A pilot study of changes in otoacoustic emissions after exposure to live music

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ABSTRACT

The objectives of this investigation were to document sound exposures at concerts and to relate them to measurable changes on hearing. Changes in the auditory function of human subjects were measured using Distortion Product Otoacoustic Emissions (DPOAE) and Transient Evoked Otoacoustic Emissions (TEOAE). Sound exposures were measured using a Behind the Ear Hearing aid (BTE) modified to log equivalent levels. The main observations from this study are: There are measurable changes in the auditory function after attendance to a single concert; The DPOAE measurements were more robust to background noise than the TEOAE measurements and may therefore be better suited for field assessments; the estimated exposure levels cannot predict the changes observed in the OAE measurements.

1. INTRODUCTION

Excessive sound exposure from amplified music has been shown to be a potential hearing hazard [1, 2]. At a European level, there are neither standards nor legislation establishing limits of sound exposure for guests at musical venues or patrons at discotheques [3]. The same report acknowledges sound exposure from leisure activities (discos, rock concerts, personal music players, noisy sport activities) a potential public health problem that affects the younger generations. Exposure to live amplified music has very different characteristics than exposure to industrial noise, which is the basis for the existing damage risk criteria [4, 5]. Therefore in order to establish limits and set regulations for sound exposures at concerts, typical sound exposure characteristics must be documented together with their effects on hearing.

When considering live amplified music, the assessment of the sound exposure requires a representative measure of an individuals' sound exposure. This is due to the large variations in sound level at different places of a musical venue and because people can move around the venue during concerts. This can be achieved using person mounted microphones, i.e. embedded in hearing protectors, hearing-aids, dosimeters, etc. The position of the microphone and its relation with the sound field value used for assessment of risk (i.e. L_{Aeq}) should be well documented.

A measure of the effects on hearing needs to be obtained immediately after the exposure. This is due to the mostly temporary nature of the changes in hearing that occur after a sound exposure. Therefore, the method chosen must be fast and sensitive to small changes of the auditory function. Traditionally this has been done using absolute hearing thresholds to derive a Temporary Threshold Shift (TTS) [6], but threshold determinations are time consuming and require low levels of background noise, making it difficult to use outside a laboratory. An alternative can be found with Otoacoustic Emissions (OAEs). OAEs are an objective measure of the peripheral auditory system (ear canal, middle ear and inner ear) that do not require active participation of the subject. Normal hearing thresholds have been measured with reduced or absent OAEs, leading to the suggestions that OAEs are more sensitive measures of peripheral auditory dysfunction than hearing thresholds [7, 8].

Previous investigations have used OAEs to assess effects on auditory function from exposure to music. [9] reported lower TEOAE reproducibility for singers than for age and gender matched non-singers with no history of noise exposure. [10] reported significant differences in DPOAE levels of subjects while no differences were found in hearing thresholds after a 30 min exposure to music from an mp3 player. [11] reported changes in TEOAE band-reproducibility and signal to noise ratio as well as reduced DPOAE levels after subjects attended a discotheque for five hours. [12] reported changes in DPOAE levels similar to TTS of subjects that attended a discotheque for a period of three hours. The main conclusions from these, and other similar investigations, are that OAEs can be used reliably to investigate changes in the auditory function produced by music sound exposure. This is currently being investigated either by comparison of OAEs form people regularly exposed to amplified music with non-exposed controls; or by observation of the changes in OAEs from single exposures to amplified music.

The main goal of the present study is to investigate the impact of live amplified music on the auditory function of typical concert audiences. The idea is to be able to document exposure characteristics and their related impact on the auditory function. This research is conducted within the *Music as Noise* project, which is running in the framework of the Danish Sound Technology Network[1].

This paper presents results from a pilot study with the following objectives: 1) To test the measurement protocol; 2) To evaluate the existing conditions for field measurements; 3) To measure typical sound exposure levels at concerts; 4) To obtain an informed opinion about the impact on DPOAE and TEOAE from live amplified music.

The results presented here, have been obtained in collaboration with Roskilde Festival[2] and Oticon[3], they represent individual cases and may not be representative for the majority of live concert attendees.

2. METHODS

2.1. Subjects

Six volunteer subjects between 23 and 39 years of age (average age of 31,9 years) participated in the experiment. All subjects had hearing thresholds ≤20 dB HL in the frequency range from 0.5 to 8 kHz in 1/2-octave steps, based on standard pure-tone audiometry. None of the subjects reported known hearing disorders and it was possible to measure TEOAEs and DPOAEs in all of them.

