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EFFECT OF WEARING HEARING PROTECTORS ON THE AUDIBILITY OF WARNING SIGNALS FOR NORMAL AND HEARING-IMPAIRED LISTENERS: EXPERIMENT AND MODEL

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ABSTRACT

The audibility of warning signals is of paramount importance in noisy industrial environments to ensure the workers' safety. In practice, several factors may compromise the audibility of warning signals, such as the presence of background noise, the use of hearing protector devices (HPDs) and the hearing impairments of the workers. In order to evaluate the effect of HPDs on the audibility of railway warning signals, masked thresholds were first measured in the laboratory in the presence of 86 dB(A) low-frequency background noises, both with and without wearing the HPDs. Seven warning signals and two HPDs (custom molded earplugs and a passive earmuff) were tested on normal-hearing (NH, N=28) and hearing-impaired (HI, N=45) subjects with various hearing loss profiles. The results show that for NH subjects, the audibility is generally improved when wearing the HPDs (i.e. the protected thresholds are lower than the unprotected thresholds). For HI subjects, the audibility may be impeded when wearing the HPDs (i.e. the protected thresholds are higher than the unprotected thresholds) and the impediment tends to increase with increasing hearing loss. Second, using these experimental data, a model was developed to predict masked thresholds. This model is based on the Signal Detection Theory (SDT) and the Glasberg and Moore excitation pattern model. This excitation pattern model was modified to take into account both enlarged auditory filters and elevated absolute thresholds of HI listeners. Using this model, the experimental trends were fairly well reproduced. However, some improvements could still be made to better the precision of the predictions.

1. INTRODUCTION

Acoustic warning signals are often used in workplaces to alert workers of a potentially dangerous situation. In practice, the audibility of warning signals may be compromised by several factors, notably the hearing status of the workers and the wearing of hearing protection devices (HPDs) [1, 2].

In railway companies such as SNCF, this issue is of particular importance because the risk of not hearing warning signals when wearing HPDs could result in fatal accidents. In a previous experimental study considering only normal hearing (NH) listeners [3], it was found that wearing earplugs hardly deteriorates the perception of

railroad warning signals (as compared to no HPD). For hearing-impaired (HI) listeners however, it is known that wearing HPDs can have a more detrimental effect [4]. This more detrimental effect for HI listeners may be due to two distinctive phenomena : first, elevated absolute thresholds (referred as "Case 1 elevation" in [5]) and second, broadened auditory filters (referred as "Case 2 elevation" in [5]). Therefore, the present experimental study was first conducted to evaluate the effect of wearing HPDs on the detection of railroad warning signals for HI listeners. Second, using these experimental data, a model was developed to predict masked thresholds.

2. METHODS

2.1 Experimental study

2.1.1 Listeners

Seventy-three listeners aged from 18 to 81 years (mean age = 51.5 years; SD = 15.8 years) participated to the experiment. The listeners were grouped into four hearing classes according to their mean absolute threshold at 500, 1000, 2000 and 4000 Hz on their best ear (denoted BIAP in this paper):

- 28 listeners are in the class $BIAP \leq 20$ dB HL (class NH)
- 16 listeners are in the class $20 < BIAP \leq 30$ dB HL (class HI1)
- 17 listeners are in the class $30 < BIAP \leq 40$ dB HL (class HI2)
- 12 listeners are in the class $BIAP > 40$ dB HL (class HI3).

Figure 1 shows the mean audiograms for the four hearing classes considered.

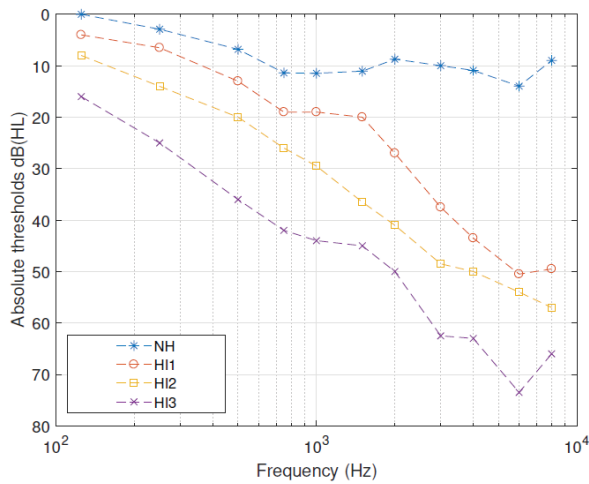


Figure 1: Mean audiograms for the four hearing classes considered.

