



HEAL 2016 SPECIAL ISSUE: Field monitoring of otoacoustic emissions during noise exposure: a pilot study within controlled environment

Journal:	<i>The American Journal of Audiology</i>
Manuscript ID	AJA-17-0003
Manuscript Type:	Special Issue
Date Submitted by the Author:	17-Jan-2017
Complete List of Authors:	Nadon, Vincent; Ecole de technologie superieure Bockstael, Annelies; Ghent University, WAVES research group Botteldooren, Dick; Ghent University, WAVES research group Voix, Jeremie; Ecole de technologie superieure, Mechanical Engineering
Keywords:	Acoustics, Otoacoustic emissions, Noise, Hearing conservation, Industrial audiology, Prevention

HEAL 2016 SPECIAL ISSUE: FIELD MONITORING OF OTOACOUSTIC EMISSIONS
DURING NOISE EXPOSURE: A PILOT STUDY WITHIN CONTROLLED ENVIRONMENT

Vincent Nadon ^{□1}, Annelies Bockstael ^{†2}, Dick Botteldooren ^{*2}, Jérémie Voix ^{□□1}

¹École de technologie supérieure, 1100, Notre-Dame Ouest, Montreal, Quebec, Canada, H3C 1K3

²Ghent University, WAVES research group, Technologiepark, Zwijnaarde 15, B-9052, Ghent, Belgium

Abstract

In spite of all the efforts to implement workplace hearing conservation programs, noise-induced hearing loss (NIHL) remains the leading cause of disability for North-American workers. And yet, an individual's susceptibility to NIHL can be estimated by monitoring changes in hearing status in relation to the ambient noise exposure. **Purpose:** To improve workplace hearing conservation practices, the aim of the study is to validate an approach consisting of continuous measurements, with high temporal resolution, of the inner-ear health status using otoacoustic emissions (OAE) which has been developed using a portable and robust OAE system designed for noisy environments. **Method :** A pilot study was conducted in laboratory conditions on human subjects, exposing them to noise recordings at realistic noise exposure levels as found in industry. Meanwhile, OAEs were measured periodically using the designed OAE system and a commercially available OAE system as a reference. **Results :** The inner-ear health monitoring results assessed with DPOAE level variations are presented and discussed along with the limitations of the reference and designed systems. **Conclusions :** The findings of the study indicate that otoacoustic emissions could be used to monitor temporary changes in hearing status induced by the ambient noise exposure.

Keywords: noise-induced hearing loss, otoacoustic emissions, inner-ear health monitoring, cochlea, digital signal processing, noise exposure, industrial noise

*vincent.nadon@etsmtl.ca

†annelies.bockstael@ugent.be

*dick.botteldooren@ugent.be

**jeremie.voix@etsmtl.ca

1
2
3 Over 22 million North American workers are exposed daily to noise doses that may induce hearing
4 loss [NIOSH2016] and despite the efforts in workplace hearing conservation programs [Canetto2009],
5 occupational hearing loss remains the most reported work-related disability. In an attempt to solve the
6 problem, current practices in hearing conservation usually involve noise control at the source or the use
7 of hearing protection devices (HPD) when noise control is not possible, in addition to periodic hearing
8 tests to monitor hearing health. . Based on the ambient noise exposure levels and local noise
9 regulations, the workers' hearing levels are monitored regularly, usually yearly, with audiograms..
10 However, the intervals between each test are generally still too long, since between appointments,
11 hearing damage can gradually increase before it is detected and before actions can be taken to
12 remediate the situation. Audiograms may need to be measured within smaller intervals depending on a
13 worker's susceptibility to noise exposure. However, the smallest measurement interval is about 8
14 hours, because tonal audiometry is time consuming and would interfere with the worker's routine.
15 Audiometry also requires a low-noise test environment since it is difficult for subjects to hear the tones
16 in noisy environments.
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37

38 At the moment, there is no way to make sure that the recommended maximum noise dose based on
39 an 8-hour work shift is suitable for a given individual, because of the individual's own susceptibility to
40 NIHL. As a result, even with the current legislation in Europe and North-America, 18% of workers run
41 the risk of developing NIHL over the course of their work life [ISO2014]. The assessment by current
42 legislation of the risk of incurring hearing trauma neither takes into account the frequency spectrum nor
43 the temporal fluctuations in the noise exposure for individual workers. Moreover, the passive
44 attenuation provided by the hearing protectors can vary over time and between individuals, resulting in
45 differences in noise exposure levels under the protector. To identify the characteristics of the noises
46 that cause hearing loss and quantify the maximum dose allowed for a worker's own susceptibility, it
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1 would be of clear benefit to have a system able to simultaneously record and process the noise
2 frequency spectrum to calculate the cumulative dose and also continuously measure the outer hair
3 cells' response, enabling true prevention of NIHL.
4
5
6
7
8
9

10
11 To achieve this type of inner-ear health measurement system, it is possible to use otoacoustic
12 emissions (OAEs). Excessive noise exposure damages hair cells in the cochlea and other structures and
13 is an early indicator of changes in ear health [Sliwinska-Kowalska et al.2001]. OAE measurements are
14 an objective and fast way to test and assess the health of outer hair cells (OHC). Since the active
15 participation of the worker is not needed. Eliminating issues found with some subjective tests such as
16 classic audiometry, which can be: affected by learning effects, time-consuming and sensitive to test
17 conditions. However, as mentioned, the clinical devices available at the moment and the test duration
18 make it impossible to monitor the cumulated hair cell harm continuously in an industrial workplace due
19 to the devices' sensitivity to ambient noise. As a consequence, very few experiments [Zare et al.2015]
20 were previously conducted in a noisy industrial work environment with available systems, as it is
21 difficult to obtain a reliable measurement due to the noise interference disturbing the recorded signal.
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39

40 A robust system able to evaluate the variations in workers' OHC health during a daily work shift was
41 designed. For the proposed approach, this system uses distortion product OAEs (DPOAEs) to test the
42 OHCs health status with an adaptive filtering noise rejection algorithm to reduce the interference of
43 noise. DPOAEs are frequency specific, enabling easy comparison with results from other hearing tests
44 such as audiograms. Eventually this DPOAE measurement will be used in addition to noise dose
45 measurements to establish the relationship between the changes in OHC activity and the noise dose to
46 which each individual worker was exposed. This type of dose-response relationship provides a direct
47 measure of the effects of noise on OHC with high temporal resolution, giving the opportunity to take
48 appropriate action at the right moment. Moreover, the relationship could provide personalized
49
50
51
52
53
54
55
56
57
58
59
60

1
2 information on an individual's susceptibility to noise and his risk of developing NIHL over time.
3
4

5
6 This study is original compared to previous studies since the DPOAE signals are processed here with
7
8 adaptive filtering noise rejection in real time on the system's processor to provide faster and more
9
10 reliable DPOAE measurements in higher ambient noise levels. Moreover, for the purpose of this study
11
12 DPOAEs were measured in sound pressure levels $Leq4h = 85\text{dBA}$, noise conditions in which DPOAE
13
14 measurements were not previously reported [Nadon et al.2015a] according to the author's knowledge
15
16 of the literature.
17
18
19

20
21 The main objective of this study is to validate that the inner-ear health monitoring approach with the
22
23 recently designed system is able to detect the early onset of outer hair cell changes by observing
24
25 variations in DPOAE levels during noise exposure. Other audiological measurements such as pure-tone
26
27 audiometry (PTA) and acoustic reflex threshold (ART) tests were conducted pre-exposure and post-
28
29 exposure for reference data.
30
31
32
33

34
35 To make sure the designed DPOAE system was measuring true physiological DPOAE changes, its
36
37 variability between consecutive measurements in noisy conditions is calculated. The designed system is
38
39 also compared to the commercial device used here as a reference system using two metrics: 1) root
40
41 mean square deviation from the baseline measurement and 2) measurement duration. The root mean
42
43 squared deviation from the baseline measurement gives information on the system's performance in
44
45 loud environments for eventual continuous monitoring of OHCs. The measurement duration to cover
46
47 the DPOAEs' frequency range for the reference system was compared with the designed system,
48
49 bearing in mind that measurements with high temporal resolution are needed for early detection and
50
51 intervention, so measurements should be as short as possible.
52
53
54
55
56
57
58
59
60

1
2 In the following section, the experiment protocol is detailed chronologically. The experimental and
3 physical setup used for the experiments are introduced between the screening and pre-exposure tests
4 sections. The results for the audiometric, acoustic reflex threshold and DPOAE tests are shown in
5 Section 2. The performance metrics of the systems in noise conditions are also presented in Section 2.
6 Results are then discussed in Section 3, followed by the conclusions of this study.
7
8
9
10
11
12
13
14
15

16 **1 Method**

17 **1.1 Screening**

18
19 Convenience sampling was used in order to find participants for the experiment, i.e. an invitation was
20 sent to university students. The 9 test volunteers (6 males and 3 females) went through a screening test
21 starting with an otoscopic examination to make sure that no cerumen could potentially clog the
22 DPOAE probes and that the moulding of the custom fit ear tips would not clog the ear canal. A
23 standard DPOAE test in each ear was recorded with the reference system to verify that the subject had
24 DPOAEs present for most of the tested frequencies. If DPOAE levels were detected over 5 dB (SPL)
25 for about 80% of the tested frequencies, based on normative data [Keppler et al.2010a], the subject was
26 then screened with a classic pure-tone audiometry test in each ear with a -10 dB/+5 dB step. Subjects
27 were retained for the study if their hearing thresholds were below 25 dB(HL) for about 85% of the
28 tested frequencies from 250 Hz to 8000 Hz, bearing in mind that frequencies ≤ 4 kHz are expected to
29 be less vulnerable to permanent threshold shifts. The ear tested for continuous DPOAE measurements
30 was randomized unless a problem was detected with one ear during the screening.
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50

51
52 For the subjects tested using the designed system, the probe tips were custom molded in the subjects'
53 ears using the proprietary SonoFit™ [Sonomax2016] automated self-fit process [Sonomax2016]. The
54 probe tips were then adapted to the DPOAE probe's electronics core. The DPOAE probes also serve as
55
56
57
58
59
60

1 hearing protectors during ambient noise exposure in this study. Therefore, the DPOAE probe passive
2 attenuation was measured, using the F-MIRE method [Voix and Laville2009], by sending a wide-band
3 noise in front of the subject with the DPOAE probes fitted in the subject's ears, and by calculating the
4 transfer function between the external and internal microphone signals for both ears. A simplified
5 probe fit-test method, based on the magnitude of the frequency response at low frequencies [Nadon
6 et al.2015b], was also integrated in the designed device. The initial F-MIRE probe fit-test data was kept
7 for reference for the subsequent probe fit-test in the field using the simplified approach.
8
9
10
11
12
13
14
15
16
17
18
19
20

21 The physical and experimental setup used for the screening and the following pre-exposure, during
22 exposure and post-exposure tests are presented in the next section.
23
24
25

26 **1.2 Experimental setup**

27
28
29 The devices used for the hearing tests, i.e. 1) audiometer, 2) otoadmittance system and 3) otoacoustic
30 emission systems are presented in the following sections.
31
32
33
34
35

36 **1.2.1 Pure-tone audiometry**

37
38
39 The pure-tone hearing threshold levels (HTL) were measured manually using the Hughson-Westlake
40 method on a commercial AC5 audiometer (Interacoustics, Middelfart, Denmark) with TDH-39
41 audiometric headphones (Telephonics, NY, USA). The threshold levels were evaluated on seven octave
42 bands 250, 500, 1000, 2000, 4000, 6000 and 8000 Hz for the screening test, and for daily monitoring
43 the 250 Hz was replaced with the intermediate 3000 Hz octave band which is more interesting to detect
44 changes caused by noise exposure.
45
46
47
48
49
50
51
52
53
54

55 **1.2.2 Otoadmittance system**

56
57
58 To test the stapedial reflex threshold also known as acoustic reflex threshold (ART), a Titan
59
60

(Interacoustics, Middelfart, Denmark) otoadmittance system was used. Before each ART measurement, a standard tympanometry was performed automatically by the system to remove any static pressure on both sides of the eardrum. The reflex was measured by sending narrowband noise, centered at three different test frequencies {1, 2, 4} kHz, in the ipsilateral ear. While the noise level was increased from 70 to 90 dBA, the probe simultaneously measured changes in ear-canal impedance to detect when the change in the acoustic immittance exceeded the deflection criteria of 0.03, set by default with the Titan system, and then recorded this noise level as the ART.

