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ASSOCIATION BETWEEN SPEECH IN NOISE PERFORMANCE AND INFERRED COCHLEAR RESPONSE FUNCTIONS

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ABSTRACT

Reduced cochlear functioning can affect speech perception in noise. Human inferred cochlear response input-output (I/O) functions can be obtained by objective measurement of distortion product otoacoustic emissions (DPOAEs) or by using psychophysical masking methods. I/O functions obtained using psychophysical methods take a longer time to acquire, than when obtained from DPOAE methods. However, psychophysical methods allow measurement of the inferred cochlear response I/O function in cases when DPOAEs may be absent. This study investigated the association between inferred cochlear response I/O functions obtained from nine normal-hearing listeners using DPOAEs and psychophysical forward-masking methods. I/O functions obtained using both methods were also compared to speech intelligibility scores obtained using the English-language Matrix speech test. The present study found that maximum cochlear compression inferred using the psychophysical method appeared to be moderately positively correlated with speech reception thresholds at noise levels of 45-65 dB SPL. Also, the maximum compression estimates obtained using DPOAEs covered a smaller range than the equivalent values obtained using the psychophysical method. Whilst the input levels associated with maximum compression covered a similar range across the two methods.

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1. INTRODUCTION

In standard clinical audiograms, hearing thresholds <20 dB HL are defined as falling within "normal/typical limits". However, hearing thresholds <20 dB HL may still be associated with some degree of damage to the auditory system, which may or may not manifest itself as real-world difficulties in hearing [1]. Evidence from small non-human mammals suggests that damage to synapses between inner-hair cells and auditory nerve fibres (cochlear synaptopathy) [2] may be present without elevated hearing thresholds. Using a mouse model, Kujawa and Liberman [2] demonstrated that 50% of synapses between inner-hair cells and auditory nerve fibres could be permanently destroyed whilst auditory sensitivity recovered [2]. In humans, the early stages of cochlear synaptopathy may not be evident as elevated hearing thresholds as measured by a standard audiogram (spanning pure-tone test signals of 0.25-8 kHz). It is possible that there still is sub-clinical cochlear hair-cell loss affecting responses to sound frequencies within the standard audiometric frequency range. Non-human animal models suggest that around 80% of inner-hair cells can be lost without affecting hearing thresholds [3]. In humans, elevated thresholds for sound frequencies beyond the range of the standard audiogram (i.e., 9-20 kHz) may be indicative of hair-cell loss/dysfunction within the standard audiometric frequency range [4,5]. Mishra et al. [5] found that distortion-product otoacoustic emissions (DPOAEs) between 2 and

5 kHz were absent in listeners with elevated thresholds for sound frequencies beyond the range included in the standard audiogram, suggesting damage to outer-hair cells [5].

DPOAEs are the result of the cochlear nonlinear interaction between two primary tones (at frequencies f_1 and f_2) that are continuously presented to the ear [6, 7]. DPOAE input-output (I/O) functions can be plotted as the DPOAE level at $2f_1 - f_2$ (output), as a function of the level of the primary tone f_2 (input). The slope of the I/O function can provide an estimate of cochlear compression [8–10].

Although DPOAE I/O functions can be used to infer outer hair-cell integrity and ability, they require distortion products to be present and measurable, which is often the case for normal-hearing listeners, but often *not* the case for those with hearing-impairment. Inferred cochlear basilar-membrane (BM) response I/O functions can be obtained using psychophysical methods [11–15] for hearing-impaired as well as normal-hearing listeners, which allow for estimates of cochlear gain and compression across a wider range of hearing profiles than may otherwise be possible with DPOAEs.

Yasin et al. [14] introduced a Fixed-Duration Masking Curve (FDMC) psychophysical method, in which the masker level at threshold is obtained for on- and off-frequency forward maskers for different complementary durations of signal and masker, with a short total combined masker-and-signal duration (e.g. 30 ms) and a masker-signal interval of 0 ms. The FDMC method helps reduce confounds due to brainstem-mediated efferent processes, such as the medial olivary complex reflex, which is known to appreciably dampen BM responses, and consequently influence masking thresholds. Since such processes have an onset delay of 43 ms (on average, with a range between 31-95 ms) [16], if the total stimulus duration is sufficiently brief, any efferent activation due to the stimuli should not confound estimates of masking thresholds and I/O functions related to cochlear excitation. These confound-reduced measures can then be used for comparisons with important hearing-related processes such as speech.

