International Journal of Audiology 2013; 52: 596–605

informa
healthcare

Original Article

Acquisition of auditory profiles for good and impaired hearing

Wendy Lecluyse*,†, Christine M. Tan†, Don McFerran‡ & Ray Meddis†

*School of Applied Social Sciences, University Campus Suffolk, Ipswich, UK, †Department of Psychology, University of Essex, Colchester, UK, and ‡ENT-department, Colchester Hospital University NHS Foundation Trust, Essex County Hospital, Colchester, UK

Abstract

Objective: The aim of this study was to develop a user-friendly way of measuring patients' threshold and supra-threshold hearing, with potential for application in clinical research. The end-product of these tests is a graphical profile summarizing absolute threshold, frequency selectivity, and compression characteristics across a spectrum of frequencies (0.25–6 kHz). *Design:* A battery of three psychophysical hearing tests consisted of measures of absolute threshold, frequency selectivity, and compression. An automated, cued, single-interval, adaptive tracking procedure was employed. The tests results were collated and used to generate a readily visualized 'profile' for each listener. *Study sample:* Participants were 83 adults (57 impaired-hearing and 26 good-hearing, age 20–75 years). *Results:* Listeners tolerated the tests well. Single-ear profiles were obtained in an average of 74 minutes testing time (range 46–120 minutes). The variability of individual measurements was low. Substantial differences between normal and impaired listeners and also among the impaired listeners were observed. Qualitative differences in compression and frequency-selectivity were seen that could not be predicted by threshold measurements alone. *Conclusions:* The hearing profiles are informative with respect to supra-threshold hearing performance and the information is easily accessible through the graphical display. Further development is required for routine use in a clinical context.

Key Words: Auditory profiles; supra-threshold measurements; normal and impaired hearing

We report a new testing procedure designed to identify individual differences in basic aspects of hearing in both normal and hearing-impaired populations. It consists of three subtests measuring sensitivity, compression and frequency selectivity. The tests are based on existing clinical or laboratory procedures but are automated and adapted to speed up data acquisition and ease of use with individuals experiencing hearing problems. The adaptations include the use of single-interval procedures and a simple, user-friendly, cued counting task. The purpose of the tests is to collect data across the audible frequency range in a single session and to present this graphically as an 'auditory profile' giving an overall impression of any deficits. The tests are described and some examples given of the range of profiles that are produced.

Currently, the pure-tone audiogram is the main source of information available to the clinician. Two recent studies have argued in favour of collecting more information about a patient's hearing abilities in order to gain a deeper understanding of the nature of the individual's impairment (Vlaming et al, 2011; Jepsen & Dau, 2011). Vlaming and colleagues (2011) describe a range of tests that sample a variety of different auditory capabilities, including measures of loudness perception, listening effort, speech perception, spectral and temporal resolution, spatial hearing, subjective judgment, and cognition. Jepsen & Dau (2011), on the other hand, use a smaller range of measures concentrating on sensitivity, cochlear compression, frequency selectivity, temporal resolution, and intensity discrimination. The narrower scope of the Jepsen and Dau study reflects their interest in the use of psychophysical measures to indicate underlying pathology of the auditory periphery such as inner and outer hair cell dysfunction.

The tests described below follow their lead in this respect although the range of tests is restricted even more narrowly to sensitivity, frequency selectivity, and compression. Measurement time is an important constraint when creating profiles because of the amount of data to be acquired, even when restricting the effort to only three measures. For this reason, considerable attention was given to finding procedures that were easy to learn and quick to administer. This endeavour is in the same spirit as a study by Sek and Moore (2011) who have published a fast method for estimating psychophysical tuning curves.

The nature of the tests was modelled on procedures developed in a series of laboratory studies of compression and frequency selectivity using forward-masking paradigms (for instance Houtgast, 1972; Moore, 1978; Nelson et al, 1990, 2001; Lopez-Poveda et al, 2003, 2005; Plack et al, 2004; Rosengard et al, 2005). However, such procedures can be very time-consuming (Sek et al, 2005) and may be too difficult for some elderly patients. A systematic assessment across all frequency regions could require many hours of measurement.

A central target of the current study was therefore to automate the testing, minimize the number of measurements and to make the

Correspondence: Wendy Lecluyse, School of Applied Social Sciences, University Campus Suffolk, Waterfront Building, Ipswich, IP4 1QJ, UK, E-mail: w.lecluyse@ucs.ac.uk

(Received 19 April 2012; accepted 12 April 2013)

ISSN 1499-2027 print/ISSN 1708-8186 online
DOI: 10.3109/14992027.2013.796530

Abbreviations

dB SPL	Decibel sound pressure level
f_m	Masker frequency
f_t	Probe frequency
GUI	Graphical user interface
IFMC	Iso forward masking contour
SIUD	Single interval up/down procedure
TMC	Temporal masking curve

tests as easy to use as possible from the patient's point of view. The procedures to be described allow a complete assessment of a single ear across five frequencies to be completed within two hours. The increase in speed is largely due to a combination of automation and the adoption of a simple counting task to elicit the patient's response. Special cues are also used to orient the listener with respect to the timing and frequency composition of the test tones. Further increases in speed come from the use of a single-interval adaptive tracking procedures to estimate thresholds. While single-interval procedures are in common use in a clinical setting, they are rarely used in laboratory work where multi-interval forced choice techniques are widely preferred. We were encouraged to adopt a single-interval approach because we found at an early stage that this procedure was much preferred by our listeners, was faster to use and required much less training. While experimentalists may have concerns about possible criterion shifts when using this method, our investigations published elsewhere (Lecluyse & Meddis, 2009) suggest that this may not be an important issue in this context.

A complete test on a single ear yields a considerable amount of information and produces a challenge in terms of how to visualize the information and gain an overall impression of a person's hearing. The proposed solution, by analogy with the audiogram, is to create a visualized 'auditory profile' showing all results in a single display.

Profiles will be illustrated by drawing on a database of profiles accumulated over a period of four years. Some of the profiles were collected while perfecting and evaluating the testing procedures. Others were collected in the context of a tinnitus study (Tan et al, 2013).

Methods

Participants

Hearing profiles were collected from 83 listeners: of whom 26 had good hearing (15 male, 11 female) and 57 had impaired hearing (37 male, 20 female). The mean age of the listeners with good hearing was 31.6 (SD = 10.2, ranging from 20–61 years old). All had normal hearing determined by standard clinical measurements and thresholds better than 20 dB HL at all test frequencies. The mean age of the impaired listeners was 59.2 (SD = 11.0, ranging from 30–75 years old). All had a sensorineural hearing loss, with thresholds worse than 20 dB HL at one or more test frequencies. Participants were recruited by advertising on the University of Essex campus and at two audiology clinics. Ethical approval was obtained from the University of Essex Ethics Committee. Informed consent was obtained from all participants.

