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## Experimental assessment of the effect of wearing hearing protectors on the audibility of railway warning signals for normal hearing and hearing impaired listeners

--Manuscript Draft--

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# Experimental assessment of the effect of wearing hearing protectors on the audibility of railway warning signals for normal hearing and hearing impaired listeners

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## 1. Introduction

In noisy workplaces, acoustic warning signals are often used to promptly alert workers of a dangerous situation. To guarantee the workers' safety, the audibility of warning signals is of paramount importance. This audibility can however be impeded in practice by the wearing of hearing protection devices (HPDs), especially for hearing impaired workers [1].

Nevertheless, according to Directive 2003/10/EC [2], HPDs should be worn when **A-weighted** daily noise exposure levels exceed 80 dB to avoid hearing impairment and, over 85 dB, this becomes strictly imperative.

In a previous study [3], the effect of wearing HPDs on the audibility of railroad warning signals was evaluated on normal hearing (NH) listeners from masked threshold measurements performed both with and without wearing the HPDs. The results of this former study evidenced that wearing the HPDs generally improved the audibility (as compared to no HPD) for warning signals having a sufficient amount of energy in the low-frequency range ( $f < 1500$  Hz). On the contrary, for hearing-impaired (HI) listeners, other previous studies suggest that HPDs can have a more detrimental effect [4, 5, 6, 7]. This is probably due to a joint effect of elevated absolute thresholds and broadened auditory filters. This result remains to be confirmed with some specific warning signals and the present study was therefore dedicated to evaluate the effect of wearing HPDs on the detection of railroad warning signals for both NH and HI listeners.

## 2. Expected effects of wearing HPDs

The influence of wearing HPDs on the audibility of a warning signal is traditionally assessed by evaluating the masked detection threshold of the signal both with and without wearing the HPD [6]. The masked detection threshold is defined as the sound level of a signal at which this signal embedded in noise is just detectable. When the masked detection threshold with the HPD is smaller (respectively larger) than the masked threshold without the HPD, wearing the HPD improves (respectively impedes) the audibility of the signal.

As described in the literature, two phenomena may explain an impediment of the audibility when wearing HPDs; while a third phenomenon could explain an improvement of the audibility [3, 6].

First, detection may be impeded because the sound attenuation provided by the HPD leads the warning signal levels to be below the absolute thresholds of the workers; so that the signal cannot be heard anymore [4]. For normal hearing workers, this over-protection effect might only appear for low to moderate noise levels in which the wearing of HPDs is not required. However, for hearing impaired workers, this over-protection effect may extend to much higher levels, especially in high frequency bands where

absolute thresholds are usually higher [8, 9] and HPD sound attenuations are usually also larger.

Second, detection may be impeded by an increase of the upward spread of masking [4] when the HPD is worn. An increase of the upward spread of masking mostly happens when a low-frequency noise is combined with a HPD having smaller sound attenuation values in the low frequency range than in the high-frequency range (which is the case for most HPDs). In such a configuration, the masking of the higher frequency bands by the lower frequency bands is only slightly modified by the HPD due to its rather reduced sound attenuation values in the low frequency range. Moreover, the high-frequency components of the warning signal are strongly attenuated by the HPD and the potential masking effect of the noise is enhanced accordingly. Since HI listeners usually exhibit broadened auditory filters [10, 11, 12], their upward spread of masking is increased compared to NH listeners. This could then contribute to a larger detrimental effect of the HPDs on the audibility for HI listeners. To avoid this detrimental effect, Standard No. EN 458:2016 [13] recommends the use of HPDs with ‘flat/uniform’ sound attenuation, defined as HPDs with high frequency (H) minus low-frequency (L) sound attenuation values less than or equal to 9 dB. This recommendation of ‘flat/uniform’ attenuation might be particularly important for HI listeners because they are more affected by steeply sloped attenuation functions than NH listeners [4]. For example, Giguère and Berger [4] suggested that the attenuation slope should not exceed 6-7 dB/octave for mild hearing loss and 3-4 dB/octave for moderate to severe high frequency hearing loss in order to minimize the adverse effects of HPDs on the speech frequency range.

Besides, as part of the German criteria proposed by Liedtke in 2009 [14], the AIP criterion<sup>1</sup> states that a HPD is suitable when the slope of the linear regression of mean values of sound attenuation (obtained according to Standard No. ISO 4869-1:2018 [15]) for 125–4000 Hz is less than 3.6 dB/octave.

Third, HPDs can also improve the detection of warning signals in noise [6]. This improvement would then be related to the non-linear growth of masking effects when noise levels increase (see Moore [16] and Moore’s method in Standard No. ANSI S3.4:2007 [17]). When wearing a HPD, the reduced noise levels at the ear increase frequency selectivity (sharpened auditory filters) and consequently reduce masking, resulting in lower masked thresholds [6].

Even though these three phenomena are well described in the literature, the influence of wearing HPDs appears to depend on several factors such as the relative spectral distributions of the noise and the warning signal, the sound attenuation of the HPD and the hearing status of the subjects (both absolute thresholds and frequency selectivity). Altogether, this makes the effect of wearing HPDs unpredictable and the experimental results may sometimes appear contradictory (see, Lazarus [5] for an extensive review).

### 3. Objective and methods

The aim of this study was then to evaluate the effect of wearing HPDs on the audibility of railroad warning signals for both NH and HI listeners. The methods involved three main steps: (1) the choice of the warning signals and background noises to be tested, (2) the measurement of the masked thresholds with and without HPDs and (3) the choice of the statistical tests used to compare the masked thresholds with and without HPDs.

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<sup>1</sup> AIP stands for “Audibility, speech Intelligibility or Perception of informative operating sound ”

These three steps are further detailed in the next three sections. Next, from the results of the statistical analyses, a criterion based on the absolute thresholds is then proposed in order to guarantee the security of HI workers when wearing HPDs.

### 3.1. Warning signals and background noises

To better match a realistic configuration, all the warning signals and background noises used in the experiment were recorded in the field, close to the ears of a worker located at his usual working area. Time recordings were performed using a calibrated class 1 sound level meter (type 2250 from Brüel & Kjær, Denmark) at a sampling frequency of 48 kHz. Seven warning signals daily used in the French railroad environment were tested. They were chosen among others to get a diversity of time and frequency characteristics (see Table 1). All but one have a harmonic structure (i.e., they are composed of a fundamental frequency  $f_0$  and of multiples of  $f_0$ ). On the contrary, the remaining RS signal is composed of two pure tones with no harmonic relationship. All but two (DAPR and GSM) signals are stationary. DAPR and GSM consisted in an alternation of two tones with high and low fundamental frequencies (see Table 1). The first four signals in Table 1 are used to warn track workers from an incoming train. The last three signals are used to inform train drivers of an event and require an action from them (like pressing or releasing a driving component).

Table 1: Temporal and spectral characteristics of the warning signals.

All track workers' signals were tested in a ballast plough background noise whereas all train drivers' signals were tested in the background noise generated by a railway vehicle at maximal speed. The third-octave spectra of both background noises are shown in Figure 1. These two background noises were chosen because much of their energy is distributed in the low-frequency range ( $f < 1000$  Hz). Such noises should then have a larger potential masking effect [5].

Figure 1: Third-octave band spectra of background noises. Ballast plough noise (—); railway vehicle noise (----).

### 3.2. Masked threshold measurements

The masked thresholds were measured using a two-interval, two-alternative forced choice (2I-2AFC) procedure. The sound intervals (one containing only the background noise, the other containing both the background noise and the warning signal) were successively presented in random order. The listener's task was then to indicate the interval with the warning signal. Each interval consisted in a 500 ms burst of noise and the two intervals were separated by a 300 ms silent gap. The warning signal was 300 ms long and was temporally centered in the middle of one burst of noise (i.e. in the middle of one interval). The A-weighted background noises level was constant and equal to 86 dB. At the beginning of the measurement procedure, the A-weighted level of the warning signals was also set at 86 dB. This level varied during the measurement procedure according to a "2 Down – 1 Up" adaptive rule to target a detection threshold corresponding to 70.7% of detection [18]. The level of the signal first varied by steps of 5 dB. After three reversals, the variation step was reduced to 3 dB. After two additional reversals, the step reached its final value of 1 dB. Once the last step of 1 dB was reached,

the test continued until four additional reversals were obtained. The masked threshold value was then computed as the mean of these four last reversals.

### **3.3. Statistical analyses**

The listeners were grouped in five different hearing classes depending on their absolute thresholds values. From the measured masked thresholds obtained for each hearing class and each HPD configuration (no HPD, earplugs, earmuffs), Shapiro–Wilk tests [19] were first performed to evaluate the normality of the threshold distributions. Since the normality assumption was not always true (i.e.  $p < 0.1$ ), Wilcoxon rank tests [20] were therefore performed (instead of Student's  $t$  tests which require a normal distribution of the data) to compare the masked thresholds of HI listeners with those of NH listeners. Next, Wilcoxon matched-pairs signed-rank tests were applied for each hearing class upon the differences between protected and unprotected thresholds in order to better characterize the beneficial or detrimental effect of HPD upon detection.

## **4. Psychoacoustic experiments**

### **4.1. Experimental set-up**

The psychoacoustic tests took place in a sound-proof room (rough dimensions  $w \times d \times h = 5.4 \text{ m} \times 5.9 \text{ m} \times 2.9 \text{ m}$ ) treated in absorption (reverberation time of 0.42 s). The listener was sat 2.6 m in front of one loudspeaker (KH 120A by Neumann, Germany) that played the warning signals. The background noises were played by two other loudspeakers (LSR6332 by JBL, USA) driven by a power amplifier (XLS 402 by Crown, USA). The positions and orientations of these two loudspeakers were experimentally determined to get a uniform sound field around the listener's head. The uniformity of the sound field has been accurately controlled with acoustic measurements performed at the center of an anticipated head and at six positions situated 15 cm from the center (right, left, front, rear, up, down). The discrepancies between each of these six positions and the center, for the two background noises used in the experiment (played by the two LSR6332 speakers) and for a pink noise played on the KH 120A loudspeaker, never exceeded 3 dB in 1/3 octave bands from 80 to 12500 Hz. All audio signals were calibrated before each test session with a microphone located at the same position than the center of the participant's head. The calibration consisted of adjusting the gain of each audio signal (background noises and warning signals) to set the **A-weighted** background noise level and the **A-weighted** warning signal level equal to 86 dB.

### **4.2. Subjects**

Before their participation, subjects were first informed of the types of tests they were going to take part in and of the anonymization process of the collected data. They were then offered the opportunity to provide their informed consent. Eighty people (25 females, 55 males) aged from 18 to 81 (mean 51.6 years, standard deviation 15.3 years) participated to the experiment. Fifty-three people were SNCF workers who volunteered to take part into the experiment during work-time. Twenty-seven additional participants were recruited and paid a hourly-wage for their participation. The participants' absolute hearing thresholds were measured performing a pure-tone audiometry at the 11 standard audiometric frequencies from 125 to 8000 Hz

(see Figure 2). The participants were then distributed into five different hearing classes according to their absolute thresholds. The participants from the first class were considered as normal hearing (NH) listeners and had absolute thresholds below 20 dB hearing level (HL) from 125 to 8000 Hz on both ears. Eighteen participants were considered as NH listeners. The remaining participants were distributed into four additional classes depending of their average absolute threshold at 500, 1000 and 2000 Hz on the best ear, noted PTA (for Pure-Tone Average) hereafter **and expressed in hearing level dB**. Four classes of hearing impaired (HI) listeners were then considered:

- HI1:  $10 < \text{PTA} \leq 20$  dB, 22 listeners
- HI2:  $20 < \text{PTA} \leq 30$  dB, 18 listeners
- HI3:  $30 < \text{PTA} \leq 40$  dB, 14 listeners
- HI4:  $\text{PTA} > 40$  dB, 8 listeners.

