequencies above 2.5 kHz. The PTC for $f_s = 4$ kHz (circles) shows two tips (one at 2 kHz and the second at f_s). The W-shape may be caused by the detection of beats or SDTs for masker frequencies just below and above f_s, and lack of these cues at f_s. Because of his good low-frequency hearing, MD may have been able to detect SDTs. When the masker was centered at 2 kHz, the frequency of the SDT was 2 kHz, so the SDT would have been masked by the main masker. This could account for the occurrence of the second tip at 2 kHz.

For subject NC, the results of both the TEN test and the PTCs indicate a DR above about 0.75 kHz. The masked thresholds in the TEN are elevated by 10 dB or more above the TEN level/ERB$_N$ for frequencies of 1 kHz and above. The tips of the PTCs obtained for $f_s = 1$, 1.5, and 2 kHz are all shifted downwards to 0.75 kHz. The PTCs for $f_s = 1$ and 1.5 kHz also have a very sharp tip at f_s, which is probably caused by the detection of beats for masker frequencies just below and above f_s and lack of this cue at f_s. Evidence supporting this interpretation is presented in Section 5.2.

The TEN-test results for RL suggest a high-frequency DR starting between 3 and 4 kHz. There may also be an "island" of damaged or poorly functioning IHCs between 1 and 2 kHz, as the masked threshold for the 1.5-kHz signal in the 70-dB TEN was 82 dB, meeting the criterion for a DR. However, for a higher level of

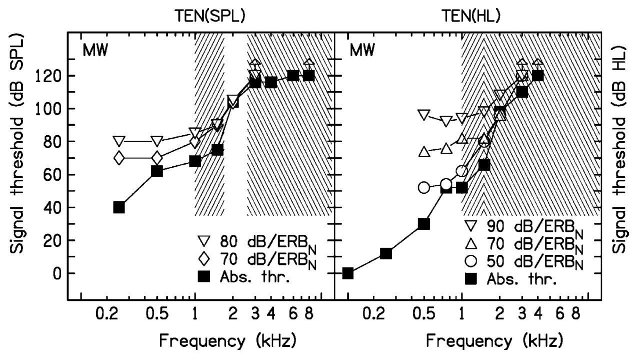

Fig. 2. TEN-test results for subject MW. The left and right panels show the results for the TEN(SPL) and TEN(HL) tests, respectively. Otherwise, as the upper panels of Fig. 1. The numerical values on the y-axis scale are the same for both panels.

the TEN (80 dB/ERB$_N$), the masked threshold was within the normal range. This may indicate that the IHCs in this region do not respond to weak sounds, but "wake up" when more intense stimuli are presented. The PTC results suggest no DR at 1 kHz (the tip of the PTC for $f_s = 1$ kHz is at f_s) and a DR above 3 kHz (the tip of the PTC for $f_s = 4$ kHz is shifted downwards to 3 kHz). The PTC for $f_s = 1.5$ kHz (circle) shows distinct irregularities around f_s. Three tips can be observed, one sharp tip at f_s, a second one below f_s (at 1 kHz) and a third one above f_s (at 2 kHz). The minimum masker level occurs at 1 kHz, which would suggest the presence of DR at 1.5 kHz, but the two remaining tips make the interpretation of this PTC difficult. The PTC for $f_s = 2$ kHz actually shows four tips, one at f_s, and other tips at about 1, 1.3 and 2.5 kHz. The tip at f_s may be a result of beat detection for masker frequencies just below and just above 2 kHz and the lack of beats at 2 kHz. The tips at 1.3 and 2.5 kHz may reflect the decreasing audibility of beats with increasing beat rate. The tip at 1 kHz may reflect the CF where the signal is detected, i.e., the edge of the DR. However, again, the interpretation of this PTC remains unclear and more testing is required.

In summary the results suggest that all subjects have a high-frequency DR, although for some subjects (MD, PM, and MW) the results of TEN test were not fully consistent with the results of the PTC measurements, and in many cases the PTCs were hard to interpret. Later in this paper we describe further results obtained for these subjects which show that the shapes of the PTCs were influenced by the detection of beats and/or SDTs, and that this was the source of the discrepancies between the results obtained using these two diagnostic methods.

3. Experiment 2: The effect of masker bandwidth on the shapes of PTCs

In this experiment, PTCs were measured for four different maskers: a sinusoidal tone, and 80-, 160-, and

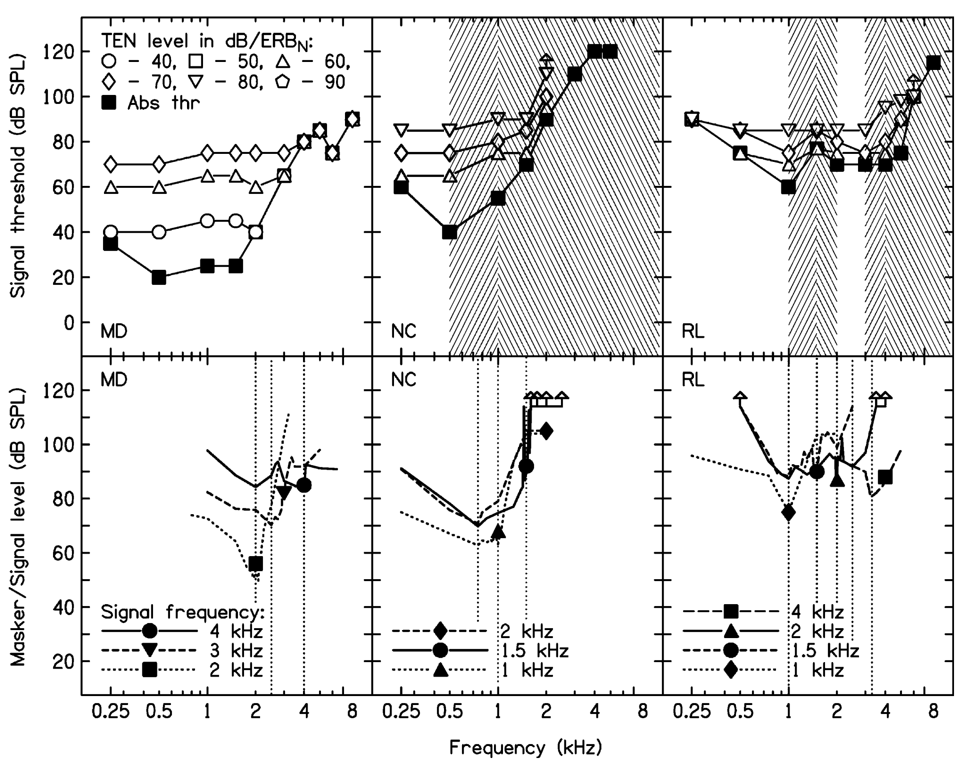

Fig. 3. As Fig. 1, but for three subjects with differing degrees of low-frequency hearing loss.