Equipment

The tests were carried out in a double-walled sound-attenuated booth. Stimuli were presented through circumaural headphones (Sennheiser HD600) linked directly to a computer sound card (Audiophile 2496, 24-bit, 96-kHz sampling rate). The procedures were automated using a MATLAB computer program[1]. Participants were equipped with a small console with four buttons. A computer monitor in front of the participant showed a graphical user interface (GUI) display of the button console. While the stimulus was presented, the button symbols on the display disappeared. Immediately after stimulus presentation the buttons reappeared on the screen, signalling that a response was required.

Procedure and stimuli

Figure 1 gives a schematic representation of the three measurement procedures. All stimuli were pure tones, ramped with raised cosine onset and offset times of 4 ms.

Absolute thresholds were assessed using a simple probe-detection task (Figure 1A). These thresholds were measured using 250-ms pure tones at frequencies (f_t) 0.25, 0.5, 1, 2, 4, and 6 kHz. Next, absolute thresholds for 16-ms tones were measured at the same frequencies and these thresholds were used as the basis for the probe-tone levels in the forward masking tasks described immediately below.

Frequency selectivity was assessed using a forward-masking task, consisting of a 108-ms masking tone followed by a 16-ms probe tone presented at 10 dB above its own (16-ms) threshold, with a masker-probe gap of 10 ms (see Figure 1B). A forward-masking task identifies the quietest masking tone still capable of preventing the detection of the probe tone. Listeners were reporting whether or not they heard the probe tone.

The masker level was varied adaptively between trials to identify the masked threshold. Between threshold measurements, the masker frequency was varied relative to the probe frequency to produce an iso-forward masking contour (IFMC). Masked thresholds were measured at seven different masker frequencies (f_m) specified relative to the probe frequency f_t, where $f_m = 0.5, 0.7, 0.9, 1, 1.1, 1.3$, and $1.6 \times f_t$ (cf. Lopez-Poveda et al, 2003). Masker frequencies were presented in random order between runs. IFMCs were determined for *probe* frequencies, 0.5, 1, 2, 4, and 6 kHz, and, for some participants, at 0.25 kHz.

Compression was also assessed using a forward-masking task consisting of a 108-ms masking tone followed by a 16-ms probe tone presented at 10 dB above its own threshold (Figure 1C). In this case, however, the gap between the masker and the probe was varied between measurements while the masker frequency was held constant. Gaps used were 20, 40, 50, 60, and 80 ms. Masker-probe gaps were presented in random order between runs. The five resulting masked thresholds generated a temporal masking curve (TMC). In Figure 1C the steepness of the slope is commonly taken to reflect the amount of compression present because compression of the masker will result in larger increases in the masker level as the gap increases between masker and probe. TMCs were determined for a range of *probe* frequencies, usually 0.5, 1, 2, 4, and 6 kHz, and, for some participants, at 0.25 kHz.

The task was made more user-friendly by the *use of cues*. All stimuli (probe alone or masker-probe tone combinations) were preceded by cue stimuli (grey shading in Figure 1). These were identical to the test stimuli in all respects except for a single difference arranged so that the cue tone/probe was always more audible in the cue stimulus compared to the test tone/probe in the test stimulus. For *absolute threshold* measurements, the cue tone was always 10 dB more intense than the test tone (Figure 1A). For *frequency selectivity and compression measures*, the cue masker was always 10 dB less intense than the test masker (Figure 1B and C)