Understanding speech in ongoing adverse acoustic environments is crucial for everyday communication. For this reason, clinical assessment of speech perception in noise is often an integral part of an auditory test battery. One such test is the Matrix speech test [17, 18]. This test uses syntactically correct sentences, which are semantically non-predictable. Speech intelligibility (%) in noise is determined as a function of the signal-to-noise ratio (SNR). A value of the speech reception threshold (SRT) can be obtained from this function to achieve a given percentage-correct speech-identification score e.g., 50% (SRT-50). Abnormal speech intelligibility, as shown by an increased SRT, may indicate damage/dysfunction at the level of the cochlea.

The present study assesses the relationship between compression estimates derived from the I/O functions obtained via DPOAE and FDMC methods, and speech performance measured using the Matrix speech in noise test. It is hypothesised that high estimates of compression will be associated with good performance on the Matrix speech test.FDMC I/O functions may provide a more robust measure compared to DPOAE I/O functions across a range of population.

2. METHOD AND PROCEDURE

2.1 Listeners

Nine listeners took part (four women, five men; mean age 26 years). All provided signed consent for the study, which had been approved by the UCL Ethics Board. The assessment was comprised of an initial audiological test session (1 hour) followed by a separate session on another day for the Matrix speech tests and DPOAE tests, followed by a total of 2-3 hours of assessments spread across separate 1-hour sessions, to collect the FDMC data. All sessions included break times for listeners as required.

2.2 Facilities and Apparatus

The measurements took place in a double-walled sound-attenuated room. Audiometric threshold measurements and the Matrix test were conducted using a calibrated Auritec Audiometer with Ear3.0 software, Earbox3.0 soundcards, and Sennheiser HDA300 headphones. DPOAE I/O functions for the left and right ears were acquired using the Otodynamics EZ-Screen 2 software and calibrated Echoport interface and measuring probe, with a procedure adapted from Grose et al. (2017) [19]. The FDMC experimentation used stimuli digitally generated on a PC located outside the sound-attenuated room, using custom software written in MATLAB R2021a, and output via an EMU 0202 (24-bit, 96 kHz) USB 2.0 soundcard external to the PC. Antialiasing was provided by built-in filters. Stimuli were presented via the right channel of a pair of Sennheiser HD 600 headphones. The headphone input came directly from the analogue output of the soundcard.

2.3 Audiometry

Audiometry was performed separately for listeners' right and left ears using pure-tone signals (0.25-8 kHz) and the procedure recommended by the British Society of Audiology (BSA). All listeners had hearing within normal limits (i.e., hearing thresholds $<$ 20 dB HL). All listeners were also asked if they experienced tinnitus; none of the listeners reported tinnitus.

2.4 The Matrix Speech in Noise Test

The Matrix speech in noise test material contained 190 sentences in the English language, each consisting of five words, with one word of each category (name, verb, numeral, adjective, and object), e.g. "Lucy kept nine green beds". Matrix test stimuli were presented diotically. A quasi-stationary noise masker started 500 ms before the beginning of each sentence and ended 500 ms after the end of each sentence. Each of these five words was taken from a list of ten alternatives and the sentences were assembled randomly [20]. Listeners were trained on one run of ten sentences at a noise level of 45 dB SPL prior to presentation with six runs of 30 sentences at noise levels of 45, 55, and 65 dB SPL. Each noise level was tested twice across six runs, which were randomised and varied for each listener. Within a run, the SNR was adaptively adjusted after each sentence presentation by taking into account the number of words correctly repeated. The SRT-50 relates to the SNR associated with the 50% SRT score on the Matrix speech test. Examples of psychometric functions fitted to the Matrix test response of a single listener are shown in Figure 1.