320-Hz wide bands of noise. We anticipated that the influence of beat detection would be reduced with increasing masker bandwidth. Hence, by measuring the effect of masker bandwidth, we could assess the role of beat detection for the smaller masker bandwidths.

3.1. Stimuli and method

The signal was a sinusoid at 10 dB SL. The masker was either a sinusoid or an 80-, 160-, or 320-Hz wide band of noise. The (center) frequencies of the maskers were chosen so as to define the PTC shape and especially its tip with reasonable accuracy. Masker levels are specified as overall levels.

The equipment and the method used for estimating thresholds were the same as described by Kluk and Moore (2004). The subjects were the same as for experiment 1.

3.2. Results

Fig. 4 shows PTCs for $f_s = 2.5$ kHz for subject PM, whose absolute thresholds were normal or almost normal at low frequencies (22 dB SPL, on average, between 0.25 and 2 kHz) and abruptly worsened between 2 and 3 kHz (92 dB SPL at 3 kHz). The PTC for the sinusoidal masker is shown in the top-left panel, and is repeated in the other panels to allow easy comparison with the PTCs obtained for the 80-, 160-, and 320-Hz wide noise maskers. The PTCs for all maskers, even the 160- and 320-Hz wide maskers, show two tips, one of which is always at f_s. The frequency at the second tip increased with increasing masker bandwidth, from 0.75 kHz for the sinusoidal masker to 1, 1.5, and 1.5 kHz for the 80-, 160-, and 320-Hz wide noise maskers, respectively. The results of Kluk and Moore (2004) and the results presented so far in this paper suggest that beats do not provide a usable cue when the masker bandwidth is 320 Hz. Therefore, the sharp tip of the PTC at f_s found for this masker probably cannot be attributed to beat detection. The most likely explanation for the sharp tip is that the subject detected SDTs. As both the masker and signal were presented at very high levels, they would have given rise to distinct SDTs, which could easily be detected by PM because of his good low-frequency hearing. The SDT would not have been detectable when the masker frequency was equal to f_s, as the SDT frequency would then fall at 0 Hz. Because of the W-shaped PTCs, and the possible involvement of SDT detection, it is very difficult to assess whether PM has a DR from these results, although the TEN-test results (Fig. 1) suggest the presence of a high-frequency DR starting at about 2 kHz. Additional tests clarifying the influence of SDT detection on the PTCs are described later.

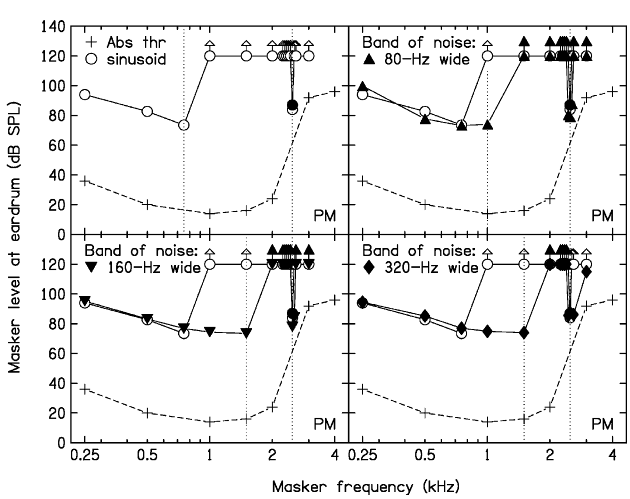

Fig. 4. PTCs for $f_s = 2.5$ kHz for subject PM. Absolute thresholds are indicated by crosses. Masker level is plotted as a function of masker frequency. Each panel shows PTCs obtained for a sinusoidal masker (open circles) and for one of three different noise maskers (filled symbols). Bandwidths of the noise maskers were 80, 160, and 320 Hz. The filled circle shows the signal level and frequency. Dotted vertical lines indicate the tips of the PTCs.

Fig. 5 shows results for subject PJ for $f_s = 2$ kHz. As noted earlier, data collection could not be completed for this subject because of his illness, so for some of the PTCs there are "missing" data. The PTCs for both the sinusoidal and noise maskers show two tips, a sharp tip at f_s and a broad tip below f_s (although the second tip is not clear for the 320-Hz bandwidth as the data are incomplete). The absolute threshold at low frequencies for subject PJ is almost normal (30 dB SPL at 0.5 kHz) and worsens above 1 kHz (50 and 75 dB SPL at 1 and 2 kHz, respectively). This makes it possible that PJ detected an SDT for masker-signal frequency separations up to at least 0.5 kHz. As for PM, the W-shaped PTCs, and the possible involvement of SDT detection make it difficult to use these results to determine whether PJ has a DR. However, the TEN-test results suggest the

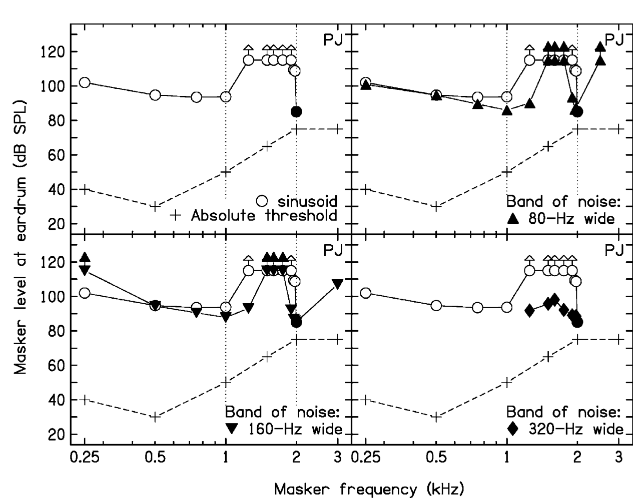

Fig. 5. As Fig. 4 but showing PTCs for subject PJ for $f_s = 2$ kHz.

presence of a DR at high frequencies, starting above around 1 kHz, perhaps with a surviving "island" around 2 kHz. Additional tests clarifying the influence of SDT detection on the PTCs for PJ are described later.

Fig. 6 shows results for $f_s = 1.25$ kHz for subject MW, whose absolute threshold in the low-to-mid-frequency region was moderately high (62 dB SPL at 0.5 kHz and 68 dB SPL at 1 kHz). The PTCs for the sinusoidal and 80-Hz noise maskers both show a distinct tip at f_s and a second broad tip below f_s. The tips at f_s were probably caused mainly by the detection of beats. The broad tips at lower frequencies probably reflect the frequency separation between masker and signal where beats stop being a cue. The detection of SDTs is not likely in this case as the absolute threshold at frequencies around 0.5 kHz (the frequency of the SDT when the masker frequency was just above the broad tip) was too high to enable the detection of SDTs (the absolute threshold at 0.5 kHz was 62 dB SPL).

