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Investigating low-frequency compression using the Grid method

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There is an ongoing discussion about whether the amount of cochlear compression in humans at low frequencies (below 1 kHz) is as high as that at higher frequencies. It is controversial whether the compression affects the slope of the off-frequency forward masking curves at those frequencies. Here, the Grid method with a 2-interval 1-up 3-down tracking rule was applied to estimate forward masking curves at two characteristic frequencies: 500 Hz and 4000 Hz. The resulting curves and the corresponding basilar membrane input-output (BM I/O) functions were found to be comparable to those reported in literature. Moreover, slopes of the low-level portions of the BM I/O functions estimated at 500 Hz were examined, to determine whether the 500-Hz off-frequency forward masking curves were affected by compression. Overall, the collected data showed a trend confirming the compressive behaviour. However, the analysis was complicated by unexpectedly steep portions of the collected on- and off-frequency forward masking curves.

INTRODUCTION

There is an ongoing debate concerning the characteristics of human basilar-membrane input-output (BM I/O) functions in the low frequency (<1000 Hz) range, particularly when they are obtained using forward-masking experiments. These methods rely on an assumption that the response of the BM is linear for a stimulus whose frequency is approximately an octave lower than the characteristic frequency (CF) for that position (Robles and Ruggero, 2001). Thus, BM I/O functions are characterized using two conditions in a temporal masking curve (TMC) paradigm (Nelson *et al.*, 2001). In the “on-frequency” condition, the masker frequency is the same as that of the masked signal. In the “off-frequency” condition, the masker frequency is set approximately one octave below that of the signal and the resulting threshold is taken as a linear reference for the corresponding on-frequency threshold. The thresholds obtained from the off- and on-frequency TMCs are paired by the masker-signal gap and the resulting scatterplot is assumed to approximate a BM I/O at the cochlear site corresponding to the signal’s frequency.

A key assumption of the TMC method is that the rate of recovery from forward masking is independent of both the level and the frequency of the masker. Recently,

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both aspects of this assumption have been questioned. Wojtczak and Oxenham (2009) observed that, for a high-level (e.g., above 83 dB SPL) off-frequency masker in normal-hearing (NH) listeners, the rate of recovery from forward masking was level dependent. Stainsby and Moore (2006) measured TMCs in three listeners with a flat mild-to-severe hearing loss and found that the rate of recovery from forward masking was larger for low (500 Hz) than for high (4000 Hz) center frequencies. Consequently, the BM I/O compression ratio (CR) would be significantly smaller at low than at high frequencies. In contrast, Lopez-Poveda and Alves-Pinto (2008) found evidence that the rate of recovery was not frequency dependent and concluded that the CR at low and high frequencies is similar.

Both physiological experiments and psychophysical data suggest that BM I/O is linear at very low levels (Plack and O'Hanlon, 2003; Lopez-Poveda and Alves-Pinto 2008). Therefore, it is assumed that the nonlinear gain at these levels is constant and that the slopes of on-frequency TMCs at masker levels near hearing threshold should be similar to the corresponding off-frequency TMC slopes, provided that the off-frequency TMCs reflect linear processing at BM. If the off-frequency reference was influenced by compression, the BM I/O curve derived from the off- and on-frequency curve pair would show slopes higher than 1 at the very low input levels.

Fereczkowski (2015) developed the Grid method as an alternative to other tracking methods. The most important difference between the standard methods and the Grid is that the latter varies more than one experimental parameter during a single experimental run. The main advantage of this approach is its relatively high time efficiency. As shown in Fereczkowski (2015), the method allows the experimenter to locate and track a single TMC threshold curve within 2-4 minutes, which is comparable to the time needed to estimate 2-3 single thresholds by means of the Single-Interval Up-Down (SIUD) method (Lecluyse and Meddis, 2009) and maximally one threshold when using transformed up-down paradigms.

The characteristics of the BM I/O estimates obtained here were compared to those of previous studies. Moreover, it was hypothesised that if the off-frequency TMC is affected by compression, the BM I/O functions obtained from pairing the low-level linear on-frequency and the off-frequency curves would show an expansive characteristic in the low-level region.

METHOD

Listeners, stimuli, and procedure

Individual ears were tested from 8 clinically normal-hearing (audiometric thresholds <20 dB HL) listeners (7 males and 1 female with a mean age of 27.8 years). All listeners provided written informed-consent and the procedure was approved by the National Research Ethics Committee of Denmark.