Figure 2: Mean absolute thresholds of the five hearing classes (**expressed in hearing level dB**). From top to bottom: NH ( $\cdot$ ); HI1 ( $\circ$ ); HI2 ( $*$ ); HI3 ( $+$ ); HI4 ( $\times$ ).

Figure 2 shows the mean absolute thresholds of the five hearing classes. Additionally, Table 2 provides the mean ages for each hearing class. For the HI classes, the increase of absolute thresholds as a function of frequency is typical of age-related hearing loss [8].

Table 2: Mean ages and *SD* for the 5 hearing classes

### 4.3. Hearing protectors

Two types of passive HPDs were tested:

- Earplugs: silicon custom-molded earplugs from ELACIN, France (model Clearsound with an RC15 acoustic filter, single number rating (SNR) = 17 dB)
- Earmuffs from Howard Leight by Honeywell (model Clarity C1, SNR = 25 dB).

Figure 3 shows the sound attenuation values provided by the manufacturers according to Standard No. ISO 4869-1:2018 [15]. These two HPD models were chosen because their sound attenuation profiles are relatively uniform as a function of frequency. The slope of the linear regression of mean values of sound attenuation from 125 up to 4000 Hz is of 2.7 dB/oct for the earplugs and of 1.9 dB/oct for the earmuffs. As a consequence, both HPDs fulfill the AIP criterion proposed by Liedtke [14] (with a slope lower than 3.60 dB/octave) along with the recommendation by Giguère and Berger [4] for moderate to severe high frequency hearing loss (with a slope lower than 3-4 dB/octave).

Figure 3: Mean sound attenuation values provided by the manufacturers for the two HPDs. Note: Error bars designate + 1 *SD* (earplugs) and – 1 *SD* (earmuffs).

### 4.4. Test procedure

For masked threshold measurements, listeners were first asked to listen to the 7 warning signals alone (i.e. without any background noise). They were then trained on how to put on the HPDs and performed at least three masked threshold measurements for practice. The presentation order of experimental conditions (combination of warning signals and HPDs configurations) was randomized for each listener. Each condition was repeated three times and the three masked thresholds values were then averaged. However, if



the standard deviation of the masked thresholds on these three measurements exceeded 3 dB, a fourth measurement was performed and the threshold was computed as the average of the three nearest values. Thus each listener performed a minimum of 63 threshold measurements (7 alarms  $\times$  3 configurations of HPD  $\times$  3 repetitions) distributed into 6 sessions of 10 or 11 measurements (the 6 sessions were distributed on several days). The duration of one session typically varied between 20 and 30 minutes leading to about 2,5 hours of testing for each participant.

## 5. Results and discussion

### 5.1. Masked thresholds measurements

Figure 4 shows the masked thresholds without HPD, plot as box and whisker<sup>2</sup>, independently for the five hearing classes and for the 7 warning signals. It appears that the differences on the medians between the HI classes and the NH class never exceed 10 dB and the difference of the medians between HI4 and NH averaged across alarms is equal to 4.9 dB. Moreover, these differences greatly depend on the warning signal considered.

Wilcoxon rank-sum tests for unmatched data were applied to these results in order to estimate the effect of hearing impairment. The results of these statistical analyses, presented in Table 3, indicate no significant differences ( $p > 0.05$ ) between the HI classes and the NH class for the signals AUTOPROVA and RS; whereas the differences are significant ( $p < 0.05$ ) between at least one HI class and the NH class for the five other signals.

Figure 4: Masked thresholds without HPDs for the seven warning signals. For each warning signal, the five box and whisker plots correspond to the five hearing classes considered, from the NH class most to the left to the HI4 class most to the right.

Table 3: Masked threshold without HPDs (see Figure 4). Statistical results ( $p$ ) of the comparisons between the HI classes and the NH class. Values in bold, italic and with the “\*” sign indicate a statistically significant difference ( $p < 0.05$ ).

Figures 5 and 6 show the masked thresholds with HPDs independently for the five hearing classes and for the 7 warning signals. Figure 5 shows the results with the earplugs and Figure 6 with the earmuffs.

The differences on the medians between the HI4 and the NH averaged across alarms are respectively 10.1 dB and 11 dB for the earplugs and the earmuffs. Hence, these differences are larger than the average difference without HPDs (4.9 dB).

This larger effect of hearing impairment when wearing HPDs is confirmed by the results of the statistical analysis (Wilcoxon rank-sum tests for unmatched data) presented in Table 4. In fact, significant effects of hearing impairment are found for all but one warning signal (VACMA). For all the other warning signals, some HI groups have significant

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2 On each box, the central mark indicates the median, and the bottom and top edges of the box (of numerical values  $q_1$  and  $q_3$ , respectively) indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' symbol. The data points are drawn as outliers if they are greater than  $q_3 + 1.5 \times (q_3 - q_1)$  or less than  $q_1 - 1.5 \times (q_3 - q_1)$ .



higher thresholds than the NH group. Moreover, it seems from Table 4 that the effect of hearing impairment increases when increasing the degree of hearing loss. Except for the VACMA warning signal, the detection performances of the HI3 and HI4 groups are always significantly poorer than for the NH group. Besides, the significance of the differences between HI and NH listeners are very similar for the two HPDs considered (earplugs and earmuffs).

Figure 5: Masked thresholds with earplugs for the seven warning signals. For each warning signal, the five box and whisker plots correspond to the five hearing classes considered, from the NH class most to the left to the HI4 class most to the right.

Figure 6: Masked thresholds with earmuffs for the seven warning signals. For each warning signal, the five box and whisker plots correspond to the five hearing classes considered, from the NH class most to the left to the HI4 class most to the right.

Table 4: Masked threshold with earplugs and earmuffs (see Figures 5 and 6). Statistical results ( $p$ ) of the comparisons between the HI classes and the NH class. Values in bold, italic and with the “\*” sign indicate a statistically significant difference ( $p < 0.05$ ).

In summary, when no HPDs are worn, the differences between the masked thresholds of the HI classes and those of the NH class are relatively small and are statistically significant only for 4 out of the 7 signals tested. With HPDs, the differences between HI and NH increase and become significant for all the warning signals except the VACMA signal. The reason why there is no difference between HI and NH for the VACMA signal is most certainly due to the fact that its audibility is governed by a dominant component in low-frequency ( $f_0=334$  Hz) that is not or little affected by the two phenomena leading to an impediment of the detection (see section 2). Moreover, both HPDs (earplugs and earmuffs) lead to the same pattern of results.

## **5.2. Differences between protected and unprotected thresholds**

To better evaluate the effect of wearing HPDs on the detection of warning signals, the differences between protected and unprotected thresholds have been computed. A positive difference value indicates that the HPD impedes the detection (as compared to no HPD); conversely a negative value corresponds to an improvement of the detection. Figures 7 and 8 show these differences for the earplugs and the earmuffs, respectively.

Figure 7: Differences between thresholds with and without earplugs for the seven warning signals. For each warning signal, the five box and whisker plots correspond to the five hearing classes considered, from the NH class most to the left to the HI4 class most to the right.

Figure 8: Differences between thresholds with and without earmuffs for the seven warning signals. For each warning signal, the five box and whisker plots correspond to the five hearing classes considered, from the NH class most to the left to the HI4 class most to the right.

340  
341 Additionally, Wilcoxon matched-pairs signed-rank tests were performed to evaluate  
342 whether these differences were statistically positive or negative. Table 5 summarizes the  
343 statistical results: an up arrow symbol<sup>3</sup> “↑” designates a statistically significant  
344 impediment ( $p < 0.05$ ); a down arrow symbol “↓” symbol designates a statistically  
345 significant improvement ( $p < 0.05$ ) and no symbol designates no statistically significant  
346 effect.

347  
348  
349 Table 5: Differences between protected and unprotected thresholds (see Figures 7 and  
350 8). Statistical results of the significant improvements (“↓” symbol,  $p < 0.05$ ) or  
351 impediments (“↑” symbol,  $p < 0.05$ ). No symbol indicates no statistically significant  
352 difference ( $p > 0.05$ ).  
353

354  
355 For NH listeners, it appears that wearing any of the two HPDs improves the detection for  
356 all the warning signals (except VACMA). These improvements for NH listeners are  
357 consistent with the results from previous studies [3, 5, 21]. For the VACMA signal, most  
358 of the audibility is due to a dominant component in low-frequency ( $f_0=334$  Hz). It can then  
359 be hypothesized that no improvement is found due to the reduced attenuation values of  
360 the HPDs around 300 Hz (which lead, as compared to no HPD, to a low reduction of the  
361 frequency masking phenomena, see section 2).  
362

363 For HI listeners, detection improves for less and less warning signals when the absolute  
364 thresholds (i.e. the hearing loss) increase. As such, for the HI1 class, detection is  
365 improved for both HPDs for three warning signals (DAPR, STDIZIER and GSM),  
366 whereas for the HI3 and HI4 classes, no statistically significant improvement is found  
367 whatever the warning signal and the HPD considered.

368 Concerning the impediments, the RS warning signal is by far the most impeded signal:  
369 the differences between protected and unprotected thresholds reach around 10 dB on  
370 the medians for the HI4 class and statistically significant differences are found for HI2,  
371 HI3 and HI4 classes for earplugs and for all the HI classes for the earmuffs. This severe  
372 impediment is most certainly due to the fact that the RS signal is made of two high-  
373 frequency components (3430 and 4084 Hz). Indeed, over 3 kHz, both the absolute  
374 thresholds values and the HPD attenuations are high (see Figures 2 and 3), leading to  
375 an over-attenuation effect due to the absolute thresholds (as described in [4], see section  
376 2). This signal is not in agreement with Standard No. ISO 7731:2003 [22], which  
377 recommends to use two dominant components between 500 and 1500 Hz and highlights  
378 that, when people wear HPDs or suffer from hearing loss, the signal must have enough  
379 energy below 1500 Hz. This signals should therefore be modified to increase its energy  
380 in the low-frequency range ( $f < 1500$  Hz) to be better detected.

381 Significant impediments are also found with earplugs for the warning signal GSM (HI4)  
382 and with earmuffs for the warning signal AIGU for HI3 and HI4 classes.

383 It is worth noting that no statistically significant impediment is found whatever the hearing  
384 class considered for the four remaining warning signals: PROVA, DAPR, STDIZIER and  
385 VACMA. This can be explained by the fact that these signals have a dominant  
386 fundamental frequency in low-frequency (between 334 and 660 Hz, see Table 1) that is  
387 not or little affected neither by the absolute thresholds effect nor by the upward spread  
388 of masking effect (see section 2). Hence these warning signals appear to be particularly  
389 adapted to HI listeners.  
390

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<sup>3</sup> The *up* arrow was chosen to indicate a threshold *elevation* when HPDs are worn (as compared to no HPD)

### 5.3. Towards a criterion for HI listeners wearing HPDs

The previous section has shown that wearing the HPDs improves the audibility for NH listeners whereas it tends to impede the audibility for HI listeners. Moreover, the impediments greatly depend on the signal considered.

