# Hearing protectors and the possibility to detect noise-induced hearing damage using otoacoustic emissions in situ.

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**Hearing conservation should allow early-detection of hearing damage. In this, otoacoustic emissions (OAEs) can be a reliable tool, but environmental noise is a serious drawback for OAE registration near the work floor. Here, noise attenuation offered by hearing protectors might help to measure OAEs in acoustically more challenging test conditions. As a proof of concept, transient evoked OAE (TEOAE) measurements are carried out in different levels of realistic industrial and broadband noise with and without earmuffs. The major research questions are (1) whether earmuffs can reduce noise sufficiently to extend tolerable background noise levels for OAE measurements, (2) how OAEs vary as a function of acoustical measurement conditions and (3) what the consequences are for pass-and-refer screening criteria. This project shows that earmuffs make TEOAE registration reliable in elevated levels of background noise, clearly too high for measurements without any additional noise attenuation. By contrast, unattenuated moderate background levels already result in refers for a considerable amount of subjects with (perfectly) present TEOAEs when measured in silence, but this classification mismatch is resolvable with earmuffs for substantially higher noise levels. However, also with earmuffs results deteriorate abruptly when background noise increases towards harmful levels.**

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## 1 INTRODUCTION

The relationship between noise exposure and hearing damage has been well-established and to-date *prevention* still is the only valid approach[1]. In this, personal hearing protectors have become a popular measure at the work floor, but nevertheless occupational hearing loss persists[2]. Several factors might be part of hearing protectors' underachievement; the apparent discrepancy between protectors' attenuation predicted from laboratory tests and actually protection achieved in situ[3], variation in attenuation over a working day[4], *and* individual susceptibility to noise[5]. To allow quick and adequate intervention whenever needed, effective hearing conservation should include regular monitoring of the protectors' attenuation[6;7] and of the user's hearing status.

In clinical practice, a wide range of audiological tests are available to assess possible hearing loss. With regard to occupational noise exposure, the selected test should not only be sensitive for early-stage noise-induced hearing loss, but also sufficiently robust to be carried out in less than optimal measurement conditions. Moreover, the whole procedure should only take a short time to make sure that hearing conservation is compatible with daily working routines.

Here, evoked otoacoustic emissions (OAEs) allow detection of pre-clinical noise-induced hearing damage[8] as their absence or reduction in amplitude reflects damage to the outer hair cells. These structures form part of the organ of Corti inside the cochlea and are altered by excessive noise exposure[9]. In addition, OAE measurements are a non-invasive objective technique[9] taking no longer than a few minutes. Their major drawback is sensitivity to the acoustical measurement situation, since even in carefully controlled conditions background noise is considered to be a limiting factor[10].

Commercially available OAE measurement equipments already includes noise-reducing signal processing[11] and more advanced hardware and software solutions are studied[12;13]. However, the primary step is controlling the noise level that actually enters the system and here probe fitting is of uttermost importance[14]. This study will therefore assess the registration of OAEs in various types and levels of background noise, relying *only* on careful probe placement *and* virtually improving the fitting by placing an earmuff on top. Tests have been carried out for two types of OAEs, Transient Evoked otoacoustic emission (TEOAE) and Distortion Product otoacoustic emission (DPOAE), here only results for the TEOAE will be reported.

In situ monitoring of OAE-responses not only requires an adequate measurement approach, but also valid screening criteria to judge the risk of hearing damage. Those criteria should be sufficiently strict so that 'fails' trigger adequate preventive measures – like checking the fit of personal hearing protectors or temporary working in more quiet areas – but at the same time unnecessary warnings should be avoided to make sure that hearing conservation does not interfere with normal working routines. The current paper hence assesses the usefulness of different pass and refer thresholds as a function of background noise and additional noise attenuation. To sum up, the major research questions are (1) whether earmuffs can reduce noise sufficiently to extend tolerable background noise levels, (2) how OAE vary as a function of acoustical measurement conditions and (3) what the consequences are for pass-and-refer screening criteria.