Masking curves were measured at two signal frequencies: 500 and 4000 Hz. In the off-frequency condition, the masker frequency was set an octave below that of the signal. The masker duration was 200 ms. The signal duration was 16 ms and 24 ms (raised cosine gating, no steady state) when the signal frequencies were 4000 and 500 Hz, respectively. Onset and offset ramps of the masker tone were the same as those for the corresponding signal. The signal level was 7 dB sensation level (SL).

The maximum masker level allowed in the procedure was 85 dB SPL for the on-frequency condition and 95 dB SPL for the off-frequency condition. The minimum level allowed was 10 dB below the individual's probe threshold. Finally, the set of all possible levels was created between these limits, with 2 dB resolution. Possible durations of the masker-signal gap (measured between zero-amplitude points) belonged to the following set: 1, 2, 3, 4, 6, 8, 12, 16, 24, 32, 48, 64, 96, 128, 160, 192, and up to 352 ms in 32-ms steps. All stimuli were generated on a PC running Matlab and a 24 bit RME soundcard. The presentation was monaural via Sennheiser HDA200 headphones in a double walled booth.

Since the maximum masker level in the on-frequency condition was set to 85 dB SPL, the BM I/O thresholds were approximated by two-section fits (i.e., two straight lines that intersected at a knee point, KP). The mean and standard deviation of the fitted parameters were estimated using the bootstrapping method. In the variant used here, a single fit to the complete data set was provided, consisting of N points, and the fitted value of the parameter under investigation was used as the estimate of the mean. Subsequently, fits were performed to all N possible N-1 element sets in order to estimate the standard deviation of the mean.

The experimental procedure consisted of three steps. First, the absolute thresholds for the signals were measured. Subsequently, the listeners were trained, for at least two hours, in the forward masking task. In the data-collection phase, three repetitions of each of the four TMC conditions were run. In each run the threshold curve was sampled once (from lowest to highest levels). The tracking rule used was 3-up 1-down, 2-alternative forced-choice (AFC) and feedback was provided to the listener after each response.

RESULTS

Using linear interpolation, TMC thresholds were estimated for each experimental run and then averaged. The left panel of Fig. 1 presents mean TMCs collected for all listeners (NH1-NH8). Each row represents data collected for a single listener and each column corresponds to a different combination of TMCs. The left column presents TMC thresholds obtained for a 4-kHz signal. The right column presents TMC thresholds obtained for a 500-Hz signal. The squares represent the on-frequency TMCs and the triangles represent the off-frequency thresholds. The filled symbols represent thresholds for which the masker-signal gap was no greater than 10 ms. The distinction has been highlighted in both panels because, in some cases, the TMC slopes increase markedly below the 10-ms gap. The mean on and off-frequency TMCs, collected for a single frequency, were paired by the masker-signal gap to estimate individual BM I/O thresholds. The right panel of Fig. 1 presents mean BM I/O thresholds, along with the corresponding two-section fits. For clarity, only the fits performed on the complete sets are shown. The leftmost columns present BM I/Os estimated from the data shown in the corresponding columns of the left panel. The rightmost column represents BM I/Os derived by pairing on-frequency TMC thresholds for a 500-Hz signal with the off-frequency TMC thresholds for a 4-kHz signal. Each row presents a single listener's data.

