Development of a fast method for determining psychophysical tuning curvesDesarrollo de un método rápido para determinar curvas psicofísicas de sintonía

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Abstract

Psychophysical tuning curves (PTCs) can be used to assess the frequency selectivity of the auditory system and to detect and delimit "dead regions" in the cochlea. However, the traditional method for determining PTCs takes too long for use in clinical practice. We evaluated a fast method for determining PTCs, using a band of noise that sweeps in centre frequency and a Békésy method to adjust the masker level required for threshold. The shapes of the PTCs were similar for the fast and traditional methods, for both normally hearing and hearing-impaired subjects. Rates of change of masker level of 2 dB/s or less gave the most reliable results. A relatively wide bandwidth (20 percent of the signal frequency or 320 Hz, whichever is the smaller) was needed to minimise the influence of beat detection. When the signal frequency fell within a dead region, the fast method gave PTCs with shifted tips.

Key Words

Psychophysical tuning curves

Dead regions

Introduction

Frequency selectivity is one of the most important properties of the auditory system. It is thought to be largely determined by the filtering that takes place on the basilar membrane, and is often modelled using the concept of the auditory filter (Fletcher, 1940; Moore, 2003). Each filter represents frequency selectivity at one centre frequency, corresponding to one specific place on the basilar membrane. Sensorineural hearing impairment, usually associated with impaired functioning of the cochlea, results in both decreased absolute sensitivity of the auditory system and reduced frequency selectivity (Pick et al, 1977; Glasberg & Moore, 1986; Moore, 1998). Thus, measurements of frequency selectivity can be used as a diagnostic tool (Zwicker & Schorn, 1978), as well as for characterizing the basic properties of the auditory system.

Frequency selectivity is usually measured in masking experiments. Two methods are in common use. One of them is the notched-noise method for determining the auditory filter shape (Patterson, 1974; 1976; Patterson & Moore, 1986; Glasberg & Moore, 1990; 2000) and the other is measurement of psychophysical tuning curves (PTCs) (Chistovich, 1957; Small, 1959; Vogten, 1974; Zwicker, 1974). To measure a PTC, the sinusoidal signal is fixed in frequency and presented at a fixed (usually low) sensation level (about 10 dB SL). A narrowband noise is usually used as the masker. For each of several masker centre frequencies, the level of the masker required just to mask the signal is determined. For normally hearing subjects, the tip of the PTC (i.e., the frequency at which the masker level is lowest) always lies close to the signal frequency (Vogten, 1974; Moore, 1978). When plotted on a logarithmic frequency scale, PTCs usually have steep slopes adjacent to the tip, and a shallower low-frequency "tail". For subjects with cochlear hearing loss, PTCs are usually broader, and sometimes lack the sharp tip (Hoekstra & Ritsma, 1977; Zwicker & Schorn, 1978; Moore & Glasberg, 1986).

In some cases of cochlear hearing loss, the inner hair cells (IHCs) and/or neurones at certain places along the basilar membrane may be completely non-functioning. Such areas are referred to as dead regions (Moore, 2001). Recently, Moore (2004) proposed a slightly different definition of a dead region, namely a region in the cochlea where IHCs and/or neurones are functioning so poorly that a tone producing peak vibration in that region is detected by off-place listening (i.e., the tone is detected at a place where the amount of basilar-membrane vibration is lower than at the peak, but the IHCs and neurones are functioning more effectively). Psychoacoustic methods for detecting dead regions are based on the concept of off-place or off-frequency listening. The extent of a dead region is defined in terms of its edge frequencies, which correspond to the characteristic frequencies (CFs) of the IHCs and/or neurones immediately adjacent to the dead region (Moore et al, 2000). Diagnosing the extent of a dead region may be important for clinical practice, since the results may be used to guide the fitting of hearing aids and to counsel the client about the likely benefit of hearing aids (Moore et al, 2000; Vickers et al, 2001; Baer et al, 2002; Moore, 2004; Mackersie et al, 2004). However, the usefulness of such diagnosis is still the subject of some debate (Rankovic, 2002; Moore, 2002; Summers, 2004).

One method for diagnosing dead regions, and determining their extent, is based upon the "TEN test" (Moore et al, 2000; 2004), which exists in two versions, called the TEN(SPL) and TEN(HL) tests. The TEN test involves measuring the threshold for detecting pure tones of various frequencies in a noise called "Threshold-Equalising Noise (TEN)". In the first version of the test (Moore et al, 2000), the TEN(SPL) was designed to produce equal masked thresholds at all frequencies (from 250 to 10000 Hz) in dB SPL. In the more recent version of the test (Moore et al, 2004), the TEN(HL) was designed to produce equal masked thresholds at all frequencies (from 500 to 4000 Hz) in dB HL. For the TEN test, a dead region at the signal frequency is indicated by a masked threshold in the TEN that is 10 dB or more higher than the TEN level/ERB_N, and at least 10 dB above the absolute threshold. ERB_N stands for the equivalent rectangular bandwidth of the auditory filter as measured in young normally hearing subjects at moderate sound levels (Glasberg & Moore, 1990; Moore, 2003). Although the TEN test is quick and easy to administer, it does not give a precise indication of the edge frequency of a dead region (Moore, 2001; Vestergaard, 2003). Also, if the signal frequency falls only just inside a dead region, that dead region may be "missed", especially when frequency selectivity is poor (Moore, 2001).

PTCs potentially provide a more accurate method for determining the frequency limits of dead regions (Thornton & Abbas, 1980; Florentine & Houtsma, 1983; Moore et al, 2000; Moore & Alcántara, 2001; Huss & Moore, 2003; Summers et al, 2003; Kluk & Moore, 2004a). When a PTC is measured for a hearing-impaired listener with a dead region, and when the frequency of the signal falls within the dead region, the tip of the PTC is shifted away from the signal frequency. When the tip of the PTC is shifted downwards in frequency, this indicates a high-frequency dead region beginning at the frequency of the shifted tip. When the tip is shifted upwards in frequency, this indicates a low-frequency dead region, whose upper boundary lies at the tip frequency of the PTC. In principle, measurement of PTCs provides a more precise method than the TEN test of estimating the edge frequency of a dead region.

The diagnosis of a dead region based on PTCs is time-consuming and the method has usually only been applied in laboratory settings. To determine a PTC for a single signal frequency it is necessary to use at least five masker frequencies, and defining the frequency of a shifted tip may require many more masker frequencies (Kluk & Moore, 2004a). This typically takes at least 2 hours, and often takes longer. Thus, PTCs measured in the traditional way are not suitable for use in routine clinical practice.

The main purpose of the present study was to develop and evaluate a fast method for determining PTCs, based on the use of a masker whose centre frequency was swept from below to above the signal frequency or vice versa. Usually a sweep range of two octaves was used. A similar method was used by Zwicker (1974) with normally hearing subjects, and by Summers et al (2003) with hearing-impaired subjects, but the effects of parameters such as the rate of change of masker level or the masker bandwidth were not determined.

It is envisaged that the initial diagnosis of possible dead regions would be based on the TEN test or TEN(HL) test. If the results of the TEN test indicate a dead region, then PTCs would be determined using the fast method to define the edge frequency of any dead region more precisely. The choice of signal frequencies would be guided by the TEN-test results, so it would be necessary to measure PTCs for only a few signal frequencies.

PTCs determined using fixed masker frequencies can be affected by the detection of beats and combination tones (especially the simple difference tone, SDT), even when a noise masker is used, as demonstrated by Kluk and Moore (2004a; 2004b). The use of a sweeping noise may help to reduce the salience of beats, since the temporal characteristics of the beats change continually as the masker sweeps. The salience of beats can also be reduced by using a relatively large masker bandwidth (Kluk & Moore, 2004a; 2004b). The effect of varying the masker bandwidth is systematically studied in this paper. The use of a sweeping masker may also help to reduce the influence of the SDT, as the subject's attention is focused on the fixed signal frequency, and the SDT is audible over only part of the sweep range of the masker. For example, when the masker frequency is an octave below the signal frequency, the SDT would fall at the masker centre frequency, and hence would not be audible.

Parameters Explored

In this section we describe our rationale for exploring various parameters that might affect the measured PTCs.

Direction of frequency sweep

A potential problem of the fast method is connected with the fact that the responses of the subject (pressing or releasing the button) lag behind the change in percept. For example, when the subject presses the button to indicate that the signal is audible, the masker level increases, and the subject then releases the button *after* the signal becomes inaudible. Because of this lag, the tip frequency of the PTC may fall above the signal frequency when the masker frequency is sweeping upwards and below the signal frequency when the signal is sweeping downwards. We refer to this as a "hysteresis" effect. To assess the magnitude of the hysteresis effect, the influence of sweep direction was systematically explored. We refer to upward frequency sweeps as "forward" sweeps, and downward sweeps as "reverse" sweeps. The hysteresis effect would be expected to be somewhat larger for slow rates of change of masker level, a parameter discussed in the next section.

Rate of change of masker level

The optimal rate of change of level of the masker depends on the balance between two competing factors. Firstly, the rate should be fast enough that the changing masker level at threshold (caused by the changing masker centre frequency) can be "followed". Secondly, the rate should not be so fast that the masker level moves well outside the range corresponding to the threshold region. To determine the optimal rate empirically, rates of change of level of 0.5, 1, 2, 4 and 8 dB/s were used.

Masker bandwidth

As described in the Introduction, PTCs can be influenced by the detection of beats, and the salience of beats as a cue varies with masker bandwidth. To reduce the influence of beats, the masker bandwidth should be relatively wide. However, if the bandwidth is too large, this may result in a broadening of the tip of the PTC, and make it hard to determine the tip frequency. The masker bandwidth was systematically varied to determine the bandwidth giving the best balance between these two competing factors.

Division of work across Poznan and Cambridge

In Poznan, the masker bandwidth was fixed at 20% of the masker centre frequency; the main parameters studied were the effect of the rate of change of masker level and the direction of the frequency sweep. In Cambridge, the effects of direction of frequency sweep and of masker bandwidth were studied, using bandwidths of 80, 160 and 320 Hz.

Method

Stimuli

For the fast method, PTCs were determined using a pure tone signal at frequency f_s and a narrowband noise masker. The signal was presented at a sensation level (SL) of 10 dB, and was pulsed on and off in a regular manner. This was done to help the subject maintain attention to the signal. Each tone pulse lasted for 500 ms (including rise and decay times of 20 ms each) and the gap between successive pulses was 200 ms. The rise and decay times were chosen to be sufficiently long to eliminate any influence of spectral splatter (Bacon & Viemeister, 1985). The centre frequency of the masker swept from f_{min} to f_{max} (=4f_{min}) for a forward sweep or from f_{max} to f_{min} for a reverse sweep, over a 4 minute period. Usually, f_{min} was chosen to be one octave below f_s, but sometimes, when pilot work indicated that the PTCs were markedly asymmetric, f_{min} was 1.5 octaves below f_s. The rate of change of the masker centre frequency was constant on a logarithmic frequency scale.

Method

The measurement method was similar to that used in Békésy audiometry. However, here the noise level required just to mask the signal was determined as a function of the masker centre frequency. The measurement of a PTC started with several pulses of the signal without the masker, so that the subject knew what to listen for. After those initial pulses, the masker was turned on with a centre frequency f_{min} or f_{max}. The starting level was 50 dB SPL for the normally hearing subjects, and 70 dB SPL for the hearing-impaired subjects. Subjects were requested to press a button when the signal was audible and to release the button when the signal was inaudible. While the button was pressed, the level of the noise increased at a rate which was chosen from the range 0.1 to 8 dB/s. When the button was released, the level decreased at the same rate. The level was changed in 0.1-dB steps.