The tip of the PTC at f_s was broader for the 80-Hz wide noise masker than for the sinusoidal masker. This may have happened because the envelope fluctuations of an 80-Hz wide band of noise are restricted to rates below 80 Hz (Lawson and Uhlenbeck, 1950) and are most effective in reducing the detectability of beats for low beat rates (Derleth and Dau, 2000). Hence, for the 80-Hz wide masker, beats were probably not useful as a cue when the masker-signal frequency separation was small, but became more useful when the separation was in the range 100–350 Hz. The PTCs for 160- or 320-Hz wide noise maskers do not show significant irregularities around f_s and are characterized by a broad tip without a distinct minimum. These results are consistent with a DR above 0.75–1.25 kHz. The results of the TEN test suggest the presence of a high-frequency DR starting between 1 and 1.5 kHz. Thus, there is a reasonable correspondence between the TEN-test results and the PTCs determined using the two wider noise maskers.

Figs. 7 and 8 show PTCs for subject MD who had almost normal hearing at low frequencies (the absolute threshold up to 1.5 kHz did not exceed 22 dB SPL; crosses) and a hearing loss increasing rapidly above 2 kHz. The PTC for the sinusoidal masker with $f_s = 2$ kHz (Fig. 7) shows distinct irregularities and is characterized by a very sharp tip at f_s. Similar very sharp tips have been observed previously for normally hearing people when a sinusoidal masker was used (Kluk and Moore, 2004). The tips are broader when noise maskers (filled symbols) are used. The levels of the noise maskers over the frequency range between 1.5 and 2.5 kHz (excluding 2 kHz) were as much as 20 dB lower than those for the sinusoidal masker. This probably results from the reduced availability of a cue associated with beats for the noise maskers (Dau et al., 1997; Egan and Hake, 1950; Ewert and Dau, 2000; Kluk and Moore, 2004; Moore et al., 1998; Patterson and Moore, 1986). For the noise maskers, the PTCs show a single tip at f_s, suggesting that no DR is present at f_s.

Fig. 8 shows the PTCs for $f_s = 3$ kHz, obtained for the same subject (MD). The absolute threshold at f_s is 62 dB SPL. The PTC for the sinusoidal masker has a sharp tip at f_s and a second tip at 1.5 kHz. The tip at f_s is absent when noise maskers are used. The level required for threshold is 2–25 dB lower for the noise maskers than for the sinusoidal masker for frequencies between 2.5 and 4 kHz (excluding 3 kHz). This is consistent with the idea that the inherent fluctuations in the noise prevented beat detection. The PTCs determined using the noise maskers have tips that are shifted downwards to about 2.65 kHz, suggesting a high-frequency DR starting at about 2.65 kHz.

Similar results were obtained for subject NC (Figs. 9 and 10). He had a moderate hearing loss at low frequencies (around 50 dB SPL with a minimum of 40 dB SPL

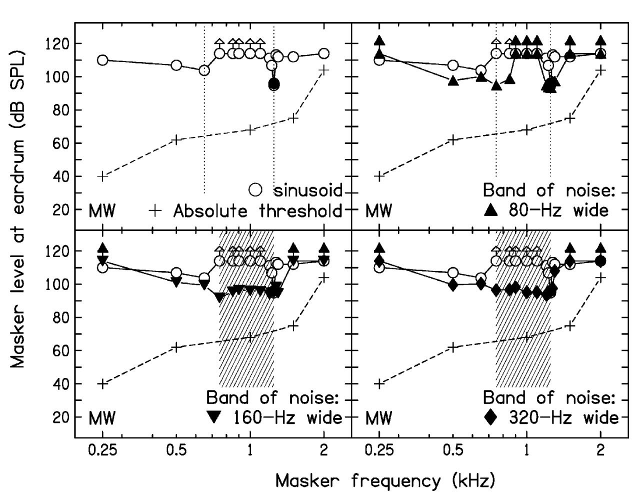

Fig. 6. As Fig. 4 but for subject MW for $f_s = 1.25$ kHz. The shaded areas mark the broad tips of the PTCs.

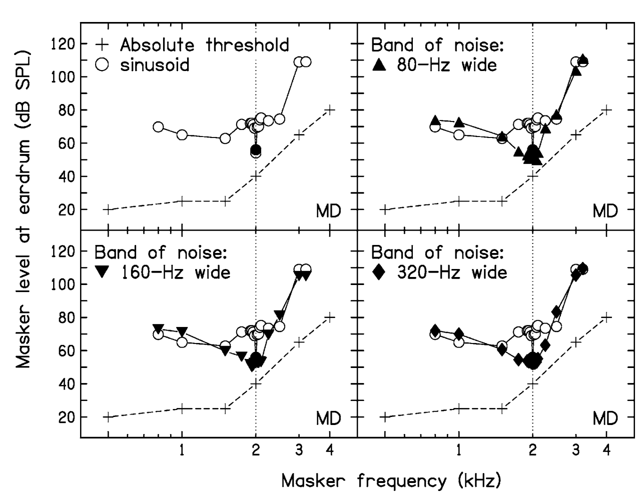

Fig. 7. As Fig. 4 but for subject MD for $f_s = 2$ kHz.

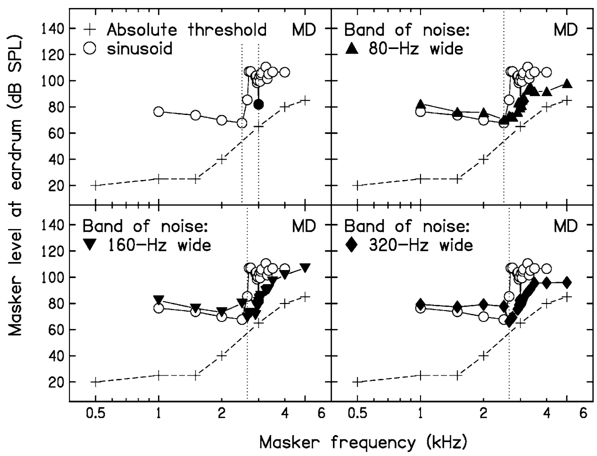

Fig. 8. As Fig. 7 but for $f_s = 3$ kHz.