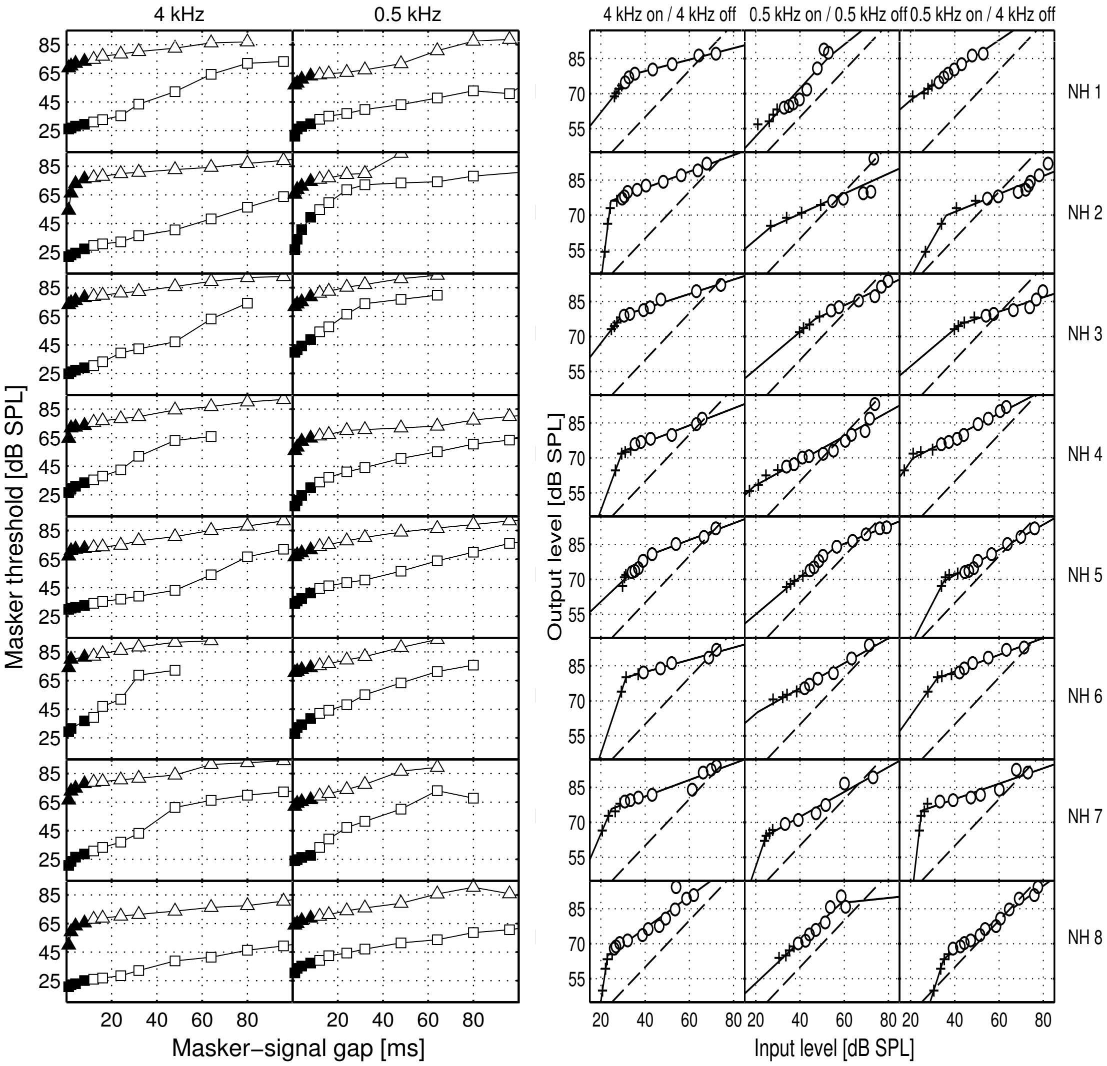

Fig. 1: TMCs (left panel) and estimated BM I/O functions (right panel) for each individual listener. In the left panel, the data for a 4-kHz and 0.5-kHz signal are shown in the left and right column, respectively. The squares and triangles represent the on- and off-frequency thresholds, respectively. In the right panel, the two leftmost columns present BM I/O functions from the two columns in the left panel. The rightmost column presents the BM I/O estimate for a 500-Hz tone using the 4000-Hz off-frequency curve as a reference. In both panels, the filled symbols or crosses indicate results obtained for masker-signal gaps shorter than or equal to 10 ms.

Each two-section fit was defined by four parameters: a linear slope at low levels, a compressive slope at medium levels, and the two coordinates of the KP. A constrained minimization routine of the fitted mean square error to the collected data-points was run. The constraints were chosen based on assumptions regarding human BM I/O functions. The slope of the "linear" part of the I/O function was assumed to be greater than 0.8 and greater than the compressive slope. Thus, the compressive slope was assumed to be between 0.1 and 0.8. This corresponds to the CR ranging between 1.25 and 10. Thus, the lower bound of the CR was assumed to be below the values typically found for NH (2.5-6, e.g., Lopez-Poveda *et al.*, 2003). This was allowed in case the behaviour of the off-frequency TMC was compressive. Finally, the input level at KP was expected to be lower than 60 dB SPL (Lopez-Poveda and Johannesen, 2012). If a fitted KP (and thus one of the two fitted slopes) lay outside the level range of the corresponding data points, such values of KP and slope were discarded.