The traditional method of determining PTCs was also used, to allow a comparison of the fast and traditional methods using the same subjects. For the traditional method, a two-alternative forced-choice (2AFC) method was usually employed, with a two-down one-up staircase procedure (Levitt, 1971). For some of the measures obtained at Cambridge a 3AFC method was used. Results were very similar for the two methods. On each trial, the masker was presented in two (or three) intervals, one of which (chosen at random) contained the signal. The subject’s task was to choose the interval that contained the signal. The level of the noise masker was increased after two successive correct responses and decreased after one incorrect response. The step size was 4 dB until four “reversals” (changes from increasing to decreasing masker level or vice versa) had occurred, and was 2 dB thereafter. Twelve reversals were obtained and the level of the masker required for threshold was calculated from the mean masker level at the last eight reversal points. The data presented below are averages of at least three separate estimates. When the standard deviation of the threshold estimates for a given masker frequency exceeded 3 dB, an extra estimate was obtained, and all estimates for that frequency were averaged.

Equipment and signal synthesis

Measurements were made in Poznan and Cambridge, using slightly different equipment, but in both cases using a Tucker Davis Technologies (TDT) system II, controlled by a PC. The masker and signal were generated using separate channels of the digital-to-analogue converter (TDT-DD1) at a sampling rate of either 25 or 32 kHz with 16-bit resolution. The signals were fed to lowpass filters with cut-off frequency of 8 kHz (TDT-PF1 or Kemo VBF8). Then, the signals were delivered to separate programmable attenuators (TDT-PA5 or PA4, used for on-line control of the masker level), a summer (TDT-SM1), and a headphone buffer (TDT-HB7 or HB5). The signals were presented monaurally via Sennheiser HD580 headphones. These were chosen because they have a broadband frequency response and low distortion. However, we believe that results for mid-range frequencies (500 to 4000 Hz) would not be markedly affected by the use of audiometric earphones such as the TDH39 or TDH49. Subjects were seated in a sound-attenuating booth.

For the fast method, the entire masker waveform was pre-synthesised, using MATLAB, and stored on the hard drive of the PC. The synthesis involved the following steps. The masker spectrum was specified in a series of time frames. Within each frame, the amplitude was specified for 2048 discrete frequency components, extending from 0 to 16000 Hz. Amplitude values were set to unity for each component within the desired passband for that frame, and were set to zero for all other components. The phase of each frequency component was randomly selected from a uniform distribution within the range 0 to 360°. The passband within each frame was chosen so that the masker centre frequency changed uniformly with time on a logarithmic frequency scale. The spectrum within each frame was converted to a time waveform using an inverse Fast Fourier Transform (FFT). Each frame resulted in a 64-ms waveform segment. The segment was windowed using a Hanning window and successive segments were overlapped by 50% (32 ms). The complete 240-s masker waveform was synthesised from 7500 segments. Prior to the start of a run, the masker waveform was retrieved from the hard drive and stored in the memory of the PC, to allow continuous replay of the waveform.

Subjects

Overall, ten normally hearing and 12 hearing-impaired subjects were tested. The hearing-impaired subjects were selected as having possible dead regions, based on the results of the TEN(SPL) or TEN(HL) tests. This paper presents only samples of the results. Audiograms of the test ears of the hearing-impaired subjects are presented in Table 1 for all subjects whose data are presented here. The Table also indicates the frequencies at which dead regions were suspected to be present, based on the TEN-test results. Ethical approval was obtained from the Cambridge Research Ethics Committee.

Results and Discussion

Correspondence between PTCs obtained using the fast and traditional methods

Examples of single measurements of PTCs obtained using the new method with normally hearing subjects are shown in Figures 1 and 2 as the jagged lines. The data in Fig. 1 were obtained in Poznan using a masker whose bandwidth was 20% of the masker centre frequency; the bandwidth was 400 Hz in this case. The data in Fig. 2 were obtained in Cambridge using a masker bandwidth of 80 Hz. The level and frequency of each signal are depicted by a filled symbol. The rate of change of masker level was 2 dB/s, because in preliminary experiments it was shown that this rate gave stable results. Forward sweeps were used in all cases. The figures also show PTCs determined using the traditional method (open symbols). As can be seen, the general shapes of the PTCs determined using the two methods are in very good agreement. These PTCs are representative of the data for all normally hearing subjects and all signal frequencies. For the data in Fig. 2, the fast PTCs mostly lie above the traditional PTCs. This was often, but not always observed, for both normally hearing and hearing-impaired subjects. It may happen because the fast method involves repeated presentation of the signal in a regular temporal pattern. This may make the signal easier to hear, requiring an increase in masker level relative to the case where the signal is presented only once during a forced-choice trial.

Smoothing the PTCs and estimating the tip frequency

The PTCs obtained using the fast method, as shown in Figures 1 and 2, are jagged, making it hard to visualise the underlying shape or to estimate the tip frequency. For diagnosing dead regions in clinical practice, the most important parameter of the PTC is the exact frequency at the tip. To provide an objective measure of the tip frequency, we have developed a numerical procedure that first smooths the PTC and then calculates the tip position based on the segments of the PTC adjacent to the minimum.

In the first step of the procedure, the raw data from each single measurement are smoothed using a two-point moving average of successive reversal points. This is illustrated in Figure 3. The thin jagged line shows a PTC determined using the fast method for a normally hearing subject. The signal frequency was 1000 Hz and the rate of change of masker level was 2 dB/s. The result of the smoothing is shown by the thicker continuous line in Figure 3. The next step is to determine the frequency at the absolute minimum of the smoothed curve. This frequency is denoted f_{Lmin}. The segments of the PTC just below and above the tip frequency can be approximated reasonably well by straight lines, although this approximation breaks down for masker frequencies well below the tip and for masker frequencies very close to the tip. Therefore, in the third step, two separate linear regression analyses are performed, one using masker frequencies in the range $0.7f_{Lmin}$ to $0.95f_{Lmin}$ and one using masker frequencies in the range $1.05f_{Lmin}$ to $1.4f_{Lmin}$. The data included in the linear regression analyses are indicated in Figure 3 by the thickest parts of the smoothed curve. The fitted regression lines are shown in Figure 3 as the thin straight lines. In the final step, the intersection point of the two fitted regression lines is determined. This intersection point provides an objective estimate of the tip frequency of the PTC. For the PTC in Figure 3, the tip frequency is 1020 Hz, which is very close to the signal frequency.

Comparison of tip frequencies for forward and reverse frequency sweeps

An example of the effect of direction of frequency sweep, obtained at Cambridge using a normally hearing subject, is shown in Figure 4; the masker bandwidth was 80 Hz and the rate of change of level was 2 dB/s. It can be seen that the tip of the PTC lies slightly above the signal frequency for the forward sweep and below the signal frequency for the reverse sweep. The example given here was chosen because it showed a particularly large effect of sweep direction, but shifts in the same direction were often found.

To quantify the effect more precisely, three normally hearing subjects were tested in Poznan, using signal frequencies of 500, 1000, 2000 and 4000 Hz. The rate of change of masker level was 2 dB/s. Three fast PTCs were obtained for each subject for each direction of frequency sweep and signal frequency. PTCs were also determined using the traditional method. Examples of the results for one subject are shown in Figures 5 and 6.

The frequency at the tip of each PTC, calculated using the procedure described above, is presented in Table 2. Averaged across the three replications, the estimated tip frequency for the forward sweep was above the signal frequency in 10 out of 12 cases; the mean tip frequency was 2% above the signal frequency. For the reverse sweep, the estimated tip frequency was below the signal frequency in 8 out of 12 cases; the mean tip frequency was 1% below the signal frequency. For every subject and every signal frequency, the mean estimated tip frequency for forward sweeps was above that for reverse sweeps.

To assess the significance of the effect of sweep direction, the estimated tip frequencies were divided by the signal frequency, and these relative estimates of tip frequency were subjected to a within-subjects analysis of variance (ANOVA) with factors sweep direction and signal frequency. Both main effects were significant: for sweep direction, $F(1,2) = 7048$, $p < 0.001$; for signal frequency, F(3,6) = 13.2, p = 0.005. The interaction was not significant.

While the hysteresis effect was significant, the effect was usually small. The estimated tip frequency was never more than 6% above the signal frequency for the forward sweeps and never more than 3% below the signal frequency for the reverse sweeps (although in Fig. 4, the upward shift was about 11%). For the data obtained in Poznan, the largest upward shift occurred for subject MR for f_s = 4000 Hz, but in that case the tip of the PTC was shifted upwards even for the reverse sweep. Comparable small shifts have been reported for traditional PTCs (Vogten, 1974; Moore, 1978). Their origin is uncertain. We conclude that the effect of hysteresis is small, and unlikely to have a material effect on the diagnosis of dead regions. However, it may be reasonable to apply a small "correction" to the estimated tip frequency to allow for the direction of the frequency sweep.

Effect of rate of change of masker level

To determine the optimal rate of change of level, three normally hearing subjects were tested in Poznan, using rates of change of level of 0.5, 1, 2, 4 and 8 dB/s and a signal frequency of 1000 Hz. The sweep was either in the forward or the reverse direction. Three fast PTCs were obtained for each subject for each rate of change of masker level. PTCs were also determined using the traditional method. Examples of the results for one subject are shown in Figures 7 and 8.

Both the "raw" fast PTCs and the smoothed PTCs became less regular as the rate of change of masker level increased. However, what is important for the present application is the extent to which the repeatability of the estimated tip frequency varies with the rate of change of masker level. To assess this, the tip frequency of each fast PTC was determined using the objective method described above. The results are shown in Table 3, which also shows the mean and standard deviation (SD) of the estimated tip frequency for each subject, each rate of change of masker level and each direction of sweep. The SD provides a measure of the repeatability of the estimates.

To assess whether the SD varied with rate of change of masker level, a within-subjects ANOVA was conducted on the SDs, with factors rate of change of masker level and direction of masker sweep. The main effect of rate of change of level was significant: F(4,8) = 4.66, p = 0.03. The main effect of sweep direction was not significant, and the interaction was not significant. The mean SDs (across subjects and sweep direction) were reasonably small (25 Hz or less) for rates of change of masker level up to 2 dB/s, but increased to 33 and 52 Hz for rates of 4 and 8 dB/s, respectively. We conclude that the rate of change should be 2 dB/s or less.

Hearing-impaired subjects usually have loudness recruitment and an associated reduced dynamic range (Fowler, 1936; Steinberg & Gardner, 1937). When assessing the effect of rate of change of masker level for hearing-impaired subjects, we found that when rates of 2 dB/s or more were used, the masker level often approached or exceeded the uncomfortably loud level. This effect was greatly reduced when the masker level changed more slowly. Hence, while the rate of 2 dB/s seems to be suitable for measuring PTCs for normally hearing subjects, rates of 0.5 or 1 dB/s are preferable for hearing-impaired subjects.

Effect of noise bandwidth

The effect of noise bandwidth was evaluated at Cambridge using masker bandwidths of 80, 160 and 320 Hz. Figure 9 shows examples of PTCs measured for a normally hearing subject, for f_S = 1000 (top panels) and 2000 Hz (bottom panels). The PTCs tend to broaden slightly with increasing noise bandwidth. Similar effects were reported by Kluk and Moore (2004a; 2004b) for PTCs determined using the traditional method. The broadening may be a consequence of two factors. Firstly, the bandwidth of the 320-Hz wide masker exceeds the "normal" bandwidth of the auditory filter for both signal frequencies and the bandwidth of the 160-Hz wide masker exceeds the bandwidth of the auditory filter at 1 kHz (Glasberg & Moore, 1990). When the bandwidth of the masker exceeds the auditory filter bandwidth, there will be a range of masker centre frequencies over which the noise power passing through the auditory filter centred at f_S hardly varies with changes in masker centre frequency; this leads to a broadened tip of the PTC.