2.2. Otoacoustic Emissions measurements

All OAE measurements were done with a custom made MATLAB program, an OAE probe microphone (ER10C, Etymotic Research) and an external USB sound card (Edirol UA-25ex, Roland).

For all subjects TEOAEs and DPOAEs were measured for both ears. The measurement procedure was to fit the probe into one of the subject's ears (selected randomly) and then measure both DPOAE and TEOAE without refitting the probe. After a short break the probe was fitted into the other ear and the measurements were repeated. With this procedure the DPOAE measurement lasted around 3 min and the TEOAE measurement around 1 min for each ear. For every subject, it took approximately 10 min to collect the data for both ears.

Before each measurement the OAE probe fitting was monitored by measuring the impulse response of the probe in the ear canal using an 80 μs impulse with peak level of 75 dB. The measurement was repeated until a good fit was obtained. The frequency response, the time signal and the peak level measured during the fitting process was recorded for comparison with subsequent fitting of the probe.

2.2.1. DPOAE

Measurements were made using primary frequencies with the following characteristics: ratio $f_2/f_1 = 1,22$; levels $f_1 = 65$ dB and $f_2 = 45$ dB; stimulus duration 1,3 s. Sixteen pairs of linearly spaced primaries were used giving distortion product frequencies (f_{dp}) between 900,8 and 3301,5 Hz.

During the measurement, the system reproduced each set of primaries for 1,3 s while recording the signals present in the ear canal. The time signal recorded was then transformed into the frequency domain using the Fast Fourier Transform (FFT), where the levels of the primary frequencies and the distortion product frequencies where calculated from the amplitude of the corresponding FFT bins. The time signal was sampled at 48 kHz and using an FFT length equal to the length of the signal (62400 samples), the frequency resolution of the measured signal was 0,769 Hz. All f_{dp} corresponded to an FFT bin, so no averaging across FFT bins was required. For each DPOAE value an estimate of the noise at the f_{dp} was determined as the average amplitude of the FFT bins falling within an Equivalent Rectangular Bandwidth

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[2] www.roskildefestival.dk
[3] www.oticon.dk

(ERB) centered at the f_{dp}, but excluding it [13]. The primary pairs were presented in ascending order and repeated five times without refitting the probe.

The stimulus levels where calibrated by filtering the probe output to give a flat response in an IEC 711 coupler up to 10 kHz. Individual level adjustments were made during the probe fitting procedure to compensate for deviation from the target level used while fitting the probe. With this procedure there are differences between the exact primary levels presented to each subject due to the differences between the IEC 711 coupler and the individuals' own ear. By ensuring a consistent fitting of the probe, the levels presented to each subject are the same for each repetition of the measurement.

2.2.2. TEOAE

Measurements were made using the "non-linear" differential stimulus block proposed by [14]. The system used a sampling frequency of 48 kHz giving a TEOAE response of 960 samples (20 ms) with a frequency resolution of 50 Hz and a bandwidth from 0,5 to 6 kHz. For each TEOAE measurement 500 repetitions of the stimulus block were recorded and divided into two groups A and B. The average from all 500 repetitions (A and B) was used as the TEOAE response and an estimate of the noise of the measurement was calculated as the difference between A and B. As a measure of repeatability, the absolute value of Pearson's correlation coefficient (in %) was calculated between A and B. A high correlation (>80%) implies a strong emission and a low correlation (<40%) implies a weak emission or a noisy measurement. The system allowed for on-line monitoring of the measurement and all measurements with equivalent levels (integrated over the measurement period) greater than 40 dB where rejected. The measurement continued until 500 repetitions where saved.

2.3. Sound Exposure Measurements

Sound exposure measurements were carried out using a behind-the-ear hearing-aid (Oticon Vigo BTE 312, here designated as BTE) reconfigured to work as a dosimeter, with a dynamic range from 40 to 115 dB SPL and a flat frequency response between 80 and 8000 Hz. Sound exposures measured in this manner do not conform with current standards for sound exposure assessment. Therefore they are only an estimate of the exposure level and are to be used for comparison with exposures measured with the same method. Here the results from these measurements will be referred to as Ear Exposure Level (EEL).

Three subjects were exposed to a single 90 min concert and were placed at a designated measurement positions in the audience next to a person wearing the BTE. The persons wearing the BTE were mapping the sound levels in front of a large outdoor stage as a part of another project. The BTE were set to log equivalent continuous sound pressure levels every 2 seconds in three frequency bands: Low <312,5 Hz, Mid 312,5 – 2500 Hz and High >2500 Hz. A broad-band A-weighted level was calculated using a three band approximation of the A-weighting curve. The exposure levels representative for the exposure of these subjects were calculated using the approximated A-weighted level for the duration of the concert (90 min).