In an attempt to propose a criterion based on the absolute thresholds of HI people that guarantees their security when wearing HPDs, two approaches have been used.

In the first approach, it was simply considered that any significant impediment should be avoided. From Table 5, the security of all HI classes could not be guaranteed because of the RS signal. However, if we exclude the RS signal, only the security of HI3 and HI4 classes would not be guaranteed. As such, these two classes of people should avoid to work in such a noisy environment.

In the second approach, the idea was to quantify how much the protected thresholds of the HI differed from the unprotected thresholds of the NH. Thus, a Wilcoxon rank-sum test for unmatched data was used to check whether the protected thresholds of the HI classes significantly exceeded the unprotected thresholds of the NH majored by 3 dB ( $T_{HI,protected} > T_{NH,unprotected} + 3 \text{ dB}$ ). This difference of 3 dB has been chosen as it seems rather small compared to the intrinsic variations of signal levels that are typically observed in the field, notably because of the variations of the positions of the workers respective to the location(s) of the warning signal device(s). The results of these new statistical analyses are shown in Table 6.

Table 6: Statistical comparison ( $p$ ) between protected thresholds of the HI and unprotected thresholds of the NH majored by 3 dB ( $T_{HI,protected} > T_{NH,unprotected} + 3 \text{ dB}$ ). Values in bold, italic and with the “\*” sign indicate a statistically significant difference ( $p < 0.05$ ).

From Table 6, it appears that the protected thresholds of HI1 and HI2 classes are not significantly different than the unprotected thresholds of NH majored by 3 dB for the seven warning signals tested, including the RS signal.

Finally, if we do not consider the RS signal because it is not suitable as a warning signal, the two approaches lead to the same conclusion: the security is assured for the HI1 and HI2 classes (i.e. pure-tone average at 500, 1000 and 2000 Hz on the best ear  $< 30 \text{ dB}$ ) but not for the HI3 and HI4 classes.

This limit of PTA  $< 30 \text{ dB}$  to avoid the impediments due to wearing HPDs is consistent with the results of Lazarus [5]. However, it is worth noting that the proposed limit of PTA  $< 30 \text{ dB}$  is more restrictive than the criterion proposed in the USA by the Federal Railroad Administration [23] which tolerates a PTA in the better ear of up to 40 dB.

## 6. Conclusion

In this study, the influence of wearing HPDs on the detection of warning signals in noise was evaluated by comparisons of the masked thresholds measured with and without wearing HPDs, for seven warning signals. The results show that wearing the HPDs improves the audibility of warning signals in noise for NH listeners whereas it tends to impede the audibility for HI listeners. Moreover, the impediments greatly depend on the warning signal acoustical characteristics.

In order to ensure the security of the workers, the RS signal should not be taken into account because it is not suitable as a warning signal [22]. In these conditions, it was found that the security is assured for the HI1 and HI2 classes wearing any of the two HPDs tested (i.e. pure-tone average at 500, 1000 and 2000 Hz on the best ear  $< 30 \text{ dB}$ ) but not for the HI3 and HI4 classes.

Future studies should focus on the influence of wearing a HPD on other aspects such as the required signal levels to identify the signal (as in the study by Lazarus [5]), the localization of the warning signal and the perceived urgency of the warning signal [18] which have not been studied here. Furthermore, whatever the current experiment attempts to mimic a realistic environmental situation, all the situations that may occur in the field have not been studied in the laboratory and the current results could not be generalized. As a consequence, the current results cannot guarantee that the signals will always be heard in practice and extra caution is required when using HPDs in the field. Further listening tests as presented in Standard N° ISO 7731:2003 (Annex C) while wearing the HPDs could be useful to provide additional information.

Despite these limitations and based on the results from this study, some general recommendations can be addressed concerning the wearing of HPDs by HI listeners.

First of all, the HPD must be chosen so as not to overprotect the wearers. Indeed, the higher the attenuation values, the higher the potential impediments due to the absolute thresholds [4]. In accordance with Standard N° EN458 [13], the HPD must be chosen to meet a **A-weighted** daily exposure level under the HPD between 70 and 75 dB.

Second, protectors with a flat/uniform attenuation profile must be privileged so as to limit the impediment due to frequency masking [4]. Because most passive HPDs show little attenuation values in the low-frequency range, special caution must be taken when the background noises dominate in low frequency and active noise reduction (ANR) HPDs [24] should be privileged in this case as they bring an additional active attenuation in low frequency.

Concerning the sound design of warning signals, it is clear that warning signals with dominant components in low-frequency must be preferred since they are less affected by the wearing of HPDs, especially for hearing impaired listeners. Conversely, signals with not enough energy in low frequency must be avoided since their audibility is more adversely affected when using HPDs. This recommendation is consistent with the requirement from Standard N° ISO 7731 to use signals that have enough energy below 1500 Hz when people wear HPDs or when they suffer from hearing impairment.

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# **Experimental assessment of the effect of wearing hearing protectors on the audibility of railway warning signals for normal hearing and hearing impaired listeners**

## **1. Introduction**

In noisy workplaces, acoustic warning signals are often used to promptly alert workers of a dangerous situation. To guarantee the workers' safety, the audibility of warning signals is of paramount importance. This audibility can however be impeded in practice by the wearing of hearing protection devices (HPDs), especially for hearing impaired workers [1].

Nevertheless, according to Directive 2003/10/EC [2], HPDs should be worn when A-weighted daily noise exposure levels exceed 80 dB to avoid hearing impairment and, over 85 dB, this becomes strictly imperative.

In a previous study [3], the effect of wearing HPDs on the audibility of railroad warning signals was evaluated on normal hearing (NH) listeners from masked threshold measurements performed both with and without wearing the HPDs. The results of this former study evidenced that wearing the HPDs generally improved the audibility (as compared to no HPD) for warning signals having a sufficient amount of energy in the low-frequency range ( $f < 1500$  Hz). On the contrary, for hearing-impaired (HI) listeners, other previous studies suggest that HPDs can have a more detrimental effect [4, 5, 6, 7]. This is probably due to a joint effect of elevated absolute thresholds and broadened auditory filters. This result remains to be confirmed with some specific warning signals and the present study was therefore dedicated to evaluate the effect of wearing HPDs on the detection of railroad warning signals for both NH and HI listeners.

## **2. Expected effects of wearing HPDs**

The influence of wearing HPDs on the audibility of a warning signal is traditionally assessed by evaluating the masked detection threshold of the signal both with and without wearing the HPD [6]. The masked detection threshold is defined as the sound level of a signal at which this signal embedded in noise is just detectable. When the masked detection threshold with the HPD is smaller (respectively larger) than the masked threshold without the HPD, wearing the HPD improves (respectively impedes) the audibility of the signal.

As described in the literature, two phenomena may explain an impediment of the audibility when wearing HPDs; while a third phenomenon could explain an improvement of the audibility [3, 6].

First, detection may be impeded because the sound attenuation provided by the HPD leads the warning signal levels to be below the absolute thresholds of the workers; so that the signal cannot be heard anymore [4]. For normal hearing workers, this over-protection effect might only appear for low to moderate noise levels in which the wearing of HPDs is not required. However, for hearing impaired workers, this over-protection effect may extend to much higher levels, especially in high frequency bands where absolute thresholds are usually higher [8, 9] and HPD sound attenuations are usually also larger.

Second, detection may be impeded by an increase of the upward spread of masking [4] when the HPD is worn. An increase of the upward spread of masking mostly happens when a low-frequency noise is combined with a HPD having smaller sound attenuation values in the low frequency range than in the high-frequency range (which is the case for most HPDs). In such a configuration, the masking of the higher frequency bands by



the lower frequency bands is only slightly modified by the HPD due to its rather reduced sound attenuation values in the low frequency range. Moreover, the high-frequency components of the warning signal are strongly attenuated by the HPD and the potential masking effect of the noise is enhanced accordingly. Since HI listeners usually exhibit broadened auditory filters [10, 11, 12], their upward spread of masking is increased compared to NH listeners. This could then contribute to a larger detrimental effect of the HPDs on the audibility for HI listeners. To avoid this detrimental effect, Standard No. EN 458:2016 [13] recommends the use of HPDs with ‘flat/uniform’ sound attenuation, defined as HPDs with high frequency (H) minus low-frequency (L) sound attenuation values less than or equal to 9 dB. This recommendation of ‘flat/uniform’ attenuation might be particularly important for HI listeners because they are more affected by steeply sloped attenuation functions than NH listeners [4]. For example, Giguère and Berger [4] suggested that the attenuation slope should not exceed 6-7 dB/octave for mild hearing loss and 3-4 dB/octave for moderate to severe high frequency hearing loss in order to minimize the adverse effects of HPDs on the speech frequency range. Besides, as part of the German criteria proposed by Liedtke in 2009 [14], the AIP criterion<sup>1</sup> states that a HPD is suitable when the slope of the linear regression of mean values of sound attenuation (obtained according to Standard No. ISO 4869-1:2018 [15]) for 125–4000 Hz is less than 3.6 dB/octave.

Third, HPDs can also improve the detection of warning signals in noise [6]. This improvement would then be related to the non-linear growth of masking effects when noise levels increase (see Moore [16] and Moore’s method in Standard No. ANSI S3.4:2007 [17]). When wearing a HPD, the reduced noise levels at the ear increase frequency selectivity (sharpened auditory filters) and consequently reduce masking, resulting in lower masked thresholds [6].

Even though these three phenomena are well described in the literature, the influence of wearing HPDs appears to depend on several factors such as the relative spectral distributions of the noise and the warning signal, the sound attenuation of the HPD and the hearing status of the subjects (both absolute thresholds and frequency selectivity). Altogether, this makes the effect of wearing HPDs unpredictable and the experimental results may sometimes appear contradictory (see, Lazarus [5] for an extensive review).

### 3. Objective and methods

The aim of this study was then to evaluate the effect of wearing HPDs on the audibility of railroad warning signals for both NH and HI listeners. The methods involved three main steps: (1) the choice of the warning signals and background noises to be tested, (2) the measurement of the masked thresholds with and without HPDs and (3) the choice of the statistical tests used to compare the masked thresholds with and without HPDs. These three steps are further detailed in the next three sections. Next, from the results of the statistical analyses, a criterion based on the absolute thresholds is then proposed in order to guarantee the security of HI workers when wearing HPDs.

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1 AIP stands for “Audibility, speech Intelligibility or Perception of informative operating sound ”

### 3.1. Warning signals and background noises

To better match a realistic configuration, all the warning signals and background noises used in the experiment were recorded in the field, close to the ears of a worker located at his usual working area. Time recordings were performed using a calibrated class 1 sound level meter (type 2250 from Brüel & Kjær, Denmark) at a sampling frequency of 48 kHz. Seven warning signals daily used in the French railroad environment were tested. They were chosen among others to get a diversity of time and frequency characteristics (see Table 1). All but one have a harmonic structure (i.e., they are composed of a fundamental frequency  $f_0$  and of multiples of  $f_0$ ). On the contrary, the remaining RS signal is composed of two pure tones with no harmonic relationship. All but two (DAPR and GSM) signals are stationary. DAPR and GSM consisted in an alternation of two tones with high and low fundamental frequencies (see Table 1). The first four signals in Table 1 are used to warn track workers from an incoming train. The last three signals are used to inform train drivers of an event and require an action from them (like pressing or releasing a driving component).