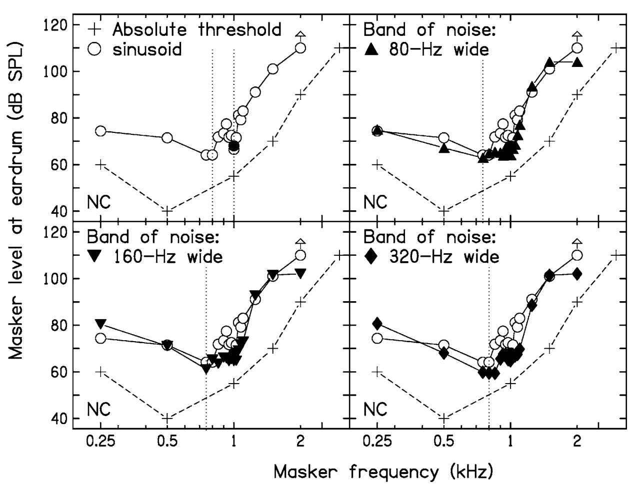

Fig. 9. As Fig. 4 but for subject NC for $f_s = 1$ kHz.

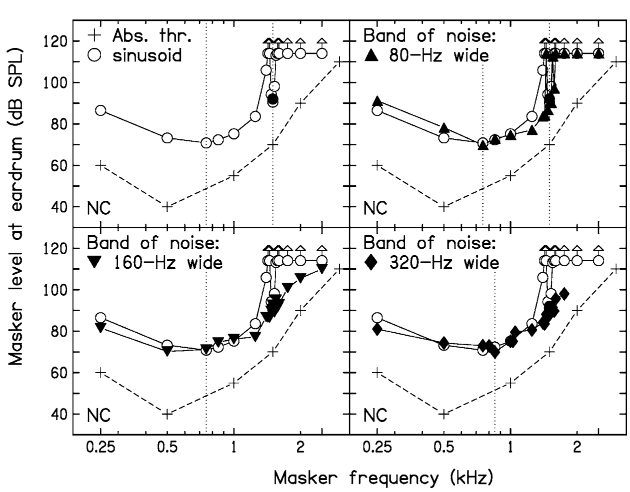

Fig. 10. As Fig. 9 but for $f_s = 1.5$ kHz.

at 0.5 kHz) and a severe hearing loss above 1 kHz. The PTCs for $f_s = 1$ (Fig. 9) and 1.5 kHz (Fig. 10) obtained using a sinusoidal masker show a sharp tip at f_s and a second broader tip at a frequency below f_s. For $f_s = 1$ kHz, the sharp tip at f_s was reduced when noise maskers were used (filled symbols in Fig. 9). The level of the noise maskers required for threshold was reduced for masker frequencies both below and above f_s. The sharp tip at f_s for the sinusoidal masker was probably caused by beat detection when the masker and signal frequencies were close and by the lack of this cue when they were equal. The tips of the PTCs for the noise maskers are always shifted downwards to 0.75–0.8 kHz, which indicates the presence of a DR above about 0.75 kHz.

The PTC for $f_s = 1.5$ kHz showed a sharp tip at f_s even when an 80-Hz wide noise masker was used. This may have been due to a residual beat cue. The detection of SDTs seems unlikely in this case as the absolute threshold at low frequencies was rather high (60 dB SPL at 0.25 kHz). The PTCs become "smoother" as the bandwidth of the masker increases, and the sharp tip at f_s disappears. It seems plausible that, for subject NC, the noise bandwidths of 160 or 320 Hz were sufficient to prevent beats from being detectable, while the 80-Hz bandwidth was too narrow to prevent beats from affecting the shape of the PTC. For the 160- and 320-Hz noise maskers, the tips of the PTCs are shifted downwards to about 0.75–0.85 kHz (bottom panels in Fig. 10). This again suggests that subject NC has a high-frequency DR starting at about 0.75 kHz, which is in agreement with the results of the PTCs for $f_s = 1$ kHz and of the TEN test.

Figs. 11 and 12 show results for subject RL for $f_s = 1.5$ and 2 kHz. The absolute threshold in the frequency region covered by the PTCs is highest at 1.5 kHz (77 dB SPL) and lowest at 1 kHz (60 dB SPL). For both signal frequencies, the PTCs for the sinusoidal masker and the 80-Hz wide noise masker are characterized by three tips, one sharp tip at f_s and two broad tips at 1 and 2 or 2.5 kHz. The sharp tips at f_s are probably

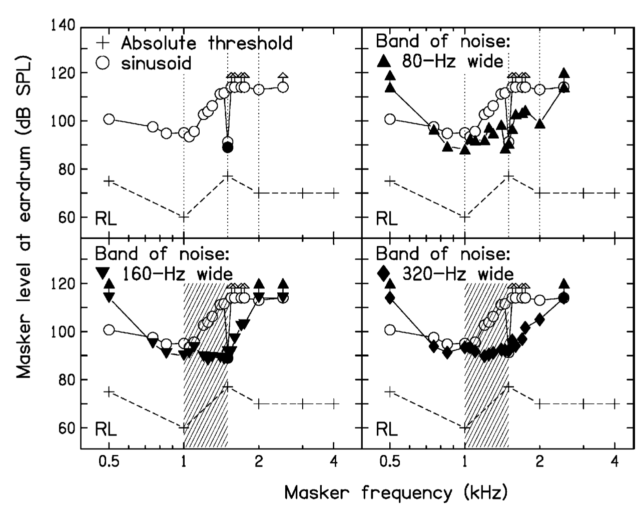

Fig. 11. As Fig. 4 but for subject RL for $f_s = 1.5$ kHz.

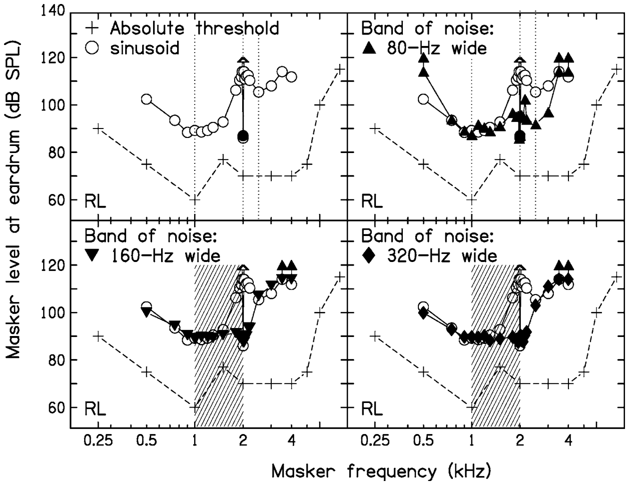

Fig. 12. As Fig. 11 but for $f_s = 2$ kHz.

caused by the detection of beats for masker frequencies close to f_s and the lack of this cue when the masker frequency equals f_s. It is unlikely that SDTs were detectable, since the absolute thresholds in the low-frequency region where these SDTs would be detected were rather high (the absolute threshold at 0.25 kHz was 90 dB SPL). Evidently, RL, like NC, was able to use the beat cue even when an 80-Hz wide masker was used. Similar findings have been reported for normally hearing people, for both PTCs (Kluk and Moore, 2004) and masking patterns (Alcántara et al., 2000), and also for masking patterns for hearing-impaired people (Alcántara and Moore, 2002).