The other three subjects were each fitted with a BTE upon arrival to the music venue and instructed to use the device throughout their entire stay. These subjects were free to move around the music venue and participate in different concerts and activities. The BTE were programmed to measure an equivalent continuous A-weighted level every 10 seconds. Individual exposure levels were calculated considering the sound exposure from the moment they arrived at the music venue until the time when the post-exposure measurements were carried out.

The main difference of the two types of sound exposures is that the first three subjects received a single intense exposure of 90 min, while the last three subjects were free to move about the music venue being exposed to high as well as low sound levels.

A summary of the measured exposure levels is presented in Tab. 1 and the distribution of measured exposure levels is presented in Fig. 1 for the range between 50 and 120 dBA in 5 dB intervals.

2.4. Experimental Procedure

Pre-exposure DPOAEs and TEOAEs were obtained before sound exposure either days prior to the concerts or during the same day, before any sound exposure. After the sound exposure, the same DPOAE and TEOAE measurements as for the pre-exposure measurements were carried out in the vicinity of the music venue, in a nearby school for three subjects (M01, M03 and F04) and in a closed area of the music venue for the other three subjects (M05, M07 and F08).

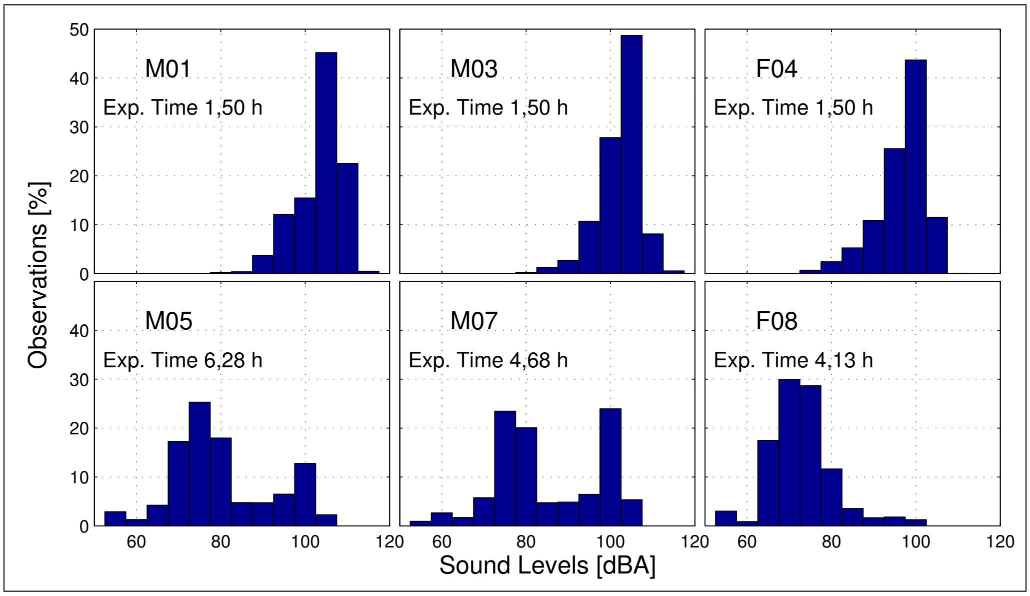


Fig. 1: Sound levels for the range between 50 and 120 dBA in 5 dB intervals for the exposures of each subject. (Top row) Exposures for the subjects that participated in the same concert, measurements every 2 s. (Bottom row) Exposure for the subjects that participated in different concerts other activities, measurements every 10 s.

Subject	EEL_{Aeq} [dB]	Exp. Time [h]	EEL_{EX} [dB]
M01	112,7	1,50	105,5
M03	111,3	1,50	104,0
F04	106,2	1,50	99,0
M05	94,2	6,28	93,1
M07	96,1	4,68	93,8
F08	83,3	4,13	80,4

Table 1: Ear Exposure Levels for each subject. The first column shows the A-weighted level measured with the BTE (EEL_{Aeq}), the second column shows the exposure duration, and the third column shows the A-weighted BTE level normalized to an 8 hour period (EEL_{EX}).

3. RESULTS

3.1. DOPAE

Fig. 2 shows the average pre-exposure DPOAE (blue), the average post-exposure DPOAE (red) and the corresponding noise floor (grey) levels for both ears of all subjects. Each point in the plots is the average of 5 measurements at each pair of primaries. The error bars denote the standard deviation over the five repetitions. For every frequency a paired t-test was used to compare the mean of the pre- and post-exposure measurements.