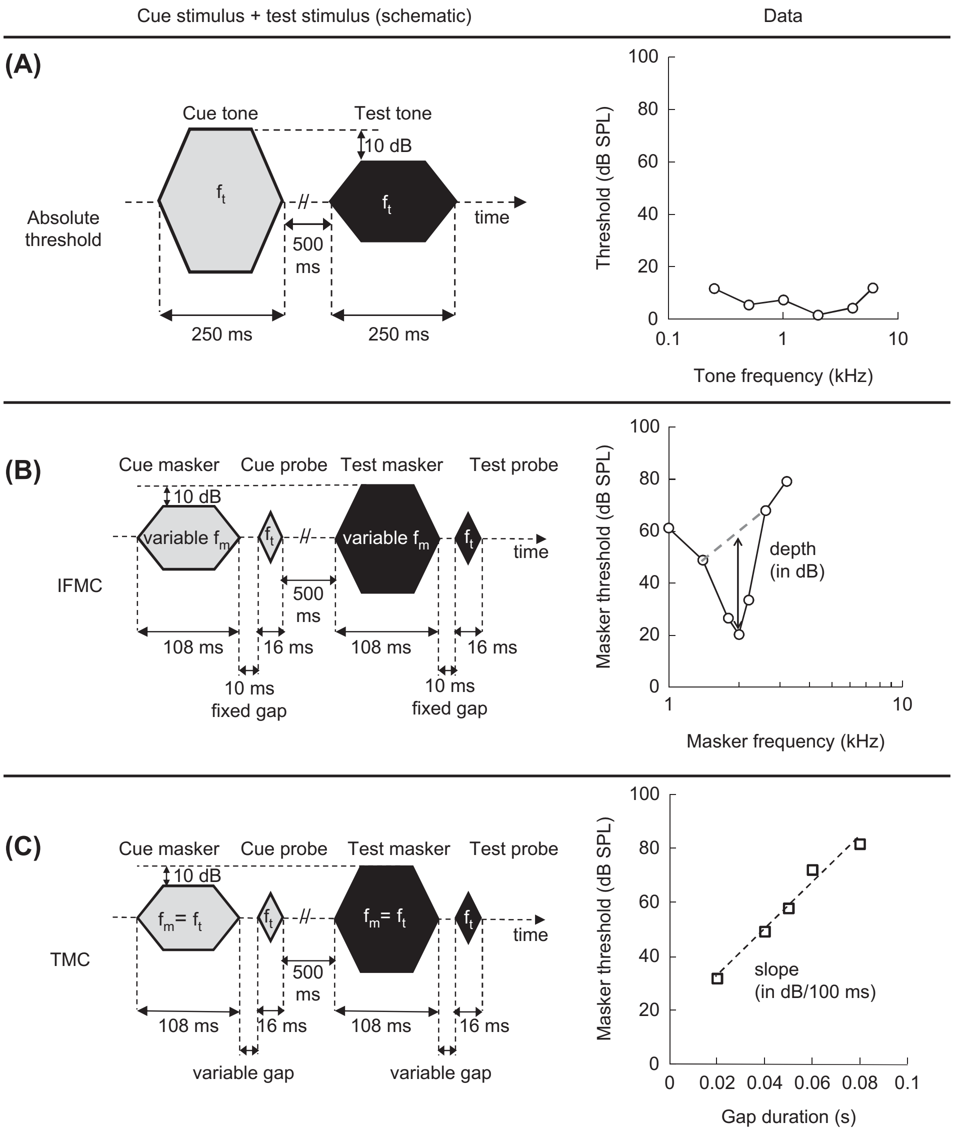


Figure 1. First column: schematic representation of the test stimuli in measures of (A) absolute threshold (250-ms tone), (B) iso-forward masking contour (IFMC), and (C) temporal masking curve (TMC) measure. Second column: examples of the data obtained in the absolute threshold, IFMC (with $f_t = 2$ kHz) and TMC measure for a listener with good hearing, plus illustration of depth and slope measure for IFMC and TMC respectively.

making the cue probe easier to detect than the test probe. The interval between the cue stimulus and the test stimulus was 500 ms.

The use of cues meant that the test could be presented to the listener as a *counting task*. Listeners were asked to say how many probe tones they heard. If 2 probes were reported, it was inferred that the test probe had been heard. If only one probe was reported it was assumed that the test tone was not heard because it was the less audible tone. In this way, the listener's '2' or '1' response could be understood as a 'yes' or 'no' response rendering the procedure a 'single-interval' paradigm.

Threshold estimation procedure

All measurements were made using an adaptive procedure previously proposed and evaluated by Lecluyse and Meddis (2009) and is based on an adaptive yes-no paradigm (e.g. Dixon & Mood, 1948; Carhart & Jerger, 1959). In this study the single-interval up/down procedure (SIUD) has been extended to the measurement of forward-masking thresholds. In the forward masking paradigm the task was made harder when the probe was detected by increasing the level of the masker. The step sizes used were 10 dB until the first reversal, after which the stimulus level was set to the mid-point between the previous two levels. A smaller, 2-dB, step size was used thereafter. The run then continued for 10 trials counting from the trial immediately before the first reversal. For the forward-masking measures the start value of the masker was set at a low level to ensure that only the probe tones were heard in the first trials.

The threshold was estimated at the end of each run of trials by fitting a psychometric function to the responses. The mean of the logistic function was identified as the threshold estimate (see Lecluyse & Meddis, 2009 for details).

One in five trials were *catch trials* where the cue probe tone was retained but the test probe tone was omitted. In this case a '0' or a '1' response was treated as correct but a '2' response was incorrect (false-positive). This was taken to indicate that the listener was not attending or was using an inappropriate listening strategy. If the participant produced a false-positive, the run was stopped and restarted, possibly after resting the participant or giving further instructions. Participants were encouraged not to guess but to report hearing a (possibly very faint) test tone only when they were confident that they had heard it. A catch trial was always presented on the second trial in a run to remind the listener of what a 'no-stimulus'-trial sounds like. Catch trials were not included in the trial count.

Data collection details

A single complete set of measurements was made for one ear in all listeners with the following exceptions. To assess the reliability of individual measurements, 21 listeners (five good-hearing and 16 impaired-hearing) were tested three times. Secondly, 23 participants from the complete cohort produced a profile for each ear for the purpose of between-ear comparison. The remaining participants contributed only one profile for one ear. This latter group was assessed in connection with a tinnitus study described elsewhere (Tan et al, 2013) for which these procedures were partly devised. Their data are included here for the light they throw on the general usefulness of the procedure. The 0.25-kHz data were not collected for this group in order to make more time available for other testing procedures.

Within the impaired-hearing group, it frequently happened that only incomplete data could be obtained, particularly at high frequencies because the probe tone was either inaudible or the masker was ineffective even at 100 dB SPL at which point the trial was routinely aborted.

Numerical descriptors

Two imperfect but useful shorthand measures were used to quantify the visual impression given by individual functions. The 'depth' of the IFMC (in dB) is defined numerically as the difference between the average of masker levels at frequencies of $0.7 \times f_t$ and $1.3 \times f_t$ and the masker level at the expected tip (i.e. with frequency f_t). This is illustrated in Figure 1B. This measure will be large when the V-shape is narrow and symmetric. Any deviation from this pattern will reduce the depth.

The 'slope' of the TMC is simply the slope of the least-squares best-fit straight line to the TMC thresholds for the gaps between 20 and 80 ms (Figure 1C). The slope is expressed as the dB rise per 100 ms increase in the masker-probe gap. This was chosen because each TMC chart is 100 ms wide and the metric agrees with the visual impression.

Results

The procedures were tolerated well by all listeners. No complaints were received and the test was generally found to be enjoyable. All were unpaid volunteers who were willing to complete the test; many were happy to come back for repeated testing. By the end of the project, 83 participants had contributed useable data in 94 ears (67 impaired ears and 27 good ears).

Training

Participants became familiar with the tasks very quickly. Typically a single training run sufficed for each of the three measures. In some cases, extra advice and training was needed but this usually did not take longer than 20 minutes. Three volunteers, all over 75 years of age, were unable to perform the discriminations necessary to complete the tests and were therefore not included in the study sample.

Total testing time

The time taken to collect one hearing profile (unilateral) was calculated from computer records for 37 profiles. This subsample was selected on the basis that all absolute threshold measurements and IFMCs and TMCs for five frequencies were measured. The average total measurement time was 74 minutes and ranged from 46 to 120 minutes. Allowing for approximately 15 minutes rest time and approximately 15 minutes training time, a complete session with instructions and rests would normally be complete within two hours.