For both signal frequencies, broadening the noise resulted in a reduction of the irregularities in the PTCs and in a reduction of the sharp tips that occurred when 80-Hz wide noise or sinusoidal maskers were used. For the 160- and 320-Hz wide maskers, defining the frequency of the tip is very difficult (the broad tip extends from 1 to 1.5 kHz for $f_s = 1.5$ kHz and from 1 to 2 kHz for $f_s = 2$ kHz). The broad tip probably results from poor frequency selectivity for frequencies at and below f_s. The auditory filters of hearing-impaired people with moderate hearing loss are usually two or three times broader than normal (Baker and Rosen, 2002; Dubno and Dirks, 1989; Glasberg and Moore, 1986; Leek and Summers, 1993; Moore, 1998; Tyler et al., 1984) and so are PTCs. These results do not provide any strong evidence for a DR at either 1.5 or 2 kHz.

4. Experiment 3: The effect of adding LF noise on the shapes of PTCs

This experiment was designed to assess the influence of SDT detection on the shapes of the PTCs. The experimental set-up was identical to that of experiment 2, but additional LF noise was added to the main masker. The LF noise was used for all cases when W-shaped PTCs were found in experiment 2.

4.1. Stimuli and method

The LF noise was intended to mask SDTs and not to have a direct masking effect on the signal. The cut-off frequency and the spectrum level of the LF noise were adjusted individually for each subject and are given in Table 2 (the cut-off frequency of the LF noise is given as the 6-dB down point). The cut-off frequency was chosen so that the noise passband covered the frequency region of suspected SDT detection. For example, for subject MW, SDTs were expected to be detectable for frequencies up to 0.5 kHz (her absolute thresholds would have been too high to allow SDT detection for higher frequencies), so the cut-off frequency was chosen to be at 0.5 kHz. To assess an appropriate level for the LF noise, excitation patterns were calculated using the model described by Moore and Glasberg (1997), taking into account the hearing loss of the individual subjects. The noise level was chosen to be high enough to mask SDTs with effective levels up to about 60 dB SPL, with the constraint that the LF noise would evoke excitation at f_s that was well below that evoked by the signal itself. The spectrum level of the LF noise was always between 40 and 55 dB (adjusted individually), which gave an overall level between 73 and 85 dB SPL (depending on the subject).

The noise was generated by an Ivie Technologies IE-20B noise generator and passed through two Kemo VBF 8/04 filters in series with a slope of 90 dB/octave/filter. The noise was presented continuously during a run. The subjects were the same as for experiment 2, except that subject RL was not tested.

4.2. Results

The results are shown in Figs. 13–17. The filled triangles show the effect on the PTCs of adding the LF noise. Results indicated by the asterisks will be described in Section 5.2.

Fig. 13 shows the results for subject PM for $f_s = 2.5$ kHz. For the sinusoidal masker, the addition of LF noise substantially reduced the masker level required for threshold over the frequency range from 1.5 to 2.35 and at 3 kHz. The most likely explanation is that, in the absence of LF noise, PM detected a SDT (at frequencies between 0.15 and 1 kHz) when the masker frequency was between 2.35 and 1.5 kHz. The LF noise prevented detection of SDTs, but did not prevent the detection of beats for masker frequencies of 2.4, 2.45, 2.55, and 2.6 kHz. Hence, the masker level at threshold remained relatively high for these frequencies, even when LF noise was present, and a sharp tip remained at 2.5 kHz (f_s).

Table 2
Parameters of the LF noise and MDI tones for each subject

Subject	Signal frequency (kHz)	LF noise		MDI tones	
		Cutoff frequency (kHz)	Spectrum level (dB)	Frequency of variable MDI tone (kHz)	Level of each MDI tone (dB SPL)
MW	1.25	0.5	50	$0.5-\Delta f$[a]	95
PJ	2.0	0.8	50	$0.3+\Delta f$	60
PM	2.5	1.1	40	$1.0+\Delta f$	60
MD	3.0	1.0	55	$1.0-\Delta f$	85
NC	1.0	0.2	50	$1.0+\Delta f$	68
NC	1.5	0.2	50	$1.0+\Delta f$	85

Signal frequencies for which PTCs were determined are also shown.

[a] $\Delta f = f_1 - f_2$, where f_1 and f_2 are the frequencies of the signal and the masker, respectively (when the masker frequency is below the signal frequency) and the frequencies of the masker and signal, respectively (when the masker frequency is above the signal frequency).

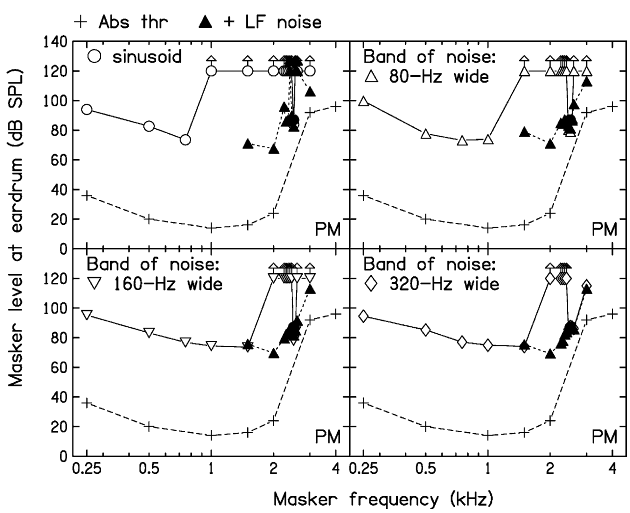

Fig. 13. PTCs for subject PM, for $f_s = 2.5$ kHz, for sinusoidal and noise maskers. The filled triangles show results with added LF noise.

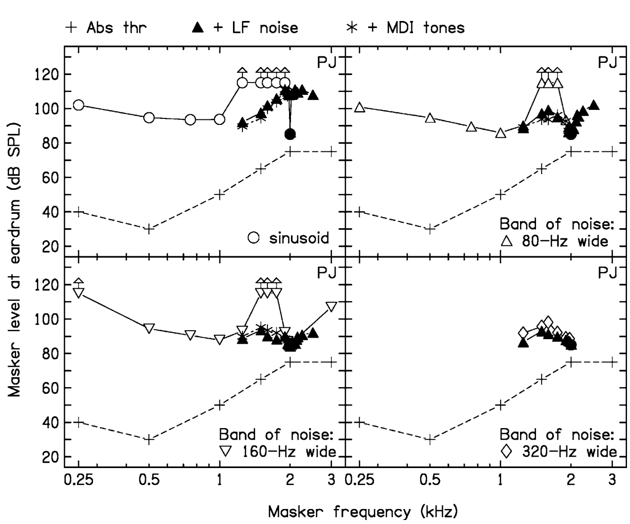

Fig. 14. As Fig. 13 but for subject PJ, for $f_s = 2$ kHz. Asterisks show results with added low-frequency MDI tones.