1.2.3 Commercial otoacoustic emissions system

The reference DPOAE system was an ER-10B+ probe and amplifier system (Etymotic Research, IL, USA) connected to a laptop computer with a Fireface 802 soundcard (RME, Haimhausen, Germany). The laptop used the EMAV software [Neely and Liu1994] to measure the DPOAEs. The ER-10B+ microphone amplifier was set at a gain of +20 dB. Pre-moulded silicone ear tips were used on the probe during the experiment and the contralateral ear was blocked with a disposable foam earplug during noise exposures. Before conducting the experiment, the probe system parameters were calibrated in EMAV, according to the instructions provided in the software's manual [Neely and Liu1994]. The software used a sampling frequency of 44.1 kHz with a window of 8192 samples and used a noise threshold limit (NTL) of 8 mPa as default. The NTL is used in EMAV to reject a DPOAE sample when an artifact is detected, i.e. when the calculated noise level is higher than this threshold. Increasing the noise threshold limit therefore results in a less restrictive artifact rejection, potentially leading to the calculation of the DPOAE level on a recorded signal with noise interference.

The 22 selected DPOAE frequencies corresponded to f_2 frequencies ranging from 1000 Hz to 6200 Hz with 8 frequencies per octave, with a f_2/f_1 ratio = 1.22. Stimuli levels were set to $L_1=65$ dB and $L_2=55$ dB. The DPOAEs signal-to-noise ratio (SNR) criterion was set at 5 dB, therefore any DPOAE

1 level not respecting this criterion was not accepted and the system re-measured that DPOAE frequency
2 until the criterion was met at least twice and then averaged the two results. To reduce the measurement
3 time duration, which was already extended in noisy conditions to fulfill the 5 dB SNR criterion, only
4 one complete scan was measured when the subjects were exposed to noise while two complete scans of
5 the 22 DPOAE frequencies were measured for the screening. To complete the measurements during
6 noise exposure with this system, the 8 mPa NTL had to be adjusted at the beginning of each
7 measurement (limits are shown in Section 2.4.3), resulting in greater disturbance recorded in the
8 DPOAE measurement, since the level measured in the DPOAE frequency bin could consist of the sum
9 of the ambient noise disturbance and the DPOAE itself. This results in an artificial increase of the
10 DPOAE level, as further discussed in Section 2.4.1. The software calculated the noise level on adjacent
11 bins, which could be lower than this DPOAE frequency bin containing artefacts. Thereby, satisfying
12 the 5 dB SNR criterion of the software, but resulting in a greater deviation from the baseline
13 measurement. When the NTL was not adjusted, the EMAV software would not pursue the
14 measurement and would repeat the measurements on the same frequencies indefinitely.

1.2.4 Designed otoacoustic emissions system

15 A DPOAE measurement device designed in laboratory, consisting of DPOAE probe earpieces and a
16 DPOAE hardware box (shown in Fig. 1), was used in the present study, and later referred to as the
17 “designed system”. Each of the two DPOAE probe earpieces contained two high-quality miniature
18 balanced armature receivers (Knowles, IL, USA) to send the two pure-tone stimuli without any sound
19 distortion, and one miniature microphone to measure the otoacoustic emission response and
20 physiological noise. A miniature microphone was placed in the probe earpiece facing outward, i.e.
21 pinna side, to measure the external ambient noise (probe details can be found in [Nadon et al.2015a]).
22 A custom moulded ear-tip, fitted to each subject's ear canals was designed into which could be slid the
23 probe's electronic components core. This way, the custom moulded ear-tips could simply be
24

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

interchanged for each subject and contain the same probe electronics, ensuring consistent electroacoustic responses across all the experiments.

The DPOAE hardware electronics were based on the Auditory Research Platform (ARP) [CRITIAS2016], and were designed specifically to record DPOAE levels in noisy conditions. It integrated a signal conditioner and a digital signal processor (DSP) and a Bluetooth communication dongle to transmit the calculated DPOAE levels and background noise levels to a smartphone. An Android smartphone application, shown in Fig. 2, was designed to display the received DPOAE data from the device and to transmit various commands to the device, such as to switch frequencies for example.

The adaptive filtering noise rejection algorithm previously developed [Nadon et al.2015a] is implemented in the DSP together with the DPOAE and noise level extraction algorithm previously developed [Nadon et al.2014]. While the ability of the system's algorithms to extract DPOAE levels in noisy conditions was already validated [Nadon et al.2015a], it was previously tested in lower noise levels than those here, which exceeded 85 dBA. Moreover, in the present study, all the algorithms ran in real time and the DPOAE level output was processed, displayed and saved "live" during the measurement, making it possible to repeat a measurement when necessary. To maintain the level of consistency across the two DPOAE devices tested, the f_2 frequency range was set at 1000 Hz to 6169 Hz with 8 tested frequencies per octave band for a total of 22 frequencies. The primary tones frequency ratio f_2/f_1 was kept at 1.22. Stimuli levels were set at $L_1=65$ dB and $L_2=55$ dB. Each frequency was tested for about 2 seconds, during which the samples were averaged, for a total of 45 seconds for a complete scan of the 22 frequencies. This sequence was repeated at least twice, and usually three times especially when the measurement was disturbed by unpredicted events such as coughing for example. The duration of the measurements are compared with the reference system and

1
2 presented in Section 2.4.4.
3
4
5
6

7 8 **1.3 Physical experimental test setup** 9

10 For optimal isolation from ambient noise disturbances, the screening, pre-exposure and post-
11 exposure measurements were conducted in a semi-anechoic room separated from the noisy
12 environment. For a more diffused and louder sound field, DPOAE measurements during noise
13 exposure were carried out in a reverberant room. The sound system to simulate a noisy environment
14 using noise recordings consisted of an amplifier connected to a laptop computer playing back industrial
15 noise from the NOISEX-92 database [Carnegie Mellon University1992] and pink noise recordings. Two
16 loudspeakers were positioned at a distance of 2.4 m of the test subjects, one on the left and one on the
17 right as seen in Fig. 3. Noise levels were calibrated with the pink noise recordings at 87 dBA in the
18 room with the SVAN 959 sound level meter (Svantek, Warsaw, Poland) placed approximately at the
19 height of the subject's ears and in the middle between the two seats, approximately 50 cm from the
20 seats, without subjects being present. Industrial and pink noise recordings were created with a high
21 noise level plateau at 87 dBA for the first 20 minutes followed by a lower noise level plateau at 67 dBA
22 for 10 minutes. As seen in the top of Fig. 7, this sequence was looped on 4 hours for the daily noise
23 exposure with an Leq_{4h} of approximately 85 dBA. To obtain the reference quiet conditions, no noise
24 recording was played through the loudspeakers during the 4 hours of experiment.
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47

48 **1.4 Pre-exposure tests** 49

50 Once the subjects were retained for the experiment, they were exposed on three different days to the
51 following noise conditions: industrial, pink noise and quiet. On the day of the DPOAE monitoring
52 measurements, the subjects first went through the pre-exposure tests, shown as block "A" in Fig. 4,
53 which consists in a manual pure-tone audiometry and stapedial reflex measurement with
54
55
56
57
58
59
60

1 tympanometry. Prior to the DPOAE measurements with the designed DPOAE monitoring system, the
2 probe fit test [Nadon et al.2015b] was executed and the result shown on the smartphone was saved. The
3 probe was refitted if the measured R_{AD} ratio [Nadon et al.2015b] differed by more than two times the
4 reference value measured after the first fit. Afterwards, the DPOAE primary tone stimuli were
5 calibrated for proper DPOAE recording. Finally, adaptation was switched on, so that the adaptive
6 filters could reject the ambient noise from the DPOAE measurements, and a pre-exposure DPOAE
7 measurement, i.e. baseline, was recorded. The adaptation stayed on for all noise conditions, including
8 quiet conditions.
9
10
11
12
13
14
15
16
17
18
19

20
21
22
23 To save time, two subjects were tested simultaneously: subject A was tested with the designed
24 system while subject B was tested with the reference DPOAE system, as seen in Fig. 3. A total of five
25 subjects were tested with the designed system and four with the reference system.
26
27
28
29
30
31

32 1.5 Tests during exposure

33
34
35 After the calibration of the DPOAE stimuli signals and probe fit measurement (block “B” in Fig. 4),
36 the noise exposure started and every 15 minutes a new DPOAE measurement (block “C”) was
37 performed at least twice with the designed system, with a complete measurement of the DPOAE
38 frequency range, approximately $f_{dp}=600$ to 4000 Hz, corresponding to $f_2=1000$ to 6169 Hz.
39
40
41
42
43
44
45

46
47 During the ambient noise exposure, one complete scan was recorded with the reference system on
48 test subject B, while the software averaged at discrete DPOAE frequencies based on two consecutive
49 measurements passing the 5 dB criterion. To perform an average on a similar number of consecutive
50 measurements with the designed system, at least two complete scans were recorded, since each discrete
51 DPOAE frequency was only repeated once per scan with this system compared to at least twice per
52 scan with the reference system.
53
54
55
56
57
58
59
60

1
2
3
4 Noise exposure was monitored and recorded during the experiment with the sound level meter
5
6 positioned in the room, as shown in Fig. 3. Subject A was protected from the noise exposure with the
7
8 passive attenuation of the two DPOAE probes necessary for the measurements, while subject B was
9
10 protected with the DPOAE probe on one side and by a disposable foam earplug on the other. Raw
11
12 signals from the designed systems' external and internal microphones were recorded via an analog
13
14 audio output of the DPOAE system with a Zoom H5 (Zoom, Tokyo, Japan) portable audio recorder
15
16 equipped with an EXH-6 TRS capsule [Zoom2016] to record the four audio outputs simultaneously.
17
18 These raw signals could be used later to calculate the in-ear noise exposure, the outer-ear exposure, the
19
20 hearing protection provided by the probe, and post-process DPOAE signals if necessary.
21
22
23
24
25
26
27

28 After about 2 hours of noise exposure, a 30 min to 1 hour break was allowed for subjects to rest and
29
30 eat. This break occurred at the same time for both test subjects, as shown in Fig. 4, so that the probes
31
32 could be refitted and calibrated before exposing the subjects to noise again.
33
34
35

36 1.6 Post-exposure tests

37
38 After being exposed to 4 hours of noise, the subjects went through the post-exposure tests, which are
39
40 similar to the pre-exposure tests ("A" in Fig. 4), except that the post-exposure test sequence begins
41
42 with a DPOAE test once the noise exposure has stopped. Therefore, DPOAEs were measured twice in
43
44 post-exposure, once immediately after the noise exposure and once at the very end of the post-exposure
45
46 tests. The post-exposure tests will make it possible to evaluate whether the noise exposure had an effect
47
48 on the pure-tone auditory thresholds and to observe the recovery mechanisms of the inner-ear by
49
50 comparing the first post-exposure DPOAE measurements with the very last post-exposure
51
52 measurements.
53
54
55
56
57
58
59
60

1.7 Post-processing

Audio artefacts, such as those resulting from the subject coughing, sneezing, talking, and probe fit changes could affect DPOAE measurement outliers. These outliers were rejected in post-processing using a thresholding method. The threshold was based on the accepted tolerance on repeated DPOAE measurements [Keppler et al.2010b] and was set to 7 dB, corresponding to double the 3 dB tolerance plus 1 dB. Any DPOAE measurement greater by 7 dB from the previous one was rejected. Such outlier rejection was applied manually, in post-processing, but could eventually be included in the real-time processing of the data.