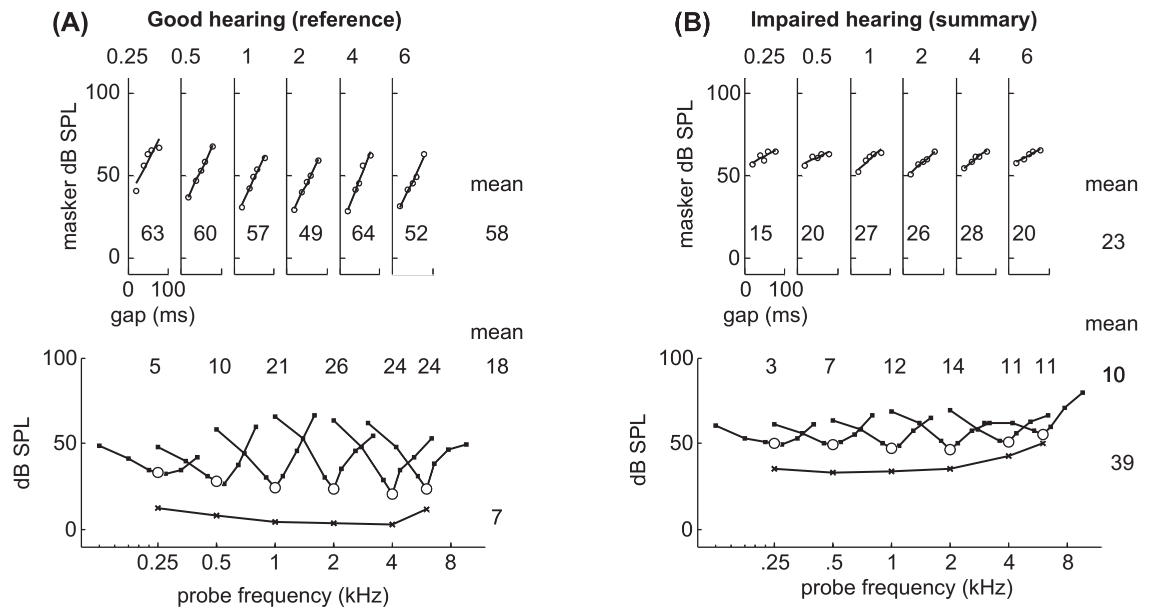
False positives.

A standard auditory profile consisted of 76 runs where each run contained an average of three catch trials. This equates to approximately 228 catch trials per profile. The catch-trial data obtained in the subsample discussed above (37 hearing profiles) was analysed. The number of false-positive responses was expressed as a percentage of the total number of catch trials. The median false-positive rate for all listeners was 4.8 % in a positively skewed distribution ranging from 0% to 14.1%. Some of these events occurred near the beginning of the session and were attributed to early confusion. These were used as an opportunity to reinstruct the listener. Other errors occurred later in the session and were often associated with fatigue. These were used to trigger short rest periods. Most of the time, however, error-free runs were obtained.

Summary profiles

Figure 2A and B, show average profiles for the good-hearing and impaired-hearing groups[2]. Absolute thresholds are represented in each profile by the line at the bottom of the lower panel reaching across probe frequencies. These are expressed in dB SPL and therefore upside down relative to an audiogram. IFMCs are located in the same panel above the absolute thresholds. The estimated depths of the V-shapes are posted immediately above each function. The IFMCs are deeper for the good-hearing group than for the impaired-hearing group. The TMCs are shown at the top of the panel. The average slopes (dB/100 ms) are posted immediately below each function. The functions are clearly shallower for the impaired-hearing group. The mean data are reproduced in the tables (bottom panel) along with standard deviations and sample sizes (number of ears) for each function.

Figure 2A, shows a good-hearing reference profile. This profile was obtained by selecting only the good-hearing listeners who contributed a complete set of data with no omissions. A straight average profile of this subset of 14 listeners was produced. The listeners in this reduced group had a mean age of 32.1 years (SD = 11.0 years). Each individual contributed data from only one ear. When complete data from both ears were available, one ear was chosen at random. Two features of the reference profile are notable. First, the slope of the TMCs is roughly constant across probe frequency. More specifically, there is no systematic change in the TMC slope



(A) Good hearing (reference)

	Test frequency (kHz) 0.25	0.5	1	2	4	6	mean
Absolute threshold (dB SPL)							
	13	**8**	**4**	**4**	**3**	**12**	**7**
sd=	5	5	6	7	7	5	
N=	14	14	14	14	14	14	
IFMC depth (dB)							
	5	**10**	**21**	**26**	**24**	**24**	**18**
sd=	4	6	9	22	11	10	
N=	14	14	14	14	14	14	
TMC slopes (dB/100 ms)							
	63	**60**	**57**	**49**	**64**	**52**	**58**
sd=	40	39	32	30	30	31	
N=	14	14	14	14	14	14	

(B) Impaired hearing (summary)

	Test frequency (kHz) 0.25	0.5	1	2	4	6	mean
Absolute threshold (dB SPL)							
	35	**33**	**34**	**36**	**43**	**51**	**39**
sd=	17	18	22	23	20	22	
N=	67	67	67	65	61	53	
IFMC depth (dB)							
	3	**7**	**12**	**14**	**11**	**11**	**10**
sd=	4	7	12	14	14	11	
N=	30	43	44	46	37	29	
TMC slopes (dB/100 ms)							
	15	**20**	**27**	**26**	**28**	**20**	**23**
sd=	14	19	23	20	23	17	
N=	19	34	39	41	36	29	

Figure 2. Profile summaries: (A) good-hearing reference. Average of data points from the good-hearing reference sample for 14 ears where complete data was available at all points in the profile (see text). (B) impaired-hearing summary. Each point in the summary is the simple average of all available data points. TMCs are at the top of the profiles and the probe frequency is posted above each function. IFMCs are shown at the top of the lower figure. The unfilled circles indicate the masker level when the masker is at the same frequency as the probe. Absolute thresholds are at the bottom of the profile. The numbers in the body of the profile give the TMC slope estimates, and the IFMC depth estimates. These values are reproduced in the statistical summary table (bottom) along with sample sizes (number of ears) and standard deviations. Some impaired listeners contributed profiles for both ears to the summary profile in B. In A however, each eligible good-hearing listener contributed only one ear.

with probe frequency. Second, the depth of the IFMC increases from only 5 dB to 26 dB between 0.25 and 2 kHz with no further increase at higher frequencies. When assessing the depth of an individual IFMC, it is clearly necessary to take the probe frequency into account.

Figure 2B is a simple average of all the data from participants with impaired hearing. As expected, the hearing-impaired group show raised absolute thresholds, reduced frequency selectivity, and reduced compression. The figures are intended only to illustrate the main features of the auditory profiling procedure and to give a general indication of the differences between the groups in the study. In particular, Figure 2B is not presented as a simple characterization of hearing impairment. In what follows we shall stress the variability of profiles particularly within the impaired-hearing group.