## 2 MATERIAL AND METHODS

### 2.1 Test subjects

Sixty-two volunteers without history of otological conditions have been tested, 34 between 18 and 30 years old (17 male, 17 female) and 28 between 31 and 46 years (16 male, 12 female). For each subject, either the right or the left ear has been randomly selected. Test subjects have been asked to avoid noise and loud music 48 hours before testing and the use of caffeine or alcohol on the testing day.

### 2.2 Audiological testing

All testing has been performed in a quiet, but not sound-proof room. During the tests, background noise has been continuously monitored with a Svantek 959 sound analyzer. Otoscopy has been carried out and a questionnaire has been distributed, addressing (familial) otological conditions.

OAEs have been measured with the Echoport ILO 292 USB II module, calibrated at the beginning of each testing day. TEOAEs have been recorded in accordance with the nonlinear differential method of stimulus presentation, using a rectangular pulse with duration of 80 ms. The clicks have been presented at a rate of 50 per second. Stimulus level of the TEOAEs is set at 80 dB SPL peak, and signals have been averaged over 520 repetitions. The artifact rejection level has been set on 8 mPa. Additionally, the built-in high pass filter has been activated.

Beside OAE measurements, tympanometry has been carried out with an Interacoustics Impedance Audiometer AT 235 and tonal audiometry with an Interacoustics Diagnostic Audiometer AD 229E in accordance to the Hugshon-Westlake method. All subjects had a pure-tone average – average audiometric threshold at 500 Hz, 1000 Hz and 2000 Hz – of 25 dB HL or better. For four participants, tympanometric results suggested somewhat lower middle ear pressure, but they were nevertheless included in the final sample because their middle ear status did not seem to influence their hearing threshold.

### 2.3 Background noise

Realistic industrial noise samples have been recorded at different locations in a carpet factory using a hand-held Svantek 959 sound analyzer. Furthermore, white noise fragments at different levels have been created with the Audacity software. Table 1 gives an overview of all included background noise fragments, recorded at the test subject's position without any subject being present. Samples have been played in random order per participants using an Adam Audio S1X loudspeaker with built-in amplifier, connected to a laptop PC with an U24XL sound card. The test subject was seated at 78 cm from the loudspeaker, the setup has been calibrated at the beginning of each testing day with the Svantek sound analyzer.

### 2.4 Attenuation

To assess objectively the potential benefits of extra noise attenuation, the attenuation of the probe as such and with an earmuff placed on top have been measured with a Head And Torso Simulator (HATS type 4128 C Brüel & Kjær). This device mimics the influence of a human head and torso on sound propagation and registers the sound pressure level where anatomically the eardrum is found. Insertion loss can be easily assessed by comparing the sound pressure level at the eardrum in an unoccluded ear canal to the level that reaches the eardrum when inserting the OAE probe or the probe-earmuff combination. Bone conduction estimates have been taken into account in accordance to the calculation procedure described by Hiselius [15]. Further specification of the test setup and measurement equipment can be found in Bockstael et al. [16].

### 2.5 Analysis

For TEOAE signal and noise levels separately, influential outliers have been detected per frequency band by comparing the mean value and the mean value excluding the 10 % most extreme observations; no major differences have been found. In addition, possible skewed distribution of the data has been investigated per frequency band per test condition, but again no substantial divergence has been observed. Mixed-model linear regression has been carried out per frequency band with signal-to-noise ratio at respectively 1 kHz, 1.5 kHz, 2 kHz, 3 kHz and 4 kHz as outcome. As independent parameters the variables *subject* (random) and *test condition* (fixed) have been selected. Subsequently, Tukey post-hoc analysis has been applied to assess the pairwise difference in signal-to-noise ratio between test conditions.