For the noise maskers, the addition of the LF noise also resulted in substantial reductions in the masker level required for threshold. This suggests that simple difference bands were detectable for the noise maskers. Some irregularities persisted for the PTC obtained with the 80-Hz wide noise, even when LF noise was present. These were probably the result of beat detection for masker-signal frequency separations of 100 and 150 Hz. The tips of the PTCs obtained in the presence of LF noise fell just below f_s, suggesting the presence of a DR starting just above 2 kHz and extending towards high frequencies; this is consistent with the results of the TEN test (Fig. 1).

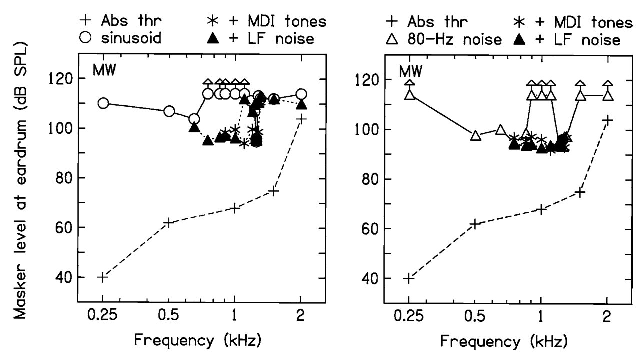

Fig. 15. As Fig. 14 but for subject MW, for $f_s = 1.25$ kHz. Results are shown only for sinusoidal and 80-Hz wide main maskers.

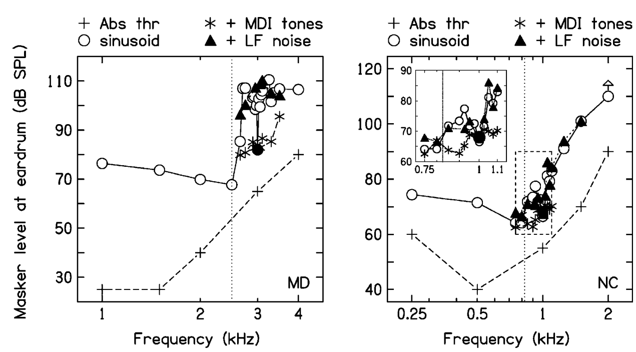

Fig. 16. As Fig. 15 but only for the sinusoidal masker for subjects MD (left panel) and NC (right panel), for $f_s = 3$ and 1 kHz, respectively. The inset in the right panel shows the tips of the PTCs in more detail.

For subject PJ (Fig. 14) the addition of LF noise to the sinusoidal masker substantially reduced the masker

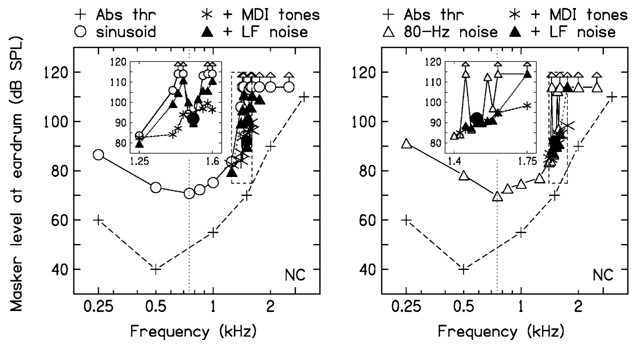

Fig. 17. As Fig. 14 but for subject NC, for f_s = 1.5 kHz. The inset in each panel shows the tips of the PTCs in more detail.

level required for threshold over the frequency range from 1.25 to 1.75 kHz. It seems likely that the LF noise prevented the detection of SDTs, which become less audible for masker frequencies close to f_s. However, beat detection probably also played an important role, since the masker level required for threshold increased with decreasing masker-signal frequency separation for masker frequencies below f_s, and the tip of the PTC was very sharp even when the LF noise was present.

The addition of LF noise also substantially decreased the masker level required for threshold when 80- and 160-Hz wide noise maskers were used, suggesting that difference bands were detectable for these maskers. The PTCs for these maskers showed a small tip at 2 kHz even in the presence of LF noise. This may indicate no DR at 2 kHz, which is consistent with the results of the TEN test (Fig. 1); this test suggested an "island" of surviving IHCs around 2 kHz with DRs above and below that. Although the PTCs for the 320-Hz bandwidth are incomplete, the pattern of masker thresholds was very similar with and without the LF noise. This suggests that, for PJ, there was a minimal or no role of difference-band detection when the masker bandwidth was sufficiently wide.

The open symbols in Fig. 15 show PTCs for subject MW for the sinusoidal and 80-Hz wide noise maskers. The LF noise had the effect of decreasing the masker level required for threshold for masker frequencies between 0.75 and 1 kHz when the sinusoidal masker was used and between 0.85 and 1.1 kHz when the 80-Hz wide noise masker was used. The LF noise did not reduce the level of the sinusoidal masker required for threshold for frequencies within 250 Hz of f_s.

It seems likely that SDTs were detectable in the absence of LF noise for frequencies of the sinusoidal masker between 0.75 and 1 kHz and frequencies of the 80-Hz wide masker between 0.85 and 1.1 kHz. Adding the LF noise produced a substantial reduction in the masker level required for threshold over this frequency range. For the noise masker, beats were probably not an effective cue for masker frequencies very close to f_s since slow beats would have been masked by the slow inherent fluctuation in the noise, as described earlier. Hence, the masker level at threshold was relatively low for masker frequencies immediately adjacent to f_s, and adding the LF noise had little effect for these frequencies. For the sinusoidal masker, beats probably did provide a salient cue for masker frequencies very close to f_s. Thus, in the absence of the LF noise, the masker level at threshold was high for these frequencies, and adding the LF noise had little effect, as it did not prevent beat detection. In summary, the results suggest that, in the absence of LF noise, the PTC for the noise masker was influenced by SDT detection, and the PTC for the sinusoidal masker was influenced by both SDT detection and beat detection.

The left panel of Fig. 16 shows results for subject MD, obtained using a sinusoidal masker with f_s = 3 kHz. The LF noise reduced the level of the masker required for threshold by 9 and 7 dB at 2.65 and 2.75 kHz, respectively. Otherwise, the LF noise had little effect, suggesting at most a minor role for SDT detection. Later measurements (Section 5.2) show the influence of beats on the PTC for subject MD.