2.5 DPOAE I/O functions

DPOAEs were measured using primary tones set at frequencies f_1 = 3841 Hz and f_2 = 4687 Hz, with a geometric mean frequency of 4243 Hz, and a distortion product at $2f_1 - f_2$ = 2996 Hz, following a procedure adapted from [19], DPOAE I/O functions were obtained by adjusting both primary tone levels, L_1 and L_2, in 10 level pairings according to the equation derived by [21]: $L_1 = 0.4L_2 + 39$. The pairings were selected such that L_2 decreases in 5 dB steps from 65 to 20 dB SPL. DPOAEs were defined as present if their magnitude at the expected frequency was greater than twice the standard deviation of the background noise level.

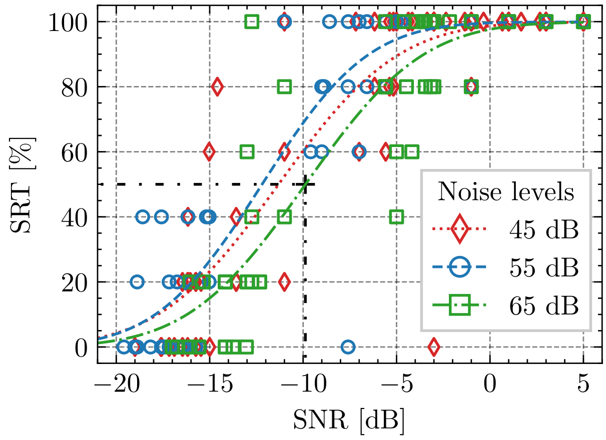

Figure 1: Illustrative results from one listener. The Matrix test responses with psychometric function fits are shown for the noise levels 45, 55, and 65 dB SPL. The SRT scores are plotted against the SNRs of the speech in noise stimuli. SRT-50 relates to the SNR associated with a 50% SRT and is shown by the cross and dash-dotted lines for the 65 dB noise level.

2.6 Psychophysical I/O functions

The FDMC method was used to measure psychophysical I/O functions. The signal (S) was a 4 kHz sinusoid, the masker (M) was a sinusoid at either 4 kHz (on-frequency) or 1.8 kHz (off-frequency), and M and S always began in sine phase. The masker preceded the signal with a 0 ms M-S gap. Both the masker and signal used 3.75 ms raised-cosine on- and off-ramps, and (across blocks) had variable steady-state durations such that the total duration of M-and-S was always maintained at 30 ms (the steady-state portions always summed to 15 ms). For masker-only stimuli, the signal portion was replaced by silence to make up 30 ms in total. Signal steady-state durations for on-frequency masking trials were 0, 5, 7.5, 10, 12.5 and 15 ms, with complementary masker steady-state durations of 15 down to 0 ms, respectively. Signal steady-state durations for off-frequency masking trials were mostly 0, 2.5 and 7.5 ms, although occasionally 5 ms was used for a listener if maskers levels approached 100 dB SPL or higher at the 7.5 ms setting.

A two-interval, two-alternative forced choice (2I-2AFC) adaptive tracking procedure was used, with an inter-stimulus interval of 500 ms. The level of the masker or signal was varied adaptively (2-up 1-down and 2-down

1-up, respectively) to obtain the level required to achieve 70.7% correct [22, 23].

For each block of trials, the initial step-size was 4 dB, which reduced to 1 dB after the first 4 reversals. Once running at the 1 dB step-size, the threshold value for a block was the average of levels at the last 8 reversals. If the standard deviation was greater than 6 dB, the block was rerun.

Listeners were seated in front of a computer screen and keyboard. A computer-simulated response box appeared on the screen, providing lights that coincided with each observation interval within a trial, and a feedback interval at the end of each trial. The decision about which interval contained the signal was recorded via key press. Correct and incorrect decisions were followed by a 500-ms green or red light (respectively) in a panel within the response box.