For the subjects that participated in the same concert (left side of Fig. 2) the time elapsed between the end of the exposure and the post-exposure measurement was different. Subject F04 was measured 1 hour after the exposure and showed the least amount of change with a maximum reduction in DPOAE level of about 3 dB ($p < 0,001$). Subject M03 was measured 45 minutes after the exposure and showed a maximum reduction in DPOAE levels of about 5 dB ($p < 0,01$). Subject M01 was measured 30 minutes after the exposure and showed a maximum reduction in DPOAE level of about 9 dB ($p < 0,001$). In general the exposure had mild reduction of the DPOAE levels.

Subjects that had longer exposures are shown on the right side of Fig. 2. Subject M05 had a reduction at all measured frequencies with a maximum reduction in DPOAE levels of about 28 dB ($p < 0,001$). For subject M07 most of the effects were observed below 2 kHz with a maximum of reduction of DPOAE levels of about 24 dB ($p < 0,001$). For this subject the post-exposure measurement of the right ear has a background noise that is close

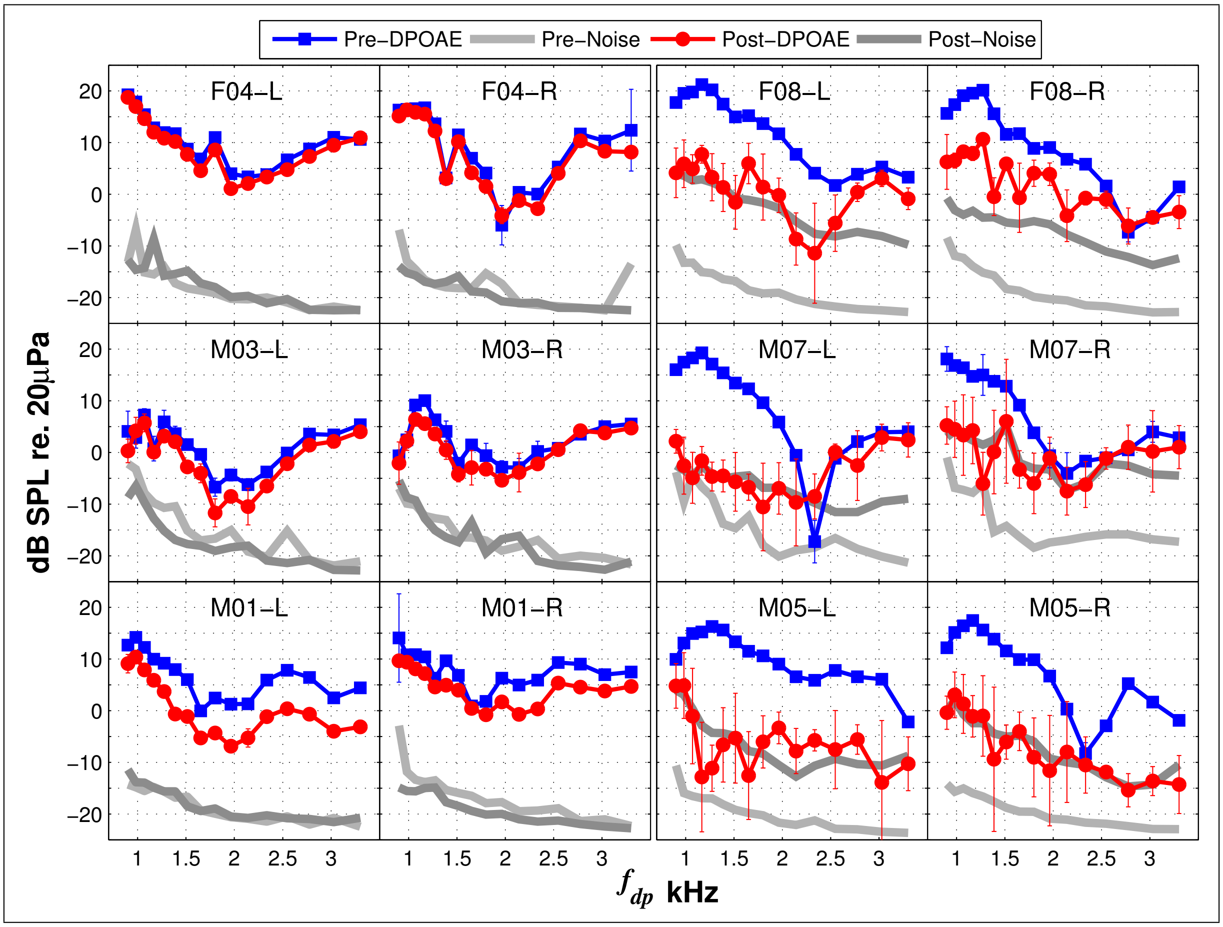


Fig. 2: Average pre- (blue) and post-exposure (red) DPOAE levels as a function of the distortion product frequency f_{dp}. (Left side) Subjects that participated in the same 90 minutes concert: F04: $EEL_{EX} = 99,0$ dB, post-exposure measurement time 1 h; M03: $EEL_{EX} = 104.0$ dB , post-exposure measurement time 45 min; M01: $EEL_{EX} = 105.5$ dB, post-exposure measurement time 30 min. (Right side) Subjects with longer exposures: F08: $EEL_{EX} = 80.4$ dB; M07: $EEL_{EX} = 93.8$ dB; M05: $EEL_{EX} = 93.1$ dB.