When audio artefacts interfered with the measurement, the measurement on the 22 DPOAE frequencies was still saved and a following attempt was started. All consecutive measurements within a five-minute interval were then averaged in post-processing after passing through the thresholding procedure.

1.8 Statistical analysis

To verify if the changes in pure-tone audiometry (PTA) hearing threshold levels (HTL) and acoustic reflex threshold between pre-exposure and post-exposure were statistically significant, a paired *t*-test or non-parametric paired Wilcoxon test was used, based on the Shapiro test and Q-Q plots. The paired *t*-tests, or Wilcoxon tests, were calculated per frequency point and per noise condition. The output of interest was the mean of differences and *p*-values indicated if the results were statistically significant. A significance level of $\alpha = 0.05$ was chosen for these tests. For the DPOAE systems, the negative DPOAE changes calculated between the baseline and the last measurement during noise or the first measurement post-exposure were tested for significance: 1) the difference from the last measurement during noise (data point 2) with the baseline (data point 1) and 2) the difference between the first measurement post-exposure (data point 3) and the baseline. Positive DPOAE changes, during the recovery phase, were tested for statistical significance on: 3) the difference between the last measurement during noise

1 exposure (data point 2) and the last DPOAE measurement post-exposure (data point 4), in addition to 4)
2
3
4 the difference between the first measurement post-exposure (data point 3) with the last DPOAE
5
6 measurement post-exposure (data point 4).
7
8
9

10 11 **2 Results**

12 13 14 **2.1 Pure-tone Audiometry**

15
16
17 The PTA tests were conducted to screen the participants and for hearing status monitoring. In the
18
19 latter case, PTA was conducted for pre-exposure and for post-exposure measurements. A box plot of
20
21 the subjects' aggregated results is presented in
22

23
24 Fig. 5. To calculate the differences in HTLs, the results for post-exposure were subtracted from the
25
26 pre-exposure results. Therefore, positive values indicate lower thresholds, i.e. better hearing, in post-
27
28 exposure results. The line in the box represents the median HTL difference at the tested frequency.
29
30

31
32
33 According to the paired data Wilcoxon signed rank test with continuity correction, only a positive
34
35 HTL change was statistically significant ($p=0.05$) at 3 kHz for industrial noise conditions. Therefore,
36
37 HTLs did not seem affected by the noise since in general subjects had slightly better auditory
38
39 thresholds after the noise exposure.
40
41
42
43
44

45 **2.2 Acoustic Reflex Thresholds**

46
47
48 The acoustic reflex threshold tests, also known as stapedial reflex thresholds, were conducted for
49
50 hearing status monitoring with pre-exposure measurements at the beginning of the day and post-
51
52 exposure at the end of the day. A box plot of the aggregated acoustic reflex threshold differences,
53
54 calculated as the pre-exposure results subtracted from post-exposure results, is presented in Fig. 6.
55
56 Positive values indicate lower thresholds in pre-exposure results, therefore a positive difference might
57
58
59
60

1
2 indicate an effect due to the noise exposure. The line in the box represents the median ART difference
3
4 at the tested frequency.
5
6
7
8

9 The changes detected are relatively small, within a measurement step of 5 dB of the otoadmittance
10 system, and are not statistically significant between post-exposure and pre-exposure within the same
11 test conditions. However, by evaluating the statistical difference across the test conditions, industrial
12 and pink noise conditions each paired with quiet conditions, a statistically significant ($p < 0.05$)
13 increase in ART was observed at 4 kHz for both industrial and pink noise conditions.
14
15
16
17
18
19
20
21
22

23 2.3 Distortion-product otoacoustic emissions

24
25 Noise exposure levels from the sound level meter were synchronized with DPOAE level
26 measurements to facilitate analysis. An example of the noise exposure and DPOAE levels is presented
27 for one subject in Fig. 7. Results were analyzed per DPOAE frequency for their variations from the
28 baseline measurement ($t=0$ min) in Fig. 8. These variations are possibly related to the effects of the
29 ambient noise exposure on the outer hair cells' mobility.
30
31
32
33
34
35
36
37
38
39

40 As the largest changes are expected to occur closest to the end of the noise exposure period (at $t \approx 4$ h)
41 and to simplify the presentation of the results, the last three DPOAE measurements (data points 2, 3
42 and 4 mentioned in Section 1.8) are shown with the baseline (data point 1) in Fig. 8. This way, effects
43 of noise exposure on DPOAE responses can be observed by comparing the last measurement during
44 noise exposure with the baseline. DPOAE level recovery between the last 2 measurements conducted
45 in ~ 45 dBA (data points 3 and 4) also indicates potential effects of noise exposure on OHC. The
46 measurements are displayed aligned with their time, in minutes, relative to the baseline. The figures are
47 aligned for easy comparison of the effects of the various noise conditions, where the least changes are
48 expected in quiet conditions.
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4 Results are then displayed in comparison with other subjects measured with the reference DPOAE
5 system in
6
7

8
9 Fig. 9 to verify the consistency, or lack thereof, across the two systems and observe possible effects
10 of noise on DPOAE levels on more subjects overall.
11
12

13
14
15
16 To validate that the designed system was able to detect the early onset of outer hair cell changes by
17 observing variations in DPOAE levels during noise exposure (>65 dBA), the second data point (~ 300
18 min) is expected below the 0 dB normalized baseline for noisy test conditions. The following DPOAE
19 levels are expected to increase, since they are recorded during the recovery phase. For most subjects
20 using the designed system, results in industrial and pink noise do correspond to this trend (Fig. 8). On
21 the other hand, the results are more scattered with the reference system (
22
23
24
25
26
27
28
29

30 Fig. 9). For both systems, it is possible that the second data point was slightly affected by the ambient
31 noise disturbance as is the case for Subject 1 at 4000 and 4362 Hz in Fig. 8(a)&(d) for example, when
32 the ambient noise level measured with the sound level meter was 86.7 dBA. This disturbance could
33 potentially mask true changes in DPOAEs. The third and fourth data points in the plots (Fig. 8
34
35
36
37
38
39

40 Fig. 9) help to visualize whether OHC changes did occur during noise exposure, by observing the
41 recovery curve.
42
43
44
45

46 2.4 Performance of systems in high ambient noise levels

47 2.4.1 Deviation from the baseline DPOAE measurements

48
49
50 To evaluate the performance of the designed and reference systems in high levels of ambient noise,
51 the effect of the disturbance on the DPOAE measurements was further assessed by computing the
52 deviation from the baseline DPOAE level. Only positive variations were included in the analysis since
53
54
55
56
57
58
59
60

1 negative variations from the baseline would in fact indicate actual changes in inner-ear activity related
2 to the noise exposure. True physiological positive DPOAE changes can also result from noise
3 exposure. Therefore, this metric should be interpreted with caution as a comparison across systems
4 relative to the measurements in lower noise exposure levels of 45 dBA, since the deviation from the
5 baseline includes the noise interference inducing an artificial increase in DPOAE levels [Nadon
6 et al.2015a], in addition to potential positive physiological changes in DPOAE levels. However, the
7 positive physiological changes would be relatively smaller than the interference of the 87 dBA noise
8 levels. These possible physiological changes are discussed further in Section 3.3.1. The deviation from
9 the baseline was computed using the root-mean square deviation (RMSD), shown in Eq. 1, for $f=1-5$
10 referring to f_2 primary tone frequencies ranging from 4000 Hz to 5657 Hz and $n=5$ total number of
11 frequencies used to compute the RMSD. For the calculations, \hat{x}_f was the baseline and x_f was the
12 DPOAE level at frequency f . Resulting deviations are compared between the two systems, in different
13 noise exposure levels, and are shown in Fig. 10.

$$RMSD = \sqrt{\frac{\sum_{f=1}^n (x_f - \hat{x}_f)^2}{n}} \quad (1)$$

2.4.2 Variability of measurements

44 To verify that the variations in DPOAE levels result from cochlear activity affected by noise
45 exposure and not simply caused by the system's variability between measurements, the test-retest
46 variability of the designed DPOAE system was estimated using the standard deviations of the DPOAE
47 levels, as measured from the consecutive measurements, saved within the 5 minute-interval usually
48 needed to complete the several DPOAE measurements. The standard deviation results are displayed per
49 noise levels in Fig. 11. It was impossible to assess the test-retest variability for the reference system, as
50 the EMVA software automatically repeated the measurement at problematic frequencies if certain

1
2 criteria were not met and only output the average result, thereby not enabling the calculation of a
3
4 standard deviation. Moreover, during noise exposure only one measurement of the DPOAE frequency
5
6 range was completed per 15 minutes. Between these measurements the subjects were exposed to a
7
8 different ambient noise level, see Fig. 7. Therefore, due to different test conditions, the standard
9
10 deviations could not be calculated across the periodic DPOAE measurements for the reference system.
11
12

13 14 15 16 **2.4.3 Noise threshold limit (NTL)**

17
18 The NTL parameter was adjusted manually in the EMAV software until the reference system could
19
20 proceed in taking the DPOAE measurement while in the presence of high ambient noise levels. The
21
22 adjusted NTLs are presented in Fig. 12. They reach up to 150 mPa for 87 dBA ambient noise levels,
23
24 resulting in a greater amount of ambient noise disturbance captured by the DPOAE measurements. As
25
26 observed in Fig. 10, the EMAV software no longer rejected noisy samples, as it would have when
27
28 using more restrictive limits such as the default 8 mPa set for lower ambient noise levels, such as
29
30
31
32
33 45 dBA.
34
35
36
37