To address the feasibility of screening criteria, the sensitivity and specificity are calculated for three different pass levels; one strict criterion where a pass requires at least four out of five frequency bands to have a signal-to-noise ratio of at least 3 dB, one milder criteria with at least three present bands and finally a relaxed criterion with at least one band present. Since this study includes test subjects without otological history and no noise-induced hearing damage will occur during the test, sensitivity and specificity are calculated to quantify the possibility that normal-hearing subjects are correctly identified as such, despite the background noise interfering with the measurements. Per condition of background noise sensitivity is therefore defined as

$$sensitivity = \frac{TruePositives}{TruePositives + FalseNegatives}. \tag{1}$$

*True positives* means that TEOAEs are present – according to the pass criteria stated above – in the baseline condition (without additional background noise) and in the test conditions under study. *False negativess* are the observation where the pass criteria are not fulfilled in the test conditions, although TEOAEs are found present in the baseline condition. Additionally, specificity is calculated as

$$specificity = \frac{TrueNegatives}{TrueNegatives + FalsePositives} \tag{2}$$

with *true negatives* the cases where failure is observed both in baseline and conditions with background noise whereas *false positives* means that TEOAEs are absent in the baseline condition but present in the test conditions.

## 3 RESULTS

### 3.1 Added value of attenuation

Attenuation of background noise by OAE probe, alone and in combination with earmuff, is shown in Figure 1. From 200 Hz and higher, the OAE probe itself provides already a certain degree of attenuation, which increases with increasing frequency. Placing an earmuff on top somewhat increases the attenuation between 100 Hz and 200 Hz, but the effect is most noticeable from 500 Hz and above.

In this particular study, linear regression reveals that for all frequency bands the signal-to-noise ratio significantly decreases as the background level increases ($p < 0.001$). An overview of the average signal-to-noise ratio per frequency band per test conditions is given in Figure 2. Tukey post-hoc analyses for all five models reveals a very clear influence of noise *level* – i.e. comparing conditions with the same type of background noise and presence/absence of the earmuff – for all frequencies ($\alpha = 0.05$); only the OAE signal-to-noise ratio for the most quiet white noise conditions (54 dB(A) and 58 dB(A)) is not ($p > 0.1$ at 1 kHz, 1.5 kHz and 4 kHz) or only marginally ($0.1 > p > 0.05$ at 2 kHz and 3 kHz) significant.

Pairwise comparison of white and industrial noise fragments with comparable levels reveals that industrial noise has a more adverse effect on the signal-to-noise ratio than white noise ($\alpha = 0.05$), especially at lower and mid frequency bands (1 kHz, 1.5 kHz, 2 kHz). For 3 kHz industrial noise appears to introduce a significant lower signal-to-noise ratio at 72.8 dB – compared to 70.8 dB white noise – but no major differences are found at lower or higher noise levels. Finally, at the 4 kHz band none of the comparisons is significant.

To record OAE, placing earmuffs has a clear advantage over all frequency bands; the signal-to-noise ratio is significantly higher ($\alpha = 0.05$) for the 70.8 dB(A) fragment with earmuffs compared to the more quiet 62.3 dB(A) condition. For all TEOAE frequencies except 1.5 kHz, the noise level with earmuffs can even be further raised up to 77.7 dB(A) ($\alpha = 0.05$). For the 1.5 kHz frequency band, this is not possible as the signal-to-noise ratio is no longer significantly better at 77.7 dB(A) with earmuff than at 62.3 dB(A) without. Looking separately at speech and noise levels of 1.5 kHz shows that the noise level is indeed relatively high in the conditions with earmuffs.

Furthermore, the signal-to-noise ratio is significantly better in 70.8 dB(A) with earmuffs compared to the more quiet white noise fragments (54.1 dB(A) and 57.2 dB(A)); and this for all frequency bands except 1.5 kHz. For the latter frequency, the signal-to-noise ratio is marginally better in 70.8 dB(A) with earmuffs than in 57.2 dB(A) without ($0.1 > p > 0.05$). Finally, the signal-to-noise ratio at 3 kHz and 4 kHz is even markedly lower in 53.3 dB(A) industrial noise without earmuffs than in 72.8 dB(A) with. Addressing the signal and noise levels separately reveals that in the highest frequency bands the high signal-to-noise ratio for 72.8 dB(A) background noise condition can be attributed to relatively low noise levels.