to the pre-exposure level. For subject F08 most of the effects were observed below 2.5 kHz with a maximum reduction in DPOAE level of about 16 dB ($p < 0,01$). For these subjects almost all the post-exposure DPOAE levels were found within the background noise. Nevertheless, the figure shows that with the exception of the right ear of subject M07 all of the post-exposure background noise estimates are below the pre-exposure DPOAE levels. If the subjects had not been affected by the sound exposures, the DPOAE levels measured after the exposure should still be above the background noise and comparable to the pre-exposure levels. They are not.

3.2. TEOAE

The results of the TEOAE measurements are presented in Fig. 3 for each subject in terms of the pre- and post-exposure correlation coefficient, emission level and noise level calculated for the broad-band signal (BB) and for the octave bands centered at 1, 2, and 4 kHz.

Fig.3 shows that the largest reduction in TEOAE amplitudes were observed for subjects M01. The amplitude reduction was also accompanied by a decreased in the correlation coefficients at the 2 and 4 kHz band. Subject

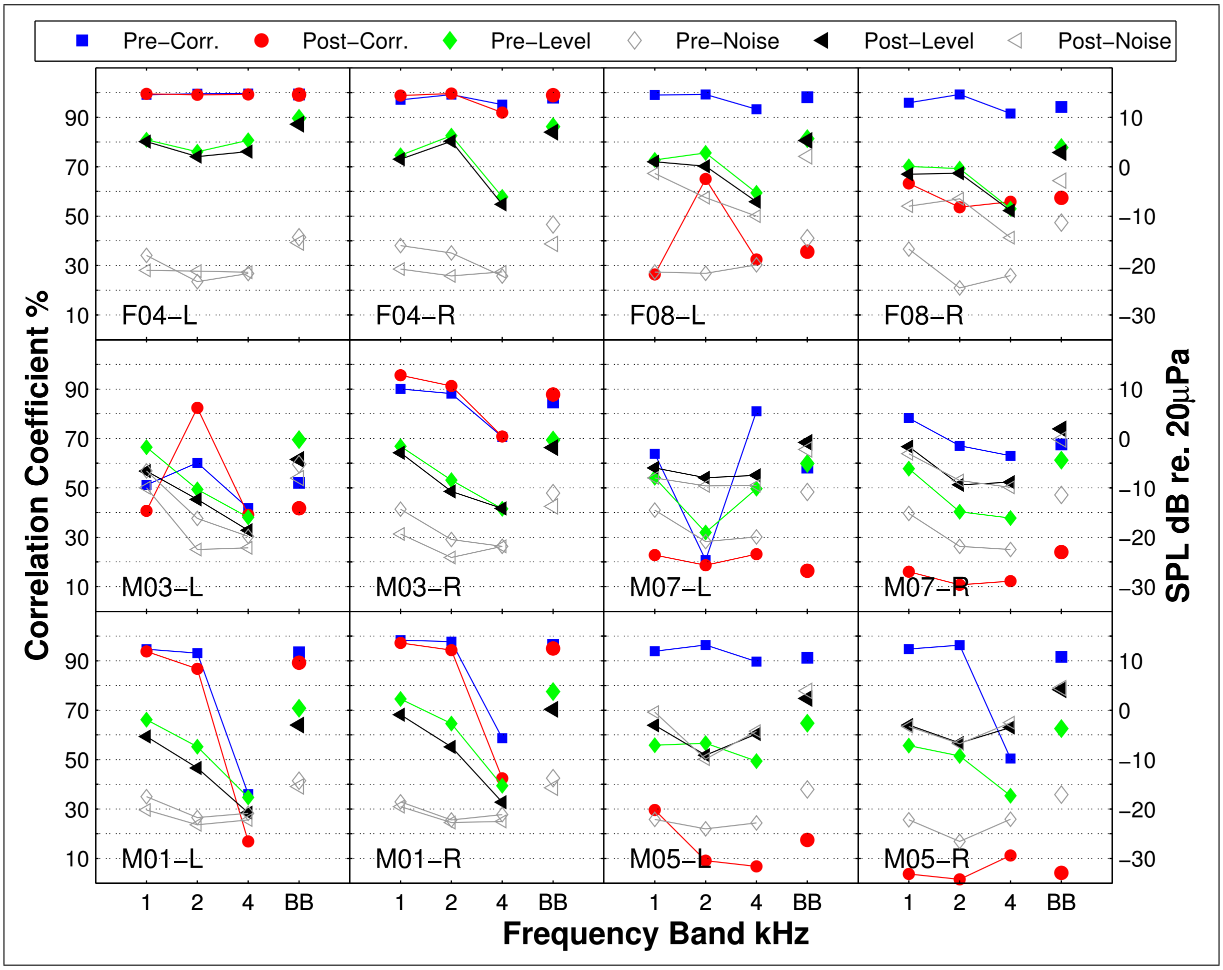
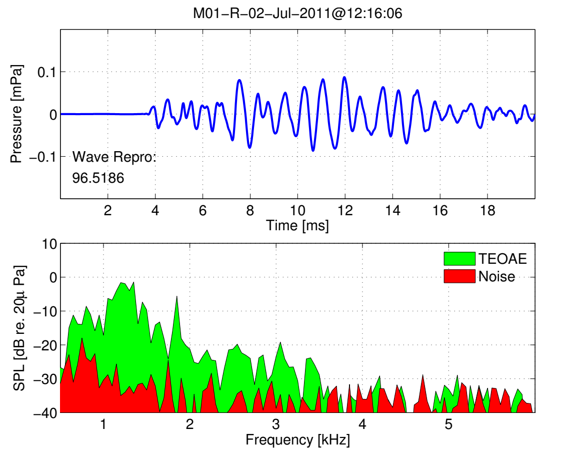