Table 1: Temporal and spectral characteristics of the warning signals.

All track workers' signals were tested in a ballast plough background noise whereas all train drivers' signals were tested in the background noise generated by a railway vehicle at maximal speed. The third-octave spectra of both background noises are shown in Figure 1. These two background noises were chosen because much of their energy is distributed in the low-frequency range ( $f < 1000$  Hz). Such noises should then have a larger potential masking effect [5].

Figure 1: Third-octave band spectra of background noises. Ballast plough noise (—); railway vehicle noise (----).

### 3.2. Masked threshold measurements

The masked thresholds were measured using a two-interval, two-alternative forced choice (2I-2AFC) procedure. The sound intervals (one containing only the background noise, the other containing both the background noise and the warning signal) were successively presented in random order. The listener's task was then to indicate the interval with the warning signal. Each interval consisted in a 500 ms burst of noise and the two intervals were separated by a 300 ms silent gap. The warning signal was 300 ms long and was temporally centered in the middle of one burst of noise (i.e. in the middle of one interval). The A-weighted background noises level was constant and equal to 86 dB. At the beginning of the measurement procedure, the A-weighted level of the warning signals was also set at 86 dB. This level varied during the measurement procedure according to a "2 Down – 1 Up" adaptive rule to target a detection threshold corresponding to 70.7% of detection [18]. The level of the signal first varied by steps of 5 dB. After three reversals, the variation step was reduced to 3 dB. After two additional reversals, the step reached its final value of 1 dB. Once the last step of 1 dB was reached, the test continued until four additional reversals were obtained. The masked threshold value was then computed as the mean of these four last reversals.

### 3.3. Statistical analyses

The listeners were grouped in five different hearing classes depending on their absolute thresholds values. From the measured masked thresholds obtained for each hearing class and each HPD configuration (no HPD, earplugs, earmuffs), Shapiro–Wilk tests [19] were first performed to evaluate the normality of the threshold distributions. Since the normality assumption was not always true (i.e.  $p < 0.1$ ), Wilcoxon rank tests [20] were therefore performed (instead of Student's  $t$  tests which require a normal distribution of the data) to compare the masked thresholds of HI listeners with those of NH listeners. Next, Wilcoxon matched-pairs signed-rank tests were applied for each hearing class upon the differences between protected and unprotected thresholds in order to better characterize the beneficial or detrimental effect of HPD upon detection.

## 4. Psychoacoustic experiments

### 4.1. Experimental set-up

The psychoacoustic tests took place in a sound-proof room (rough dimensions  $w \times d \times h = 5.4 \text{ m} \times 5.9 \text{ m} \times 2.9 \text{ m}$ ) treated in absorption (reverberation time of 0.42 s). The listener was sat 2.6 m in front of one loudspeaker (KH 120A by Neumann, Germany) that played the warning signals. The background noises were played by two other loudspeakers (LSR6332 by JBL, USA) driven by a power amplifier (XLS 402 by Crown, USA). The positions and orientations of these two loudspeakers were experimentally determined to get a uniform sound field around the listener's head. The uniformity of the sound field has been accurately controlled with acoustic measurements performed at the center of an anticipated head and at six positions situated 15 cm from the center (right, left, front, rear, up, down). The discrepancies between each of these six positions and the center, for the two background noises used in the experiment (played by the two LSR6332 speakers) and for a pink noise played on the KH 120A loudspeaker, never exceeded 3 dB in 1/3 octave bands from 80 to 12500 Hz. All audio signals were calibrated before each test session with a microphone located at the same position than the center of the participant's head. The calibration consisted of adjusting the gain of each audio signal (background noises and warning signals) to set the **A-weighted** background noise level and the **A-weighted** warning signal level equal to 86 dB.

### 4.2. Subjects

Before their participation, subjects were first informed of the types of tests they were going to take part in and of the anonymization process of the collected data. They were then offered the opportunity to provide their informed consent. Eighty people (25 females, 55 males) aged from 18 to 81 (mean 51.6 years, standard deviation 15.3 years) participated to the experiment. Fifty-three people were SNCF workers who volunteered to take part into the experiment during work-time. Twenty-seven additional participants were recruited and paid a hourly-wage for their participation. The participants' absolute hearing thresholds were measured performing a pure-tone audiometry at the 11 standard audiometric frequencies from 125 to 8000 Hz (see Figure 2). The participants were then distributed into five different hearing classes according to their absolute thresholds. The participants from the first class were considered as normal hearing (NH) listeners and had absolute thresholds below 20 dB hearing level (HL) from 125 to 8000 Hz on both ears. Eighteen participants were considered as NH listeners. The remaining participants were distributed into four

additional classes depending of their average absolute threshold at 500, 1000 and 2000 Hz on the best ear, noted PTA (for Pure-Tone Average) hereafter and expressed in hearing level dB. Four classes of hearing impaired (HI) listeners were then considered:

- HI1:  $10 < \text{PTA} \leq 20$  dB, 22 listeners
- HI2:  $20 < \text{PTA} \leq 30$  dB, 18 listeners
- HI3:  $30 < \text{PTA} \leq 40$  dB, 14 listeners
- HI4:  $\text{PTA} > 40$  dB, 8 listeners.

Figure 2: Mean absolute thresholds of the five hearing classes (expressed in hearing level dB). From top to bottom: NH ( $\cdot$ ); HI1 ( $\circ$ ); HI2 ( $*$ ); HI3 ( $+$ ); HI4 ( $\times$ ).

Figure 2 shows the mean absolute thresholds of the five hearing classes. Additionally, Table 2 provides the mean ages for each hearing class. For the HI classes, the increase of absolute thresholds as a function of frequency is typical of age-related hearing loss [8].

Table 2: Mean ages and SD for the 5 hearing classes

### 4.3. Hearing protectors

Two types of passive HPDs were tested:

- Earplugs: silicon custom-molded earplugs from ELACIN, France (model Clearsound with an RC15 acoustic filter, single number rating (SNR) = 17 dB)
- Earmuffs from Howard Leight by Honeywell (model Clarity C1, SNR = 25 dB).

Figure 3 shows the sound attenuation values provided by the manufacturers according to Standard No. ISO 4869-1:2018 [15]. These two HPD models were chosen because their sound attenuation profiles are relatively uniform as a function of frequency. The slope of the linear regression of mean values of sound attenuation from 125 up to 4000 Hz is of 2.7 dB/oct for the earplugs and of 1.9 dB/oct for the earmuffs. As a consequence, both HPDs fulfill the AIP criterion proposed by Liedtke [14] (with a slope lower than 3.60 dB/octave) along with the recommendation by Giguère and Berger [4] for moderate to severe high frequency hearing loss (with a slope lower than 3-4 dB/octave).

Figure 3: Mean sound attenuation values provided by the manufacturers for the two HPDs. Note: Error bars designate + 1 SD (earplugs) and - 1 SD (earmuffs).

### 4.4. Test procedure

For masked threshold measurements, listeners were first asked to listen to the 7 warning signals alone (i.e. without any background noise). They were then trained on how to put on the HPDs and performed at least three masked threshold measurements for practice. The presentation order of experimental conditions (combination of warning signals and HPDs configurations) was randomized for each listener. Each condition was repeated three times and the three masked thresholds values were then averaged. However, if the standard deviation of the masked thresholds on these three measurements exceeded 3 dB, a fourth measurement was performed and the threshold was computed as the average of the three nearest values. Thus each listener performed a minimum of 63 threshold measurements (7 alarms  $\times$  3 configurations of HPD  $\times$  3 repetitions) distributed into 6 sessions of 10 or 11 measurements (the 6 sessions were distributed on

several days). The duration of one session typically varied between 20 and 30 minutes leading to about 2,5 hours of testing for each participant.

## 5. Results and discussion

### 5.1. Masked thresholds measurements

Figure 4 shows the masked thresholds without HPD, plot as box and whisker<sup>2</sup>, independently for the five hearing classes and for the 7 warning signals. It appears that the differences on the medians between the HI classes and the NH class never exceed 10 dB and the difference of the medians between HI4 and NH averaged across alarms is equal to 4.9 dB. Moreover, these differences greatly depend on the warning signal considered.

Wilcoxon rank-sum tests for unmatched data were applied to these results in order to estimate the effect of hearing impairment. The results of these statistical analyses, presented in Table 3, indicate no significant differences ( $p > 0.05$ ) between the HI classes and the NH class for the signals AUTOPROVA and RS; whereas the differences are significant ( $p < 0.05$ ) between at least one HI class and the NH class for the five other signals.

Figure 4: Masked thresholds without HPDs for the seven warning signals. For each warning signal, the five box and whisker plots correspond to the five hearing classes considered, from the NH class most to the left to the HI4 class most to the right.

Table 3: Masked threshold without HPDs (see Figure 4). Statistical results ( $p$ ) of the comparisons between the HI classes and the NH class. Values in bold, italic and with the “\*” sign indicate a statistically significant difference ( $p < 0.05$ ).

Figures 5 and 6 show the masked thresholds with HPDs independently for the five hearing classes and for the 7 warning signals. Figure 5 shows the results with the earplugs and Figure 6 with the earmuffs.

The differences on the medians between the HI4 and the NH averaged across alarms are respectively 10.1 dB and 11 dB for the earplugs and the earmuffs. Hence, these differences are larger than the average difference without HPDs (4.9 dB).

This larger effect of hearing impairment when wearing HPDs is confirmed by the results of the statistical analysis (Wilcoxon rank-sum tests for unmatched data) presented in Table 4. In fact, significant effects of hearing impairment are found for all but one warning signal (VACMA). For all the other warning signals, some HI groups have significant higher thresholds than the NH group. Moreover, it seems from Table 4 that the effect of hearing impairment increases when increasing the degree of hearing loss. Except for the VACMA warning signal, the detection performances of the HI3 and HI4 groups are always significantly poorer than for the NH group. Besides, the significance of the differences between HI and NH listeners are very similar for the two HPDs considered

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2 On each box, the central mark indicates the median, and the bottom and top edges of the box (of numerical values  $q_1$  and  $q_3$ , respectively) indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' symbol. The data points are drawn as outliers if they are greater than  $q_3 + 1.5 \times (q_3 - q_1)$  or less than  $q_1 - 1.5 \times (q_3 - q_1)$ .

(earplugs and earmuffs).

Figure 5: Masked thresholds with earplugs for the seven warning signals. For each warning signal, the five box and whisker plots correspond to the five hearing classes considered, from the NH class most to the left to the HI4 class most to the right.

Figure 6: Masked thresholds with earmuffs for the seven warning signals. For each warning signal, the five box and whisker plots correspond to the five hearing classes considered, from the NH class most to the left to the HI4 class most to the right.

Table 4: Masked threshold with earplugs and earmuffs (see Figures 5 and 6). Statistical results ( $p$ ) of the comparisons between the HI classes and the NH class. Values in bold, italic and with the “\*” sign indicate a statistically significant difference ( $p < 0.05$ ).