After a practice block to familiarise listeners with the equipment, task, and the stimuli, each listener completed three signal-only, silent-masker, signal-varying blocks, where the signal was set to the shortest duration of 7.5 ms (0 ms steady-state), and the masker was set to the longest duration of 22.5 ms (15 ms steady-state). If the range of the three threshold estimates was more than 4 dB, another block would be run. The average across these runs was used as the estimate of absolute threshold. For the main masking blocks, the signal was fixed in level at +10 dB above absolute threshold, and the masker varied adaptively. Off-frequency data was collected first, on-frequency data was collected last, and duration conditions were randomised across blocks per masker frequency. Each listener completed 2 blocks at each setting and the average used across runs for data analysis. Time-permitting, more runs were collected for specific settings if the variability in threshold setting was high (> 12 dB difference across runs).

3. RESULTS AND DISCUSSION

This study assessed the relationship between compression estimates derived from I/O functions obtained using DPOAE and FDMC methods. These estimates were compared with speech-in-noise performance obtained using the Matrix speech text.

I/O functions were obtained from DPOAE data by plotting the measured distortion product level in dB SPL against the level of the L2 tone. Inferred I/O functions were obtained from FDMC data as follows. Per listener, both off- and on-frequency thresholds (in dB SPL) were plotted as a function of signal duration (in ms). A linear least-squares fit was made to the off-frequency data, which can be well described by a linear function in (ms, dB) coordinates [14, 15]. Next, I/O functions were derived by plotting on-frequency thresholds (input) versus off-frequency linear fit values (output) for each on-frequency signal duration used, resulting in data points as shown in Figure 2.

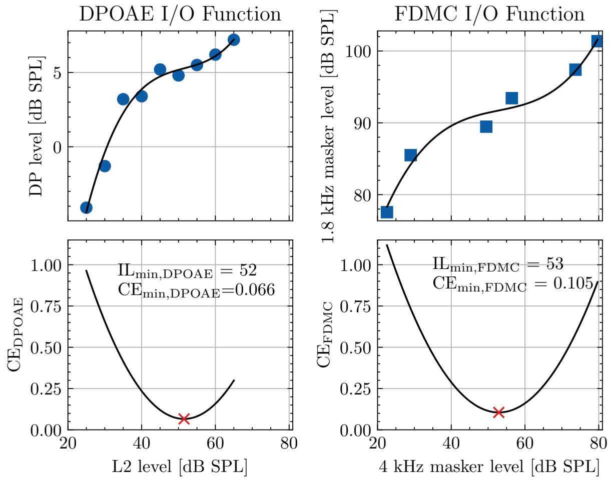

Figure 2: Illustrative results from one listener. Example DPOAE I/O function and FDMC I/O function fitting procedures applied to the listener data. Third-order polynomial fits to the data from both DPOAE and FDMC methods to obtain I/O functions are shown in the upper panels. Estimates of the compression exponent (CE) are shown in the lower panels. Value of minimum compression exponent (CE_{min}) is marked with a red cross, and was obtained by finding the minimum of the quadratic derivative.

3.1 FDMC and DPOAE Measures of Compression

Per listener, a 3rd-order polynomial least-squares fit was made to each data-set, and the derivative (2nd-order polynomial) provided estimates of compression exponent as a function of input level. For DPOAE data, input level refers to the level of L_2. For FDMC data, input level refers to on-frequency 4-kHz masker threshold level. The minimum compression exponent value (CE_{min}) and the input level at which it occurs (IL_{min}) were calculated. If 3rd-order fits resulted in negative slope values for a portion of the input range, which happened occasionally but only slightly, then CE_{min} was defined as 0, and IL_{min} was the average input level in this range.

Figure 2 shows example DPOAE (left-hand panels) and FDMC (right-hand panels) I/O function data, along with polynomial regression functions, obtained from one listener. Upper panels show data and 3rd-order polynomial fits. Lower panels show 2nd-order polynomials derived from the fitted functions in the upper row. The value of the minimum compression exponent (CE_{min}) corresponded to the minimum of the quadratic derivative. CE_{min} is marked with a red cross, and lies at the coordinate (IL_{min} , CE_{min}).