The second factor is related to beat detection. Even when a noise masker is used, beats can provide a salient detection cue that leads to a sharpening of the tip of the PTC (Kluk & Moore, 2004a; 2004b). The salience of beats decreases with increasing masker bandwidth, and this may also contribute to the broadening of the tips of the PTCs with increasing masker bandwidth.

While the masker bandwidth has little or no effect on the tip frequencies of the PTCs for normally hearing subjects, this is not always the case for hearing-impaired subjects, especially when the signal frequency falls in a dead region. This is illustrated in Figures 10 and 11 for a subject (JR) who probably has a high-frequency dead region starting between 1000 and 1500 Hz. The subject had near-normal hearing for frequencies up to 250 Hz, and a loss that increased rapidly for frequencies above that (see Table 1). The signal frequency was 1500 Hz. Figure 10 shows results obtained using a masker bandwidth of 80 Hz. Both traditional and fast PTCs are shown. For the latter, the rate of change of masker level was either 0.5 dB/s (left panels) or 1 dB/s (right panels), and both forward sweeps (top panels) and reverse sweeps (bottom panels) were used. All of the PTCs show two tips, one close to f_S and one at about 1000 Hz. The double-tipped PTCs resemble those reported by Kluk and Moore (2004a) for similar cases. The tip around f_S probably occurs because beats can be used as a detection cue when the masker frequency is close to f_S, but beats are not available when the signal frequency equals f_S. The PTCs determined using the fast method show a less distinct local maximum in the masker level than the traditional PTC for masker frequencies around 1300 Hz, suggesting that the use of a sweeping masker reduces the effects of beat detection. However, the influence of beat detection is clearly not eliminated.

The objective method for determining the tip frequency does not always work well when the PTC has two tips. In three of the four cases shown in Fig. 10, the objective method led to an estimate of the tip frequency close to the lower of the two tips, in the region of 800-900 Hz. However, in one case (bottom left panel) the tip frequency was estimated to be 1734 Hz, as the absolute minimum value of the smoothed PTC fell close to that value. Thus, the estimate of the tip frequency can vary substantially depending on which of the two minima (tips) is deeper.

Figure 11 shows the PTCs obtained using a masker bandwidth of 320 Hz. For the traditional PTC, the tip at f_S is reduced, but not quite eliminated (The remaining tip may reflect detection of a simple difference band. Another example of this is described below). For the fast PTCs, the tip at f_S is small, or eliminated in some cases. All of the fast PTCs show a broad minimum well below f_S.

The objective estimates of the tip frequency all fall in the range 850 – 1042 Hz, consistent with a dead region starting at about 1000 Hz.

To avoid problems associated with the use of beats as a cue, it seems desirable to use as wide a masker bandwidth as possible. However, if the masker bandwidth is too wide, this may make it difficult to define the tip frequency of the PTCs. A reasonable compromise is to use a masker bandwidth of about 0.2 f_s for values of f_s up to about 1500 Hz, and to use a bandwidth of 320 Hz for values of f_s above that. This is consistent with the recommendations of Kluk and Moore (2004a) for traditional PTCs.

Further examples of PTCs for subjects with dead regions

To check whether the fast method was suitable for the diagnosis of dead regions, the method was used with several further subjects who had previously been diagnosed with dead regions based on PTCs obtained using the traditional method and/or based on the results of the TEN test (Moore et al, 2000; 2004). Generally, there was good agreement between the results of the traditional and the fast methods, and the results showed good repeatability. An example of repeatability for subject PJ is shown in Figure 12. These data were obtained using a rate of change of masker level of 1 dB/s and a masker bandwidth of 320 Hz. The signal frequency was 1500 Hz. The subject had near-normal hearing for frequencies up to 1500 Hz and a symmetrical hearing loss that increased progressively to 85 dB at 8000 Hz (see Table 1). PTCs were obtained using the fast method three times; each panel shows one of the PTCs. For this subject, the low-frequency side of the PTC had a very shallow "tail", which makes it difficult to estimate the tip frequency precisely. Hence, the tip frequencies estimated using the objective method, which are indicated in the individual panels, vary somewhat across repetitions, from 908 to 1057 Hz. However, in all cases, the estimated tip frequency is well below the signal frequency, so application of the fast method would lead to the diagnosis that the signal frequency fell in a dead region, and that the dead region started between 908 and 1057 Hz. These outcomes were consistent with results from the TEN test and from PTCs obtained with the traditional method.

Figure 13 shows examples of PTCs obtained from subject MH, who had a hearing loss that was relatively flat for medium and high frequencies (see Table 1). The left panels show PTCs determined with the traditional method and the right panels show PTCs determined with the fast method. For a signal frequency of 1900 Hz (top panels), both the traditional and fast PTCs show tips that are shifted upwards. For a signal frequency of 3000 Hz, the PTCs show no clear shift in the tip frequency. These results suggest that the subject had a restricted mid-frequency dead region, whose upper edge lay at about 2000 Hz.

In some cases of high-frequency hearing loss with good low-frequency hearing, PTCs determined using the traditional method showed two tips, even when a 320-Hz wide masker was used. An example of this was presented earlier (Fig. 11). A further example, for subject NC, is shown in Fig. 14. The signal frequency was 1000 Hz. It seems very likely that the increase in masker level for frequencies just below 1000 Hz was caused by detection of a simple difference band (Kluk & Moore, 2004a). For this subject, PTCs were determined using the fast method with forward and reverse sweeps, and with a masker bandwidth of 320 Hz. These PTCs did not show two tips, but showed a single tip that was clearly below 1000 Hz. It seems likely that the results for the PTCs determined using the fast method were not influenced by detection of the SDT, as the SDT was potentially detectable only over a small part of the sweep range of the masker, and the subject's attention remained focussed on the signal frequency throughout the sweep.

In some cases of high-frequency hearing loss, the shallow low-frequency sides of the PTCs made the tip frequency of the PTC somewhat indeterminate. This was true in the example given above (subject NC, Fig. 14). The tip frequency estimated using the objective method differed quite markedly for the forward sweep (875 Hz) and the reverse sweep (575 Hz). In a few cases, the absolute minimum in the PTC occurred for a frequency that was well away from the tip frequency of the corresponding traditional PTC, and the objective method for determining the tip frequency gave an unrealistic answer. An example, for subject MD, is shown in Fig. 15. The signal frequency was 3000 Hz. The PTC determined using the traditional method (open symbols) showed a tip at about 2700 Hz, consistent with a dead region starting at that frequency. The PTC determined using the fast method with a forward sweep and a masker bandwidth of 320 Hz also showed a tip that was shifted a little below 3000 Hz, but that tip was much less sharp than for the PTC determined with the traditional method and there was a very broad second minimum around 1500 Hz. The absolute minimum in the smoothed version of the PTC determined with the fast method (thick line without symbols) occurred for a frequency, f_{Lmin}, just above 1500 Hz. The lower of the two fitted regression lines (fitted using masker frequencies in the range $0.7f_{Lmin}$ to $0.95f_{Lmin}$) was almost horizontal, and the objective method for determining the tip frequency led to an estimate of 1178 Hz. Clearly, the results of the objective method need to be treated with caution when the low-frequency side of the PTC is very flat.

General Discussion

Our results suggest that the fast PTC measurement technique can be used for defining the edge frequency of dead regions with reasonable accuracy, except perhaps when the low-frequency side of the PTC is very flat. As described in the Introduction, we envisage that the initial diagnosis of dead regions would be done using the TEN(HL) test (Moore et al, 2004), as this takes only 4-5 minutes per ear to apply, using signal frequencies from 500 to 4000 Hz, in half-octave steps. This is the range that is of most importance for the fitting of hearing aids. If a dead region is diagnosed using the TEN(HL) test, then the fast PTC method can be used to define the edge frequency of the PTC more precisely. The most important advantage of the fast method is that it takes only 4 minutes to determine a complete PTC. Even if PTCs are measured for several signal frequencies, the total testing time should not exceed about 30 minutes.

A practical problem that remains to be solved is how to make the test generally available to the clinician. It is not possible to put the test on a compact disc (CD), as the masker level has to be adaptively controlled according to the responses of the listener, and even audiometers that incorporate Békésy tracking do not allow adaptive control of the level of external sound sources. Given that most modern audiometers have microprocessors incorporated in them, it would not be difficult to build the fast PTC test into an audiometer. We hope that it will be possible to do this in the near future. Alternatively, the method could be implemented on a PC fitted with a high-quality sound card. The main difficulty here is calibration of levels, since output levels vary widely depending on the type of sound card.

Conclusions

1. The fast method for determining PTCs proposed in this paper gives very similar results to the traditional method for measuring PTCs. For normally hearing subjects, the two methods led to very similar estimates of the slopes on the low- and high-frequency sides of the PTCs and of the positions of the tips.
2. An objective method has been developed for determining the tip frequency of a PTC measured using the fast method, based on fitting linear regression lines to limited segments of the PTC adjacent to the tip. For normally hearing subjects, the tip frequency determined using this method always lies close to the signal frequency.
3. The direction of frequency sweep of the masker has some influence on the estimated tip frequency of the PTC. The estimated tip frequency is slightly higher for forward sweeps than for reverse sweeps. The magnitude of this effect is small for normally hearing subjects, but can be appreciable for hearing-impaired subjects.
4. The standard deviation of the estimated tip frequency tends to increase with increasing rate of change of masker level. For testing hearing-impaired subjects, rates of change of 0.5 or 1 dB/s are recommended, as they lead to low variability and they reduce the likelihood of the masker becoming uncomfortably loud.
5. The detection of beats can influence the shapes of PTCs when a small bandwidth (80 Hz) is used. For subjects with dead regions, this can lead to a tip of the PTC at the signal frequency even when the signal frequency falls in a dead region. A relatively wide bandwidth (20 percent of the signal frequency or 320 Hz, whichever is the smaller) is recommended to minimise the influence of beat detection on the results.
6. For several subjects diagnosed as having dead regions using the TEN test and measurement of

traditional PTCs, the PTCs determined using the fast method showed good repeatability and were consistent with the PTCs obtained using the traditional method.

7. The fast method of determining PTCs, combined with the objective method for determining the position of the tip, may provide a useful tool for estimating the edge frequencies of dead regions in the cochlea. However, the results of the objective method should be treated with caution when the low-frequency side of the PTC is very shallow.

8. For hearing-impaired subjects with good low-frequency hearing, PTCs may be influenced by the detection of simple difference bands. However, this influence appears to be less pronounced for the fast method than for the traditional method. In such cases, it is advisable to add a low-level lowpass noise to the sweeping masker, as proposed by Kluk and Moore (2004a) for traditional PTCs.

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Table 1. Absolute thresholds of the test ears of the hearing-impaired subjects, in dB HL. An asterisk indicates frequencies for which the TEN test suggested the presence of a dead region. 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.

			Frequency, kHz								
Subject	Ear	Age	0.25	0.5	1.0	1.5	2.0	3.0	4.0	6.0	8.0
MD	R	67	10	10	25	25	25	55*	70*	65*	80*
NC	L	80	20	25	35*	60*	70*	95*	↑*	↑*	↑*
PJ	L	74	20	20	40*	55*	65	65*	65*	75*	85*
JR	L	22	20	50	60	72*	86*	104*	100*	↑*	↑*
MH	R	27	35	40	55	60*	65	60	60	65	70

Table 2. Tip frequencies (Hz) of PTCs estimated using the objective method. For each subject and each signal frequency (f_s), a fast PTC was measured three times using a forward sweep and three times using a reverse sweep. The table shows the estimated tip frequency for each repetition, and for the mean of the three.