Individual profiles

Six individual profiles from the impaired group are shown in Figure 3. They were chosen to illustrate some of the variety of patterns that were observed.

The top two panels, A and B, show profiles with an equal hearing loss at the majority of frequencies. #IH75 shows a loss of frequency selectivity with very shallow IFMCs associated with shallow TMC functions. #IH14 has more frequency selectivity and steeper

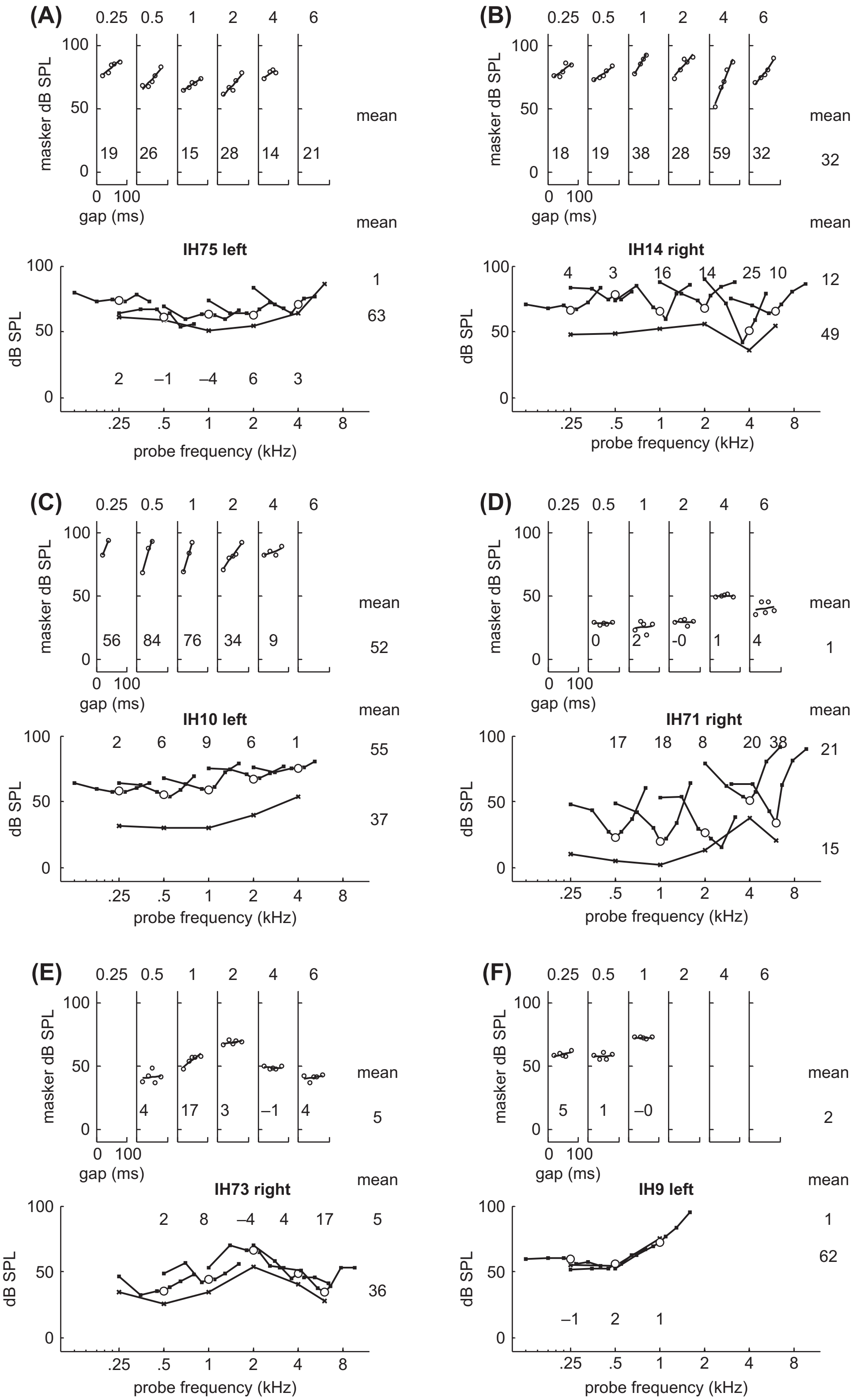


Figure 3. Six individual auditory profiles from the impaired group individually discussed in the text.

TMCs. However, both are substantially worse than the good-hearing reference. Panel C shows a listener with some hearing loss at all frequencies but the greatest loss is at high frequencies. Frequency selectivity is greatly reduced but the TMC is almost as steep as the good-hearing reference indicating good residual compression despite the raised absolute thresholds. Panel D indicates only a mild hearing loss restricted to frequencies above 2 kHz. IFMCs are clearly V-shaped but shallower than the good-hearing reference.

Surprisingly, however, the TMC functions are essentially flat at all probe frequencies. Panel E features a listener with a mid-frequency loss concentrated around 2 kHz. Frequency selectivity is largely absent and the TMC slopes are shallow at all frequencies even where thresholds are close to normal. Finally, in panel F, the profile indicates a severe hearing loss with no measurable hearing above 2 kHz. In this case the TMCs are all almost flat and the IFMCs are essentially superimposed on the absolute threshold function indicating that the maskers become effective almost as soon as they become audible. The flat TMCs observed in panels D and F were unexpected because they appear to indicate little or no recovery from forward masking. These will be analysed in more detail below. It is noteworthy that no profile in this collection resembles the summary profile for this group shown in Figure 2B.

Measurement reliability

The test-retest reliability of the measurements can be considered at different levels of analysis; individual threshold measurements, compound measures (IFMC depth or TMC slope) or the overall pattern of the profile.

The reliability of a single data point depends largely on the number of trials in a single run and any degree of accuracy can be achieved by extending the length of a run. The choice of 10 trials per run is a trade-off between accuracy and availability of clinical time. In this study, the test-retest reliability was estimated by finding the average absolute difference between two corresponding measurements in profiles measured in a different session. These differences were computed for absolute thresholds, IFMCs and TMCs from 21 listeners (5 good-hearing listeners, 16 impaired-hearing listeners). These data were collected at an early stage of the project when all measurements were repeated at least twice. Across all 1093 pairs of threshold estimates, the median *absolute* difference between the first and second measurement was 4.6 dB for absolute threshold, 4.9 dB for IFMC, and 5.6 dB for TMC. There was no (order) bias in the sense that the overall averages of the thresholds in the first session were almost identical to the averages of the thresholds in the second session.