Table 1 presents the details of the two-section fits from the right panel of Fig. 1. The last row of Table 1 presents the averages computed from individual data.

4 kHz signal			**0.5 kHz signal**			**0.5 kHz on / 4 kHz off**		
KP [dB SPL]	**CR**	**Lin. slope**	**KP [dB SPL]**	**CR**	**Lin. slope**	**KP [dB SPL]**	**CR**	**Lin. slope**
34 /34	4.1/4.1	1.2/1.3	- /52	1.3/1.6	- /1.4	- / 47	1.6/6.8	- /0.8
25 /32	2.8/3.1	7.6/1.0	- / -	2.3/1.6*	- / -	36/ -	2.6/2.0	1.7/ -
30 /31	3.2/3.3	1.2/0.9	47 / -	2.2/2.2	0.8/ -	43/ -	3.3/2.9	0.8/ -
30 / -	2.7/3.0	2.6/ -	20 / -	1.9/1.8	0.9/ -	21/ -	2.0/1.8	1.3/ -
43 /42	2.8/2.8	0.9/1.0	56 /53	2.6/2.6	0.8/1.1	36/51	1.9/1.8	1.4/0.8
31 /39	3.8/3.8	2.9/0.8	- / -	1.9/1.6	- / -	30/47	2.8/3.3	2.5/0.8
25 / -	2.8/2.9	2.2/ -	25 / -	1.9/1.8	2.8/-	25/ -	3.0/2.8	8.3/ -
23 / -	1.5/1.5	6.4/ -	59 /58	10*/10*	0.9/1	35/ -	1.4/1.4	3/ -
30 /36	***3.0/3.1***	***3.1/ 1.0***	***41 /55***	***2.0/1.8***	***1.2/1.2***	***33/48***	***2.3/2.9***	***2.5/0.8***

Table 1: Individual parameters from BM I/O fits plotted in Fig. 1. Additional fits were performed to the BM I/O data points represented by circles alone. The values of the corresponding parameters are shown after a slash (/). A hyphen is used when the fitted parameter value was discarded, as described in the Method. Unreliable CR estimates (i.e., with standard deviations greater than 1) are marked with a star. The last row presents the averages of the estimates in the corresponding columns.

Applying the Grid method to discrimination tasks

Stainsby and Moore (2006) performed their forward masking experiments using a 3-interval forced choice procedure with a 3-up 1-down tracking method and their average threshold acquisition time was 10 minutes. Here, a 2-interval 3-up 1-down method was tested and the average threshold acquisition time was about 1 minute. Taking the difference in number of intervals into consideration, the average threshold acquisition time for the Grid method can be estimated to be about 1.5 minutes, which suggests that the Grid method can be to 6-7 times faster than the reference method. However, this comparison of the time-efficiency between the methods is not complete, because it does not take possible differences in the accuracy of both methods into account. In Fereczkowski (2015), the Grid method was shown to offer a similar accuracy as the SIUD method. Further experiments and/or Monte Carlo simulations are needed for a more direct comparison of the accuracy of the transformed up-down and Grid methods.

DISCUSSION

KP and CR estimates

When the 4-kHz off-frequency TMC data were used as the linear reference in BM I/O estimations, the KP estimates could be found in 15 out of 16 tested cases. The average estimated KP levels were 33 and 30 dB SPL for 0.5 and 4 kHz, respectively. This difference was not statistically significant.

The individual CR estimates reported by Lopez-Poveda *et al.* (2003) varied between 2.5 and 6 and most of the estimates fell between 3 and 5. Further, it was found that the CR estimated for a CF of 500 Hz was similar to that estimated at 4 kHz. Moreover, the off-frequency TMCs collected for the 500-Hz signal were found to be steeper than those collected for the 4-kHz signal. Thus, the CRs estimated based on the 500-Hz reference would be lower than those estimated using the 4-kHz off-frequency TMC as the reference. All these findings were replicated in the present study. When using the 4-kHz reference, CR estimates for CFs of 0.5 and 4 kHz were not significantly different ($p = 0.076$). However, the CRs estimated at 0.5 and 4 kHz obtained with the 0.5 and 4-kHz linear references, respectively, were significantly different ($p = 0.013$) with the CR estimate at 4 kHz being, on average, greater by a factor of 1.7. However, the average CR values estimated here are lower than those reported in Lopez-Poveda et al. (2003). An explanation for the discrepancy could be that here, in some cases, the masker-signal gap ranges tested in the on-frequency condition were greater than the corresponding ranges tested in the off-frequency condition. Since the collected off-frequency TMCs were not extrapolated, the dynamic range of the corresponding BM I/O functions that were tested was limited. This can be seen in the case of the BM I/O functions estimated for listener NH8 and the two BM I/O functions of listener NH1, where the 500-Hz on-frequency TMC was used. For these three cases, the values of CR estimated were the lowest of all of the CR estimates. Note that the estimate of CR = 10 was omitted as it was considered unreliable due to the large uncertainty of the estimate. However, excluding listener NH8 and the two BM I/O curves of listener NH1 where the 500-Hz on-frequency TMC was used, did not affect the conclusions.