	Subject	f_s	Rep1	Rep2	Rep3	Mean
Forward	TS	500	489	478	542	503
		1000	999	997	1059	1018
		2000	2139	2060	2023	2074
		4000	4268	4185	4014	4155
Forward	MR	500	498	503	496	499
		1000	1034	1020	1025	1026
		2000	2044	2033	2041	2039
		4000	4231	4197	4230	4219
Forward	AW	500	503	515	493	503
		1000	979	976	993	982
		2000	2040	2005	2019	2021
		4000	4215	4296	4079	4196
Reverse	TS	500	504	486	486	492
		1000	1008	977	1040	1008
		2000	1936	1992	1992	1973
		4000	4059	4034	4073	4055
Reverse	MR	500	494	496	490	493
		1000	995	985	1001	993
		2000	1976	2015	1986	1992
		4000	4053	4075	4084	4070
Reverse	AW	500	482	483	480	481
		1000	980	986	967	977
		2000	1994	1980	1979	1984
		4000	4053	4063	3973	4029

Table 3. Tip frequencies (Hz) of PTCs estimated using the objective method. The signal frequency was 1000 Hz. For each subject and each rate of change of masker level, a fast PTC was measured three times using a forward sweep and three times using a reverse sweep. The table shows the estimated tip frequency for each repetition, and also shows the mean and standard deviation (SD) of the three.

	Subject	Rate, dB/s	Rep1	Rep2	Rep3	Mean	SD
Forward	TS	0.5	1068	1105	1029	1067	38.0
		1.0	939	947	1104	996	93.0
		2.0	999	997	1059	1018	35.2
		4.0	881	919	1047	949	87.0
		8.0	1243	1104	966	1104	138.5
Forward	MR	0.5	1035	1044	1042	1040	4.7
		1.0	1027	1022	1042	1030	10.4
		2.0	1034	1020	1025	1026	7.1
		4.0	1030	1032	1048	1036	9.9
		8.0	1008	1041	1017	1022	17.1
Forward	AW	0.5	936	985	974	965	25.7
		1.0	971	970	994	978	13.6
		2.0	979	976	993	982	9.1
		4.0	1008	996	1010	1004	7.6
		8.0	905	968	972	948	37.6
Reverse	TS	0.5	990	971	994	985	12.3
		1.0	992	1007	976	991	15.5
		2.0	1008	977	1040	1008	31.5
		4.0	1030	1021	938	996	50.7
		8.0	1056	1012	1038	1035	22.1
Reverse	MR	0.5	977	989	993	986	8.3
		1.0	991	998	1020	1003	15.1
		2.0	995	985	1001	993	8.1
		4.0	966	967	938	957	16.4
		8.0	1099	931	1013	1014	84.0
Reverse	AW	0.5	967	962	980	969	9.3
		1.0	965	968	972	968	3.5
		2.0	980	986	967	977	9.7
		4.0	999	984	945	976	27.9
		8.0	993	975	972	980	11.4

Figure 1. Example of a PTC determined using the fast method (jagged line) and the traditional method (circles) for a normally hearing subject tested in Poznan, using a signal frequency of 2000 Hz. The filled star indicates the signal level and frequency.

Figure 2. As Figure 2, but for a subject tested in Cambridge using signal frequencies of 1000 and 2000 Hz. The filled symbols indicate the signal level and frequency.

Figure 3. Illustration of the objective procedure for calculating the tip frequency of a PTC determined using the fast method. The thin jagged line shows the “raw” PTC. The smoother line is a two-point running average of successive reversal points in the raw PTC. The thicker parts of this line indicate the two regions used to fit linear regression lines. The intersection point of these lines gives the estimated tip frequency. The open circles show a PTC determined using the traditional method, for comparison.

Figure 4. Examples of fast PTCs obtained using forward frequency sweeps (masker sweeping upwards in frequency) and reverse sweeps (masker sweeping downwards). The faint lines show the fast PTCs, and the bold lines show the PTCs smoothed using a two-point running average, as described in the text. The signal frequency was 1000 Hz.

Figure 5. Examples of fast PTCs obtained using forward frequency sweeps for signal frequencies of 500, 1000, 2000 and 4000 Hz. The open circles show PTCs determined using the traditional method.

Figure 6. As Figure 5, but for reverse frequency sweeps.

Figure 7. The jagged lines show fast PTCs obtained for various rates of change of masker level (0.5 to 8 dB/s) using forward frequency sweeps and a signal frequency of 1000 Hz. The bold lines show the smoothed PTCs. Open circles indicate the PTC obtained using the traditional method.

Figure 8. As Figure 7, but for reverse sweeps.

Figure 9. Effect of masker bandwidth on PTCs determined using the fast method, for a normally hearing subject. The masker bandwidth was 80 Hz (left), 160 Hz (middle) or 320 Hz (right). The signal frequency was 1000 Hz (top) or 2000 Hz (bottom).

Figure 10. Comparison of PTCs obtained using the fast method (jagged lines) and traditional

method (open circles) for a subject with a high-frequency dead region. The rate of change of masker level was 0.5 dB/s (left) or 1 dB/s (right), and the sweep direction was either forward (top) or reverse (bottom). The signal frequency was 1500 Hz and the masker bandwidth was 80 Hz.

Figure 11. As Figure 10, but with the masker bandwidth increased to 320 Hz.

Figure 12. Illustration of the repeatability of fast PTCs for a subject with a high-frequency dead region. The panels show three fast PTCs, all obtained under the same conditions. The masker bandwidth was 320 Hz. The tip frequency estimated using the objective method is shown in each panel.

Figure 13. PTCs obtained using the traditional method (left) and the fast method (right) for a subject with a mid-frequency dead region. When the signal frequency was 1900 Hz, the tip frequency of the PTC was shifted upwards, for both methods. When the tip frequency was 3000 Hz, the tip was not markedly shifted, for either method.

Figure 14. PTCs obtained using the traditional method (open symbols, PTC repeated in each panel) and using the fast method with forward (left panel) and reverse (right panel) sweeps, for subject NC. The signal frequency was 1000 Hz and the masker bandwidth was 320 Hz. The double tip of the traditional PTC was probably caused by detection of a simple difference band. The fast PTCs show only a single broad tip.

Figure 15. Illustration of the difficulty in estimating the tip frequency when the low-frequency side of the PTC is very flat. PTCs were obtained using the traditional method (open symbols) and using the fast method with a forward sweep, for subject MD. The signal frequency was 3000 Hz and the masker bandwidth was 320 Hz.

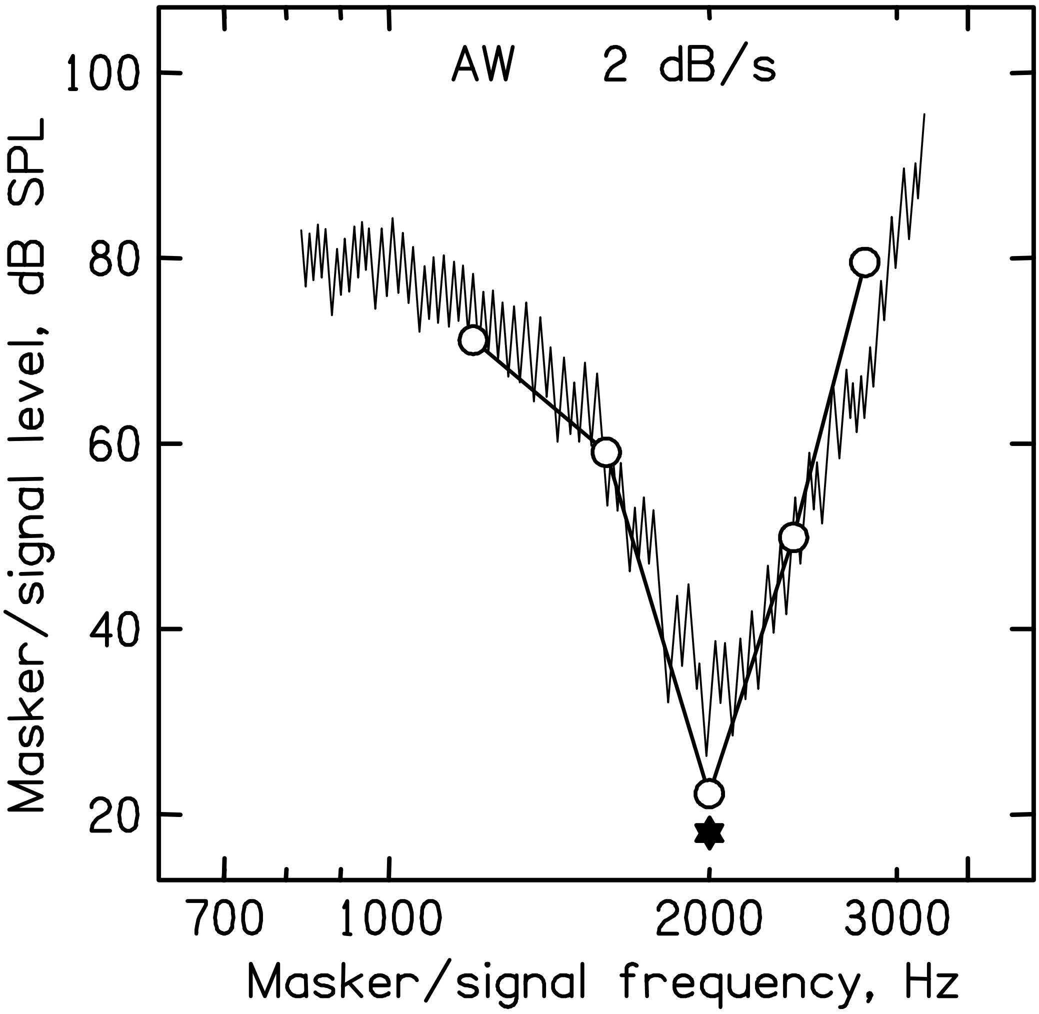

AW 2 dB/s
Masker/signal level, dB SPL
100
80
60
40
20
700
1000
2000
3000
Masker/signal frequency, Hz

Figure 1

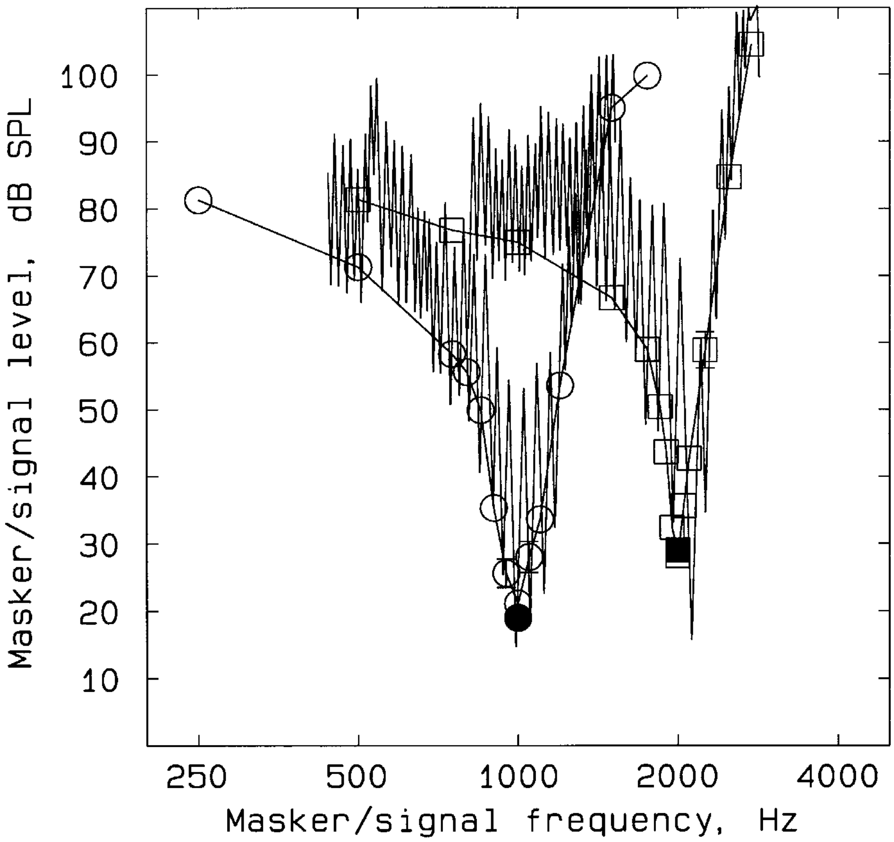

Masker/signal level, dB SPL
100
90
80
70
60
50
40
30
20
10
250
500
1000
2000
4000
Masker/signal frequency, Hz