The reliability of individual measures of TMC slope or IFMC depth is more relevant in a clinical context. The average absolute difference between the first and second measurements was 5.0 dB for IFMC depth and 4.6 dB/100 ms for TMC slope measured across 129 measurements. If an individual listener is characterized by an average IFMC depth across all frequencies or an average TMC slope, we obtain a test/retest correlation of $R^2 = 0.66$ and 0.89 across all participants.

Further insight into the consistency of measurements can be obtained by comparing left and right ear profiles of an individual listener. Twenty-three participants produced complete profiles for both ears. In most cases the profiles from both ears were similar. If we restrict the sample to cases of bilateral hearing impairment where the average absolute thresholds in left and right ear were within 15 dB of each other, the similarity in the IFMC and TMC functions was *always* visually striking. This is illustrated with two pairs of left/right profiles (Figure 4). The overall impression is that there is little difference between the left and the right ear. The threshold slope and depth metrics also correspond closely. Insofar as the left and right ears are likely to be impaired in similar ways, this indicates that the measurements are identifying key features of the impairment.

To assess this quantitatively, the average slope and depth metrics for each profile were correlated between left and right ears for 17 hearing-impaired participants who (1) had provided complete data for both ears, and (2) showed a difference between corresponding absolute thresholds in the left and right ear of no more than 15 dB. The left/right ear correlation for the mean IFMC slope and the mean TMC depth was strong ($R^2 = 0.94$ and 0.92 respectively). The correspondence between left and right ear measurements in these bilateral impairments is offered as additional evidence of the consistency of the IFMC and TMC measurement techniques.

Shallow TMC slopes

Some listeners with good hearing showed shallow TMCs more typical of the impaired-hearing group. This does not need to indicate pathology but is more likely to be related to a finding by Plack et al (2004) showing that the normal auditory response is linear close to threshold and compressed only at higher levels. Figure 5B, shows the distribution of all TMC slope estimates irrespective of frequency in the good-hearing group including many slope estimates below 40 dB/100 ms. By contrast, the impaired-hearing group (Figure 5C) produced very few slope estimates above 50 dB SPL. Some of the slope estimates are as low as 10 dB/100 ms. These unexpectedly flat functions were identified in eight members of this group. None of these listeners showed high false positive rates or experienced particular difficulty with the testing procedure. The average age of this group was 62.3 years (SD = 8.8), only slightly older than the impaired group as a whole (59.2 years). To check that a mistake had not been made in these cases, some of these subjects were informally tested using very long masker probe gaps of up to 200 ms. It was found that the extended TMC function was always a simple linear continuation of the original function, showing a very gentle recovery of a few dB per 100 ms. Two listeners were tested with higher level probes (25 and 45 dB above probe threshold) where it was found that the TMC functions simply moved up the scale but remained flat.

Discussion

Laboratory procedures, aimed at measuring absolute threshold, compression, and frequency selectivity, have been adapted for use with a clinical population by simplifying the task and speeding up data collection. It was found that almost all of a large number of volunteer listeners were able to carry out the tasks. For most participants a single ear could be assessed in less than two hours. This may be acceptable for clinical research purposes. It may also be acceptable in a clinical context where routine procedures have not resulted in a satisfactory diagnosis or successful treatment and further clinical insight is required. Alternatively, future clinical applications may require less data to be collected.

The increased speed of data collection compared with current laboratory procedures are the result of a number of factors: (1) the use of single-interval procedures rather than the multiple-alternative forced-choice method, (2) a reduction in training time by employing the simplified ‘one’/’two’ counting task, and (3) the use of fewer testing trials. In particular, it was found that the use of a cue prior to each test stimulus made the task very much easier to learn. It gave the listener an example of a positive stimulus at the beginning of each trial and helped keep the listener focussed on the appropriate features of the stimulus. Of course the duration of the test depends on the number of trials used per run and the number of frequencies tested. For some clinical applications where less accuracy is acceptable, fewer trials could be used and fewer frequencies tested with further time savings. However, for more exacting research