Figure 3 shows the CE_{min} and IL_{min} values obtained using FDMC and DPOAE methods. The values of CE_{min} (FDMC) range between 0-0.8, and values of CE_{min} (DPOAE) range between 0-0.2. IL_{min} (FDMC) range between 40-65 dB SPL, and CE_{min} (DPOAE) range between 51-72 dB SPL, covering a similar range of values. Previous studies using the FDMC method and another psychophysical masking technique, the temporal Masking curve (TMC) method, to estimate CE_{min} for 4 kHz signals with a normal-hearing population, have also reported CE_{min} within a similar range [24,25]. The range of IL_{min} (FDMC) values obtained in the present study correspond with previously-cited range of values for the IL_{min} (FDMC) range in a normal-hearing population [24]. The FDMC method has been shown to provide CE_{min} estimates associated with lower input masker levels (IL_{min}) compared to the TMC method [26]. Gregan et al. [27] also showed that using a psychophysical Growth-of-Masking technique (GOM), estimates of CE for a 4-kHz signal covered a range of 0-0.6.

Figure 3 (left panel) shows that there is minimal correlation between the IL_{min} obtained between the two methods (DPOAE and FDMC). There is a stronger correlation between CE_{min} (DPOAE) and CE_{min} (FDMC), as shown in Figure 3 (right panel), although not significant. This correlation is negative, i.e., higher estimates of CE_{min} (FDMC) (less compression) are correlated with lower estimates of CE_{min} (DPOAE) (more compression).

Glavin et al. [28] showed that overall, DPOAE I/O functions can be variable in a younger normal-hearing (<25 dB HL, 0.25-8 kHz) population. In a normal-hearing group, CE_{min} estimates obtained from I/O functions using the TMC method and DPOAE measures also appear to cover a similar range of 0-0.5 (for 1- and 2-kHz signals) [29]. Johannesen et al. [30] reported a reasonable correspondence between TMC and DPOAE I/O function

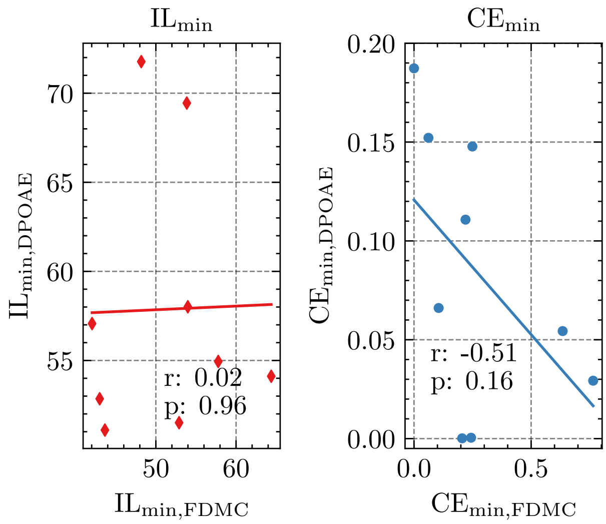

Figure 3: Data from all listeners. The plots present the relationship between the Input Level corresponding to the value of CE_{min} (IL_{min}) obtained from both DPOAEs and FDMC methods (left panel) and the value of CE_{min} obtained from both DPOAEs and FDMC methods (right panel). The Pearson correlation (r) values are shown inset within the legend.

slopes and CE_{min} estimates for 4-kHz signals (they found no relation between CE_{min} estimates obtained using the TMC method and DPOAE measures for signals below 4 kHz). Their estimates of the range of CE_{min} (TMC) (0-0.2) values cover a smaller range than the values obtained using the FDMC in the current study, whilst their estimates of CE_{min} (DPOAE) (-0.2-0.3) correspond with the CE_{min} range of values reported in the present study.

3.2 Compression and Speech in Noise Performance

Figure 4 shows the relationship between the averaged speech reception thresholds (SRT) for achieving 50% correct on the Matrix speech test (SRT-50) and the metrics obtained using both FDMC and DPOAE methods (IL_{min} and CE_{min}).