Figure 2

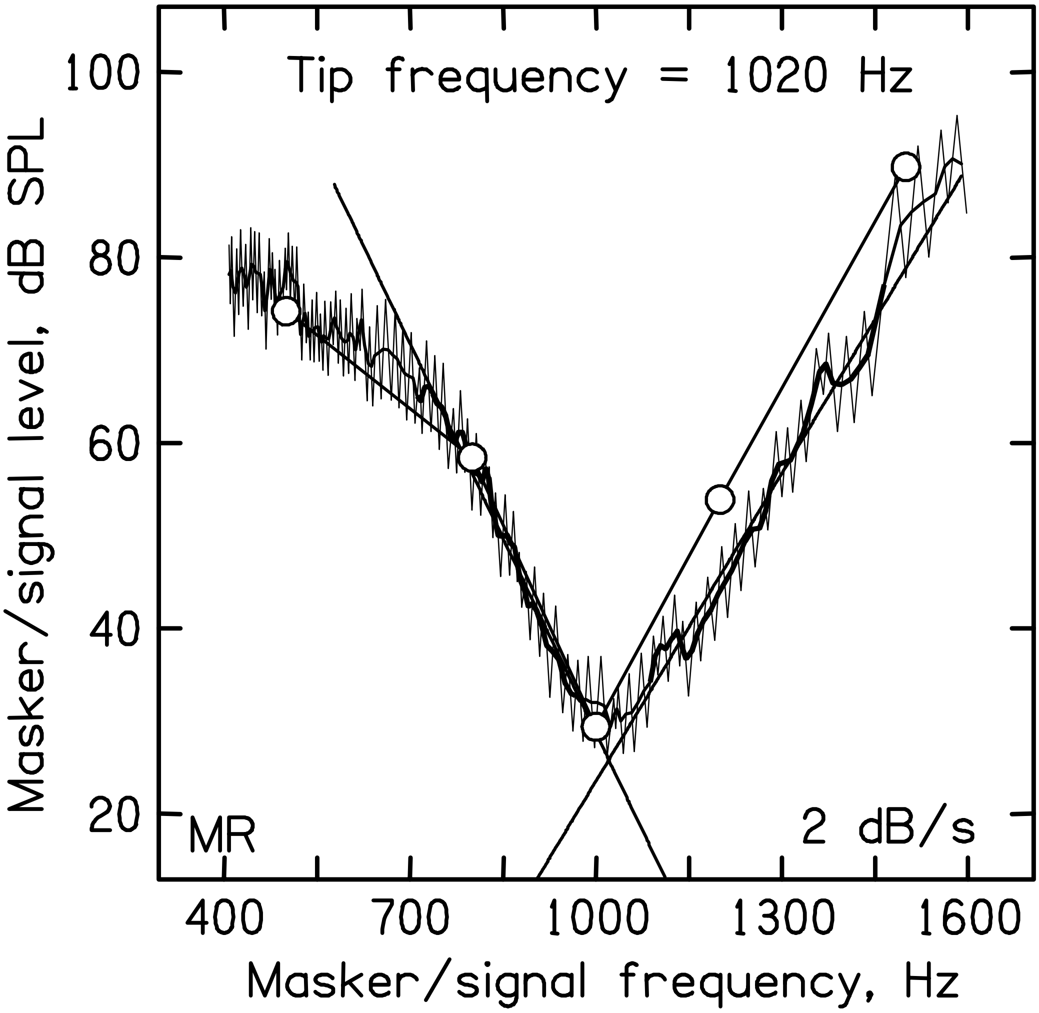

Tip frequency = 1020 Hz
Masker/signal level, dB SPL
100
80
60
40
20
MR
2 dB/s
400
700
1000
1300
1600
Masker/signal frequency, Hz

Figure 3

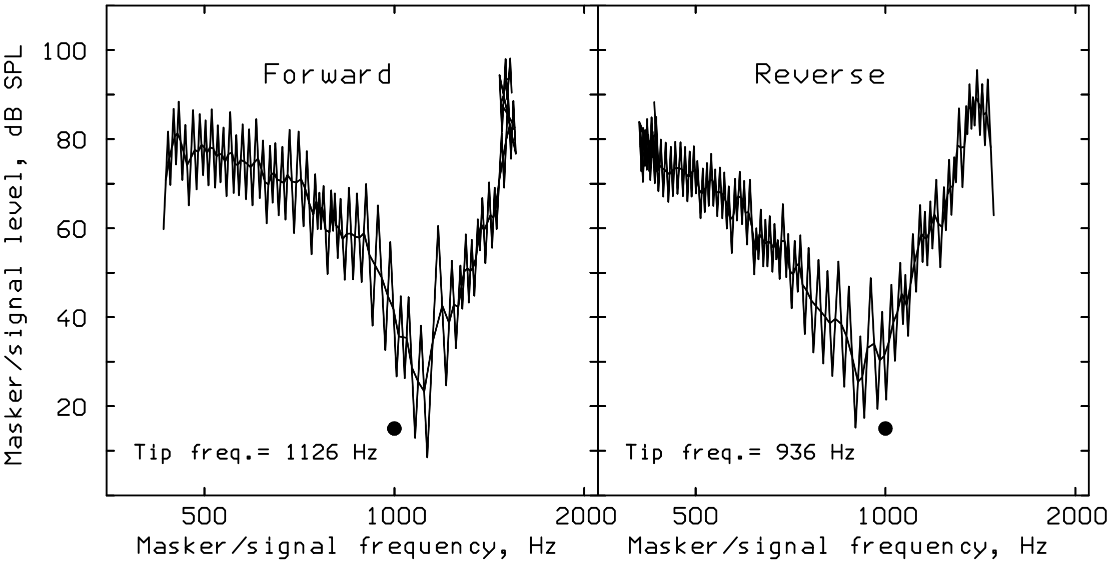

Forward
Reverse
Masker/signal level, dB SPL
100
80
60
40
20
Tip freq.= 1126 Hz
Tip freq.= 936 Hz
500
1000
2000
Masker/signal frequency, Hz
Masker/signal frequency, Hz

Figure 4

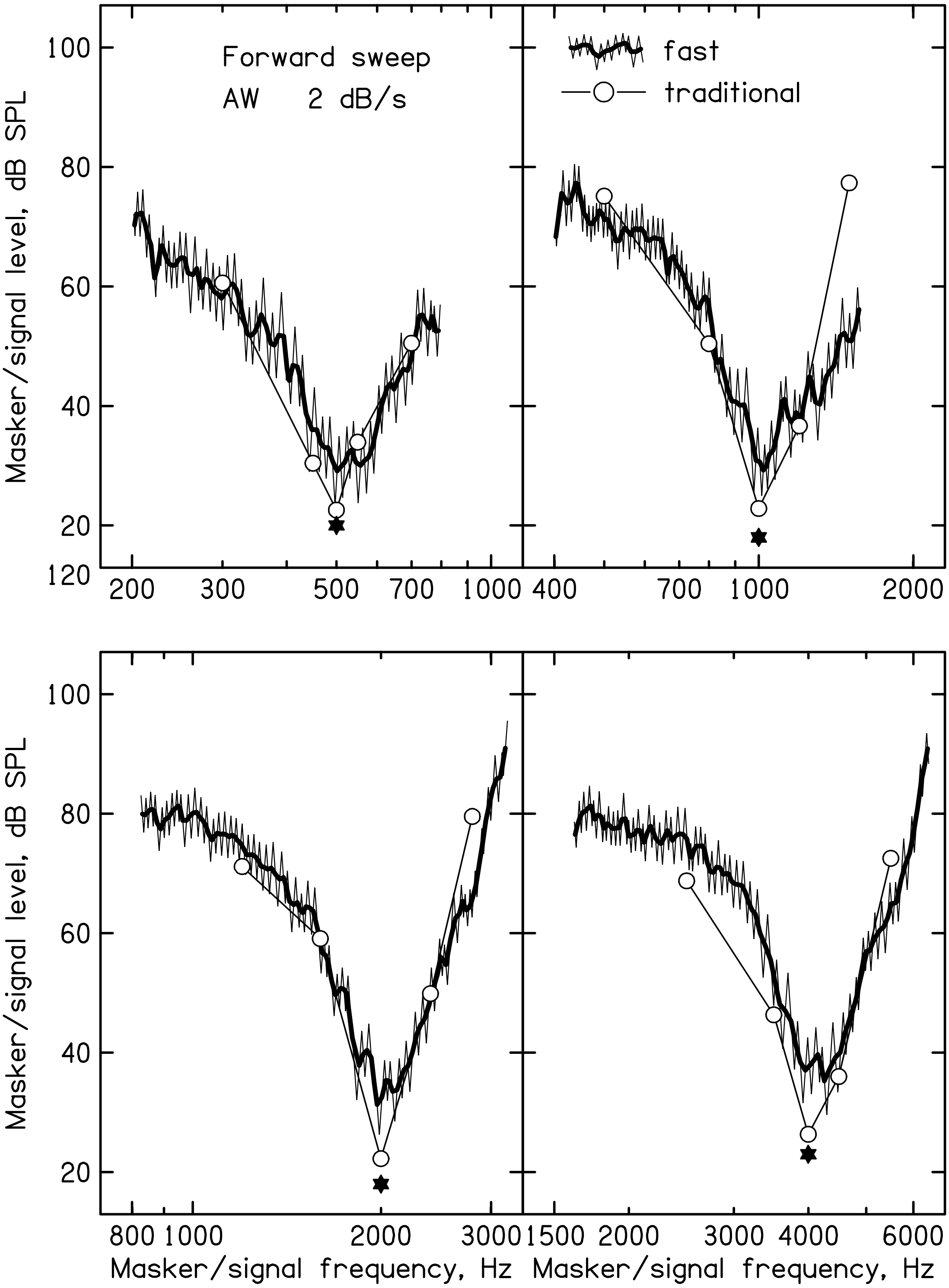

Forward sweep
AW 2 dB/s
fast
traditional
Masker/signal level, dB SPL
100
80
60
40
20
120
200 300 500 700 1000
400 700 1000 2000
800 1000 2000 3000
1500 2000 3000 4000 6000
Masker/signal frequency, Hz

