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Comparison of objective and subjective measures of cochlear compression in normal-hearing and hearing-impaired listeners

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Among several behavioural methods for estimating the basilar membrane input/output function, the temporal masking curve is the most popular. Distortion product otoacoustic emissions provide an objective measure for estimating cochlear compression. However, estimates from both methods have been poorly correlated in previous studies. We hypothesise that this could be due to the interplay between generator and reflection components in the recorded otoacoustic emissions. Here, compression estimates obtained with the two methods were compared at three audiometric frequencies (1, 2, and 4 kHz) for 10 normal-hearing and 6 hearing-impaired listeners. Distortion-product otoacoustic emissions were evoked using continuously-swept tones, to separate the generator component and investigate the corresponding compressive characteristic. For hearing imapired listeners, the estimates from the two methods were highly correlated.

INTRODUCTION

While it is not possible to directly measure the basilar membrane input-output (BMI/O) characteristic in humans, several indirect methods have been proposed. They can be classified into psychophysical and physiological.

Currently, the temporal masking curve paradigm (TMC, Nelson *et al.*, 2001) is the most widely used behavioural method for estimating BMI/O. However, the validity of the method and its several assumptions have been questioned. For instance, Wojtczak and Oxenham (2010) suggested that BM compression may be overestimated in TMC experiments, due to slower recovery from forward-masking for an off-frequency masker than for an on-frequency masker.

While distortion-product otoacoustic emissions (DPOAEs) may be difficult to obtain for hearing-impaired (HI) listeners, their presence is an indicator of active outer hair cells (OHC) and BM compression is believed to depend on OHC activity. Specifically, DPOAEs arise in the presence of two tonal signals (with frequencies $f1 < f2$) and the strength of the $2f1 - f2$ DP component is assumed to reflect the strength of the nonlinearity close to the $f2$ characteristic place on the BM. As the levels of the two

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primaries increase, so does the DPOAE response and a DPI/O characteristic can be derived, as a function of the $f2$-level ($L2$). Several level rules ($L1$ as a function of $L2$) have been proposed to maximize the DPOAE, such as the scissors rule (DP-SC, Kummer *et al.*,1998) or equal-level rule (DP-EQ). The response-level maximization is desired in order to improve the SNR of DP recordings. However, it is not clear whether any of these rules guarantees maximum DP response at all $L2$ levels, for individual listeners.

Investigations of DPI/Os are often complicated by distinctive fine structure in the recorded DPOAE spectrum. The fine structure arises due to interference between the generator and reflection DP components. Since the reflection component does not directly reflect the state of the OHCs in the generator region (Abdala and Kalluri, 2017), the isolated generator component is a more accurate measure of the DPI/O at the $f2$ place.

A comparison of BMI/Os estimated with TMCs and DPOAEs was made for normal hearing (NH) listeners (Johannesen and Lopez-Poveda, 2008). Correlation between the corresponding compression exponent estimates was found at 4 kHz, but not at other frequencies. So far, no correlation has been found in hearing-impaired (HI) listeners. If the two methods gave correlated results, this would support both methods. Therefore, the main aim of the study was to reassess the correlation between the compression ratios (CR) of the BMI/O functions inferred from behavioural and objective methods for NH and HI listeners, taking into account recent developments in both physiological and psychophysical procedures. Specifically, a source-unmixing technique (Long *et al.*, 2008) was employed here. Additionally, forward pressure level (FPL, Scheperle *et al.*, 2008) calibration was performed to reduce the influence of ear-canal acoustics on the DPI/O input. Moreover, to assure the testing of a wide BMI/O dynamic range, TMCs were obtained using the Grid method (Fereczkowski *et al.*, 2016).

METHOD

Listeners

Single ears from ten NH (all thresholds $\leq$ 20 dB HL, 125-8000 Hz) and six HI listeners with sensorineural hearing loss participated in the experiments. The audiometric thresholds of the HI listeners varied between 25 and 70 dB HL at the tested frequencies (1, 2, and 4 kHz).

Measurement of DPOAEs

An Etymotic Research ER-10X probe was used for collection of the DPOAE recordings. DP-primaries were continuously swept tones with a frequency ratio of 1.22 and the sweep rate was set to 2 s/octave, as in Long *et al.* (2008). Since measurements were made for three discrete frequencies, the following sweep frequency ranges of the second primary were chosen: 0.75-1.5 kHz, 1.5-3 kHz, and

3-6 kHz. The ranges were selected to place the target frequencies near the temporal centre of the sweep to avoid edge effects.