Fig. 3: Pre- (blue: *Pre-Corr.*) and post-exposure (red: *Post-Corr.*) TEOAE correlation in percentage, scale to the left. Pre- (green: *Pre-Level*) and post-exposure (black: *Post-Level*) TEOAE level with the corresponding noise levels (grey open symbols: *Pre-Noise* and *Post-Noise*) in dB, scale to the right. The data is presented for the octave-bands centered at 1, 2, and 4 kHz as well as for the broad-band signal (BB). Each panel presents de data for one ear of each subject (i.e. F04-L: subject F04 left ear).

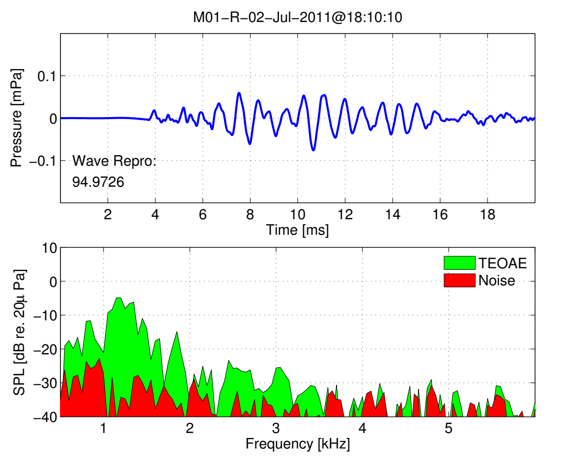
M03 also showed a decreased TEOAE amplitude more pronounced in the left ear. For this subject the increase in post-exposure correlation at 2 kHz is due to the increased signal to noise ratio in that band. Subjects F04 and F08 showed a very small decrease in TEOAE amplitude. The main difference between these two subjects is that for subject F08, there is a substantial increase in the post-exposure noise level reducing the correlation values. For subjects M05 and M07 the post-exposure measurements are affected by external noise giving the same levels for TEOAE and noise. This also the reason for the low correlation values.

Figures 4, 5, 6 and 7 show examples of pre- and post-exposure TEOAE measurements of four different ear. The examples are chosen to illustrate the different types of measurement outcomes.