38 **2.4.4 Measurement duration**

39
40 Due to the relatively fast recovery rate of DPOAE levels, i.e. within a few minutes, the measurement
41
42 duration can be a crucial factor in the detection of temporary cochlear activity changes [Bourgoin2004,
43
44 Sutton et al.1994, Engdahl2004, de Toro et al.2010, Vinck et al.1999]. The measurement durations for
45
46 the designed DPOAE system were compared to those obtained with the reference system and are
47
48 presented in Fig. 13. It is important to remember, from the above sections, that only one measurement
49
50 could be performed every 15 minutes for the reference system in noisy conditions and that the noise
51
52 limit threshold had to be modified in order to proceed to the measurement. During that period, several
53
54 complete measurements were performed with the designed system as one complete scan of the DPOAE
55
56
57
58
59
60

1 frequencies takes only 45 seconds and no parameter needed to be adjusted. This results in test durations
2 ranging approximately from 3 to 6 minutes for a single measurement with the reference system,
3 compared to a much shorter duration ranging from 90 to 135 seconds (~2 minutes) for 2-3
4 measurements with the designed system.
5
6
7
8
9

10 11 12 13 **3 Discussion**

14 15 16 **3.1 Pure-tone audiometry**

17
18
19 In this experiment, pure-tone audiometry was used as a reference in the screening test to verify that
20 test subjects did not suffer from a permanent threshold shift. The participants were asked about their
21 latest noise exposure history prior to the screening PTA, therefore a full recovery of past temporary
22 changes was expected. PTA was also used to verify if any temporary inner-ear status changes could be
23 detected between pre-exposure and post-exposure. It was expected that PTA would be less sensitive,
24 compared to DPOAEs, to detect early the onset of cochlear changes [Bourgoin2004, Vinck et al.1999,
25 Sliwinska-Kowalska et al.2001]. According to the results presented in the previous section and in
26
27
28
29
30
31
32
33
34

35
36 Fig. 5, the subjects' hearing threshold levels, as expected, did not appear to be affected by the noise
37 exposure and subjects had overall slightly better (lower) hearing thresholds after the exposure to
38 ambient noise. This could be explained by a learning effect of the psychophysical procedure involved
39 in PTA, in addition to a lack of resolution caused by the 5 dB increment steps used for the PTA
40 assessment.
41
42
43
44
45
46
47
48
49

50 51 **3.2 Acoustic reflex thresholds**

52
53 The acoustic reflex threshold differences between pre-exposure and post-exposure were analyzed to
54 show the potential effect of the noise exposure on the middle-ear muscle contraction, which could be
55 used to detect early changes in hearing status, earlier than the onset of a noise-induced hearing loss
56
57
58
59
60

[Venet et al.2014]. As observed in Fig. 6, the ART is lower in post-exposure measurements for the quiet condition, whereas for the industrial and pink noise conditions the ART slightly increased. An increase in ART such as this would indicate the fatigue of the middle-ear muscle [Borg et al.1979], which could be caused by the noise exposure. On the other hand, a slight decrease in ART as observed in the quiet conditions may be explained by either: 1) the effect of the DPOAE probes' passive attenuation on ART levels since subjects were actually protected in conditions where they would not usually wear HPDs, and/or 2) the circadian rhythm could have an effect on the middle-ear muscle contractions [Nadon et al.2016]. ART variations at 4 kHz for industrial and pink noise conditions are in agreement with the expected DPOAE shifts around 4 kHz and suggest a possible temporary change in hearing status induced by the noise exposure.

3.3 Otoacoustic emissions

3.3.1 Detection of noise induced DPOAE changes

The DPOAE frequencies of interest analyzed for this study corresponded to f_2 ranging from 4000 Hz to 5657 Hz since this range of frequencies is more susceptible to temporary hearing changes, and the passive attenuation of the probe and adaptive filtering in the DSP of the designed system both reduce the ambient noise disturbance in DPOAE signals more effectively at these frequencies. Unfortunately, the way the system was designed, the $f_2=6169$ Hz could not be analyzed in the study possibly because of Bluetooth communication latency issues in the system, which sometimes affected the selection of the correct band-pass filters, resulting in more noise interference disturbing the first DPOAE frequency measured.

Furthermore, some outlier data points are visible in Fig. 8. For example, Subject 1 had very low absolute otoacoustic emission levels, less than -10 dB for $f_2 \geq 5657$ Hz and therefore closer to the noise

1 floor of the DPOAE measurement system. In this case, DPOAE levels varied from inside to outside the
2 range of normal system operation and this caused DPOAE level changes compared to the baseline.
3
4 This variation caused by absolute DPOAE levels outside the range of normal operation was also seen
5
6 in quiet conditions, resulting in greater DPOAE changes than the expected changes of approximately
7
8 0 dB. For Subject 4, the subject was the very first to be tested with the designed system and some
9
10 problems related to the connection between the DPOAE system and the portable audio recorder,
11
12 affecting both the DPOAE level calculated by the DSP and the portable recorder signal, were noticed
13
14 straightaway and immediately corrected for the following measurements. Therefore some
15
16 improvements in performance are observed between the industrial noise (first day, Fig. 8.d) and other
17
18 noise conditions (following days, Fig. 8.e and f).
19
20
21
22
23
24
25
26
27

28 For the reference system, according to the last DPOAE measurement in noise exposure (second data
29
30 point on the x-axis in
31

32 Fig. 9), DPOAE levels are higher than the following DPOAE measurements in the recovery phase,
33
34 especially at 4 kHz. This suggests that the ambient noise disturbed the DPOAE measurement. Although
35
36 positive physiological DPOAE changes are possible, referring here to the two-minute bounce as
37
38 mentioned in [Kemp1986, Kirk and Patuzzi1997, Bourgoin2004], these positive changes are expected
39
40 to be relatively smaller for the $2f_1-f_2$ DPOAE frequency [Kirk and Patuzzi1997] than the noise
41
42 interference masking this potential DPOAE change. Especially since the reference system was not
43
44 designed to measure in high ambient noise levels. Moreover, results with the reference system are more
45
46 scattered than those recorded with the designed system (see
47
48
49
50

51 Fig. 9) for which DPOAE levels are more concentrated below the baseline for the second data point
52
53 on the x-axis. According to these observations, the software processing and probe fit for the reference
54
55 system appears to be more affected by the ambient noise disturbance than the designed system.
56
57
58
59
60

1
2 For the designed system, the last measurement in the recovery phase tends towards the baseline
3 levels (Fig. 8), and is sometimes higher than the baseline, possibly due to recovery mechanisms of the
4 inner-ear after noise exposure. An observation also reported by Bourgoïn [Bourgoïn2004]. This
5 recovery effect is more noticeable in Fig. 8(a)&(i). Moreover, a greater change in DPOAE level was
6 detected for DPOAE measurements in industrial noise as shown with Subjects 3 and 5 in
7
8

9
10
11 Fig. 9(a) to (g). Minor variations in DPOAE levels (~1-2 dB) were observed for most subjects in
12 quiet conditions as shown in Fig. 8, as is expected when there is no noise exposure. On the other hand,
13 the pink noise conditions did trigger greater DPOAE level variations than in quiet conditions, but it is
14 not as obvious as with industrial noise conditions (for example Fig. 8(g) vs. Fig. 8(h)). The greater
15 variations in DPOAE levels are visible for higher DPOAE frequencies. This effect can be observed by
16 comparing Fig. 8(a), (d), (g), (j) and (m). Maximum effects of noise exposure on DPOAEs were
17 observed at 4757 Hz and 5187 Hz in industrial noise conditions. However, negative DPOAE changes
18 in industrial noise were not statistically significant for the designed system, possibly due to large
19 differences between subjects and the small number of subjects. On the other hand, the DPOAE changes
20 for the pink noise conditions were more consistent between subjects and were statistically significant (p
21 < 0.05) mostly around 4757 Hz for negative changes induced by the noise exposure and for the positive
22 DPOAE changes during the recovery phase. The maximum negative DPOAE shift from the baseline,
23 measured from the second and third data points, across frequencies ($f_2 = 4000$ to 5657 Hz) ranged from
24 -5.9 to -22.3 dB in industrial noise, -2.7 to -6.4 dB in pink noise conditions, and in quiet conditions -1.4
25 to -2.6 dB, the latter possibly explained by some minor changes in the probe fit over the day.
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50

51 For the reference system, the significance of the negative DPOAE changes was evaluated based on
52 the difference between the first post-exposure measurement and the baseline. Since the DPOAE
53 measurements during noise exposure were affected by the ambient noise disturbance, these DPOAE
54 changes were not statistically significant. DPOAE changes in pink noise were not statistically
55
56
57
58
59
60

1 significant possibly due to the small number of subjects and the smaller magnitude of the changes
2 induced by this noise exposure. The negative changes between the first post-exposure measurement
3 and the baseline were statistically significant ($p < 0.05$) in industrial noise at $f_2 = 4021$ Hz and 4382 Hz.
4
5
6
7
8 However, the positive DPOAE change between the first post-exposure and last post-exposure
9 measurements was not significant, suggesting that DPOAE levels did not sufficiently recover between
10 the two post-exposure measurements with the reference system. This slower recovery was confirmed (p
11 < 0.05) by testing whether the difference between the last post-exposure measurement and the baseline
12 was still statistically significant. The slower recovery can be explained by the passive attenuation of the
13 pre-moulded probe ear tip used with this reference system, which may not provide adequate passive
14 attenuation depending on the subjects, therefore slightly increasing the subjects' total noise exposure
15 compared to subjects tested with the designed system.
16
17
18
19
20
21
22
23
24
25
26
27
28
29

30 According to Bourgoïn [Bourgoïn2004], DPOAE levels recover faster after low noise level
31 exposures. For example, only 2 minutes are necessary to recover DPOAE levels to baseline levels
32 around 4 kHz after a 77 dBA 10-minute noise exposure. This justifies the use of fast DPOAE
33 measurements as soon as possible following the noise exposure to measure greater DPOAE variations,
34 i.e. before DPOAE levels recover [de Toro et al.2010]. Therefore, DPOAE measurements during the
35 noise exposure are definitely interesting with the designed system since this is the earliest moment at
36 which DPOAE levels can be measured.
37
38
39
40
41
42
43
44
45
46
47
48

49 For the current study, the maximum noise level was set at around 87 dBA so that the resulting
50 exposure in the ear canal protected under the HPD was about 70-80 dBA. A review by Melnick
51 [Melnick1991] pointed that the levels estimated to produce measurable temporary threshold shifts
52 range from approximately 74 dB(SPL) at 4000 Hz to 86 dB(SPL) at 250 Hz. Later, Bourgoïn's study
53 [Bourgoïn2004] showed that post-exposure DPOAE variations were observed for noise levels ranging
54
55
56
57
58
59
60

1
2 from 77 to 93 dBA even if the noise exposure was as short as 10 minutes. In the current study subjects
3
4 were exposed to 4 hours (240 minutes) of ambient noise, a sufficient noise exposure to trigger
5
6 temporary DPOAE changes, as was demonstrated in Fig. 8.
7
8
9

10 11 3.3.2 Deviation from the baseline DPOAE measurements 12 13 14 15

16
17 The median deviation from the baseline remains lower for the designed system than the reference
18
19 system in all tested conditions (from 45 dBA to 87 dBA) as observed in Fig. 10 where the median of
20
21 RMSDs is 4.7 dB for the designed system versus 7.6 dB for the reference system in 87 dBA. The lower
22
23 deviation from the baseline is also visible in
24