Figure 5

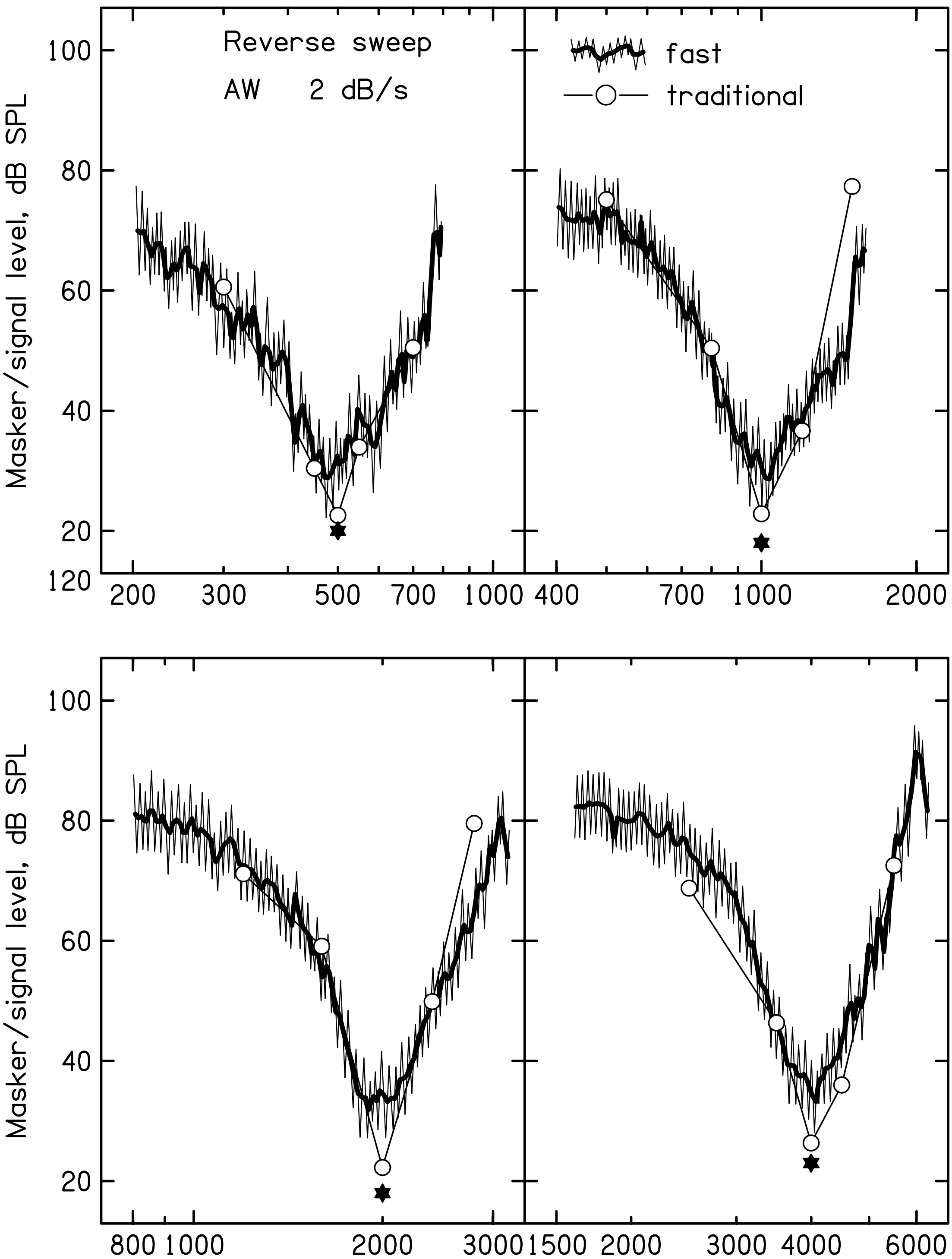

Reverse sweep
AW 2 dB/s
fast
traditional
Masker/signal level, dB SPL
100
80
60
40
20
120
200
300
500
700
1000
400
700
1000
2000
800 1000
2000
3000
1500 2000
3000 4000
6000
Masker/signal frequency, Hz
Masker/signal frequency, Hz

Figure 6

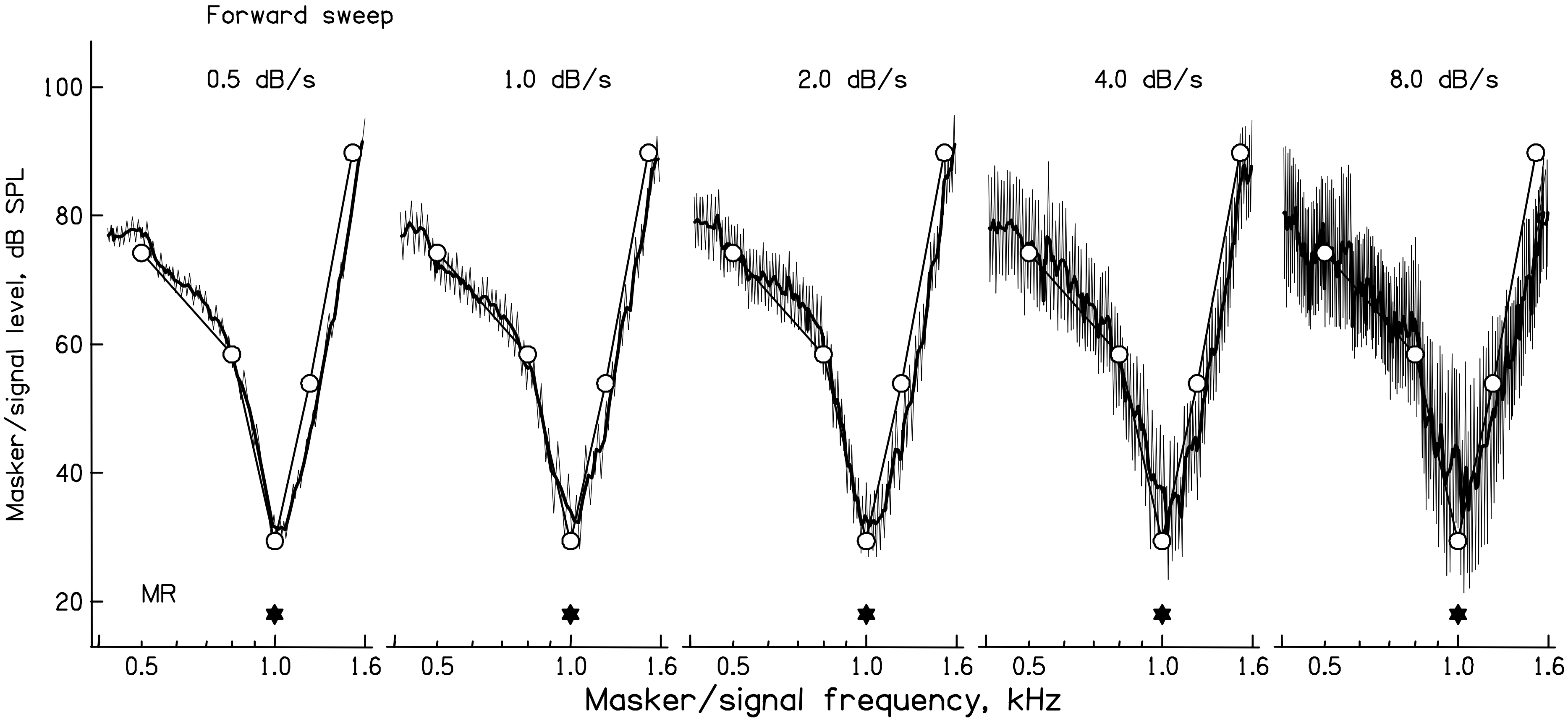
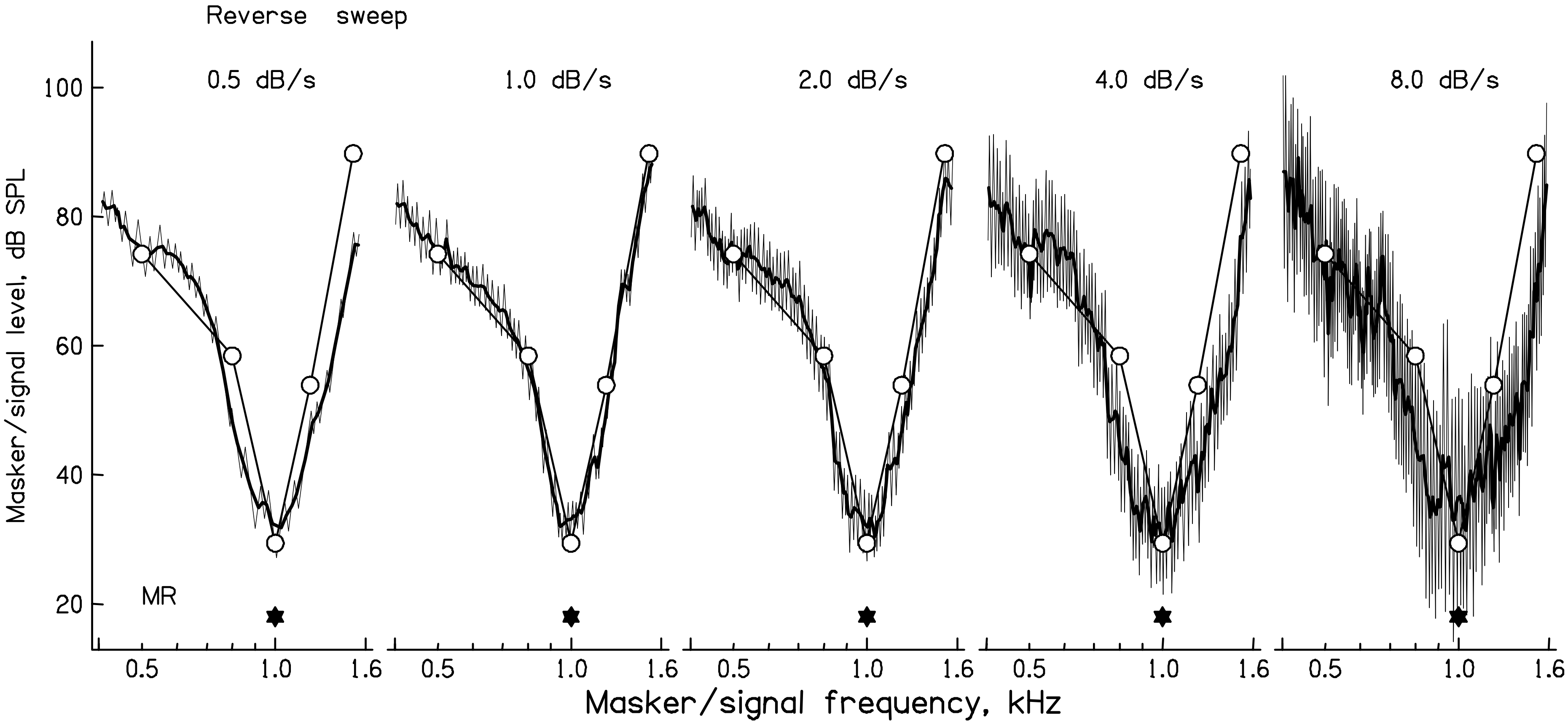

Forward sweep
0.5 dB/s
1.0 dB/s
2.0 dB/s
4.0 dB/s
8.0 dB/s
Masker/signal level, dB SPL
100
80
60
40
20
MR
0.5
1.0
1.6
Masker/signal frequency, kHz

Figure 7



Reverse sweep
0.5 dB/s
1.0 dB/s
2.0 dB/s
4.0 dB/s
8.0 dB/s
Masker/signal level, dB SPL
100
80
60
40
20
MR
0.5
1.0
1.6
Masker/signal frequency, kHz