Fig. 4 shows the TEOAE obtained for the right ear of subject M01. The figure shows that there is a decrease in the TEOAE amplitude in the 2 kHz frequency region. This subject also showed low emissions above 3.5 kHz

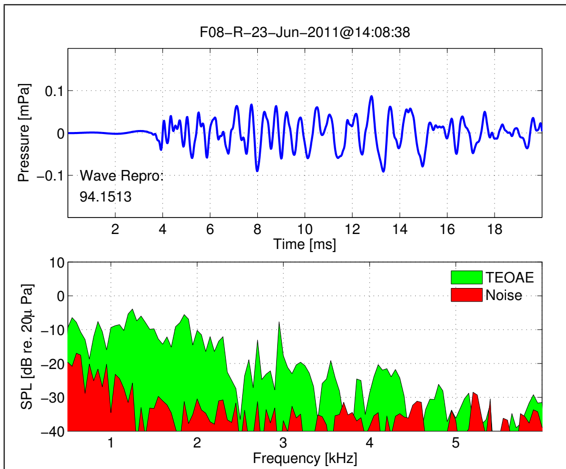


(a) Pre-exposure

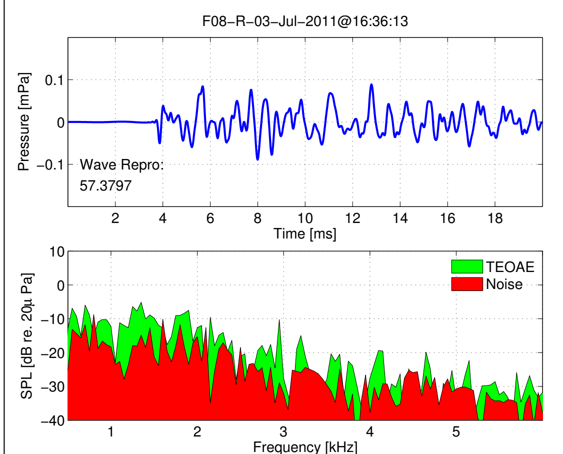


(b) Post-exposure

Fig. 4: TEOAE measurements for the right ear of subject M01. (a) Pre-exposure TEAOE as a function of time (top), pre-exposure TEOAE amplitude and noise estimate amplitude as a function of frequency (bottom). (b) Post-exposure TEOAE as a function of time (top), post-exposure TEOAE amplitude and noise estimate as a function of frequency (bottom). Correlation coefficients are denoted in the figure as Wave Repro.



(a) Pre-exposure



(b) Post-exposure

Fig. 5: TEOAE measurements for the right ear of subject F08. Plotted in the same manner as Fig. 4.

which explains the low correlation and amplitude values shown for the 4 kHz band in Fig. 3.

Fig. 5 shows the TEOAE obtained for the right ear of subject F08. In this example there is little decrease of TEOAE amplitude, but there is a considerable increase in the noise level giving a low post-exposure correlation value.

Fig. 6 shows the TEOAE obtained for the left ear of subject F04. This subject showed almost no change one hour after the 90 minutes exposure. All the prominent features of the emission are present in the post-exposure measurement. Any effects this subject may have experienced after the exposure had receded by the time of the post-exposure measurement.

Fig. 7 shows the TEOAE obtained for the left ear of subject M05. The figure shows that the post-exposure

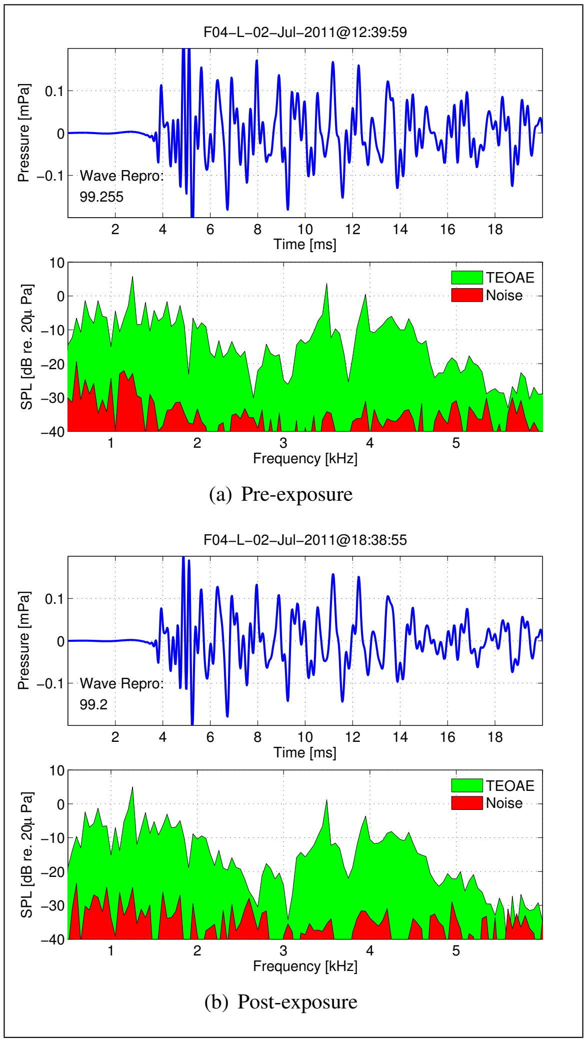


Fig. 6: TEOAE measurements for the left ear of subject F04. Plotted in the same manner as Fig. 4.