In summary, when no HPDs are worn, the differences between the masked thresholds of the HI classes and those of the NH class are relatively small and are statistically significant only for 4 out of the 7 signals tested. With HPDs, the differences between HI and NH increase and become significant for all the warning signals except the VACMA signal. The reason why there is no difference between HI and NH for the VACMA signal is most certainly due to the fact that its audibility is governed by a dominant component in low-frequency ( $f_0=334$  Hz) that is not or little affected by the two phenomena leading to an impediment of the detection (see section 2). Moreover, both HPDs (earplugs and earmuffs) lead to the same pattern of results.

## **5.2. Differences between protected and unprotected thresholds**

To better evaluate the effect of wearing HPDs on the detection of warning signals, the differences between protected and unprotected thresholds have been computed. A positive difference value indicates that the HPD impedes the detection (as compared to no HPD); conversely a negative value corresponds to an improvement of the detection. Figures 7 and 8 show these differences for the earplugs and the earmuffs, respectively.

Figure 7: Differences between thresholds with and without earplugs for the seven warning signals. For each warning signal, the five box and whisker plots correspond to the five hearing classes considered, from the NH class most to the left to the HI4 class most to the right.

Figure 8: Differences between thresholds with and without earmuffs for the seven warning signals. For each warning signal, the five box and whisker plots correspond to the five hearing classes considered, from the NH class most to the left to the HI4 class most to the right.

Additionally, Wilcoxon matched-pairs signed-rank tests were performed to evaluate whether these differences were statistically positive or negative. Table 5 summarizes the

statistical results: an up arrow symbol<sup>3</sup> “↑” designates a statistically significant impediment ( $p < 0.05$ ); a down arrow symbol “↓” symbol designates a statistically significant improvement ( $p < 0.05$ ) and no symbol designates no statistically significant effect.

Table 5: Differences between protected and unprotected thresholds (see Figures 7 and 8). Statistical results of the significant improvements (“↓” symbol,  $p < 0.05$ ) or impediments (“↑” symbol,  $p < 0.05$ ). No symbol indicates no statistically significant difference ( $p > 0.05$ ).

For NH listeners, it appears that wearing any of the two HPDs improves the detection for all the warning signals (except VACMA). These improvements for NH listeners are consistent with the results from previous studies [3, 5, 21]. For the VACMA signal, most of the audibility is due to a dominant component in low-frequency ( $f_0=334$  Hz). It can then be hypothesized that no improvement is found due to the reduced attenuation values of the HPDs around 300 Hz (which lead, as compared to no HPD, to a low reduction of the frequency masking phenomena, see section 2).

For HI listeners, detection improves for less and less warning signals when the absolute thresholds (i.e. the hearing loss) increase. As such, for the HI1 class, detection is improved for both HPDs for three warning signals (DAPR, STDIZIER and GSM), whereas for the HI3 and HI4 classes, no statistically significant improvement is found whatever the warning signal and the HPD considered.

Concerning the impediments, the RS warning signal is by far the most impeded signal: the differences between protected and unprotected thresholds reach around 10 dB on the medians for the HI4 class and statistically significant differences are found for HI2, HI3 and HI4 classes for earplugs and for all the HI classes for the earmuffs. This severe impediment is most certainly due to the fact that the RS signal is made of two high-frequency components (3430 and 4084 Hz). Indeed, over 3 kHz, both the absolute thresholds values and the HPD attenuations are high (see Figures 2 and 3), leading to an over-attenuation effect due to the absolute thresholds (as described in [4], see section 2). This signal is not in agreement with Standard No. ISO 7731:2003 [22], which recommends to use two dominant components between 500 and 1500 Hz and highlights that, when people wear HPDs or suffer from hearing loss, the signal must have enough energy below 1500 Hz. This signals should therefore be modified to increase its energy in the low-frequency range ( $f < 1500$  Hz) to be better detected.

Significant impediments are also found with earplugs for the warning signal GSM (HI4) and with earmuffs for the warning signal AIGU for HI3 and HI4 classes.

It is worth noting that no statistically significant impediment is found whatever the hearing class considered for the four remaining warning signals: PROVA, DAPR, STDIZIER and VACMA. This can be explained by the fact that these signals have a dominant fundamental frequency in low-frequency (between 334 and 660 Hz, see Table 1) that is not or little affected neither by the absolute thresholds effect nor by the upward spread of masking effect (see section 2). Hence these warning signals appear to be particularly adapted to HI listeners.

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<sup>3</sup> The *up* arrow was chosen to indicate a threshold *elevation* when HPDs are worn (as compared to no HPD)



### 5.3. Towards a criterion for HI listeners wearing HPDs

The previous section has shown that wearing the HPDs improves the audibility for NH listeners whereas it tends to impede the audibility for HI listeners. Moreover, the impediments greatly depend on the signal considered.

In an attempt to propose a criterion based on the absolute thresholds of HI people that guarantees their security when wearing HPDs, two approaches have been used.

In the first approach, it was simply considered that any significant impediment should be avoided. From Table 5, the security of all HI classes could not be guaranteed because of the RS signal. However, if we exclude the RS signal, only the security of HI3 and HI4 classes would not be guaranteed. As such, these two classes of people should avoid to work in such a noisy environment.

In the second approach, the idea was to quantify how much the protected thresholds of the HI differed from the unprotected thresholds of the NH. Thus, a Wilcoxon rank-sum test for unmatched data was used to check whether the protected thresholds of the HI classes significantly exceeded the unprotected thresholds of the NH majored by 3 dB ( $T_{HI,protected} > T_{NH,unprotected} + 3 \text{ dB}$ ). This difference of 3 dB has been chosen as it seems rather small compared to the intrinsic variations of signal levels that are typically observed in the field, notably because of the variations of the positions of the workers respective to the location(s) of the warning signal device(s). The results of these new statistical analyses are shown in Table 6.

Table 6: Statistical comparison ( $p$ ) between protected thresholds of the HI and unprotected thresholds of the NH majored by 3 dB ( $T_{HI,protected} > T_{NH,unprotected} + 3 \text{ dB}$ ). Values in bold, italic and with the “\*” sign indicate a statistically significant difference ( $p < 0.05$ ).

From Table 6, it appears that the protected thresholds of HI1 and HI2 classes are not significantly different than the unprotected thresholds of NH majored by 3 dB for the seven warning signals tested, including the RS signal.

Finally, if we do not consider the RS signal because it is not suitable as a warning signal, the two approaches lead to the same conclusion: the security is assured for the HI1 and HI2 classes (i.e. pure-tone average at 500, 1000 and 2000 Hz on the best ear  $< 30 \text{ dB}$ ) but not for the HI3 and HI4 classes.

This limit of PTA  $< 30 \text{ dB}$  to avoid the impediments due to wearing HPDs is consistent with the results of Lazarus [5]. However, it is worth noting that the proposed limit of PTA  $< 30 \text{ dB}$  is more restrictive than the criterion proposed in the USA by the Federal Railroad Administration [23] which tolerates a PTA in the better ear of up to 40 dB.

## 6. Conclusion

In this study, the influence of wearing HPDs on the detection of warning signals in noise was evaluated by comparisons of the masked thresholds measured with and without wearing HPDs, for seven warning signals. The results show that wearing the HPDs improves the audibility of warning signals in noise for NH listeners whereas it tends to impede the audibility for HI listeners. Moreover, the impediments greatly depend on the warning signal acoustical characteristics.

In order to ensure the security of the workers, the RS signal should not be taken into account because it is not suitable as a warning signal [22]. In these conditions, it was found that the security is assured for the HI1 and HI2 classes wearing any of the two HPDs tested (i.e. pure-tone average at 500, 1000 and 2000 Hz on the best ear  $< 30 \text{ dB}$ ) but not for the HI3 and HI4 classes.

Future studies should focus on the influence of wearing a HPD on other aspects such as the required signal levels to identify the signal (as in the study by Lazarus [5]), the localization of the warning signal and the perceived urgency of the warning signal [18] which have not been studied here. Furthermore, whatever the current experiment attempts to mimic a realistic environmental situation, all the situations that may occur in the field have not been studied in the laboratory and the current results could not be generalized. As a consequence, the current results cannot guarantee that the signals will always be heard in practice and extra caution is required when using HPDs in the field. Further listening tests as presented in Standard N° ISO 7731:2003 (Annex C) while wearing the HPDs could be useful to provide additional information.

Despite these limitations and based on the results from this study, some general recommendations can be addressed concerning the wearing of HPDs by HI listeners.

First of all, the HPD must be chosen so as not to overprotect the wearers. Indeed, the higher the attenuation values, the higher the potential impediments due to the absolute thresholds [4]. In accordance with Standard N° EN458 [13], the HPD must be chosen to meet a **A-weighted** daily exposure level under the HPD between 70 and 75 dB.

Second, protectors with a flat/uniform attenuation profile must be privileged so as to limit the impediment due to frequency masking [4]. Because most passive HPDs show little attenuation values in the low-frequency range, special caution must be taken when the background noises dominate in low frequency and active noise reduction (ANR) HPDs [24] should be privileged in this case as they bring an additional active attenuation in low frequency.

Concerning the sound design of warning signals, it is clear that warning signals with dominant components in low-frequency must be preferred since they are less affected by the wearing of HPDs, especially for hearing impaired listeners. Conversely, signals with not enough energy in low frequency must be avoided since their audibility is more adversely affected when using HPDs. This recommendation is consistent with the requirement from Standard N° ISO 7731 to use signals that have enough energy below 1500 Hz when people wear HPDs or when they suffer from hearing impairment.