### 3.2 Noise characteristics and TEOAE

The results described above show that industrial noise recordings have a larger negative effect on TEOAE signal-to-noise ratio than white noise fragments at comparable levels, especially for frequency bands up-to 2 kHz. This is most likely due to different spectral characteristics of the noise fragment: Figure 3 shows that all industrial noise fragments are dominated by lower frequencies. Tukey-post hoc testing described above confirms that the difference in signal-to-noise ratio follows variation in background noise *around the frequency band under study*. For frequencies up-to 2 kHz, the noise levels are higher for the industrial noise recordings than for the white noise samples with comparable overall levels. For the highest frequencies, signal-to-noise ratios are never significantly better in industrial noise conditions compared to white noise, although in some cases the levels are (slightly) lower than the corresponding white noise fragments.

Unlike white noise, industrial noise recordings have some level variation over time, especially the most quiet recording shows several peaks up-to 60 dB(A) and more. Naturally, distinct increases in noise level will have a detrimental influence on TEOAE, but since the OAE recording system sends out 520 repeated stimuli, short-time level increases will most likely be averaged out. Additionally, in this particular fragment overall levels are most of the time below the most quiet white noise fragment whereas the signal-to-noise ratio is worse for industrial noise, hence the more distinct spectral differences described above are thought to be more important than temporal variation.

As the background noise increases, the earmuff's attenuation clearly has an added value for TEOAE registration. This effect is more pronounced in mid and higher TEOAE frequencies, which is perfectly in line with increasing attenuation for increasing frequency (see Figure 1).

### 3.3 Screening criteria

As explained in the Methodology Section 2.5 sensitivity and specificity are calculated to address the possibility that subjects correctly pass the TEOAE screening, despite acoustically sub-optimal test conditions. Figure 4 reveals that the sensitivity decreases substantially in 72 dB(A) industrial noise when severe or even mild pass/refer criteria are used. This means that a considerable part of subjects with TEOAE present in quiet conditions, fail the test due to (excessive) background noise. Using these criteria in practice would lead a major part of workers wrongly thought to be at risk of noise-induced hearing loss – and hence requiring extra preventive measures – whereas in reality TEOAE measurement reflect the adverse measurement conditions rather than any hearing loss.

Only with a relaxed pass-refer criterion, sensitivity is found to be acceptable up-to 77 dB(A) white noise. However, with this screening protocol, noise-induced hearing damage is only suspected when *all* frequency bands have a signal-to-noise ratio lower than 3 dB, which undermines the idea of *early* detection. In this data set, for example, all but one participant pass the baseline TEOAE test under this relaxed criterion, whereas individual inspection of the audiograms suggests that at least two subjects have hearing thresholds worse than 20 dB HL.

To find a better balance between early detection and false refers, a more frequency specific criterion is applied for which TEOAE responses should be at least present at 3 kHz or 4 kHz. This screenings protocol leads to a more than acceptable sensitivity up to 77 dB(A) whereas 11 subjects fail the baseline TEOAE, confirming that the risk of not detecting noise-induced hearing loss would be actually lower with this criterion. Specificity is slightly lower than for the relaxed criterion because some participants with absent TEOAE in the baseline condition achieve a pass in background noise levels between 70 dB(A) and 77 dB(A) (respectively 4 and 2 subjects).

## 4 DISCUSSION

Analyzing TEOAE response as a function of background noise shows that even moderate levels of industrial noise can interfere strongly with TEOAE measurements. The condition with lowest noise level has for instance been recorded in a rather quiet storage area of the company, well away from noisy machinery and with only few workers passing by. But even then, the signal-to-noise ratio is substantially reduced up-to 2 kHz and screening criteria need to be relaxed to avoid overestimation of potential hearing loss. In general, OAE measurements are becoming a popular tool for field measurements thanks to the portable equipment and easy procedure. However, this study confirms that the quality of OAE recordings largely depends on background noise, even when the OAE probe is carefully placed.