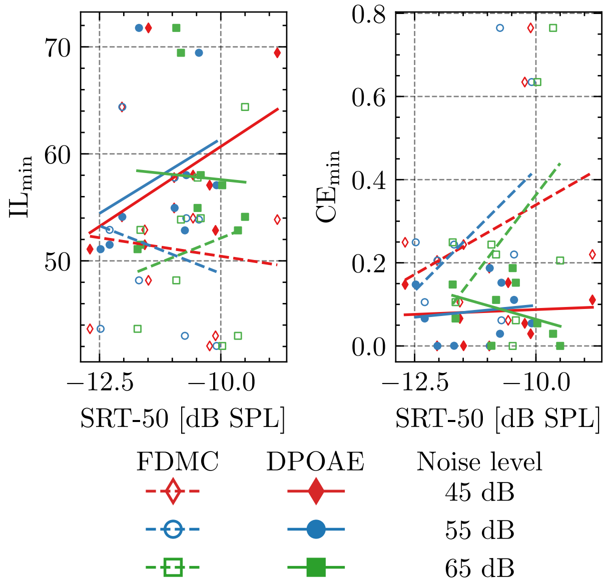

Figure 4: Data from all listeners. The figure shows compression metrics obtained with the DPOAE and FDMC methods as a function of averaged speech reception thresholds (SRT-50) at noise levels 45, 55 and 65 dB. SRT-50 represents the SNR required to achieve 50% correct on the Matrix speech in noise test. Left panel shows the relationship between input levels (ILmin) corresponding to CE$_{min}$ values, and SRT-50. Right panel shows the relationship between CE$_{min}$ values and SRT-50. Corresponding Pearson correlations are presented in Table 1.

Table 1 presents the correlations between IL$_{min}$ and CE$_{min}$ with SRT-50 (corresponding to the data in Fig. 4). Overall, none of the correlations are significant. However, there are some noteworthy trends. IL$_{min}$ (DPOAE) values for noise levels of 45 and 55 dB SPL appear to be positively correlated with SRT-50. This suggests that at lower noise levels, minimal CE$_{min}$ (which is related to IL$_{min}$) is achievable with lower input levels, whilst the the value of CE$_{min}$ (DPOAE) itself looks to be highly variable and minimally correlated with SRT-50. Conversely, IL$_{min}$ (FDMC) looks to be highly variable and minimally correlated with SRT-50, whereas CE$_{min}$ (FDMC) is moderately positively correlated with SRT-50 at all noise levels (45-65 dB SPL), and increases with noise level.

Johannesen et al. [31] also reported associations between compression and speech in noise performance. In the latter case, a correspondence was reported between residual cochlear compression and SRT, as measured using the Hearing in Noise Test (HINT) [32] with a speech-shaped noise masker for a hearing-impaired population.

Table 1: Pearson correlations (r) and p-values for IL$_{min}$ and CE$_{min}$ as function of SRT-50 as plotted in Fig. 4.

			Noise level [dB SPL]		
			45	**55**	**65**
IL$_{min}$	**DPOAE**	r:	0.46	0.32	-0.05
		p:	0.22	0.4	0.9
	FDMC	r:	-0.11	-0.21	0.19
		p:	0.78	0.6	0.62
CE$_{min}$	**DPOAE**	r:	0.08	0.14	-0.38
		p:	0.84	0.71	0.31
	FDMC	r:	0.3	0.39	0.47
		p:	0.43	0.29	0.2

4. CONCLUSION

It was hypothesised that high estimates of compression would be associated with good performance on the Matrix speech test, and that FDMC I/O functions may provide a more robust measure compared to DPOAE I/O functions for a range of hearing profiles. The present study found that CE$_{min}$ (FDMC) appeared to be moderately positively correlated with SRT-50 scores at noise levels of 45-65 dB SPL, and increased with noise level. The CE$_{min}$ values obtained using DPOAEs covered a smaller range than CE$_{min}$ values obtained using FDMCs. Whilst IL$_{min}$ values obtained using DPOAE and FDMC methods covered a similar range.

5. ACKNOWLEDGMENTS

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