## **Acknowledgements**

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Warning signal name	Temporal characteristics	Spectral characteristics	Frequency content
PROVA	Stationnary	Harmonic	$f_0 = 660$ Hz + 3 first harmonics. Most of the energy to the first and second harmonics
AIGU	Stationnary	Harmonic	$f_0 = 647$ Hz + many harmonics. Main components at 647, 1941 and 2588 Hz
DAPR	Two-tones (high-low)	High: harmonic	$f_0 = 656$ Hz + many harmonics with a flat energetic distribution up to 3000 Hz
		Low: harmonic	$f_0 = 427$ Hz + many harmonics with a flat energetic distribution up to 3000 Hz
STDIZIER	Stationnary	Harmonic	$f_0 = 358$ Hz + many harmonics. A loud component at 1432 Hz and a flat energetic distribution for the other components from 350 to 4000 Hz
GSM	Two-tones (high-low)	High: almost pure tone	$f_0 = 1800$ Hz (all other harmonic components are strongly attenuated)
		Low: almost pure tone	$f_0 = 1400$ Hz (all other harmonic components are strongly attenuated)
RS	Stationnary	Two inharmonic components	3430 Hz et 4084 Hz
VACMA	Stationnary	Harmonic	$f_0 = 334$ Hz + a few harmonics. Most of the energy at 334 and 1002 Hz

Hearing class	Mean age (years)	<i>SD</i> (years)
NH	36,9	11,4
HI1	50	8,6
HI2	55,2	17,6
HI3	62	14,1
HI4	58,6	12,7

Hearing class	Warning signal name						
	PROVA	AIGU	DAPR	STDIZIER	GSM	RS	VACMA
HI1	0,8172	<b>0,0307*</b>	0,0750	0,0750	0,0626	0,2479	<b>0,0487*</b>
HI2	0,9874	<b>0,0018*</b>	<b>0,0130*</b>	<b>0,009*</b>	<b>0,0184*</b>	0,1708	0,0967
HI3	0,4361	<b>0,0004*</b>	<b>0,0093*</b>	<b>0,0015*</b>	<b>0,0022*</b>	0,1335	0,0654
HI4	0,7180	<b>0,0002*</b>	0,0801	<b>0,0211*</b>	<b>0,0157*</b>	0,5977	0,0801



Hearing class	Warning signal name													
	PROVA		AIGU		DAPR		DIZIER		GSM		RS		VACMA	
	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs
HI1	0,2592	0,3624	<i>0,0010*</i>	<i>0,0005*</i>	0,0893	<i>0,0004*</i>	<i>0,0232*</i>	0,6934	0,1615	0,1313	<i>0,0375*</i>	<i>0,0139*</i>	0,2829	0,4226
HI2	0,0642	0,0517	<i>0,0001*</i>	<i>0,0001*</i>	<i>0,0062*</i>	<i>0,0042*</i>	<i>0,0002*</i>	<i>0,0090*</i>	<i>0,0016*</i>	<i>0,0130*</i>	<i>0,0018*</i>	<i>0,0014*</i>	0,4018	0,4765
HI3	<i>0,0216*</i>	<i>0,0052*</i>	<i>0,0000*</i>	<i>0,0001*</i>	<i>0,0001*</i>	<i>0,0000*</i>	<i>0,0000*</i>	<i>0,0047*</i>	<i>0,0000*</i>	<i>0,0001*</i>	<i>0,0001*</i>	<i>0,0000*</i>	0,0839	0,0654
HI4	<i>0,0244*</i>	<i>0,0050*</i>	<i>0,0001*</i>	<i>0,0001*</i>	<i>0,0014*</i>	<i>0,0001*</i>	<i>0,0014*</i>	<i>0,0001*</i>	<i>0,0030*</i>	<i>0,0030*</i>	<i>0,0001*</i>	<i>0,0005*</i>	0,1917	0,1566

Hearing class	Warning signal name													
	PROVA		AIGU		DAPR		DIZIER		GSM		RS		VACMA	
	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs
NH	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	-	-
HI1	-	↘	↘	-	↘	↘	↘	↘	↘	↘	-	↗	-	-
HI2	-	↘	-	-	↘	↘	-	↘	-	-	↗	↗	↘	-
HI3	-	-	-	↗	-	-	-	-	-	-	↗	↗	-	-
HI4	-	-	-	↗	-	-	-	-	↗	-	↗	↗	-	-

Hearing class	Warning signal name													
	PROVA		AIGU		DAPR		DIZIER		GSM		RS		VACMA	
	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs	Plugs	Muffs
HI1	0,9983	0,9999	0,8259	0,7808	0,9847	0,9983	0,9884	0,9996	0,9554	0,9996	0,9786	0,876	0,9377	0,7206
HI2	0,9777	0,9946	0,1	0,2482	0,9	0,8693	0,4185	0,8693	0,1921	0,8327	0,328	0,1651	0,9204	0,8247
HI3	0,8767	0,9748	<b>0,0159*</b>	<b>0,0009*</b>	0,1481	0,2654	0,0575	0,3879	<b>0,0159*</b>	<b>0,0492*</b>	0,0667	<b>0,0058*</b>	0,4025	0,207
HI4	0,4668	0,5552	<b>0,0004*</b>	<b>0,0007*</b>	0,0567	<b>0,0355*</b>	<b>0,0314*</b>	<b>0,0355*</b>	<b>0,0042*</b>	<b>0,0067*</b>	<b>0,0025*</b>	<b>0,0162*</b>	0,6615	0,1946