In this, extra attenuation provided by earmuffs or – in general – by improved probe fitting is certainly beneficial and enables reliable measurements for background levels up to 70 dB(A). This range is even extended up to 77 dB(A) when high-frequency response is considered. Conversely, with the current test equipment it remains impossible to actually perform test *at* the work floor; more quiet areas like office spaces would still be needed.

Additionally, these results suggest that more frequency-specific analysis of OAE is beneficial. The selected industrial fragments are more dominated by lower frequency content, but also in general attenuation of standard hearing protectors increases with increasing frequency. Moreover, emphasizing high-frequencies analysis might be beneficial from a diagnostic point of view, since normal hearing and hearing issues are more easily distinguished in the frequency range between 2 kHz and 4 kHz[17]. Based on these findings, DPOAE might be more suitable for in situ monitoring as their frequency range can be expanded up to 8 kHz[12].

Apart from the selected frequencies, implementing OAE monitoring in hearing conservation requires adequate pass and refer criteria; sufficiently strict to allow early detection of hearing damage and sufficiently relaxed to avoid needless interference with working routines. This study with subjects without otological complaints is mostly suited to assess the risk of unnecessary intervention where measurement conditions and not hearing loss result in TEOAE refer. To avoid this, the overall threshold for passing has to be set (very) low for the current data set. Because this strategy might substantially lower the possibility to actually detect noise-induced hearing loss, a more selective approach is applied where screening is limited to higher frequency bands. This way, most people with TEOAE in low-levels of background noise still pass the test in background noise up-to 77 dB(A), but also the number of people with an initial refer is more in line with their data from other audiological testing. Whether these criteria are really sufficiently strict for early detection of noise-induced hearing loss should be investigated further for a test group with actual hearing loss.

## 5 CONCLUSION

Measuring OAEs is as such a promising approach to monitor workers' hearing status more closely. Conversely even moderate – in terms of realistic industrial settings – background levels already limit the applicability of the pure clinical implementation. Improved attenuation of background noise and more frequency-specific analyses are shown to be beneficial. This should be implemented and further improved by probe design and signal processing. This way, in situ OAE response monitoring can be used as a regular hearing damage screening tool around the work floor; triggering preventive actions and/or more precise audiological testing whenever needed.

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*Table 1 – Overview of the test condition with different types and levels of background noise, i.e. without added noise (quiet), with white noise or with industrial noise. The column HPD indicates whether an earmuff has been placed on top of the OAE probe ('yes' or 'no').*

| No | Noise | HPD | level [dB(A)] |
|---|---|---|---|
| 1 | quiet | no | 24.7 |
| 2 | industrial | no | 53.3 |
| 3 | white | no | 54.1 |
| 4 | white | no | 57.2 |
| 5 | white | no | 62.3 |
| 6 | white | yes | 70.8 |
| 7 | industrial | yes | 72.8 |
| 8 | white | yes | 77.7 |
| 9 | industrial | yes | 83.2 |
| 10 | white | yes | 83.4 |
| 11 | white | yes | 90.3 |