Results for NC for a sinusoidal masker with f_s = 1 kHz are shown in the right panel of Fig. 16. The masker level required for threshold is almost the same with and without LF noise for all masker frequencies tested, suggesting no influence of SDT detection on the results. This is not unexpected as the level of the signal was relatively low (68 dB SPL) and the absolute threshold at low frequencies was generally above 40 dB SPL.

Fig. 17 shows results for NC for f_s = 1.5 kHz, using both a sinusoidal masker (left) and an 80-Hz wide noise masker (right). The addition of LF noise had only small effects, and did not abolish the sharp tips of the PTCs at f_s. Again, we conclude that there was little or no influence of SDT detection on the results.

In summary, the results show a clear influence of SDT detection on the PTCs for subjects MW, PJ and PM. SDT detection occurred both for the sinusoidal masker and for the noise maskers. Generally, SDT detection seems to play a role when low-frequency hearing is reasonably good and when the hearing loss at f_s is relatively severe.

5. Experiment 4: The effect of adding MDI tones on the shapes of PTCs

In this experiment we studied the effect of reducing the salience of beats by adding a pair of low-frequency tones to the main masker. The beats produced by the added tones were intended to interfere with detection of the beats produced by the main masker and the signal via the phenomenon of MDI (Alcántara et al., 2000; Kluk and Moore, 2004; Moore et al., 1998; Yost and Sheft, 1989; Yost et al., 1989).

5.1. Stimuli and method

The frequency separation of the MDI tones was always equal to the frequency separation of the main masker and the signal. The frequencies and levels of the MDI tones were adjusted individually for each subject and are given in Table 2. The column labelled "Frequency of variable MDI tone" shows the frequency of the fixed MDI tone and defines the frequency of the variable MDI tone. For example for subject MW, when the signal and masker frequencies were 1.25 and 1.1 kHz, respectively, the frequencies of the MDI tones were 0.5 and 0.35 kHz. The level of the MDI tones was chosen so that the beats they produced were as salient as possible, while avoiding direct masking of the signal. Initially the level of each of the MDI tones was set to be equal to the level of the signal. To check that the MDI tones would not have a significant direct masking effect on the signal, excitation patterns were calculated for the MDI tones and for the signal, using the method described by Glasberg and Moore (1990). When the excitation level evoked by the MDI tones at f_s was not at least 25 dB below the excitation level evoked by the signal, the level of the MDI tones was reduced until this criterion was achieved. The experimental set-up was identical to that of experiment 3, but instead of LF noise, MDI tones were added. The subjects were the same as for experiment 3. Again, the effect of adding the MDI tones was explored only for cases where the PTCs in the absence of the MDI tones were W-shaped.

It should be noted that, as the MDI tones fell in a low-frequency region, they would be expected not only to impair beat detection, but also to mask SDTs. Thus, an effect of the MDI tones on beat detection would be revealed as an effect *additional* to that produced by the LF noise.

5.2. Results

The asterisks in Figs. 14–17 show the PTCs obtained in the presence of the MDI tones. For subject PM (Fig. 13), it was not possible to obtain meaningful results in the presence of the MDI tones (the masker level required for threshold over the frequency region of interest was too high to be measured, as was also the case when the MDI tones were absent). Probably PM was not susceptible to MDI. A lack of susceptibility has been reported previously for some normally hearing subjects, especially experienced subjects (Bacon and Opie, 1994).

For most cases where the original PTC was W-shaped, the addition of the MDI tones reduced the masker level required for threshold for masker frequencies within a few hundred Hertz of f_s. For two of the subjects with good low-frequency hearing (PJ and MW in Figs. 14 and 15), the MDI tones had similar effects to the LF noise when the PTCs were determined using noise maskers. This suggests that the effect of the MDI tones in those cases was mediated by masking of difference bands rather than by interference with beat detection. This interpretation is consistent with the idea that beat cues are minimal when noise bands are used as maskers, at least when the masker bandwidth is 160 or 320 Hz.

For subject PJ (Fig. 14), the effect of the MDI tones with the sinusoidal masker was similar to the effect of the LF noise. This was somewhat surprising, as the very sharp tip of the PTC suggests that beats were used as a cue. Possibly, the MDI tones were ineffective in interfering with beat detection because PJ was too highly trained (Bacon and Opie, 1994) or because the MDI tones were not sufficiently loud relative to the signal and main masker.

For subject MW (Fig. 15), when the sinusoidal masker was used, the effect of addition of the MDI tones was somewhat different from that of adding the LF noise; specifically, the MDI tones substantially reduced the masker level required for threshold for masker frequencies of 1.1, 1.2, 1.225 and 1.275 (f_s was 1.25 kHz), while the LF noise had little effect for these masker frequencies. For these cases, the MDI tones probably had their effect by interfering with beat detection.

The left panel of Fig. 16 shows the effect of adding MDI tones to a sinusoidal masker for subject MD, who had near normal hearing at low frequencies. The addition of the MDI tones substantially reduced the level of the masker required for threshold for frequencies around f_s (3 kHz), and the effect of the MDI tones was much greater than the effect of the LF noise. This is consistent with our earlier conclusion that beat detection played a strong role for MD, while SDT detection played only a minor role. The shifted tip of the PTC suggests a DR starting at about 2.5 kHz, which is broadly consistent with the shifted tips of the PTCs obtained using noise maskers, as shown in Figs. 3 and 8.

The right panel of Fig. 16 shows results for NC, obtained using a sinusoidal masker with $f_s = 1$ kHz. The addition of the MDI tones again reduced the level of the masker required for threshold for frequencies around f_s, and the effect of the MDI tones was somewhat greater than the (negligible) effect of the LF noise. The clear effect of the MDI tones, combined with the lack of effect of the LF noise, again suggests a role for beat detection, but not for SDT detection. The PTC obtained in the presence of the MDI tones shows a single tip at 0.85 kHz, which suggests a high-frequency DR starting at about 0.85 kHz.

Fig. 17 shows the results for NC with $f_s = 1.5$ kHz for a sinusoidal masker (left) and an 80-Hz wide masker (right). The addition of the MDI tones eliminated the sharp tips of the PTCs at f_s and led to PTCs each with one broad tip shifted downwards to around 0.75 kHz. The effect of the MDI tones was greater than the effect of the LF noise. Again these findings indicate a strong role for beat detection. The shifted tips of the PTCs when the MDI tones were present are consistent with a high-frequency DR starting at about 0.75 kHz. The estimated edge frequency of the DR differs very slightly from that estimated using the 1-kHz signal (Fig. 16), but small discrepancies of this type are to be expected given the relatively broad tips of the PTCs.