Figure 8

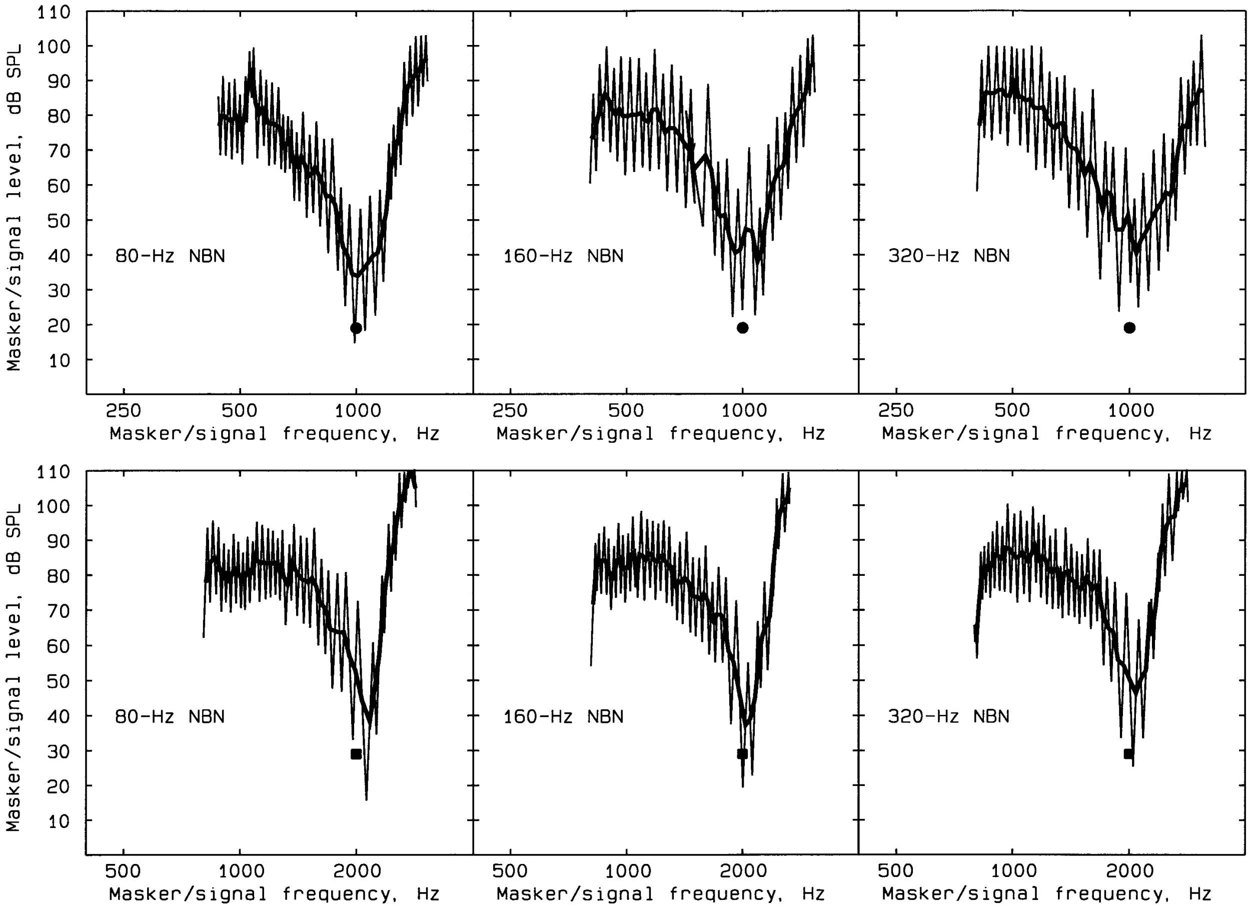
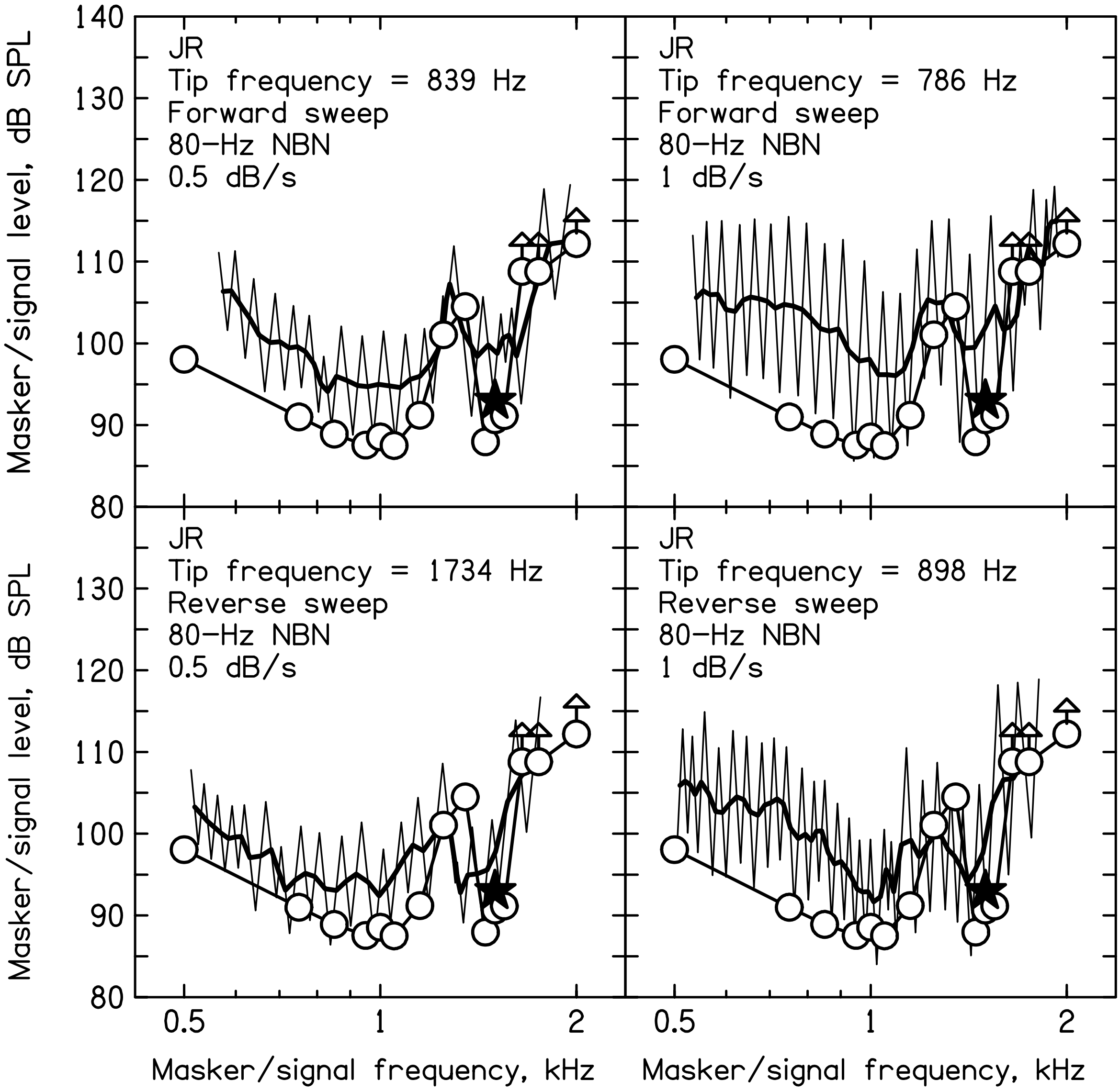

Masker/signal level, dB SPL
110
100
90
80
70
60
50
40
30
20
10
80-Hz NBN
160-Hz NBN
320-Hz NBN
250
500
1000
Masker/signal frequency, Hz
2000

Figure 9



140
130
120
110
100
90
80
Masker/signal level, dB SPL
JR
Tip frequency = 839 Hz
Forward sweep
80-Hz NBN
0.5 dB/s
JR
Tip frequency = 786 Hz
Forward sweep
80-Hz NBN
1 dB/s
JR
Tip frequency = 1734 Hz
Reverse sweep
80-Hz NBN
0.5 dB/s
JR
Tip frequency = 898 Hz
Reverse sweep
80-Hz NBN
1 dB/s
0.5
1
2
Masker/signal frequency, kHz

Figure 10

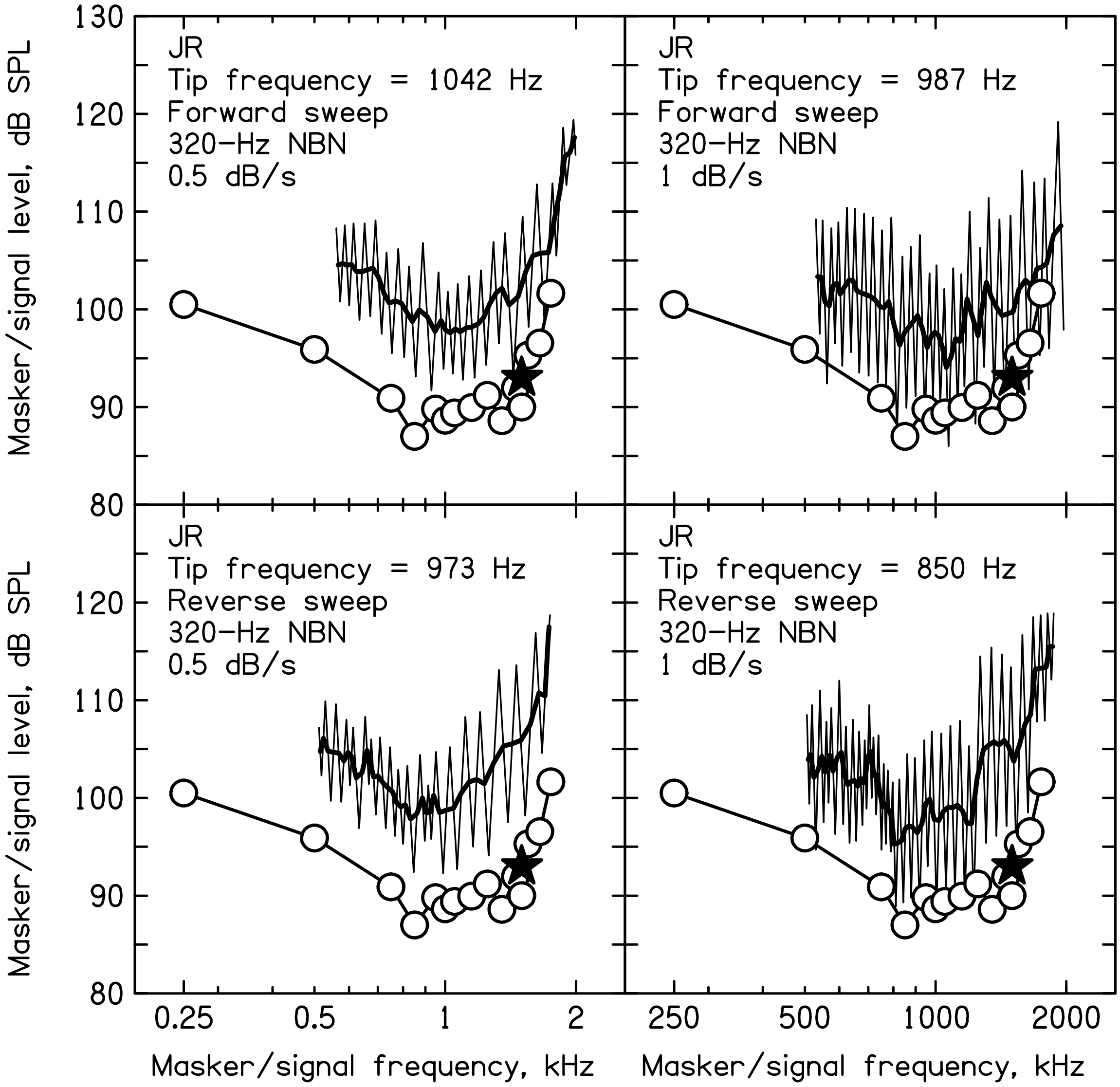

JR
Tip frequency = 1042 Hz
Forward sweep
320-Hz NBN
0.5 dB/s
JR
Tip frequency = 987 Hz
Forward sweep
320-Hz NBN
1 dB/s
JR
Tip frequency = 973 Hz
Reverse sweep
320-Hz NBN
0.5 dB/s
JR
Tip frequency = 850 Hz
Reverse sweep
320-Hz NBN
1 dB/s
Masker/signal level, dB SPL
80
90
100
110
120
130
0.25
0.5
1
2
250
500
1000
2000
Masker/signal frequency, kHz
Masker/signal frequency, kHz