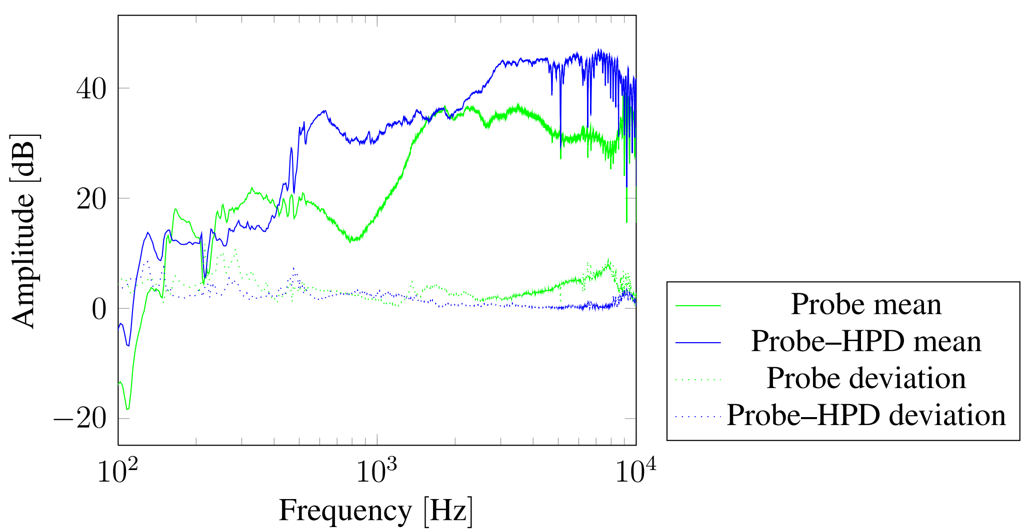


*Fig. 1 – Insertion loss measured on a HATS for the OAE probe alone (Probe) and with an earmuff placed on top (OAE–HPD). For four repetitive measurements, the average value (mean) and standard deviation (deviation) are shown.*

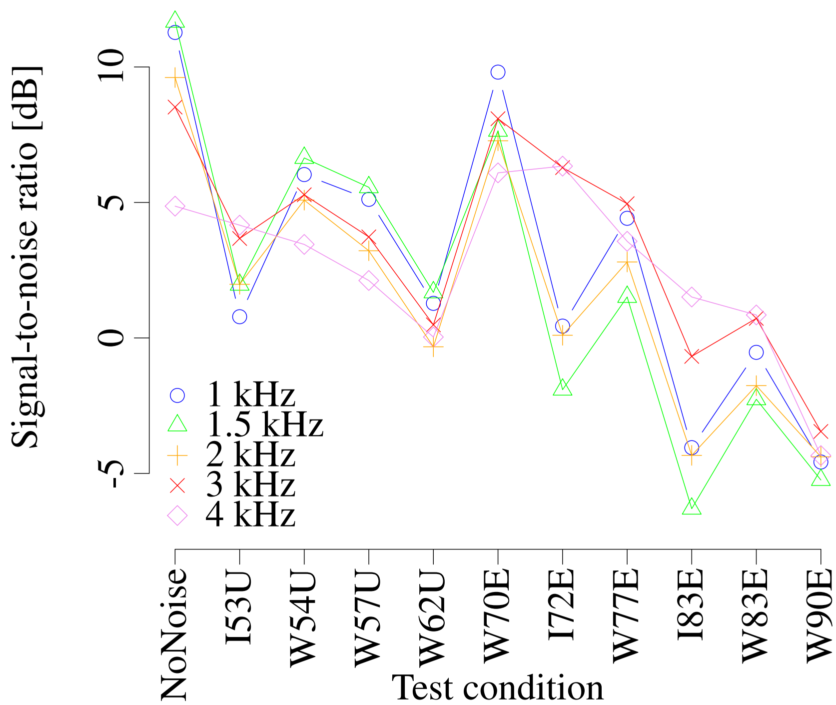


*Fig. 2 – TEOAE signal-to-noise averaged per frequency band (1 kHz, 1.5 kHz, 2 kHz, 3 kHz and 4 kHz) per test condition, i.e. without additional background noise (NoNoise) and in different noise levels. For the labels on the horizontal axis, the first character indicates the noise type (industrial (I) or white (W) noise), the second the noise level and the last whether earmuffs are included (E – earmuff) or not (U – uncoverd).*