2.1.2 Warning signals and HPDs

Seven warning signals used by the French National Railway Company (SNCF) have been tested. Four of them are dedicated to warn track workers and were tested in a ballast plough background noise. The three other signals are used to warn drivers and were tested in the background noise of a railway vehicle at maximal speed. The two masking noises dominate in the low frequency range ($f < 500$ Hz) and have most of their energy below 3 kHz. Six out of the seven warning signals are harmonic sounds that differ greatly by their frequency content (i.e. they have different fundamental frequencies and different repartitions of their dominant harmonic components). The non-harmonic warning signal is made of the sum of two pure tones at 3430 and 4084 Hz.

Two HPDs were tested: silicon custom molded earplugs and passive earmuffs (in this paper, only the results for the earplugs are presented).

2.1.3 Masked thresholds measurements

Masked thresholds were estimated using an adaptive, two-interval, forced choice (2IFC) procedure with a two-down one-up adaptive rule. This procedure leads to a 70.7 % of detection [6]. The levels of the noises were fixed at 86 dB(A) while the warning signals started at 86 dB(A) and varied according to the listener's answers. The initial step size of 5 dB was first reduced to 3 dB after the first three reversals and finally to 1 dB after two more reversals. Thresholds were computed as the average level of the last four reversals.

For each situation (i.e. for a given warning signal and a given protection condition), the masked threshold measurement was repeated three times and the retained masked threshold is the mean of the three thresholds. When the standard deviation of the three thresholds exceeded 3 dB, a fourth measurement was performed and the retained threshold was computed as the mean of the three nearest thresholds.

2.2 Predictive model

The proposed model is based on the excitation pattern model of Glasberg and Moore [7] upon which is applied

the signal detection theory (SDT) [8]. In a detection task where the listener has to choose between two stimuli ("noise alone" and "noise + signal") which one contains the signal, SDT states that a detectability index d' can be computed as :

$$d' = \frac{\Delta\mu}{\sigma}, \quad (1)$$

where $\Delta\mu$ is linked to the levels of the stimuli and σ represents the « internal noise » of the listener. In order to take into account the ear's ability to integrate information over a large frequency spectrum, the detectability index d' is expressed in terms of the detection index d'_i in each independent frequency band [9] (σ is considered equal in all bands) as:

$$d' = \sqrt{\sum_{i=1}^{N_b} d_i'^2} = \sqrt{\sum_{i=1}^{N_b} \frac{\Delta\mu_i^2}{\sigma_i^2}} = \frac{\sqrt{\sum_{i=1}^{N_b} \Delta\mu_i^2}}{\sigma}, \quad (2)$$

where the terms $\Delta\mu_i$ represent the differences in independent bands between the excitation pattern of the « noise + signal » and the excitation pattern of the « noise alone » and N_b is the number of independent bands.

First, the values of internal noise were evaluated for each listener from the thresholds measured without HPDs (see section 2.1). This evaluation shows that the values of internal noise increase with increasing absolute thresholds. Second, once the internal noise values are known, it is then possible using Eq.2 and after choosing a detection percentage (expressed through d') to compute the level of the target signal (expressed through $\Delta\mu_i$).

To take into account hearing impairment, the original excitation pattern model [7] was modified in two ways. First, since hearing-impaired listeners may have wider auditory filters [10], the average Equivalent Rectangular Bandwidths (ERBs) were measured (at 500, 1000, 2000 and 3000 Hz) and then used in the Glasberg & Moore's model in order to compute the excitation patterns. The measured ERBs are also used to define the independent frequency bands used in Eq.2; which are fewer but wider for hearing-impaired. Second, the absolute hearing thresholds are accounted for by limiting the levels of the excitation pattern: if the level in a band is below the absolute threshold, then this band does not contribute to detection and the term $\Delta\mu_i$ is equal to 0 in this band. In short, the ERBs are first used to modify the way the excitation pattern is computed, then the absolute hearing thresholds are used to correct the values of $\Delta\mu_i$ in each band.

For comparisons to the measured masked thresholds, the predicted thresholds presented in section 3 were obtained using the following input parameters:

- Detectability index $d'=0.78$ (detection percentage of 70.7%, as for the measurements);
- One mean internal noise value for each one of the four hearing classes considered;
- Individual absolute thresholds and ERBs for each listener;
- One unique set of attenuation values for the earplugs (obtained from measurements on an artificial head).