Four levels of the second primary ($L2$) were used (35, 50, 65, and 80 dB SPL), to span the compressive range of the BMI/O for NH listeners (Neely *et al.*, 2003). Two primary-level rules were used: (1) the scissors rule (DP-SC), where $L1 = 0.4 * L2 + 39$ for $L2$ below 65 dB SPL and $L1 = L2$ at and above 65 dB SPL; and (2) the equal-level rule (DP-EQ), where $L1 = L2$ for all L2 values. When L2 was at or above 65 dB SPL, the two rules resulted in the same L1. The primaries were calibrated in situ approximately once per minute via the FPL, in order to control the level of the stimuli at the eardrum.

In each of the six tested conditions (three target frequencies and two level-rules) 108 recordings were performed per L2 level. The SNR acceptance criterion was set at 5 dB. The least-squares-fit procedure was used to isolate the DP-generator component and thus reduce the fine structure in the DP spectrum (Long *et al.*, 2008). If the generator-component response levels could be estimated for at least two $L2$ values, the correspondiing CR was estimated as an inverse of the regression slope.

Temporal masking curves (TMC)

The TMC method is based on forward masking, where the listener's task is to detect a target tone following a masker tone. Pure tones were used with a duration of 200 ms (masker) and 16 ms (target). All tones were gated with 8 ms raised-cosine ramps, hence the target had no steady-state portion. The target frequencies were the same as in the DPOAE experiment (1, 2, and 4 kHz). Four conditions were used. In three on-frequency conditions, the masker frequency was same as the target frequency. The fourth condition was the off-frequency condition, where a 2.2-kHz masker and 4-kHz target served to obtain a single linear reference for all on-frequency conditions. The single-reference approach is similar to that of Johannesen and Lopez-Poveda (2008) and is based on the assumption of frequency-independence of post-cochlear decay. When elevated thresholds and the maximum level limitation rendered the 4 kHz off-frequency TMC unobtainable, a 2-kHz off-frequency TMC was collected instead (with the masker frequency set to 1.1 kHz). The on-frequency thresholds were taken as BMI/O input estimates and the off-frequency thresholds (obtained for corresponding masker-target time gaps) served as output-level estimates (Nelson *et al.*, 2001). To aid comparability with the DP-based fits, only the TMC-BM I/O points within the input range of 35-80 dB SPL were considered for a regression fit. CR estimates were obtained as in the DPOAE case.

The Grid method (Fereczkowski *et al.*, 2016), which adaptively varies masker-target gap and masker level in each experimental run was used to estimate the masked thresholds of a 12 dB SL target as a function of the time gap. A 3-alternative forced-choice paradigm with a 1-up 2-down step-rule variant of the Grid method was employed. This method was used to enable testing a wide range of masker-target gaps and thus maximize the tested range of the estimated masked thresholds in each

condition (Fereczkowski *et al.*, 2017). The set of testable gaps was defined as 10-250 ms with a 5-ms step. The corresponding set of testable masker-levels was -10 to 95 dB SPL for NH listeners and up to 100 dB SPL for HI listeners. The step size was 3 dB. The maximum level was reduced if a listener reported discomfort due to excessive loudness. At least two hours of training were administered to each listener. Six test runs were performed per test condition, to reduce the variability of the threshold estimates (Rosengard *et al.*, 2005).

RESULTS

Figure 1 illustrates the BMI/O estimates obtained for a representative NH listener (top panels) and HI listener (bottom panels). Each panel-column presents data for a single target frequency (1, 2, and 4 kHz from left to right). For the NH listener (top three panels), the slopes of the fitted lines are comparable between methods, particularly between the TMC and the DP-SC paradigms at 2 and 4 kHz. CE estimates from DP-EQ were usually higher than both TMC and DP-SC estimates (e.g., at 1 and 2 kHz). In some cases (1 kHz), the three methods returned estimates that did not show any clear correspondence. As shown in the bottom three panels of Fig. 1, several of the DPOAE data points failed to reach the 5 dB SNR criterion, particularly for frequencies above 1 kHz. This limited the number of compression slope estimates obtained for the HI listeners. Since the measured DP-EQ responses were generally lower than those from the SC paradigm, the 5-dB criterion was met less often in the EQ paradigm. Out of six HI listeners, only two returned more than 1 DP response at 2 kHz (two cases per paradigm), and just one at 4 kHz (DP-SC paradigm only).