Behaviour of the BM I/O curves at low levels

The main motivation for choosing a very low probe level (7 dB SL) was to test very low masker levels and thus enable testing very low BM I/O levels at 500 Hz. It was expected that, if the 500-Hz off-frequency TMC characteristic was influenced by compression, the corresponding BM I/O function would show an expansive characteristic at the low-level input range. The average of the fitted low-level slopes of the collected 500 Hz BM I/Os was 1.2, which supports this hypothesis. However, there are reasons to question the reliability of this result.

First, the corresponding average slope measured at 4 kHz was 3.1. This is much higher than any of the values reported in the literature for high CFs (e.g., 1.46 at 8 kHz in Lopez-Poveda *et al.*, 2003). Second, examination of the TMCs collected at 4 kHz revealed very steep (up to 10 dB/ms) portions of the TMCs for very low masker-signal gap values (1-10 ms, listeners 2, 4, 6-8 at 4 kHz and listeners 1, 2, and 4 at 500 Hz). The reason for this behaviour is not clear. It is unlikely that this is an effect of the test procedure, since the effect was not found in all cases. In some cases it was observed in the off-frequency functions but not in the corresponding on-frequency functions (the cases at 4 kHz). In some cases, it was observed in both TMCs (listeners 2 and 4 tested at 500 Hz). It is unlikely that the effect was due to insufficient training as listeners 6 and 8 had more than 10 hours of experience in forward masking tasks prior to conducting the present experiment.

In order to further investigate this effect, linear extrapolation was used to find the expected masker level of the collected on-frequency TMCs at 0 ms masker-signal gap. The extrapolated value was compared to the signal level. It was found that the mean difference between the compared values was 1.8 ± 5.1 dB, similar to the expected masker threshold in the simultaneous masking task. Thus, the observed effect might be due to a difference in the acoustic cues used by listeners for very short vs. longer masker-signal gaps.

The analysis of the collected TMC thresholds was repeated but without the thresholds collected for gaps ≤ 10 ms. The CR estimates from this second analysis did not differ significantly (paired t-test returned $p = 0.45$). This was not surprising since the compressive region of the BM I/O generally corresponds to the thresholds obtained for the masker-signal gaps above 10 ms. However, while 20 low-level slope estimates were obtained from the original analysis, only 11 were obtained in the re-analysis. In the case of TMCs obtained for the 4-kHz signal (on- and off-frequency), 5 low-level slope estimates were obtained and their average was 1.0. In the case of TMCs obtained for the 0.5-kHz signal (on- and off-frequency), 3 low-level slope estimates were obtained and their average was 1.2, with the minimum of 1.0. This supports the initial hypothesis that the off-frequency TMC collected for the 500-Hz signal is affected by compression, which is in line with the conclusions of

Lopez-Poveda and Alves-Pinto (2008) regarding the nature of compression at low CFs.

SUMMARY

In this study, TMCs were obtained with a 2-interval 3-up 1-down Grid procedure and the corresponding BM I/O functions were estimated for 8 NH listeners at two frequencies: 500 and 4000 Hz. The KP and CR estimates derived from the BM I/O estimates were found to be comparable to those from the literature. The time-efficiency was estimated to be 6-7 times higher than that of the reference AFC method.

Some of the obtained TMCs exhibited steep portions for low masker-signal gaps, which was not expected and inconsistent with the data shown in other studies. This behaviour may be due to listeners using different cues when performing the task with the small masker-signal gaps. The collected data showed a trend confirming the hypothesis that the off-frequency TMCs at low CFs may be subject to cochlear compression.

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