Figure 1

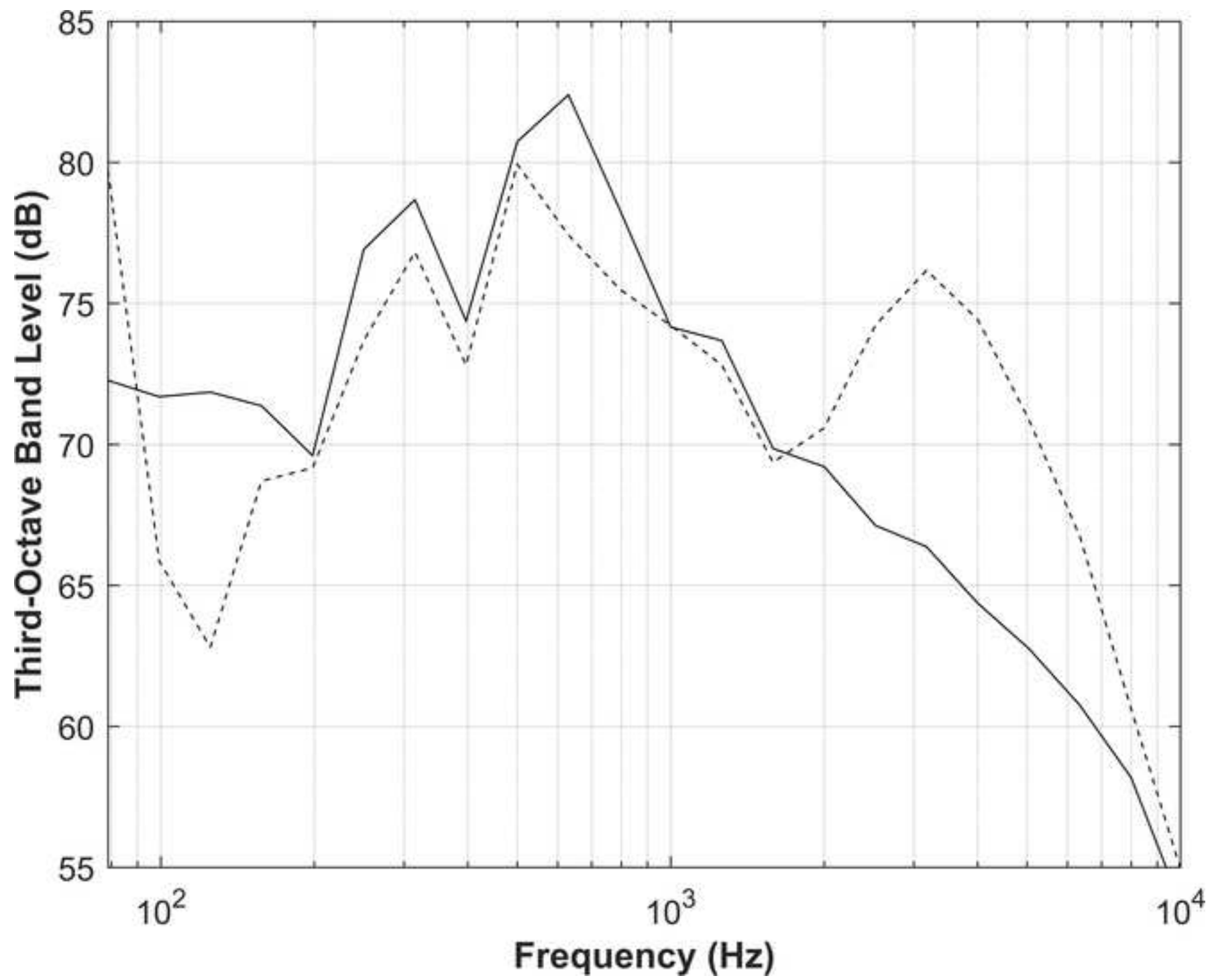


Figure 2

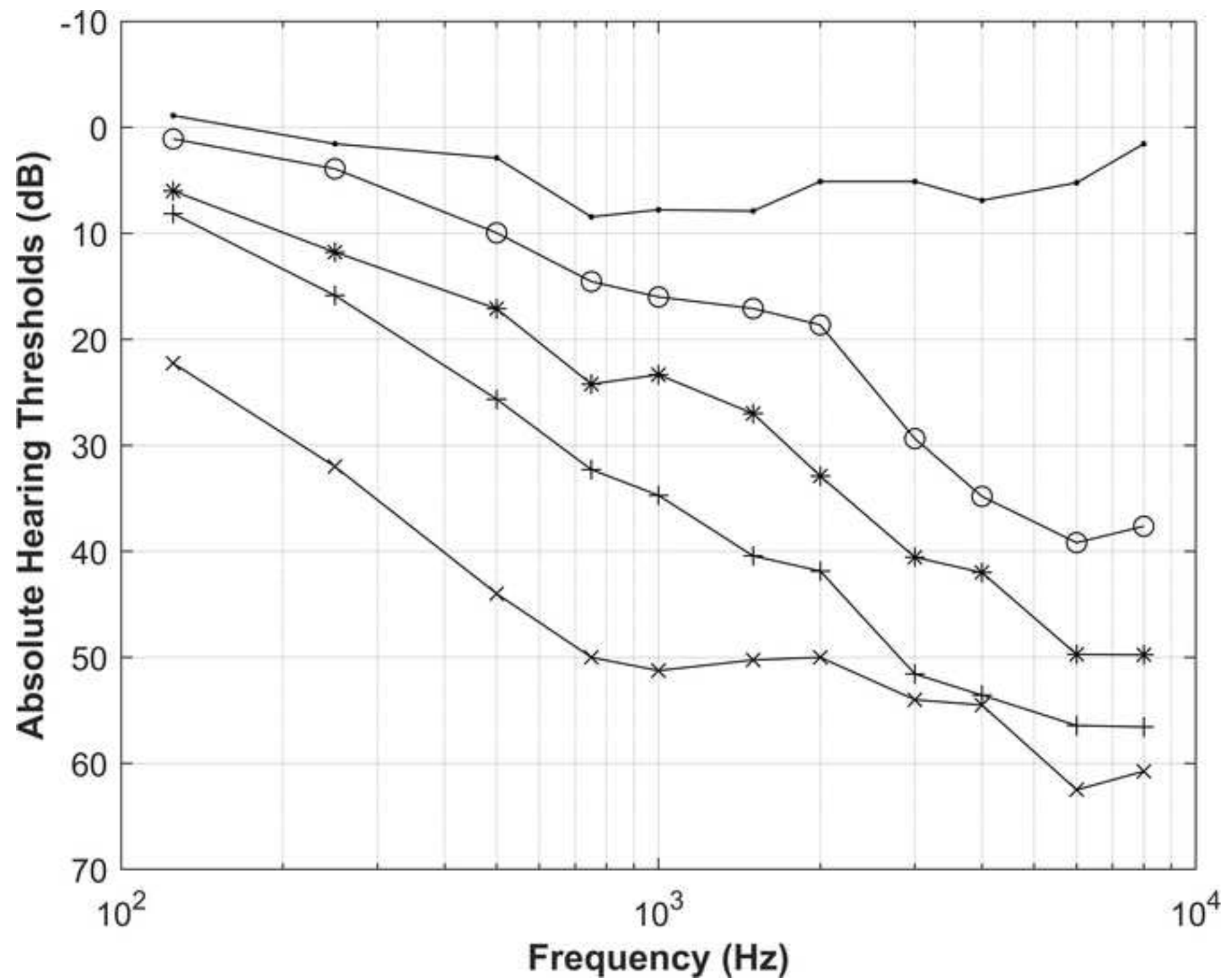


Figure 3

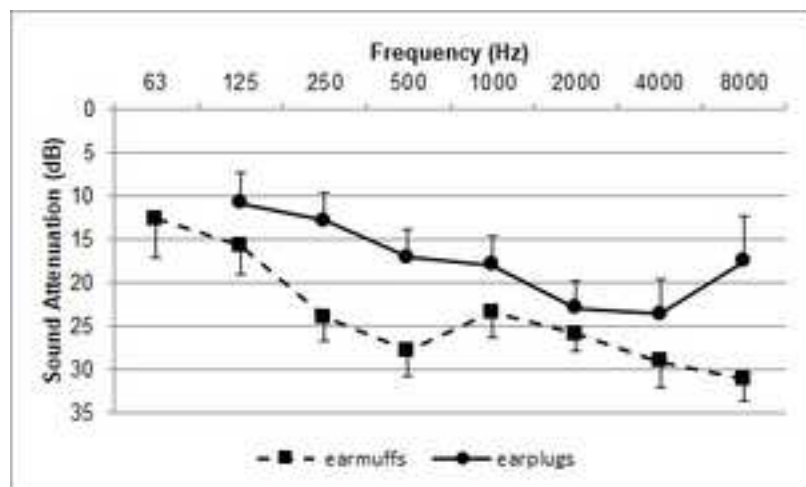


Figure 4

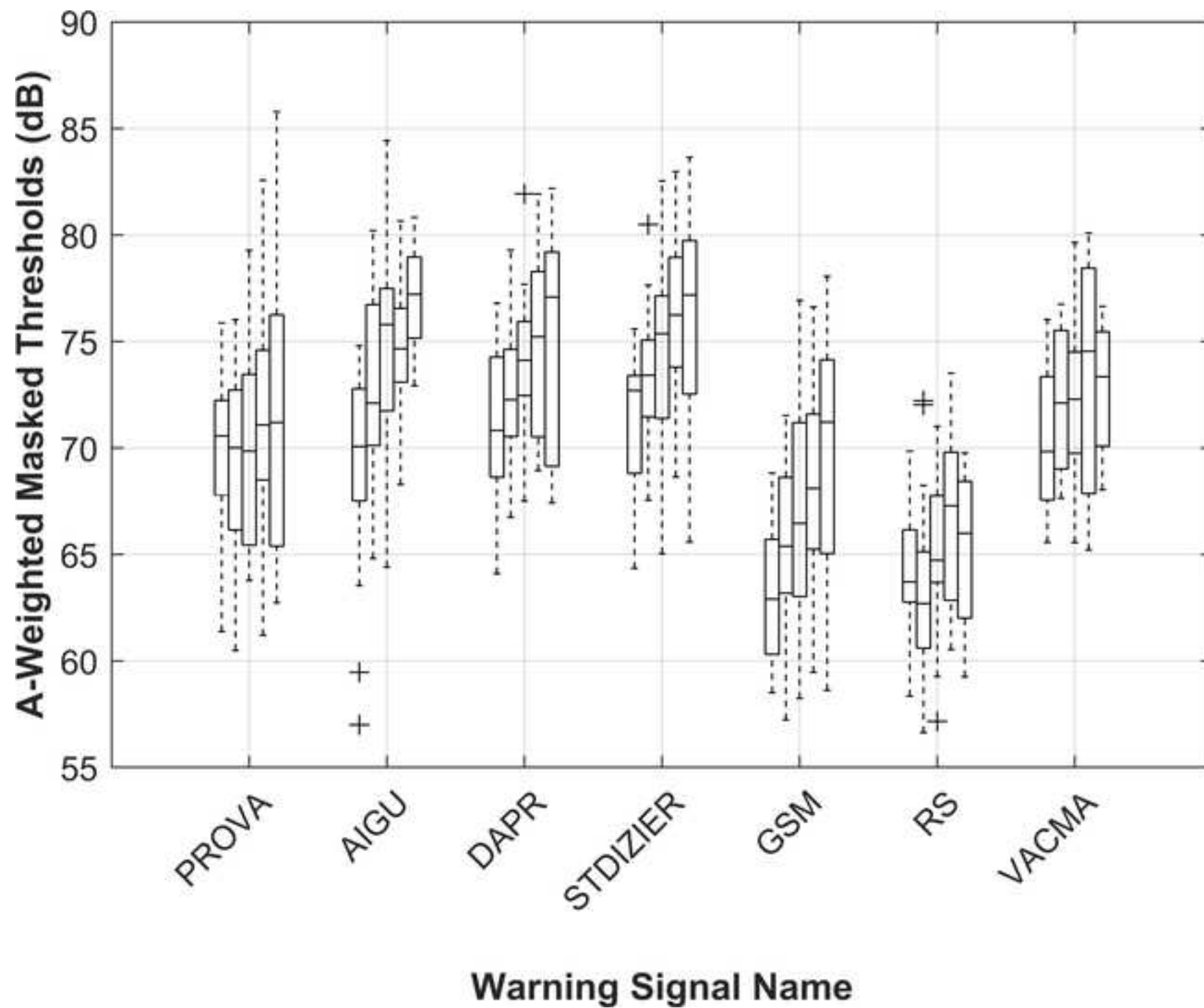




Figure 5

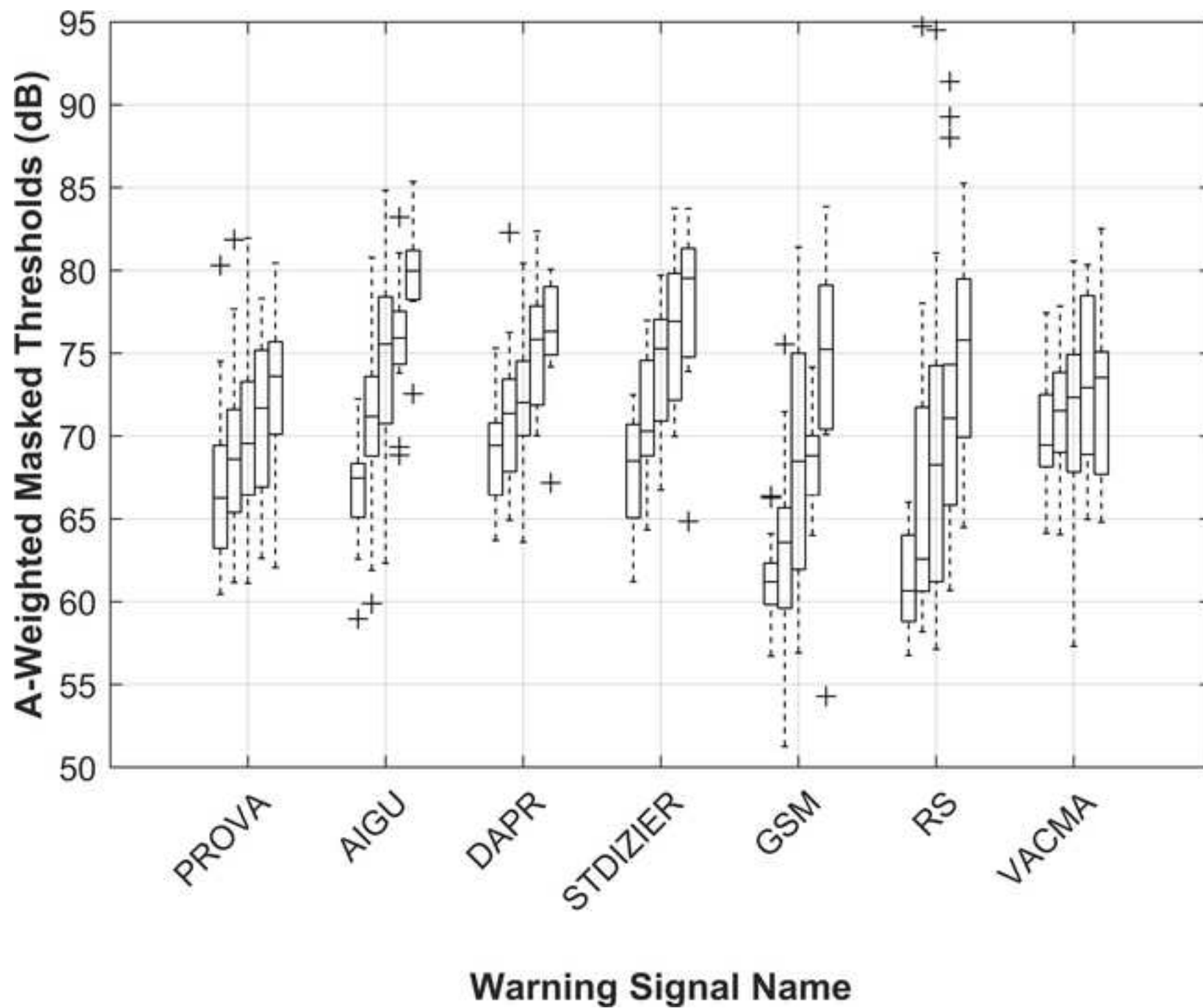


Figure 6

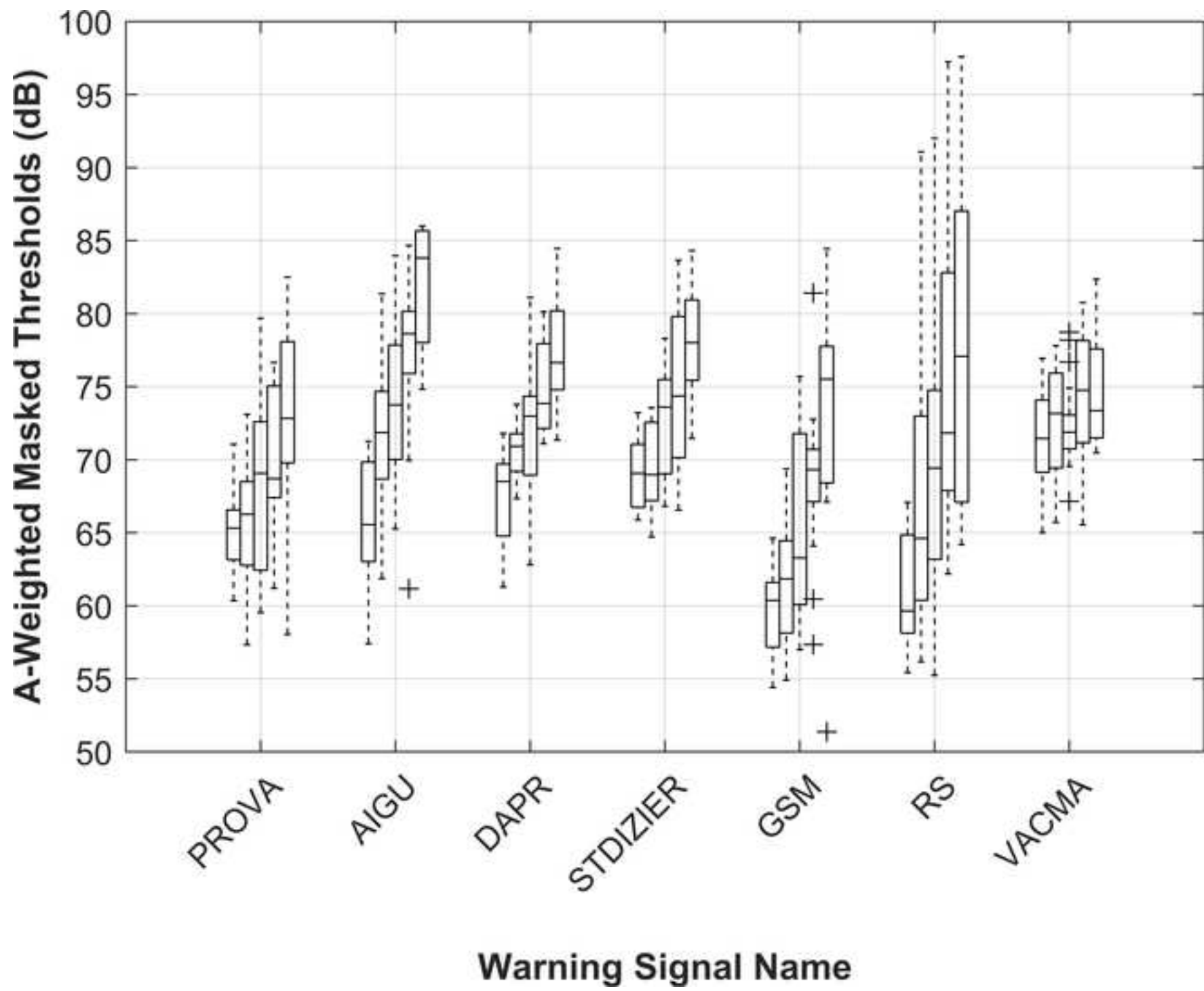


Figure 7

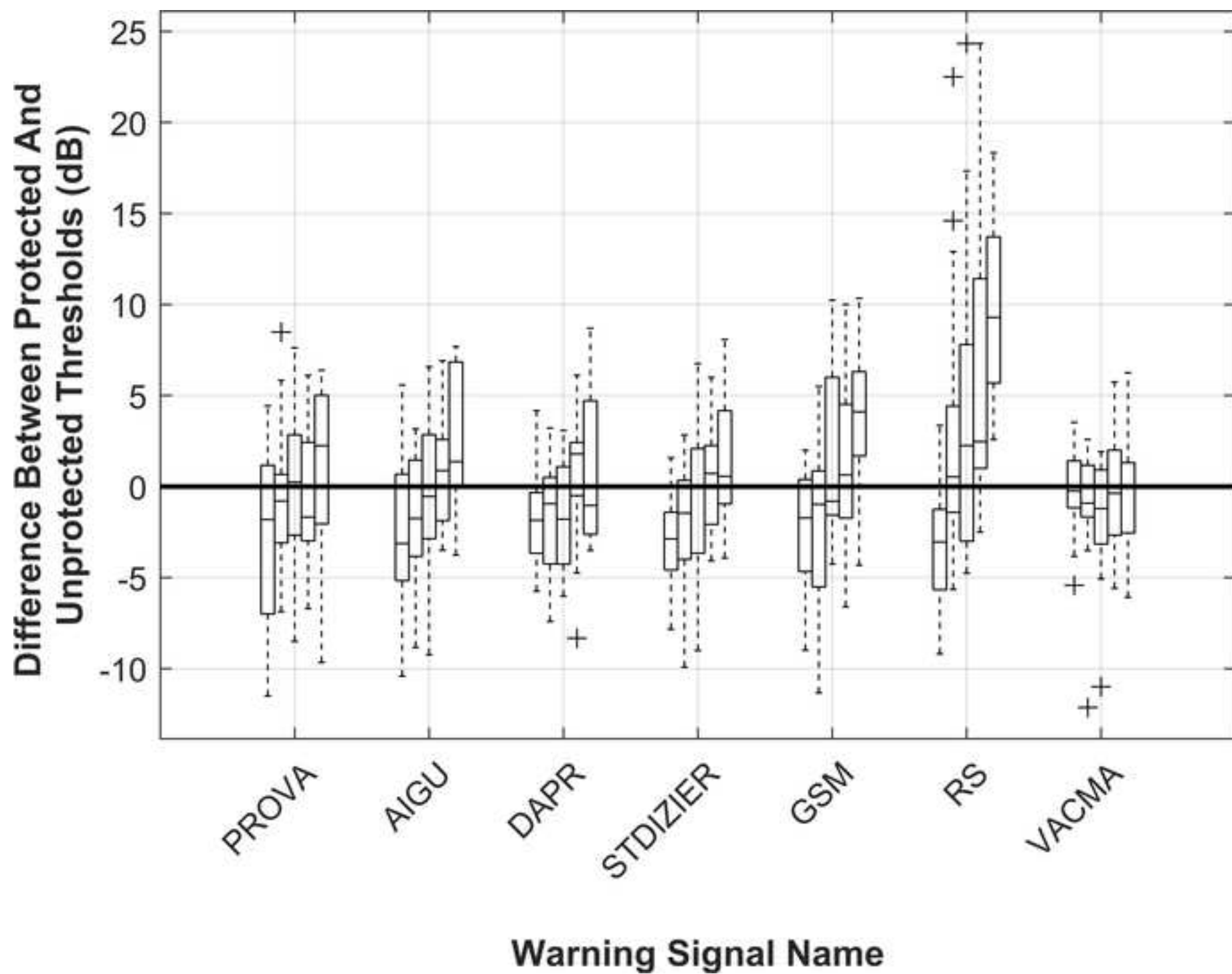
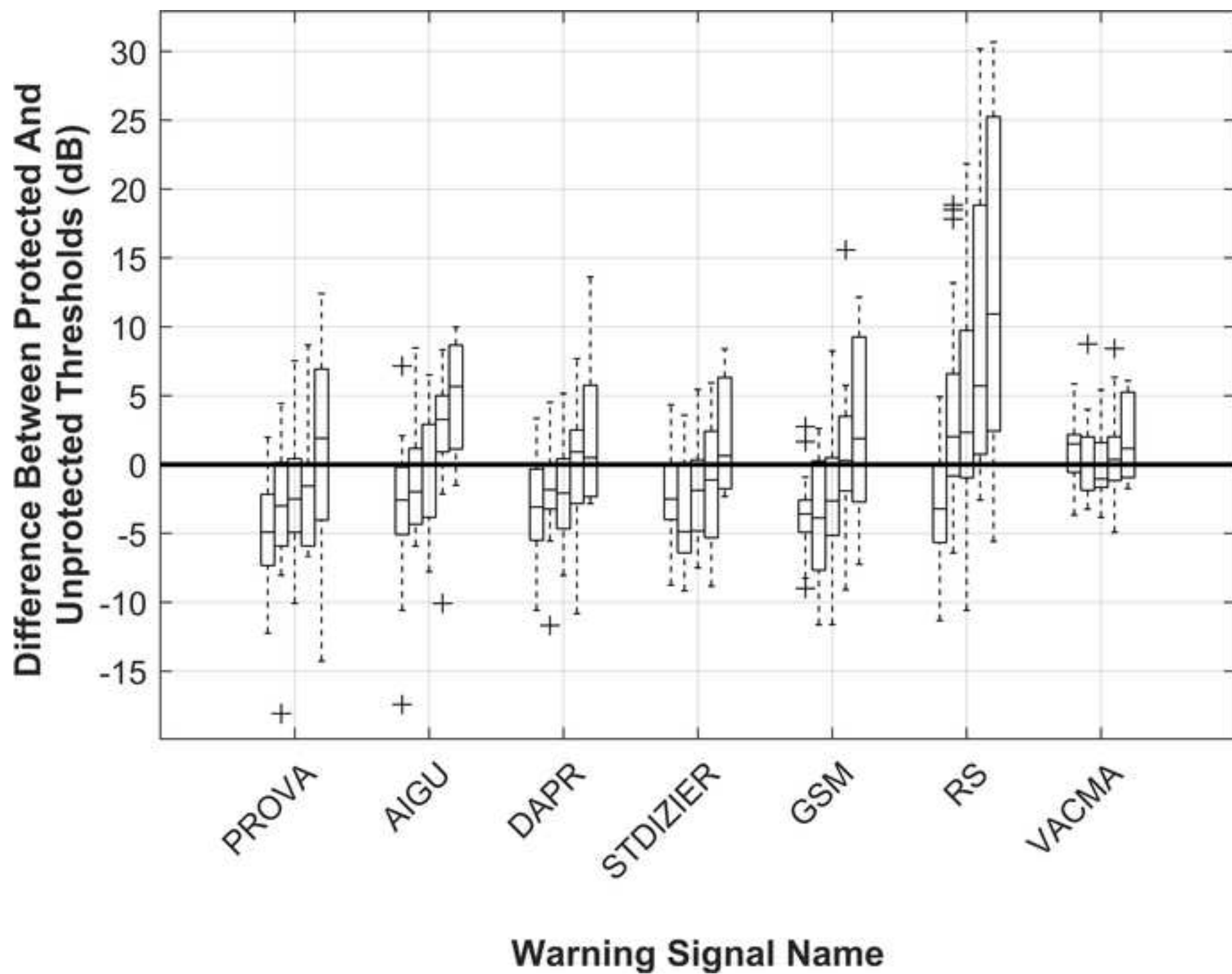


Figure 8



Reviewer #1: The article deals with issues important for security reasons. The manuscript is well prepared. The following comments can be made, which will further improve its quality:

1. The advantage of work is the use of actual recorded audio signals. Inquisitive readers would like to know how they were registered (what equipment was used, what technique was used, what were the registration parameters?).

The following sentence has been added:

"Time recordings were performed using a calibrated class 1 sound level meter (type 2250 from Brüel & Kjær, Denmark) at a sampling frequency of 48 kHz."

2. The truth is that you can find many instances of writing units like "dBA" or "dB (A)" even in Directive 2003/10 / EC. This way of writing units is convenient e.g. in the interface of sound level meters. However, such notations should be avoided in a scientific article. The notation "dB" is acceptable, but if you need to include A-weighting information, write it in the parameter name, e.g. "LA", "LAeq" etc. The unit will then be "dB". These notations are defined in the relevant standards (ISO 9612). A similar situation applies to the phrase like "dB HL", where information about the hearing level should be included in the parameter name. Please take this into account in the manuscript and in the descriptions of the figure axes.

Relevant modifications have been made through the whole manuscript and figures.

3. Lines 55-56: "Since HI listeners usually exhibit broadened auditory filters..." - this is not obvious information to the reader. Please support this with references to literature.

The three following references have been added:

Moore, B.C.J. and B.R. Glasberg, *Formulae describing frequency selectivity as a function of frequency and level, and their use in calculating excitation patterns*. Hear Res, 1987. **28**: p. 209–225.

Leek, M.R. and V. Summers, *Auditory filter shapes of normal-hearing and hearing-impaired listeners in continuous broadband noise*. The Journal of the Acoustical Society of America, 1993. **94**(6): p. 3127-3137.

Glasberg, B.R. and B.C.J. Moore, *Derivation of auditory filter shapes from notched-noise data*. Hearing Research, 1990. **47**(1-2): p. 103-138.

Reviewer #2: Congratulations. Well done!