6. Discussion

The results of experiment 1 revealed some discrepancies between the results of the TEN test and PTCs determined using an 80-Hz wide noise masker. The discrepancies occurred when the PTCs were characterized by two tips, one sharp tip at f_s and a second broader tip at a masker frequency below f_s (W-shaped PTCs). Nine out of the seventeen PTCs measured in this experiment were W-shaped, with the sharp tip at f_s even when f_s fell in a DR (as diagnosed with the TEN test). We suggested that the W-shaped PTCs were influenced by the detection of SDTs and beats, although it was not obvious which of these two factors was dominant for any specific subject.

Experiment 2 explored the effect of increasing the bandwidth of the masker, which was expected to reduce the use of beats as a cue. The results showed that the sharp tips of the PTCs at f_s were eliminated when the 320-Hz wide band of noise was used for all subjects with moderate low-frequency hearing-loss and a high-frequency DR (NC, RL, and MW). The effect was also observed for one subject with good low-frequency hearing (MD). From these data, it cannot be determined whether there is a masker bandwidth at which beats become completely unusable as a cue, although it seems likely that the bandwidth of 320 Hz was sufficient to greatly reduce the salience of beats. This conclusion was also reached in our previous work using normally hearing people (Kluk and Moore, 2004).

The sharp tips of the PTCs at f_s were not eliminated by increasing masker bandwidth for subjects with near-normal low-frequency hearing and a DR at high frequencies (PM and PJ). This is consistent with the idea that the sharp tips in those cases were caused by detection of SDTs.

Experiment 3 explored the effect of adding LF noise to the sinusoidal and noise maskers. The noise was intended to mask SDTs while having a minimal direct masking effect on the signal. The results showed a strong influence of the LF noise on the W-shaped PTCs for two of the three subjects with near-normal low-frequency hearing and a DR at high frequencies (PM and PJ). However, for the remaining subject of this type (MD), the LF noise had only a small effect. This subject appeared to be highly sensitive to beats and probably focused on using these as a detection cue rather than "listening for" SDTs. Overall, the results indicate that SDT detection *can* have a strong influence on PTCs when low-frequency hearing is good, although this does not always occur. There was no evidence of SDT detection for subjects with poor low-frequency hearing (RL and NC).

Experiment 4 explored the effects of adding MDI tones to the sinusoidal and noise maskers. In cases where the PTCs were W-shaped for the sinusoidal and 80-Hz wide noise maskers presented alone, the addition of the MDI tones usually eliminated the sharp tips of the PTCs at f_s, leading to PTCs with single broad tips that were often centered below f_s. These results indicate that the PTCs determined for the sinusoidal and 80-Hz wide maskers, in the absence of the MDI tones, were strongly influenced by beat detection for masker frequencies within about 500 Hz of f_s. The results are similar to those found for normally hearing people (Kluk and Moore, 2004).

For two of the three subjects with good low-frequency hearing (MW and PJ), adding the MDI tones to the main masker had a broadly similar effect to adding the LF noise. For these subjects, the MDI tones probably produced an effect mainly by masking SDTs, rather than by reducing the detection of beats. For subject PJ, the PTC for the sinusoidal masker had a very sharp tip at f_s, even when the MDI tones were present, perhaps indicating that this subject was not susceptible to MDI. This may have occurred because the MDI tones sounded quieter than the main masker and signal. Subject PM also appeared to be resistant to the effects of MDI, as described earlier.

The incidence of W-shaped PTCs in our results was relatively high, perhaps because the signal frequencies were selected so as to fall within or close to the edge of suspected DRs. As described in Section 1, several previous researchers have reported W-shaped PTCs, most recently Summers et al. (2003). They tested seventeen listeners with steeply sloping moderate-to-severe high-frequency hearing loss and near-normal hearing at low frequencies. In the PTC measurements, a sinusoidal signal at a level of 10, 15 or 20 dB SL was presented with a narrowband noise masker (100-Hz bandwidth) that continuously increased in center frequency at a rate of 1/3 octave/minute. A method resembling Békésy tracking was used to determine the PTCs. Their subjects were also assessed using the TEN test with TEN levels of 70, 85 or 90 dB/ERB$_N$. For each of four subjects (their Figs. 1–3; subjects MA, MG, BA, and EF), the PTC had a sharp tip at f_s, together with a second broader tip at a lower frequency (W-shaped PTCs) while the masked threshold in the TEN at f_s was markedly elevated. Our results suggest that the sharp tip at f_s was probably caused by detection of beats or SDTs for masker frequencies close to f_s and the lack of these cues when the masker frequency equaled f_s. Since many of the subjects of Summers et al. had good low-frequency hearing, a strong role of SDT detection seems likely. Thus, the sharp PTC tips at f_s were not indicative of DRs. It seems very likely that the discrepancies between the TEN test and PTC results reported by Summers et al. (2003) originated from the PTCs being affected by beat and/or SDT detection.

It is useful to consider what might be the "optimal" stimulus parameters for determining PTCs when the main objective is to use them as a tool for diagnosing DRs. To minimize the influence of beats, we recommend using narrowband noise maskers with a bandwidth of 160 or 320 Hz. A bandwidth of 320 Hz is probably best, as this appears to effectively prevent the use of beat detection as a cue, but is likely to be less than the auditory filter bandwidth of subjects with impaired hearing for most center frequencies (Moore and Glasberg, 1997). A bandwidth less than 320 Hz may be needed when the edge frequency of the suspected DR is very low, and the auditory filter bandwidth is correspondingly small.

In cases of near-normal hearing at low-frequencies, we recommend using an additional LF noise to mask SDTs. However, it may not be easy in clinical practice to choose an appropriate cutoff frequency for the noise and an appropriate level for the noise. In our experiment 3, the cutoff frequency of the LF noise was always more than one octave below f_s and the noise spectrum level was usually 50 dB or less; these parameters may work well in the majority of cases.

7. Conclusions

The following conclusions can be drawn from this study:

(1) PTCs for subjects with good low-frequency hearing and high-frequency DRs can be influenced both by the detection of SDTs and by the detection of beats, the former having the greater effect. The influence of SDTs is greatest for masker frequencies within 1000 Hz of f_s.
(2) The use of a narrowband noise as the main masker does not prevent detection of distortion components, as in this case a simple distortion band may be detected.
(3) The influence of SDT detection can be reduced or eliminated by adding a LF noise to the main masker.
(4) PTCs for subjects with moderate low-frequency hearing loss and a high-frequency DR can be influenced by the detection of beats (when sinusoidal and 80-Hz wide noise maskers are used). The influence of beats is greatest for masker frequencies within 500 Hz of f_s.
(5) The use of bandpass noise as the main masker reduces the influence of beat detection, and this reduction increases with increasing masker bandwidth.
(6) To minimize the influence of beats, we recommend using narrowband noise main maskers with a bandwidth of 160 or (preferably) 320 Hz.
(7) In cases of near-normal hearing at low-frequencies, we recommend using an additional LF noise to mask SDTs.

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