25
26 Fig. 9 with more coherent results for the designed system. As expected, the deviation from the
27
28 baseline increases slightly with the noise exposure levels due to the artificial increase in DPOAE levels
29
30 mentioned earlier.
31
32
33
34

35 3.3.3 Variability of measurements 36 37

38
39 The median standard deviation calculated on the same consecutive measurements used to calculate
40
41 the mean DPOAE levels is estimated at about 0.8 dB for all noise conditions, indicating that results did
42
43 not vary more across consecutive measurements when the subject was exposed to higher ambient noise
44
45 levels. This can be explained by the performance of the adaptive filtering noise rejection. When the
46
47 DPOAE level during or post-exposure is lower than the baseline, the negative DPOAE variation being
48
49 greater than the test-retest variability could be considered a real change in inner-ear activity.
50
51
52
53

54
55 The greater number of outliers in the 45 dBA box plot (Fig. 11) can be explained by the number of
56
57 DPOAE measurements recorded for the first probe fit. After a problem was noticed at one of the
58
59
60

1 DPOAE frequencies, possibly caused by a primary tone level that needed recalibration after the probe
2 was dislodged, the probe was refitted and a new calibration and DPOAE measurement was recorded.
3
4 The primary tones were rarely recalibrated during higher ambient noise levels (67-87 dBA).
5
6
7
8
9

10 11 **3.3.4 Noise threshold limit** 12

13
14 For the reference system, noise threshold limits had to be adjusted according to the ambient noise
15 level in order to complete the measurements. Therefore, it is coherent that the limits follow the noise
16 level as shown in Fig. 12. Again, these limits increased the ambient noise disturbance in recorded
17 DPOAE levels from a median deviation of 2.8 dB from the baseline in 45 dBA ambient noise levels, to
18 a deviation of 7.6 dB in 87 dBA ambient noise levels as shown in Fig. 10.
19
20
21
22
23
24
25
26
27

28 **3.3.5 Measurement duration** 29

30
31 The test duration for the reference system was imposed by the selected EMAN software and was a
32 minimum of about 3 minutes in 45 dBA and up to 6 minutes in 87 dBA ambient noise levels, which is
33 much longer than the 45 seconds required to perform one complete measurement with the designed
34 system (Fig. 13). However, in more difficult measurement conditions, such as 67-87 dBA, the
35 reference system has similar measurement duration limitations as other commercial systems [Smith
36 et al.2001].
37
38
39
40
41
42
43
44
45
46
47

48 For the designed system, the variations in measurement duration for the 45 dBA noise conditions can
49 be explained by the several fit/refit of the probe at the beginning of the day to obtain the most stable
50 and highest DPOAE levels. However in higher noise levels, the duration of measurements were more
51 consistent since the probes were already correctly fit and no refit was necessary between consecutive
52 measurements. Regardless of the ambient noise levels, about 2-3 attempts were performed with each
53
54
55
56
57
58
59
60

1 attempt lasting about 45 seconds to cover the complete range of DPOAE frequencies for a total
2 duration ranging from about 90 to 135 seconds (~2 minutes). Therefore, overall faster DPOAE
3 measurements were performed with the designed system than with the reference system, as observed in
4 Fig. 13. This shorter measurement duration will definitely help to detect the cochlear changes at the
5 optimal moment, i.e. within the first 5 minutes after a possible traumatic noise exposure event and
6 preferably before the cochlea fully recovers [Bourgoin2004, de Toro et al.2010]. Ideally, as it is the
7 case in this study, DPOAE measurements should be conducted while subjects are exposed to noise to
8 detect maximal DPOAE changes. Shorter measurement duration also means that DPOAE levels do not
9 have much time to recover while other DPOAE frequencies are tested [de Toro et al.2010].
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24

25 **4 Conclusions**

26
27
28 To improve the protection of workers against the risk of NIHL, continuous monitoring of their inner-
29 ear activity could give the opportunity to detect temporary changes in cochlear status and take the
30 appropriate actions before the damage is irreversible. By monitoring their inner-ear activity and the
31 noise exposure level they have been exposed to, each worker's own susceptibility to NIHL could be
32 identified. A robust system was designed to monitor OHC activity in high ambient noise levels using
33 DPOAEs. The main objective of this study was to validate that the approach using an inner-ear
34 monitoring system designed in laboratory is able to detect the early onset of OHC changes by
35 observing variations in DPOAE levels during and after noise exposure.
36
37
38
39
40
41
42
43
44
45
46
47
48

49 The experiment was conducted on 9 subjects in three noise conditions: industrial noise, pink noise
50 and quiet conditions. The subjects underwent various hearing tests, including DPOAE measurements,
51 in pre-exposure, during exposure and post-exposure conditions.
52
53
54
55

56 As demonstrated in the study, it is possible to measure DPOAEs in ambient noise exposure levels
57 exceeding 85 dBA at high frequencies with the designed system, for subjects with naturally high
58
59
60

1 DPOAE levels. Overall, it is possible to monitor DPOAEs in noise levels of at least 65 dBA regardless
2 of the OAE probe fit and subjects' natural DPOAE levels. The designed system is able to detect
3 changes in DPOAE levels in noise exposure with low test-retest variability and low deviation from the
4 baseline. The temporary DPOAE level changes indicate that OHC activity is potentially affected by
5 ambient noise exposure.
6
7
8
9
10
11
12
13
14
15

16 The designed system has a clear advantage over the reference system in measurement duration, 2
17 minutes compared to the reference system which can take up to 6 minutes. Shorter measurement time
18 means that DPOAEs can be measured at all frequencies of interest and almost immediately after a
19 traumatic noise event.
20
21
22
23
24
25
26
27

28 The reference system was tested in noisy conditions to observe DPOAE changes induced by
29 exposure to ambient noise and clearly showed that this commercial system was not designed for high
30 ambient noise levels. In the end, it did not perform as well as the designed system in these conditions.
31 However, the reference system was useful to measure post-exposure DPOAE changes relative to the
32 pre-exposure DPOAE levels.
33
34
35
36
37
38
39
40
41

42 Future research shall consider a larger scale study conducted with more test subjects and with noise
43 exposure conditions adapted to trigger more DPOAE changes, in addition to an improved version of
44 the designed system's hardware and software that should improve the detection of physiological
45 DPOAE changes. Besides, by reducing the time spent on other audiological tests, more post-exposure
46 DPOAE measurements could be measured closer to the possible traumatic noise events. For example,
47 one DPOAE measurement could be conducted every 2 minutes in post-exposure and would help to
48 analyze more precisely the relationship between the noise dose received from the ambient noise and the
49 shift in DPOAE levels.
50
51
52
53
54
55
56
57
58
59
60

Acknowledgments

Dr. Annelies Bockstael is a postdoctoral fellow of the Research Foundation-Flanders (FWO); the support of this organization is gratefully acknowledged. The ETS-affiliated authors are thankful to the *Natural Sciences and Engineering Research Council* (NSERC) Individual Discovery Grant Program and the *Fond de recherche Nature et technologies* (FRQNT) Nouveau Chercheur award for financial support, as well as for technical support provided by *EERS Technologies 4.0 Inc.* through the *NSERC-EERS Industrial Research Chair in In-Ear Technology* for prototyping the experimental OAE probes. Vincent Nadon is especially grateful to the *Institut de recherche Robert-Sauvé en santé et sécurité du travail* (IRSST) for its financial support and would also like to thank Mr. Georges Hart at Lapperre for granting him access to the otoadmittance system.

References

- [Borg et al.1979] Borg, E., Nilsson, R., and Lidén, G. (1979). Fatigue and recovery of the human acoustic stapedius reflex in industrial noise. *The Journal of the Acoustical Society of America*, 65(3):846–848.
- [Bourgoin2004] Bourgoin, J. (2004). L'effet sur les émissions oto-acoustiques de la stimulation sonore produite par l'administration des potentiels évoqués auditifs du tronc cérébral. Technical report, Université de Montréal.
- [Canetto2009] Canetto, P. (2009). Hearing protectors: Topicality and research needs. *International Journal of Occupational Safety and Ergonomics*, 15(2):141–153.
- [Carnegie Mellon University1992] Carnegie Mellon University (1992). NOISEX-92 database. <http://www.speech.cs.cmu.edu/comp.speech/Section1/Data/noisex.html>.
- [CRITIAS2016] CRITIAS (2016). Chaire de recherche industrielle en technologies intra-auriculaire CRSNG-EERS (CRITIAS). <http://s11403.p20.sites.pressdns.com/the-technology/arp/>. Visited on December 8th.
- [de Toro et al.2010] de Toro, M., Ordonez, R., Reuter, K., and Hammershøi, D. (2010). Recovery of distortion-product otoacoustic emissions after a 2-kHz monaural sound-exposure in humans: Effects on fine structures. *Journal of the Acoustical Society of America*, 128(6):3568–3576.

- [Engdahl2004] Engdahl, B. (2004). Effects of noise and exercise on distortion product otoacoustic emissions. *Hearing Research*, 187(1-2):12–24.
- [ISO2014] ISO (2014). ISO 1999:2013 - Acoustics – Estimation of noise-induced hearing loss. http://www.iso.org/iso/catalogue_detail.htm?csnumber=45103. Visited on 24 september.
- [Kemp1986] Kemp, D. (1986). Otoacoustic emissions, travelling waves and cochlear mechanisms. *Hearing research*, 22(1):95–104.
- [Keppler et al.2010a] Keppler, H., Dhooge, I., Corthals, P., Maes, L., D’haenens, W., Bockstael, A., Philips, B., Swinnen, F., and Vinck, B. (2010a). The effects of aging on evoked otoacoustic emissions and efferent suppression of transient evoked otoacoustic emissions. *Clinical Neurophysiology*, 121(3):359–365.
- [Keppler et al.2010b] Keppler, H., Dhooge, I., Maes, L., D’haenens, W., Bockstael, A., Philips, B., Swinnen, F., and Vinck, B. (2010b). Transient-evoked and distortion product otoacoustic emissions: A short-term test-retest reliability study. *International journal of audiology*, 49(2):99–109.
- [Kirk and Patuzzi1997] Kirk, D. and Patuzzi, R. (1997). Transient changes in cochlear potentials and dpoaes after low-frequency tones: the two-minute bounce revisited. *Hearing research*, 112(1):49–68.
- [Melnick1991] Melnick, W. (1991). Human temporary threshold shift (tts) and damage risk. *The Journal of the Acoustical Society of America*, 90(1):147–154.
- [Nadon et al.2015a] Nadon, V., Bockstael, A., Botteldooren, D., Lina, J.-M., and Voix, J. (2015a). Individual monitoring of hearing status: Development and validation of advanced techniques to measure otoacoustic emissions in suboptimal test conditions. *Applied Acoustics*, 89:78–87.
- [Nadon et al.2015b] Nadon, V., Bockstael, A., Botteldooren, D., and Voix, J. (2015b). Assessment of otoacoustic emission probe fit at the workfloor. In *10th European Congress and Exposition on Noise Control Engineering (Euronoise 2015)*, pages 1955–1960.
- [Nadon et al.2016] Nadon, V., Bockstael, A., Botteldooren, D., and Voix, J. (2016). Pilot study on individual dose-response relationship evaluated through otoacoustic emission measurements in controlled noise exposure: influence of circadian rhythm. *Canadian Acoustics*, 44(3):162–163.
- [Nadon et al.2014] Nadon, V., Voix, J., Bockstael, A., and Botteldooren, D. (2014). Signal processing techniques for continuous monitoring of distortion product otoacoustic emissions in noisy industrial environments. In *Forum Acusticum 2014, Krakow (Poland)*.
- [Neely and Liu1994] Neely, S. and Liu, Z. (1994). Emav: Otoacoustic emission averager. Technical report, Technical Memo.
- [NIOSH2016] NIOSH (2016). National Institute for Occupational Safety and Health : NOISE AND HEARING LOSS PREVENTION. <https://www.cdc.gov/niosh/topics/noise/>.
- [Sliwinska-Kowalska et al.2001] Sliwinska-Kowalska, M., Kotylo, P., et al. (2001). Otoacoustic emissions in industrial hearing loss assessment. *Noise and Health*, 3(12):75.
- [Smith et al.2001] Smith, S., Kei, J., McPherson, B., and Smyth, V. (2001). Effects of speech babble on transient evoked otoacoustic emissions in normal-hearing adults. *JOURNAL-AMERICAN ACADEMY OF AUDIOLOGY*, 12(7):371–378.
- [Sonomax2016] Sonomax (2016). SonoFit. <http://sonomax.com/assets/files/pdf/Sonomax-SonoFitSystem-Sheet.pdf>. Visited on December 23rd.