The left panel of Fig. 2 presents scatterplots of CR estimates from the NH (top subpanels) and HI (bottom subpanels) listeners. The two left subpanels compare the TMC-based CRs (abscissa) and DP-SC inferred CRs (ordinate). The two right subpanels show the corresponding comparison between the TMC-based CRs and those from the DP-EQ paradigm. The data is aggregated across frequencies, due to the low number of DP-CR estimates at frequencies above 1 kHz obtained for HI listeners. For NH listeners, the CR estimates from both objective methods were not normally distributed. A Friedman's test showed a significant difference between the CR estimates obtained from the behavioral and objective methods [$\chi^2(2) = 35.4$, $p < 0.001$]. A post-hoc Bonferroni-corrected Yuen's paired-sample test showed that the TMC CR estimates were significantly higher than the corresponding DP-EQ estimates (trimmed mean difference of 2.06, $p < 0.001$) and that there was a trend towards TMC-CR estimates being higher than the corresponding DP-SC estimates (trimmed mean difference of 0.68, $p < 0.034$). The DP-EQ estimates were also significantly lower than the DP-SC estimates [$t(17) = 8.7, p < 0.001$] and the trimmed-mean difference was 1.38. Spearman's rank correlation coefficients between TMC- and DP-based estimates were low and insignificant ($\rho = -0.1$, $p < 0.57$ for DP-SC method and $\rho = 0.26$, $p < 0.18$ for DP-EQ method). The Spearman's correlation coefficient between the two DP methods was low (0.27) and insignificant ($p < 0.153$).

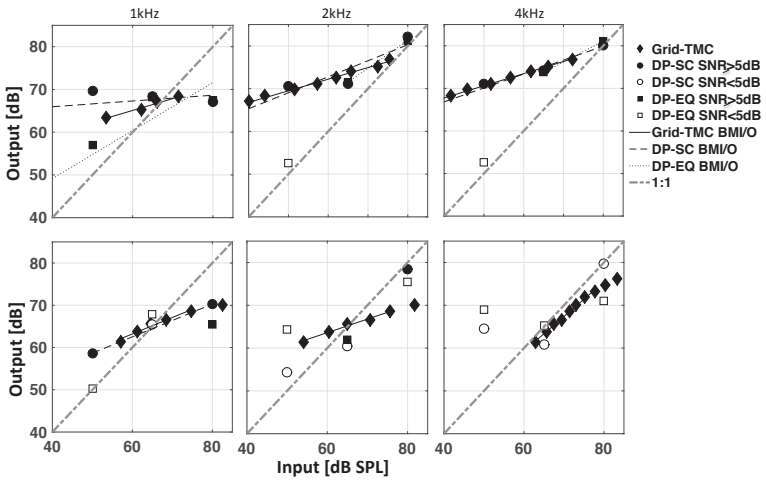

Fig. 1: BM I/O estimates from a representative NH listener (top panels) and a representative HI listener (bottom panels). Diamonds, circles and squares represent data points inferred from TMC, DP-SC and DP-EQ paradigms, respectively. Open symbols correspond to DP responses that did not meet the 5 dB SNR criterion. The solid circles and squares were fitted with straight lines, to estimate the CR of the corresponding DPI/O function. The dashed and dotted lines show the fits to the DP-SC and EQ paradigm data, respectively. The solid line represents the linear fit to the TMC-based estimates. The dash-dot line represents the linear reference (1 dB/dB). To aid visual comparability, an offset was added to each DPI/O curve, such that it coincides with the corresponding TMC-based I/O curve at the 75 dB input level.

For HI listeners, CR estimates from all three methods were normally distributed. The DP-SC CR estimates were significantly correlated with those from the TMC method (Pearson's $r = 0.77, n = 8, p < 0.026$) and the TMC CR estimates were on average lower (0.41), but the difference was not significant [$t(7) = 1.49, p < 0.18$]. The Pearson's correlation coefficient between the DP-EQ and TMC CR estimates was 0.8, i.e., comparable to the DP-SC case, but it did not reach significance ($n = 6, p < 0.057$). The average difference between the DP-EQ and TMC CR estimates was low (0.06) and not statistically significant [$t(5) = 0.24, p < 82$].

DISCUSSION

Out of the two physiological CR estimates, the DP-SC showed a better correspondence with the TMC-based estimate. First, the average difference between the DP-SC and TMC CR estimats was insignificant in NH and Hi listeners. Second, both measures