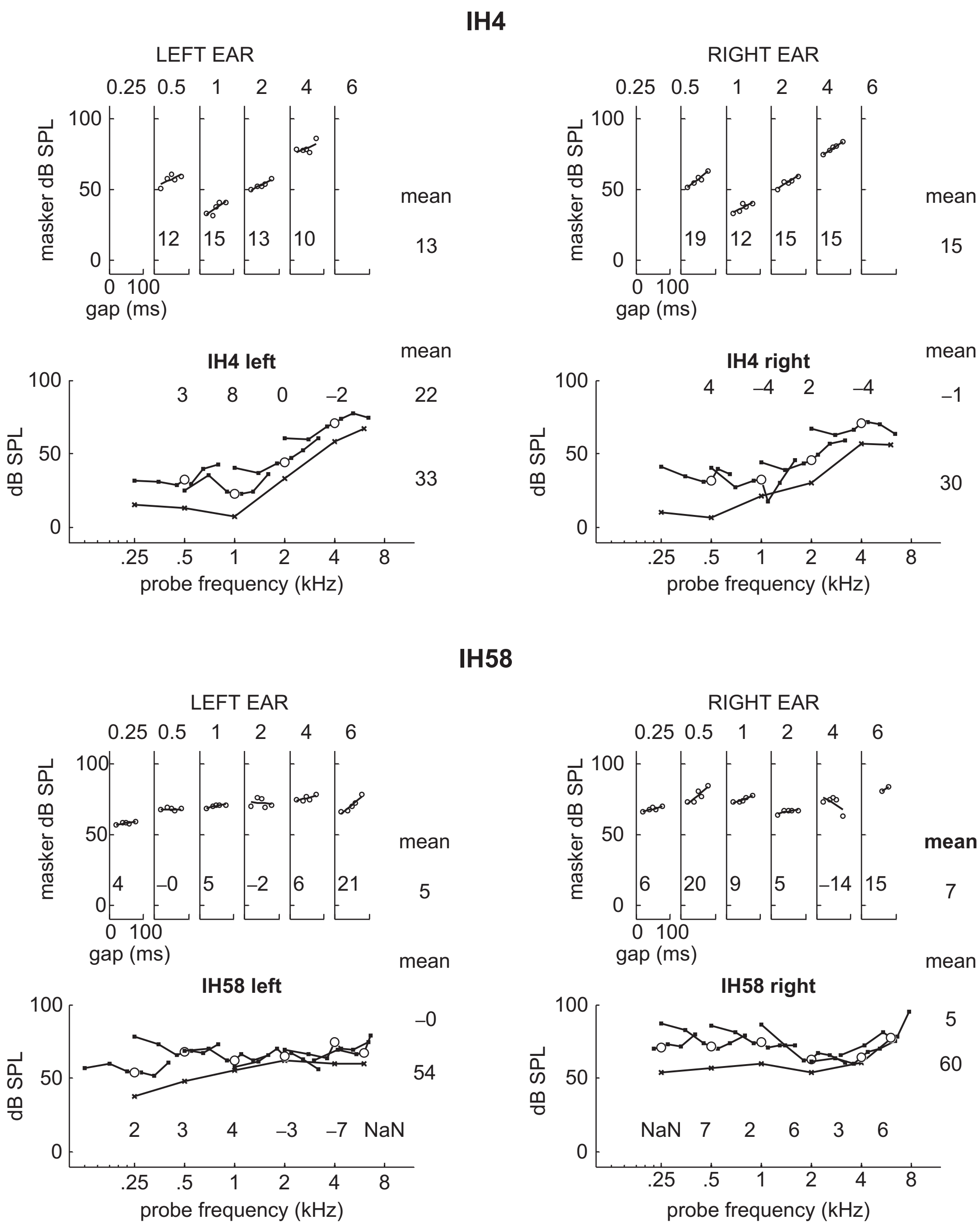


Figure 4. Left and right profile of two impaired listeners (IH4 and IH58).

investigations, accuracy can be increased at the cost of longer measurement sessions by using more trials.

The inclusion of catch trials provides a check on whether the participant has understood the task. It also gives the operator early warning of the need to intervene and, if necessary, provide further guidance or simply to introduce a rest period. The purpose of the catch trials is not to estimate an error rate but to keep error rates low by giving the user feedback and requiring the run to be restarted when one occurs. A catch trial was routinely inserted on the second trial of each run with a view to identifying problems at an early stage. This conferred an additional benefit in that listeners were given an example of a missing test probe early in the series to act as a standard for later trials.

Most laboratory applications of compression measure a 'linear reference'; a TMC using a masker with a frequency well below the probe frequency (Nelson et al, 2001). This is used to estimate the amount of compression by comparing the slope of the on-frequency with the off-frequency function. Omitting this step saves a great deal of time but means that it is not possible to estimate compression directly. Instead, loss of compression is identified more simply by comparison of the TMCs of listeners with a reference group of listeners with good hearing. The abandonment of this numerical compression estimate may not be a serious problem. The procedure remains controversial because of uncertainties concerning the assumptions that underpin this procedure, particularly the assumption that the rate of recovery from forward masking is independent of masker level (Wojtczak & Oxenham, 2010). It is also likely that off-frequency maskers are not as linear as originally supposed (Plack & Arifianto, 2010). Moreover, psychophysical studies of phenomena attributable

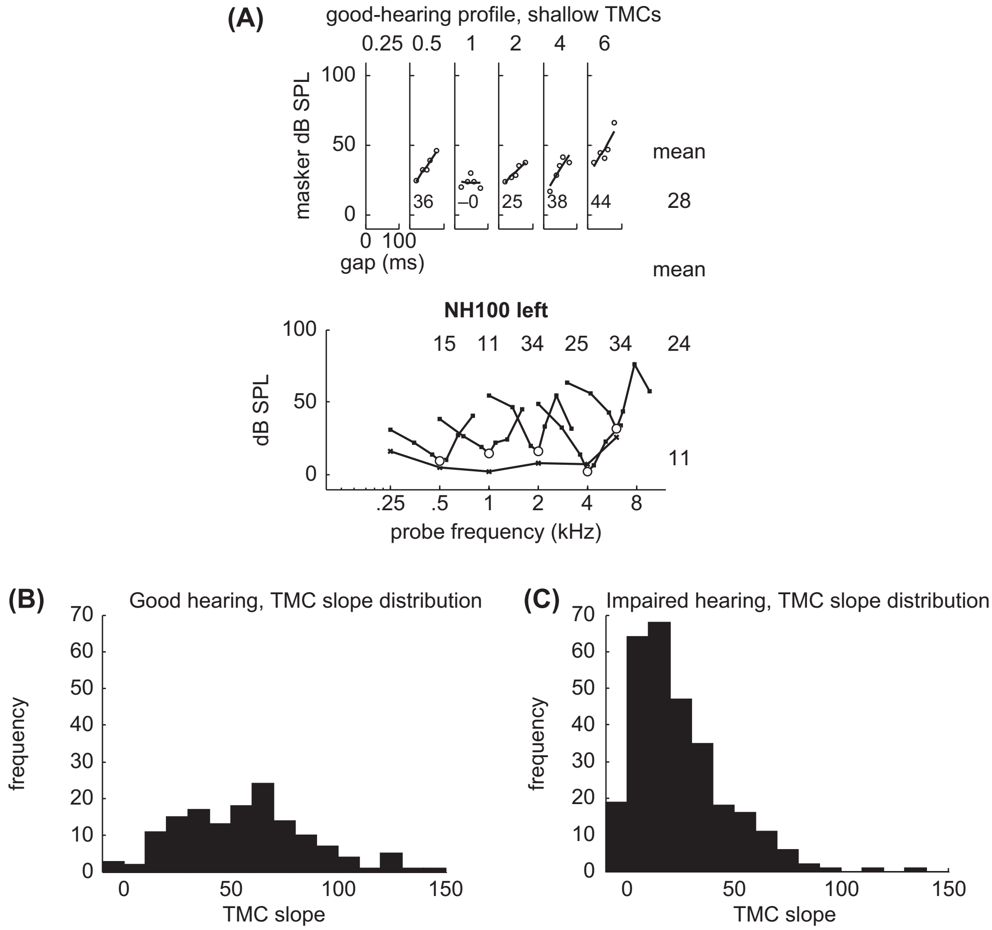


Figure 5. (A) example of a good-hearing profile showing shallow TMCs. (B) and (C) Frequency distribution of TMC slope measurements for (B) good-hearing group, and (C) impaired-hearing group. All available slope estimates are used and data are included irrespective of probe frequency.

to the peripheral auditory efferent system (e.g. Strickland & Krishnan, 2006) are leading to a more complex view of what is happening during forward masking. This view stipulates that recovery from forward masking involves a gain function that is changing in time following the masker and that the strength of this effect is itself a function of hearing impairment. Perhaps the value of the TMC function is not its ability to estimate compression per se, but to give a general insight into how sounds mask each other over time for a given patient.