1
2 [Sutton et al.1994] Sutton, L. a., Lonsbury-Martin, B. L., Martin, G. K., and Whitehead, M. L.
3 (1994). Sensitivity of distortion-product otoacoustic emissions in humans to tonal over-exposure: time
4 course of recovery and effects of lowering L2. *Hearing research*, 75(1-2):161–174.
5

6 [Venet et al.2014] Venet, T., Campo, P., Rumeau, C., Thomas, A., and Parietti-Winkler, C. (2014).
7 One-day measurement to assess the auditory risks encountered by noise-exposed workers.
8 *International journal of audiology*, 53(10):737–744.
9

10 [Vinck et al.1999] Vinck, B. M., Van Cauwenberge, P. B., Leroy, L., and Corthals, P. (1999).
11 Sensitivity of transient evoked and distortion product otoacoustic emissions to the direct effects of
12 noise on the human cochlea. *International journal of audiology*, 38(1):44–52.
13

14 [Voix and Laville2009] Voix, J. and Laville, F. (2009). The objective measurement of individual
15 earplug field performance. *The Journal of the Acoustical Society of America*, 125(6):3722–3732.
16

17 [Zare et al.2015] Zare, S., Nassiri, P., Monazzam, M. R., Pourbakht, A., Azam, K., and
18 Golmohammadi, T. (2015). Evaluation of distortion product otoacoustic emissions (dpoaes) among
19 workers at an industrial company exposed to different industrial noise levels in 2014. *Electronic
20 physician*, 7(3):1126.
21

22 [Zoom2016] Zoom (2016). Zoom H5. [https://www.zoom.co.jp/products/handy-recorder/h5-handy-
23 recorder](https://www.zoom.co.jp/products/handy-recorder/h5-handy-recorder). Visited on December 8th.
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60



Fig. 1: The DPOAE measurement device designed in laboratory with its electronic hardware box and its two measurement probes featuring custom moulded ear-tips.

For Peer Review

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

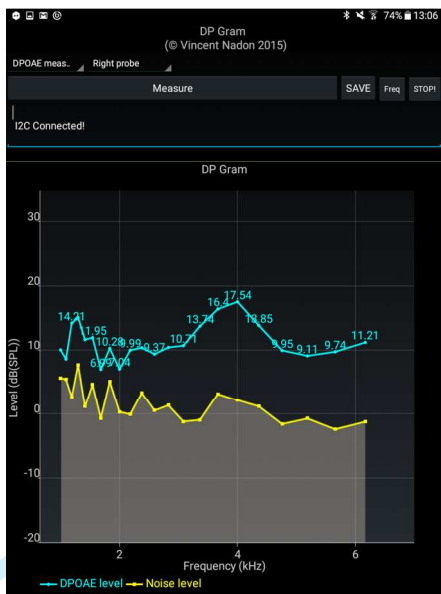
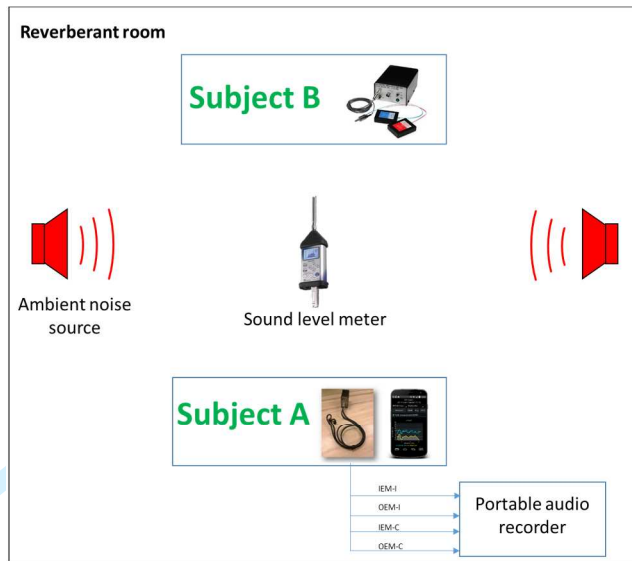


Fig. 2: Screenshot of the designed Android smartphone application showing the DPOAE measurement data received over Bluetooth from the DPOAE device designed in laboratory.

For Peer Review



23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Fig. 3: Physical setup used for the tests during the ambient noise exposure. The schematic shows the sound level meter in the middle between the test subjects to record the ambient noise sound pressure levels, with subject A tested by the designed system and subject B tested by the reference system. The loudspeakers used for the ambient noise exposure are shown on the left and the right. The portable audio recorder is recording the ipsilateral in-ear microphone (IEM-I), ipsilateral outer-ear microphone (OEM-I), contralateral IEM (IEM-C) and contralateral OEM (OEM-C) signals of the designed system.

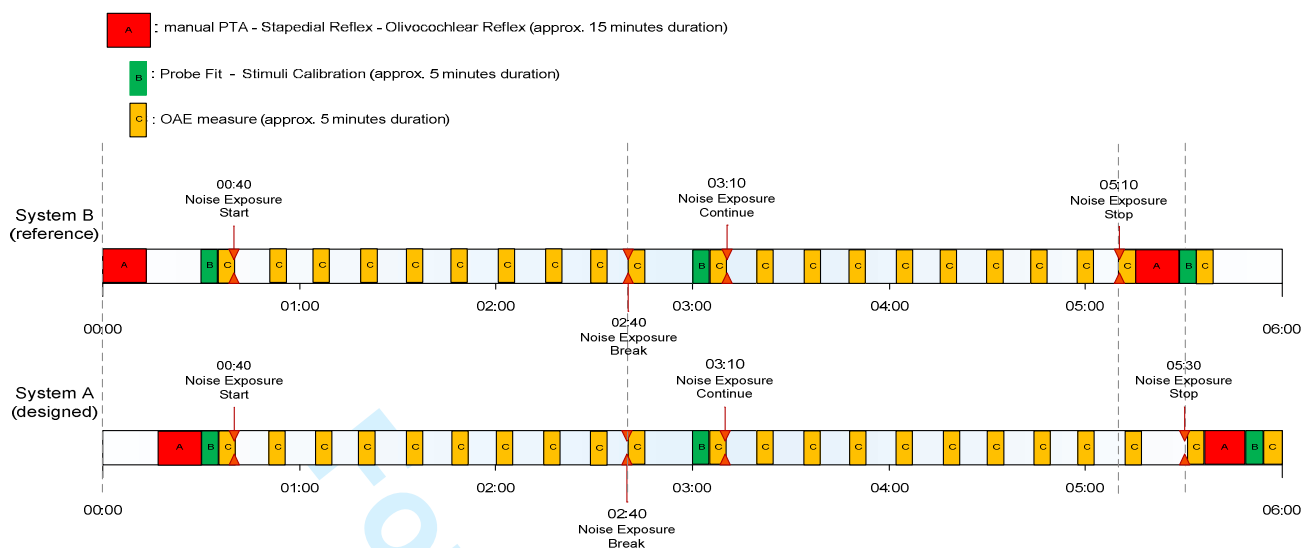


Fig. 4: Timeline of the experiment protocol for subjects A and B periodically tested using 2 OAE systems, the designed system and the reference system, while continuously exposed to noise

Preprint Peer Review

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

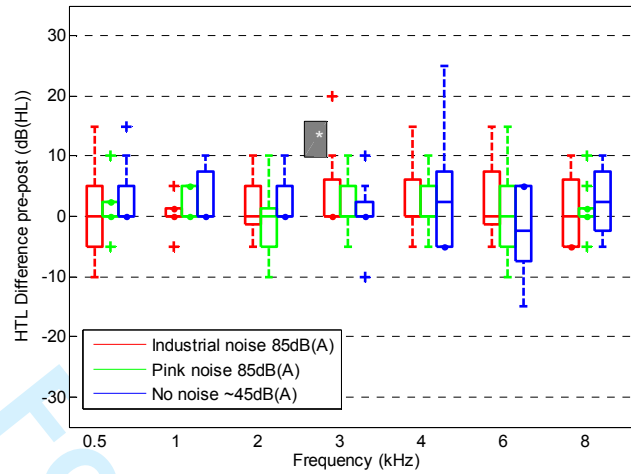


Fig. 5: Differences in PTA HTLs on 9 subjects as a function of frequency between pre-exposure and post-exposure measurements for the industrial, pink noise and quiet conditions. Mostly, positive changes are observed and are only statistically significant ($p < 0.05$) at 3 kHz for industrial noise conditions (*). No significant temporary threshold shift induced by the ambient noise exposure is visible. The (+) symbol represents outliers.