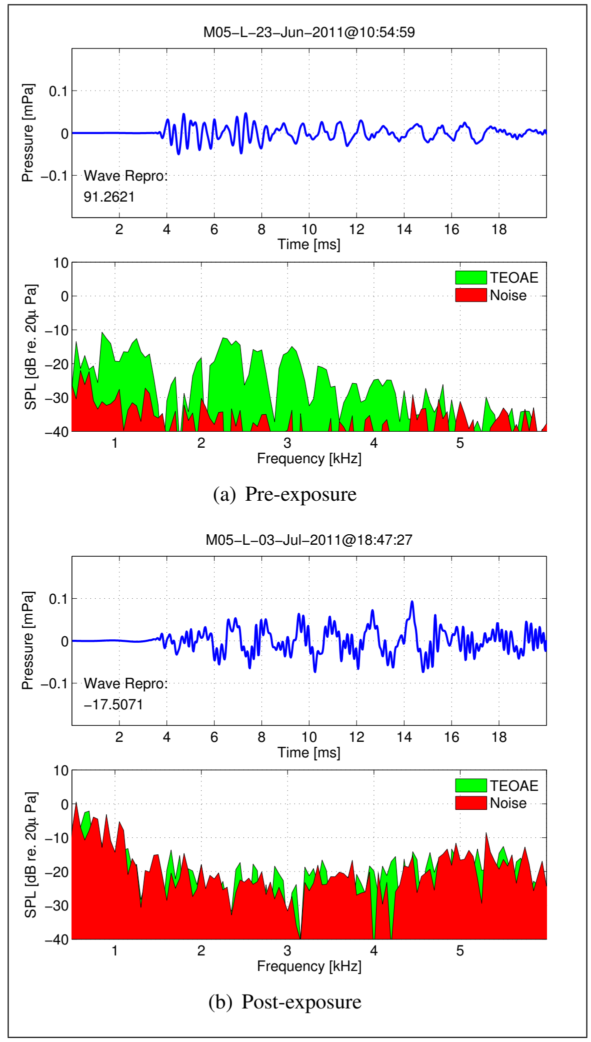


Fig. 7: TEOAE measurements for the left ear of subject M05. Plotted in the same manner as Fig. 4.

measurements are contaminated by high levels of background noise giving the same post-exposure emission and noise levels. This example illustrates the adverse noise conditions existing at the measurement site during these measurements.

4. DISCUSSION

It is clear from the present results that hearing is affected by exposure to amplified live music. DPOAEs and TEOAEs of subjects M01 and M03, showed reduced amplitudes 30 minutes (M01) and 45 minutes (M03) after a 90 minutes concert with a level over 110 dB (see Tab. 1). One hour after the same concert, subject F04 exposed to level of 106,2 dB showed a slight reduction in DPOAE amplitudes and almost no change in TEOAEs.

For the subjects with longer exposures (M05, M07 and F08), there effects of the respective exposures is confounded by the high levels of background noise. Nevertheless DPOAE measurements do show a reduction of the emission levels down to the background noise of the post-exposure measurement, indicating that the was an effect of the exposures.

The TEOAE measurements proved to be more susceptible to background noise than DPOAE measurements. This is probably due to the stimuli used in the measurements. For DPOAEs tonal stimuli deliver high amounts of energy concentrated in narrow frequency ranges, while for TEOAE measurements 80μs pulses excite the entire measured frequency range.

The main differences in the sound exposures were due to the exposure duration and to the fluctuations in level (Tab. 1 and Fig. 1). Both types of exposure are typical exposure situations of concert and festival attendees. Further research is needed to determine the specific influence on hearing of these exposure parameters.

The exposure measurement method used in this investigation is very practical and easy to use, providing a good basis for comparison between sound exposures measured in the same way. The main issue with the method is that it is not directly comparable to standardized exposure measurements done with a dosimeter or a field microphone.

For future measurements with a representative group of subjects a better post-exposure measurement site needs to be chosen. For this pilot experiment the first site was too far from the concert area, unnecessarily extending the post-exposure measurement time. The second site, close to the concert area, was too noisy contaminating the post-exposure measurements.

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