The meaning of the TMC slope estimate is brought into sharp focus by a number of profiles where the slope was unexpectedly low, only a few dB per 100 ms and so close to the noise floor that some estimates were registered as negative. Similar flat TMC functions at different frequencies have been observed in Lopez-Poveda et al (2005), using more traditional laboratory methods. Typically, listeners with very shallow slopes showed these at all frequencies and, where both ears were studied, the same slopes were observed in the opposite ear. The shallow slopes persisted when the probe level was increased and the maskers were forced to higher intensities. These very shallow slopes are often accompanied by IFMCs where the level of the on-frequency masker is very close to or occasionally below the masker threshold (see for example, Figure 3F). While this may seem counter-intuitive, masking at this low level is not unknown (Plack et al, 2006). Whatever the mechanism, masking by very low level sounds must have considerable functional implications for listening in everyday life.

As expected, listeners with good hearing typically produced profiles with low absolute thresholds, steep TMC slopes, and deep, V-shaped IFMC functions. Some listeners, however, showed TMC functions that were observed to be shallow and close to the mean of the hearing-impaired listeners. These observations are consistent with a previous report of a linear response near threshold (Plack et al, 2004). These observations complicate the interpretation of TMC slope estimates. While very steep TMCs slopes indicate intact processing at the auditory periphery, a less steep slope must be interpreted with caution. It might indicate pathology or it might indicate normal hearing that is being assessed in a linear region close to threshold.

From a clinical point of view, the profiles give a clearer picture of the *functional* difficulties faced by the patient in everyday life in terms of reduced frequency selectivity and excess forward masking by relatively quiet sounds. It gives a clearer account of the nature of the problem that requires intervention. In this respect, the current study is part of an increasingly active movement to collect more comprehensive data concerning the individual nature of a patient's impairment (Vlaming et al, 2011; Jepsen & Dau, 2011). In a research context, profiling offers the possibility of refining group membership in studies that contrast a normal-hearing group of listeners with a second 'hearing-impaired' group. The profiles obtained in this study suggest that there may be substantial qualitative differences in the nature of hearing impairment even with the sensorineural category. Sub-dividing the impaired group on the basis of TMC slopes or IFMC depth might lead to more clear-cut study outcomes.

Notes

1. The software is available from the authors on request.
2. The complete set of profiles is available from the authors on request.

Acknowledgements

The authors would like to thank the participants for donating time and effort to the study, the collaborators of Phonak and the Hearing Care Centre in Colchester for all the advice and support, and finally to three anonymous reviewers for their comments and suggestions on preliminary versions of the manuscript.

Declaration of interest: The authors report no declarations of interest. This work was supported by the Engineering and Physical Sciences Research Council UK (EPSRC).

References

Carhart R. & Jerger J.F. 1959. Preferred method for clinical determination of pure-tone thresholds. *J Speech Hear Dis*, 24, 330–345.

Dixon W.J. & Mood A.M. 1948. A method for obtaining and analyzing sensitivity data. *J Am Stat Assoc*, 43, 109–126.

Houtgast T. 1972. Psychophysical evidence for lateral inhibition in hearing. *J Acoust Soc Am*, 51, 1885–1894.

Jepsen M.L. & Dau T. 2011. Characterizing auditory processing and perception in individual listeners with sensorineural hearing loss. *J Acoust Soc Am*, 129, 262–281.

Lecluyse W. & Meddis R. 2009. A simple single-interval adaptive procedure for estimating thresholds in normal and impaired listeners. *J Acoust Soc Am*, 126, 2570–2579.

Lopez-Poveda E.A., Plack C.J. & Meddis R. 2003. Cochlear nonlinearity between 500 and 8000 Hz in listeners with normal hearing. *J Acoust Soc Am*, 113, 951–960.

Lopez-Poveda E.A., Plack C.J., Meddis R. & Blanco J.L. 2005. Cochlear compression in listeners with moderate sensorineural hearing loss. *Hear Res*, 205, 172–183.

Moore B.C.J. 1978. Psychophysical tuning curves measured in simultaneous and forward masking. *J Acoust Soc Am*, 63, 524–532.

Nelson D.A., Chargo S.J., Kopun J.G. & Freyman R.L. 1990. Effects of stimulus level on forward-masked psychophysical tuning curves in quiet and in noise. *J Acoust Soc Am*, 88, 2143–2151.

Nelson D.A., Schroder A.C. & Wojtczak M. 2001. A new procedure for measuring peripheral compression in normal-hearing and hearing-impaired listeners. *J Acoust Soc Am*, 110, 2045–2064.

Plack C.J., Drga V. & Lopez-Poveda E.A. 2004. Inferred basilar-membrane response functions for listeners with mild to moderate sensorineural hearing loss. *J Acoust Soc Am*, 115, 1684–1695.

Plack C.J., Oxenham A.J. & Drga V. 2006. Masking of inaudible sounds and the linearity of temporal summation. *J Neurosc*, 26, 8767–8773.

Plack C.J. & Arifianto D. 2010. On- and off-frequency compression estimated using a new version of the additivity of forward masking technique. *J Acoust Soc Am*, 128, 771–786.

Rosengard P.S., Oxenham A.J. & Braida L.B. 2005. Comparing different estimates of cochlear compression in listeners with normal and impaired hearing. *J Acoust Soc Am*, 117, 3028–3041.

Sek A., Alcantara J., Moore B.C.J., Kluk K. & Wicher A. 2005. Development of a fast method for determining psychophysical tuning curves. *Int J Audiol*, 44, 408–420.

Sek A. & Moore B.C.J. 2011. Implementation of a fast method for measuring psychophysical tuning curves. *Int J Audiol*, 50, 237–242.

Strickland E.A. & Krishnan L.A. 2006. The temporal effect in listeners with mild to moderate cochlear hearing impairment, *J Acoust Soc Am*, 118, 3211–3217.

Tan C.M., Lecluyse W., McFerran D. and Meddis R. 2013. Tinnitus and patterns of hearing loss. *J Assoc Res Otolaryng*, 14, 275–282.

Vlaming S.M.G., Kollmeier B., Dreschler W.A., Martin R., Wouters J. et al. 2011. HearCom: Hearing in the communication society. *Acta Acustica united with Acustica*, 97, 175–192.

Wojtczak M. & Oxenham A.J. 2010. Recovery from on- and off-frequency forward masking in listeners with normal and impaired hearing. *J Acoust Soc Am*, 128, 247–256.