Figure 11

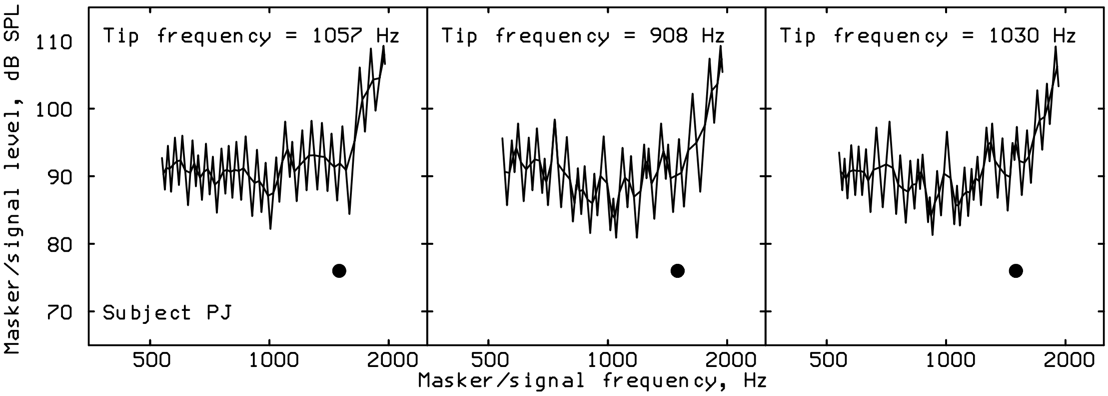

Tip frequency = 1057 Hz
Tip frequency = 908 Hz
Tip frequency = 1030 Hz
Subject PJ
Masker/signal level, dB SPL
110
100
90
80
70
500
1000
2000
Masker/signal frequency, Hz

Figure 12

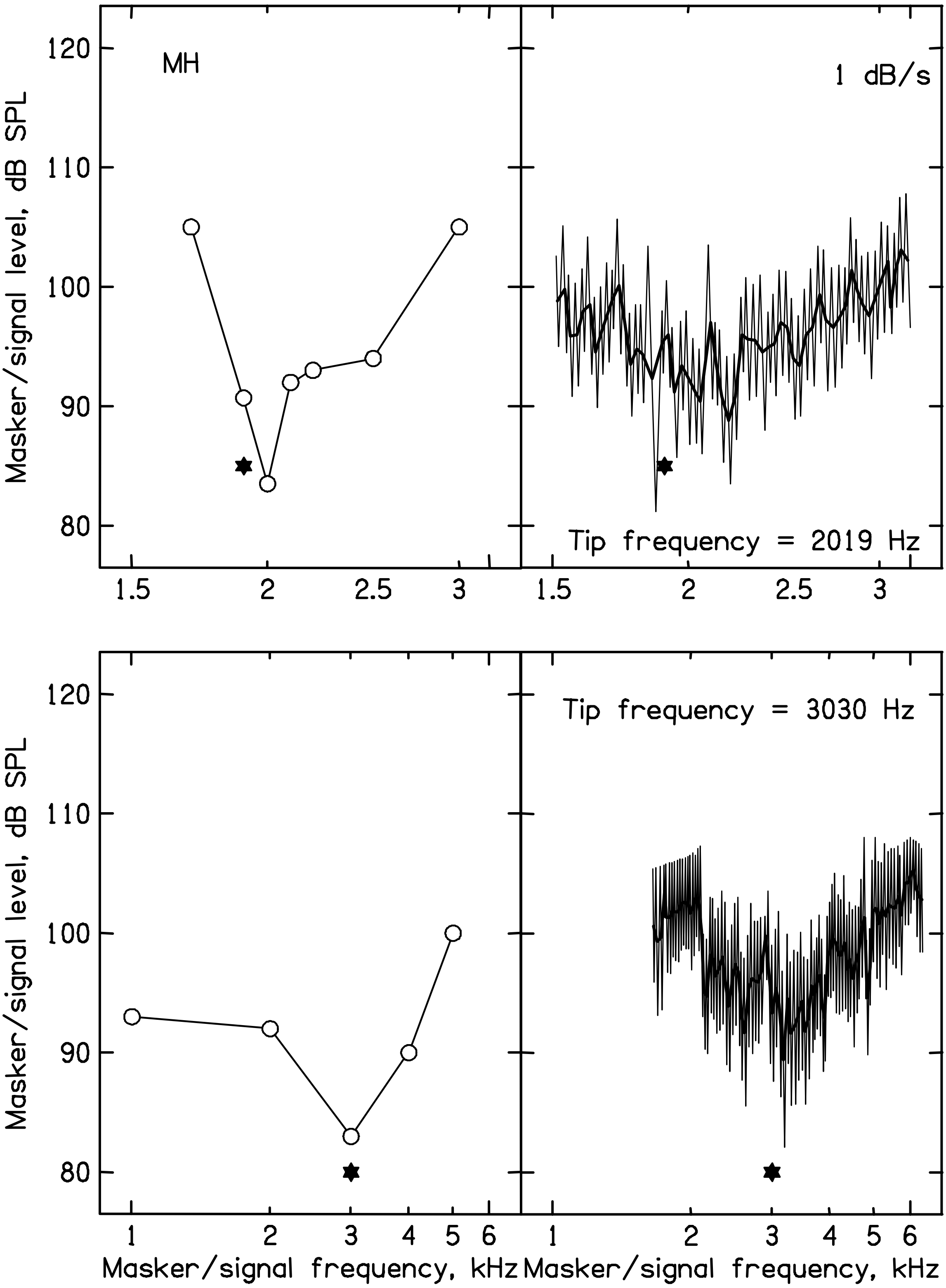

MH
1 dB/s
Tip frequency = 2019 Hz
Tip frequency = 3030 Hz
Masker/signal level, dB SPL
120
110
100
90
80
1.5
2
2.5
3
1
4
5
6
Masker/signal frequency, kHz

Figure 13

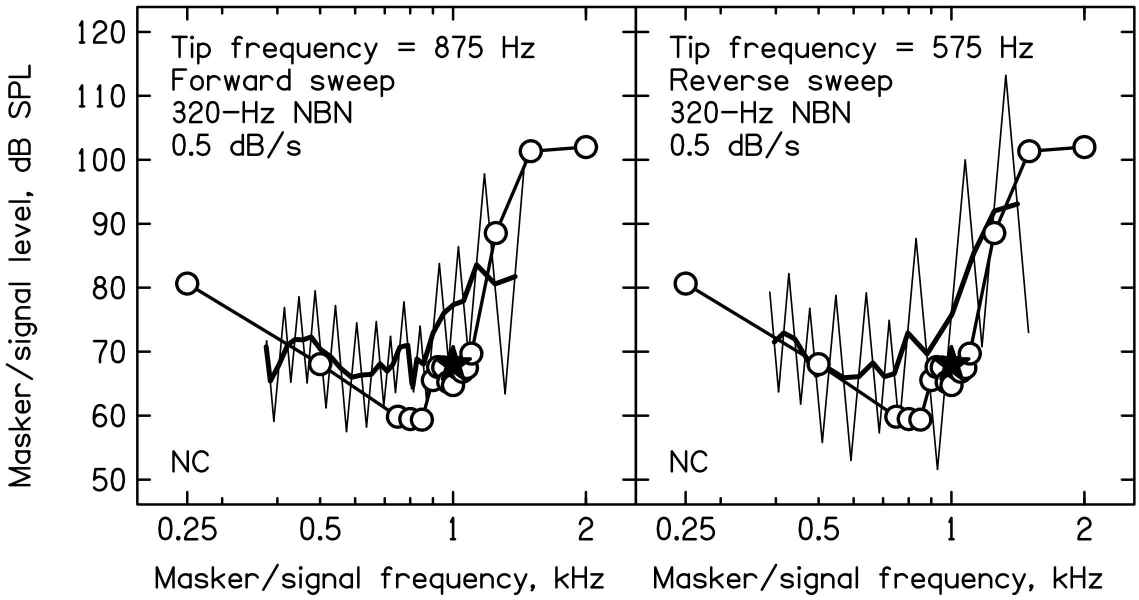

Tip frequency = 875 Hz
Forward sweep
320-Hz NBN
0.5 dB/s
NC
Tip frequency = 575 Hz
Reverse sweep
320-Hz NBN
0.5 dB/s
NC
Masker/signal level, dB SPL
120
110
100
90
80
70
60
50
0.25
0.5
1
2
Masker/signal frequency, kHz
Masker/signal frequency, kHz

Figure 14

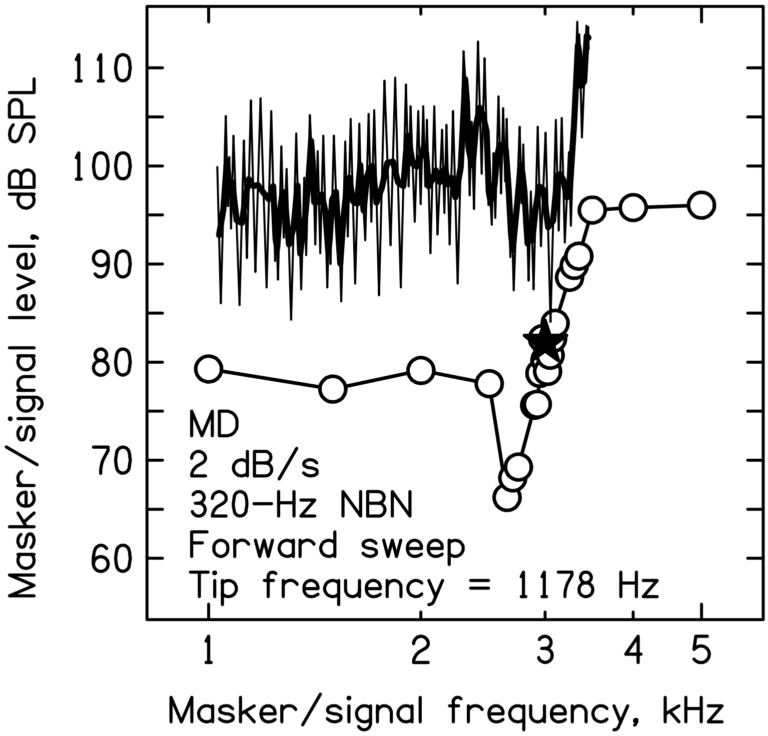

110
100
90
80
70
60
Masker/signal level, dB SPL
MD
2 dB/s
320-Hz NBN
Forward sweep
Tip frequency = 1178 Hz
1
2
3
4
5
Masker/signal frequency, kHz

Figure 15