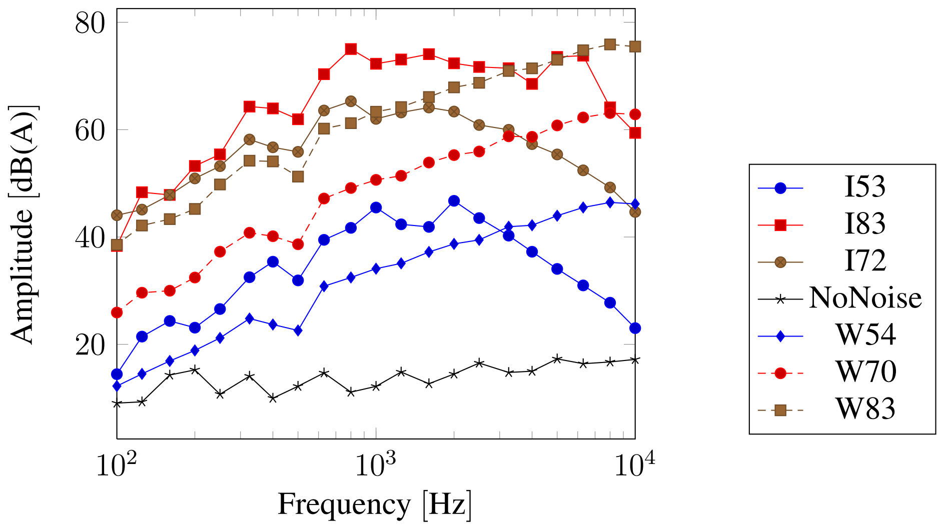


*Fig. 3 – $\frac{1}{3}$-octave band spectra of the background noise conditions; without additional background noise (NoNoise), with white (W) and industrial (I) noise at different levels.*

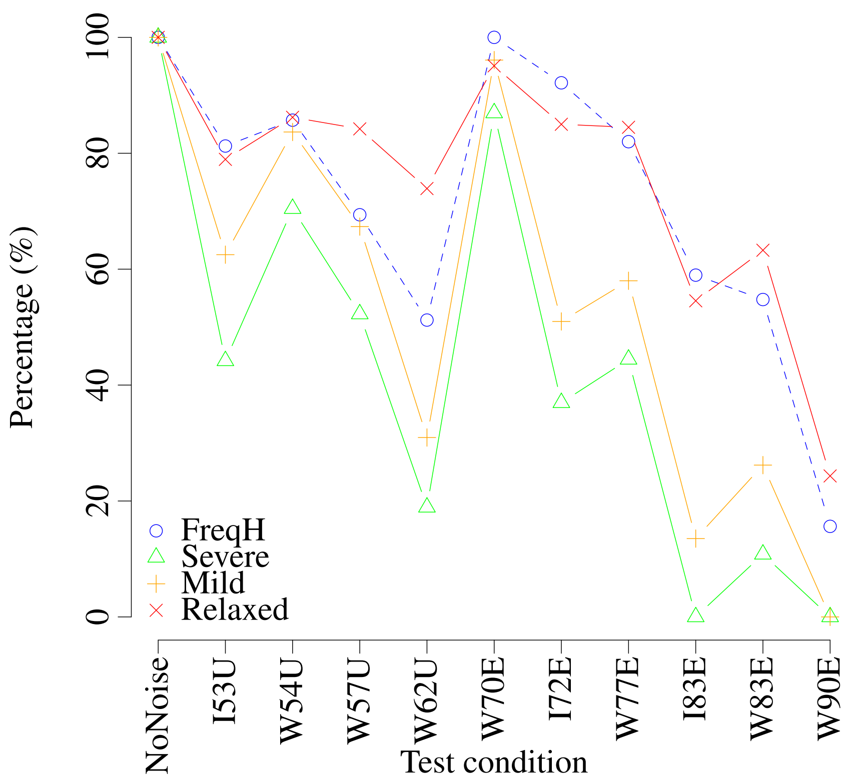


*Fig. 4 – Sensitivity in percentage for different test conditions (for abbreviations, see Figure 2) and different pass-refer criteria; TEOAE present at 3 kHz and/or 4 kHz (FreqH), at minimal one frequency band (Relaxed), at minimal three frequency bands (Mild) and at minimal four frequency band (Severe).*