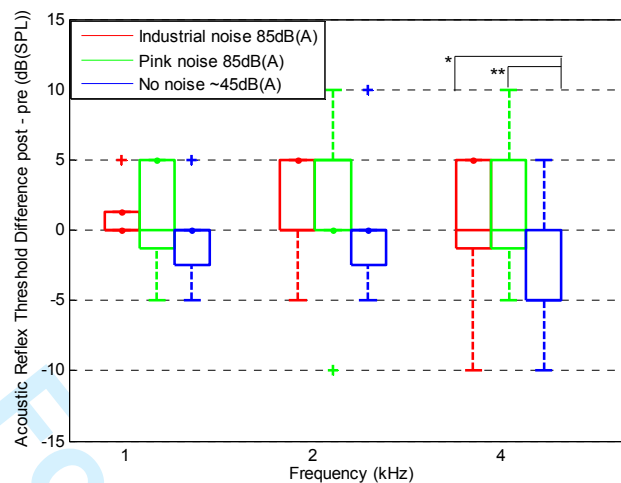


Fig. 6: Differences in Acoustic Reflex Threshold on 9 subjects between pre-exposure and post-exposure measurements, as a function of the tested narrow-band noise frequency, for the industrial noise, pink noise and quiet conditions. A statistically significant ($p < 0.05$) increase in ART was observed at 4 kHz for both industrial (*) and pink noise (**). The (+) symbol represents outliers.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

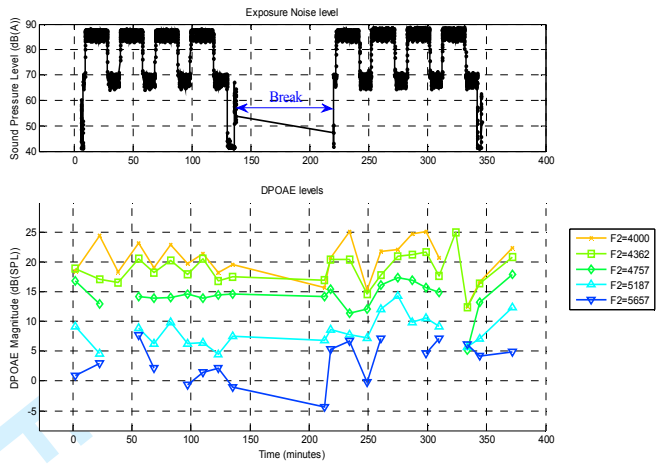


Fig. 7: Typical timeline of exposure noise level (top) synchronized with DPOAE variations at 5 test frequencies during the experiment on a subject (bottom). Blank data points for certain frequencies result from the post-processing threshold method removing outliers.

TO Peer Review

f_2
(Hz)

Industrial noise

Pink noise

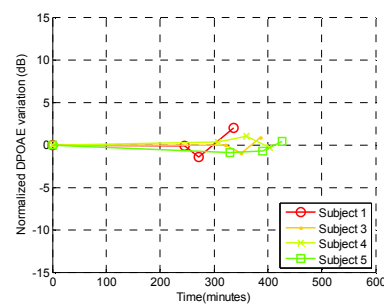
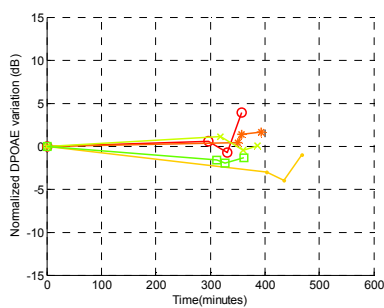
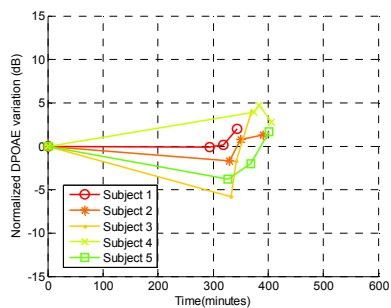
Quiet

a)

b)

c)

4000

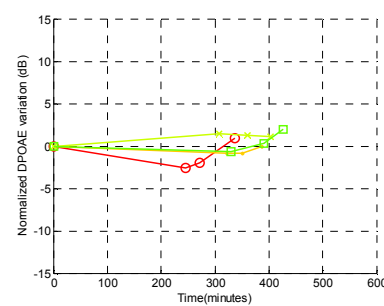
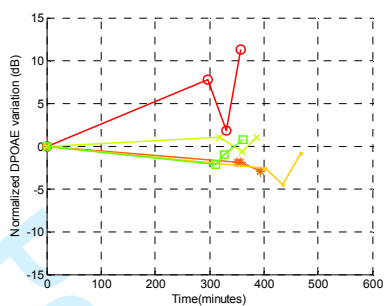
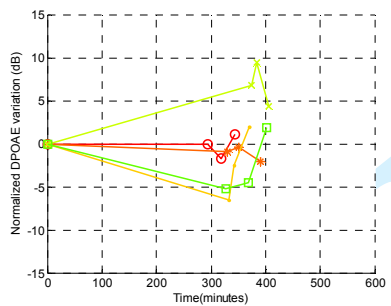


d)

e)

f)

4362

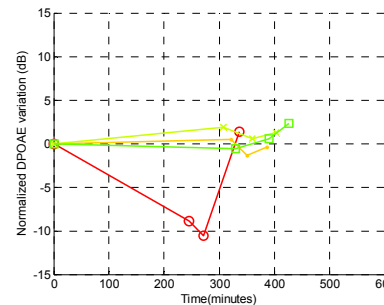
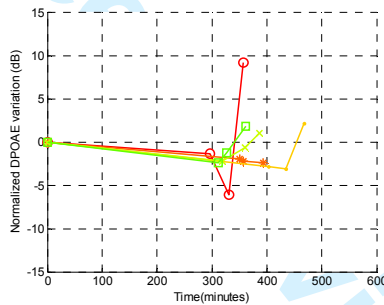
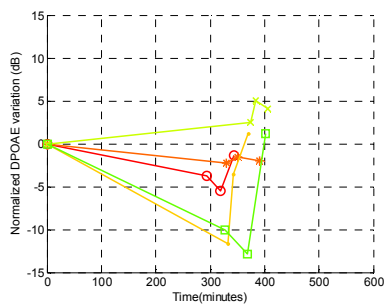


g)

h)

i)

4757



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

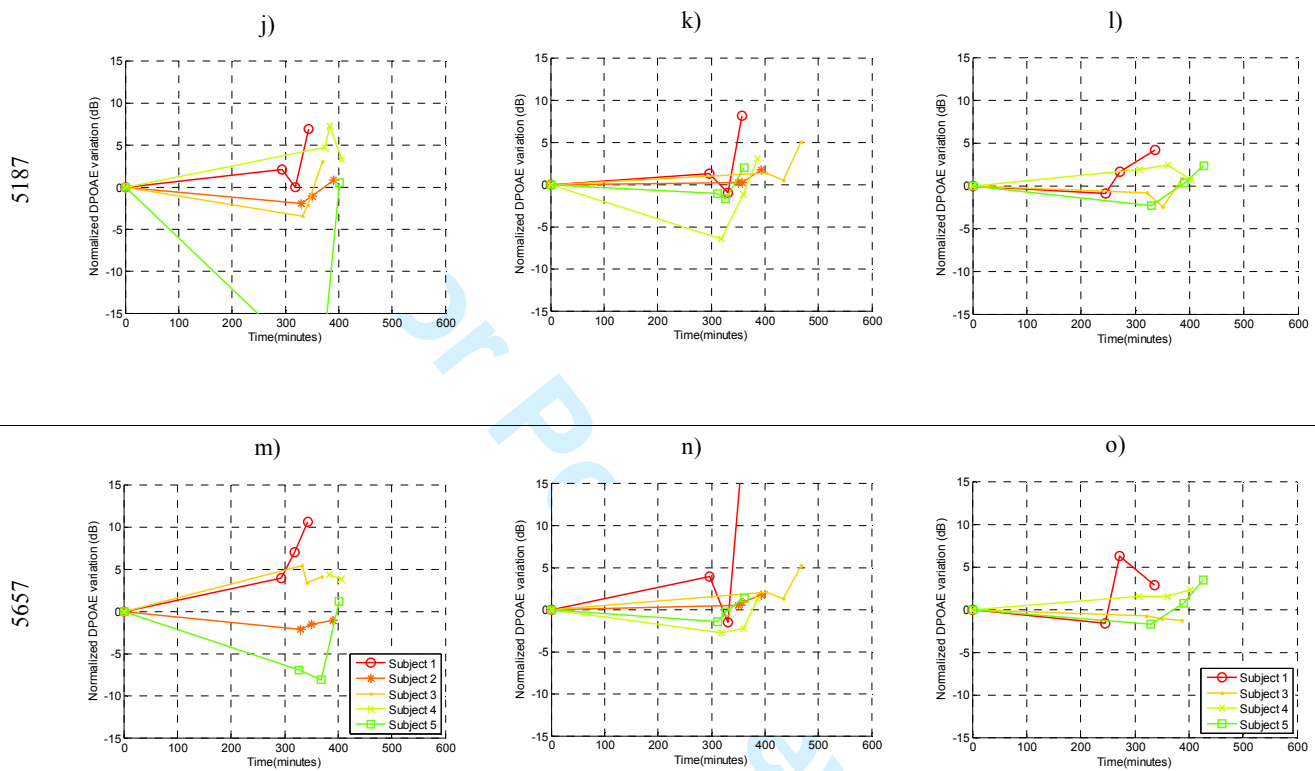


Fig. 8: Comparison of DPOAE variations over time for the designed system between the three types of noise conditions, variations are normalized with the baseline (at t=0 min) DPOAE level. The second point represents the last measurement conducted in noisy conditions (67-87 dBA), the third point represents the first measurement post-exposure and the last point on the right represents the last measurement post-exposure. The legend is the same for industrial and pink noise conditions, but only 4 subjects were tested in quiet conditions. The second and third data points are usually below the baseline for industrial and pink noise conditions indicating possible effects of noise exposure on outer hair cells. The last data point is usually closer or above the baseline indicating the possible recovery of the inner-ear.

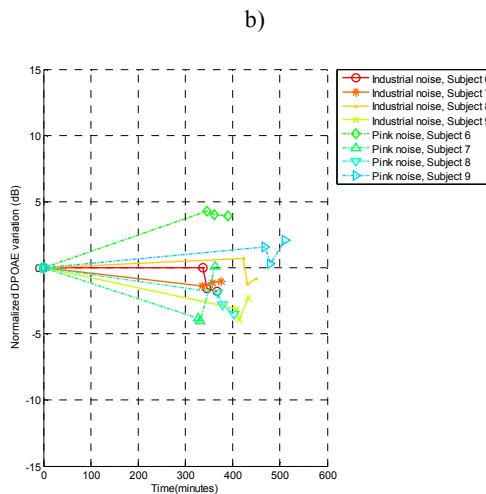
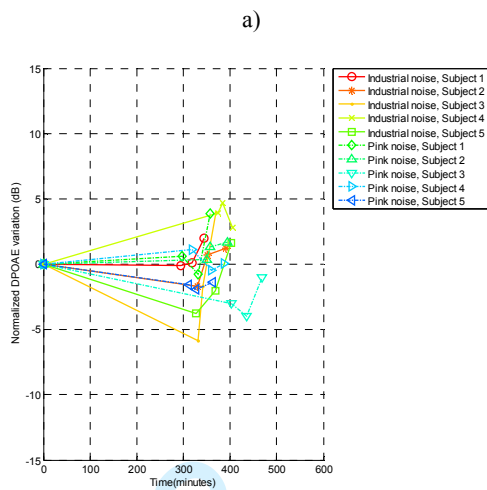
f_2 (Hz)