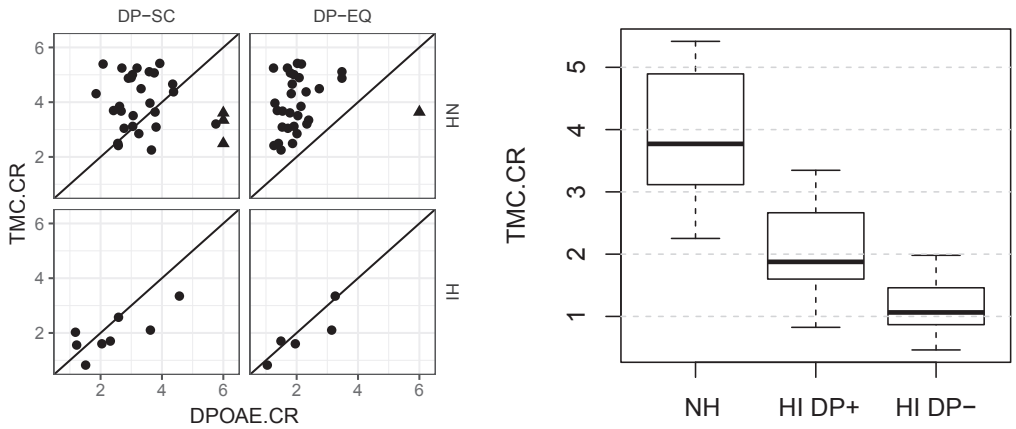

Fig. 2: Left: Scatterplots between the TMC and DP-SC (top panels) and DP-EQ (bottom panels) inferred CEs for the three tested frequencies. Right: DPOAE presence as indicator of BM compression. Each boxplot represents the TMC-inferred CRs from NH listeners and HI listeners with and without DPOAEs measured above the SNR criterion (see Discussion).

were strongly and significantly correlated in HI listeners. The lack of correlation between NH-CR estimates from the two methods is expected, under the assumption that the sporead in NH listeners data is an effect of measurement noise. In case of HI listeners, the dynamic range of the obtained estimates was larger than in NH listeners, hence the effect of measurement noise was smaller. To test this assumption, the between-method variability of the estimates was tested in NH and HI listeners by comparing geometric standard deviations (GSD) of the ratios of corresponding CR estimates obtained from the two methods. The GSD was 2.10 in NH and 1.48 in HI listeners. The NH value is inflated by three individual DP-SC CR estimates above 8, i.e., 2 times higher than the average NH value of 4 found in literature. Excluding these three values from the analysis returns a NH GSD of 1.43. This suggests that the between-method variability in NH listeners is comparable to or even higher than that in HI listeners, supporting the tested assumption. Thus, the good agreement between DP-SC and TMC results in HI listeners suggest that both methods estimate the same quality of the auditory pathway. Since DPOAEs are assumed to be generated by the cochlear nonlinearity and the generator component is assumed to reflect the state of OHCs near the $f2$ characteristic place, the observed correlations provide evidence that the TMC method is estimating BM compression. However, this conclusion is based on just eight data-points from HI listeners where CR could be estimated from DP-SC recordings.

In contrast, the CR estimates from the DP-EQ method were on average lower than the TMC and DP-SC based estimates in NH listeners, and no significant correlation was found between the DP-EQ and TMC estimates. However, the average difference between DP-EQ and TMC CR estimates was low and insignificant in HI listener group. The lower CR estimates from the DP-EQ method are a consequence of lower DP response levels elicited by this method, compared to those elicited by the DP-SC method for $f2$ levels below 65 dB SPL. In some cases the difference in responses levels exceeded 15 dB (e.g., top-right panel of Fig. 1). This suggests that the equal-level rule is less effective in eliciting BM response than the DP-SC rule, for input levels lower than 65 dB SPL, at least for NH listeners. Moreover, the DP-EQ method returned fewer CR estimates than the DP-SC method, in HI listeners at 2 and 4kHz.

DPOAE presence as indicator of compression

If an HI listener does not have functioning OHCs at some frequencies, then no measurable DP response should be obtained, regardless of the level rule. Thus, it can be hypothesized that such HI listeners will show lower behavioural CR estimates than those HI listeners with measurable DPOAEs. To test this hypothesis, a comparison was made between the TMC inferred CRs from cases with no DP data points above the SNR criterion and from cases with at least one data point above the SNR criterion. The right panel of Fig. 2 illustrates this comparison. The three boxplots show TMC-CRs from three groups of listeners: NH and HI with and without measurable DP responses. The median TMC-CR for NH listeners was 3.77. The median value of the TMC inferred CRs of the cases with and without DP responses were 1.88 and 1.06. A linear mixed-effect model was fitted to the data. The fixed effects selected for the model were hearing threshold, tested frequency, DP-response presence and the interaction of DP presence and the hearing threshold. The subject was selected as the random effect. According to the model, the DP presence was the only significant fixed predictor of the CR $(p < 0.001)$ in the HI groups, which also means that there was a significant difference betweren the two HI groups. Moreover, since the median CR of the no-DP group was close to 1, it can be hypothesized that the lack of measurable DPOAEs indicates a linear BMI/O.

CONCLUSION

BMI/O estimates were inferred from a behavioural method (TMC) and two physiological paradigms (DPOAEs with scissors and equal-level rules) in NH and HI listeners. While the DP-EQ method seems not to elicit maximum response from the BM, the CR estimates from the DP-SC method were comparable to those from the TMC method, particularly in HI listeners, where no significant bias and a significant correlation was found. However, this finding is based on few data points, since physiological CR estimate was obtained in 8 out of 18 HI cases. The median TMC CR estimates in HI listeners with and without measured DP responses were 1.88 and 1.06, respectively, and the difference between the two groups was significant. Altogether, these results suggest that both the DP-SC and the TMC method estimate peripheral compression.

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