Designed / Reference

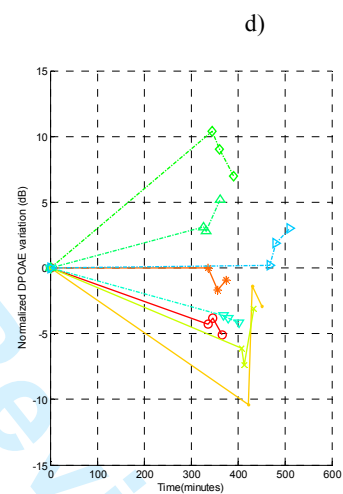
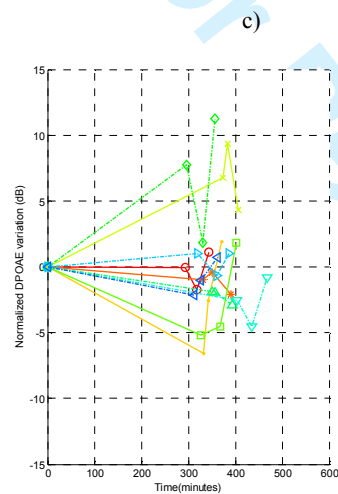
Designed system

Reference system

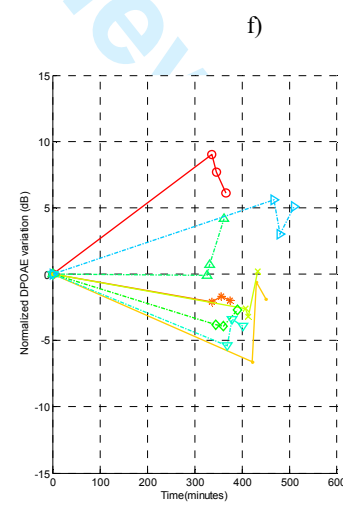
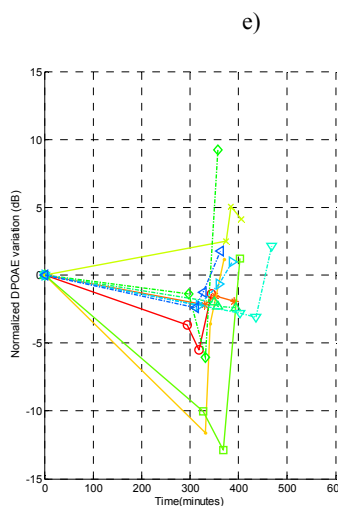
4000 / 4021



4362 / 4382



4757 / 4780



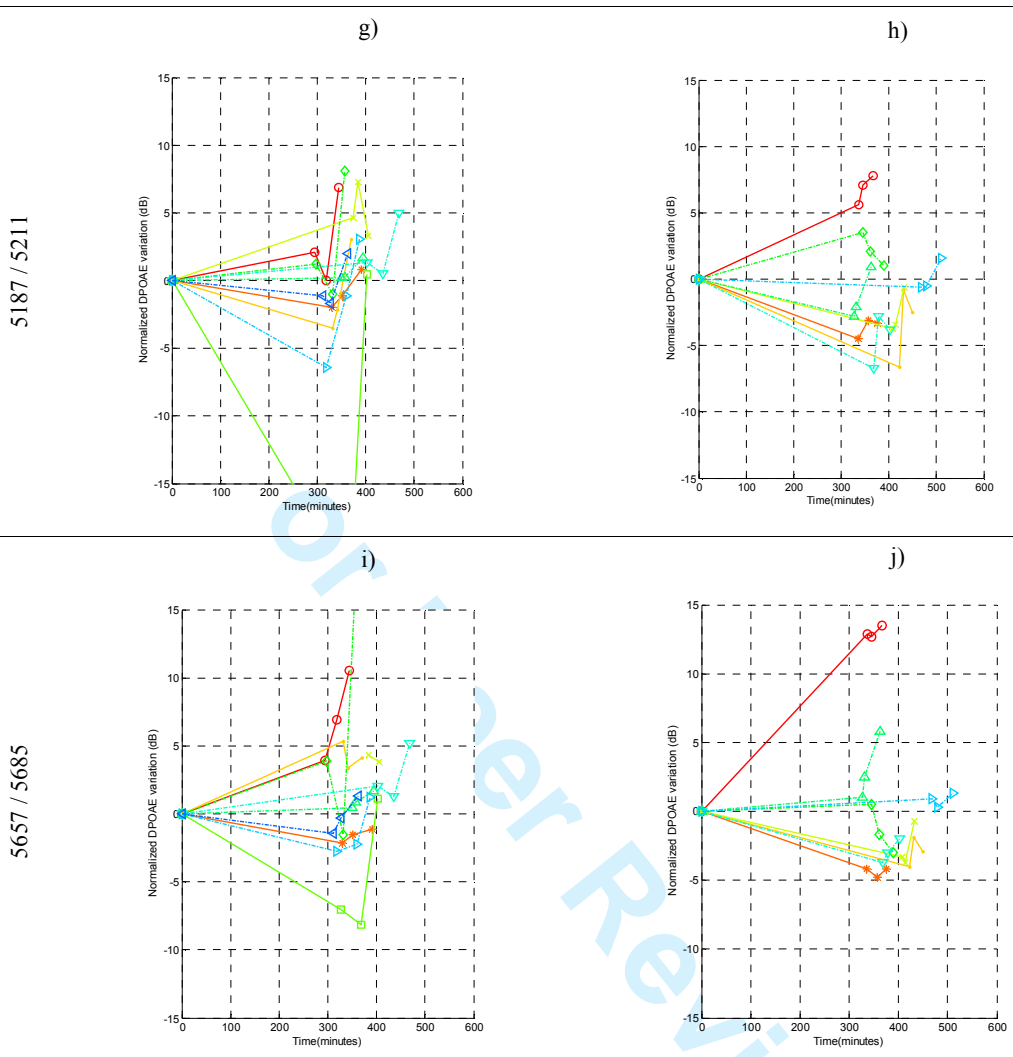


Fig. 9: Comparison of DPOAE variations over time for the designed and reference system; variations are normalized with the baseline DPOAE level at $t=0$ min. The second point represents the last measurement conducted in noisy conditions (67-87 dBA), the third point represents the first measurement post-exposure and the last point on the right represents the last measurement post-exposure. The legends are the same across the tested frequencies, however the subjects tested with the designed and reference systems are not the same. Results with the reference system are more scattered than with the designed system indicating that the reference system is probably less robust to test for DPOAE changes in high ambient noise levels.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

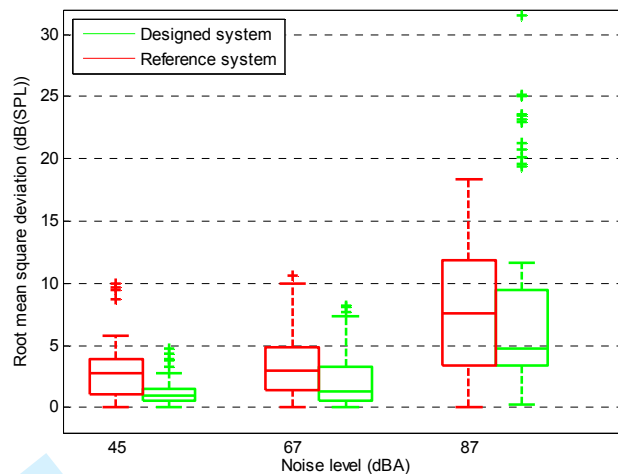


Fig. 10: DPOAE deviation from the baseline in ambient noise levels of 45 dBA, 67 dBA and 87 dBA (all sources i.e. industrial, pink noise and quiet conditions, merged). Overall, a better immunity, i.e. smaller deviation from baseline, to ambient noise levels is observed for the designed system than for the reference system. The (+) symbol represents outliers.

Peer Review

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

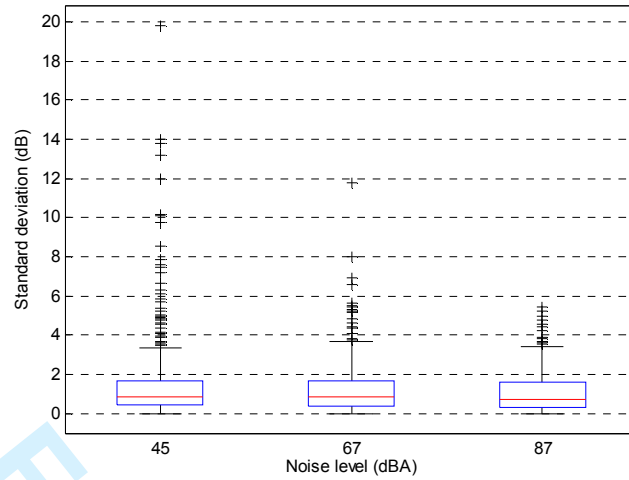


Fig. 11: Test-retest variability between consecutive measurements for the designed DPOAE system in 45 dBA, 67 dBA and 87 dBA ambient noise levels (all sources i.e. industrial, pink noise and quiet conditions, merged). The (+) symbol represents outliers.

For Peer Review

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

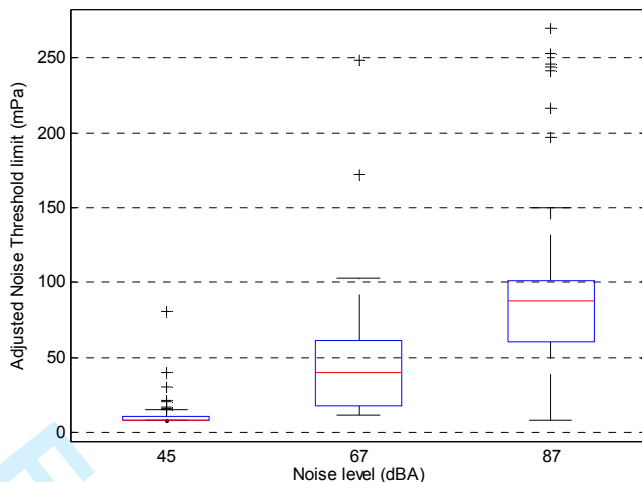


Fig. 12: Adjusted noise threshold limit required for the reference system to proceed to DPOAE measurements in 45 dBA, 67 dBA and 87 dBA ambient noise levels (all sources i.e. industrial, pink noise and quiet conditions, merged). The (+) symbol represents outliers. Noise threshold limits in 87 dBA are higher than for other ambient noise levels.

For Peer Review

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

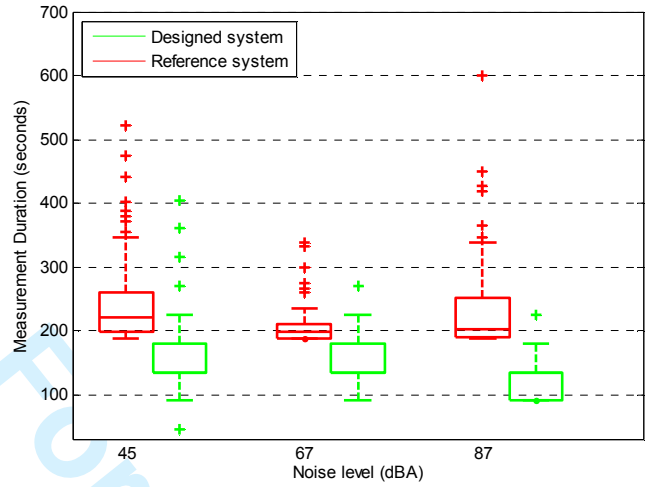


Fig. 13: Comparison of the DPOAE measurement duration for the reference system and the designed system in 45 dBA, 67 dBA and 87 dBA ambient noise levels (all sources i.e. industrial, pink noise and quiet conditions, merged). The (+) symbol represents outliers.