3. RESULTS

Figures 2 and 3 show comparisons between measured and predicted thresholds, averaged across the seven warning signals.

The experimental data show that masked thresholds increase with increasing absolute thresholds. Moreover, the increase is greater when earplugs are worn than without HPD. For the unprotected condition, the experimental thresholds are well reproduced by the predictive model (repeated measures ANOVAs with the warning signal as repeating factor show no statistically significant differences between measurements and predictions, i.e. $p > 0.05$). However, for protected thresholds, predictions tend to overestimate the measured thresholds (repeated measures ANOVAs show statistically significant differences for groups HI2 and HI3, i.e. $p < 0.05$). This overestimation could be explained by the fact that the unique set of attenuations values used for the predictions are higher than those experienced by several listeners, leading to increased masked thresholds.

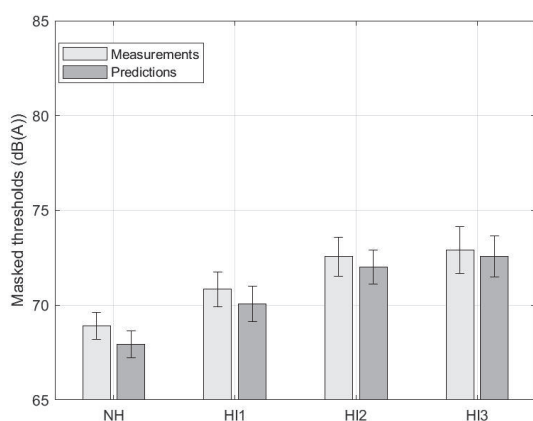


Figure 2: Comparisons of masked thresholds obtained from measurements and predictions when no HPD is worn.

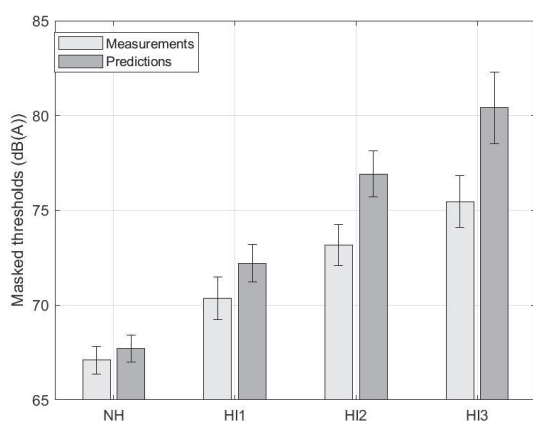


Figure 3: Comparisons of masked thresholds obtained from measurements and predictions when the earplugs are worn.

To gain better insights into the influence of wearing HPDs, Figure 4 compares the differences between protected and unprotected thresholds obtained from measurements and predictions.

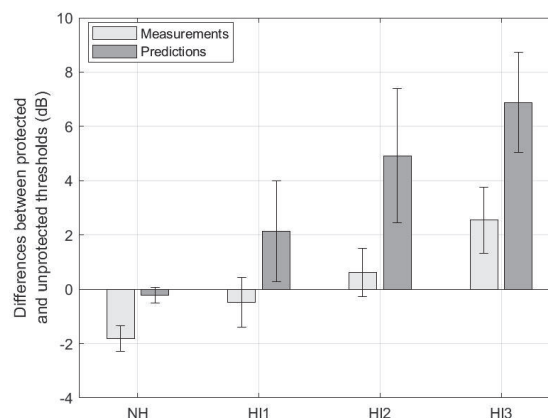


Figure 4: Differences between protected and unprotected thresholds obtained from measurements and predictions.

For NH listeners, the measurements show that wearing the earplugs improves detection (i.e. protected thresholds are lower than unprotected thresholds). This result is in agreement with the results of the previous experimental study performed on NH listeners [3] and can be explained by the reduction of the upward spread of masking when HPDs are worn [2]. Always from measurements, wearing the earplugs tends to deteriorate the detection for HI listeners, (i.e. protected thresholds are greater than unprotected thresholds) and this deterioration increases with increasing absolute thresholds.

Concerning the predictions, even if the general experimental trend is qualitatively reproduced, it appears that the improvement of the detection for NH is underestimated whereas the deteriorations for HI are overestimated. An explanation to this behavior could be that the sharpening of the auditory filters due to the reduction of the sound levels, which is responsible for the improvement of the detection [2], is larger than the sharpening used in the model.

4. CONCLUSION

The experimental study on the influence of wearing HPDs on the audibility of warning signals shows that the audibility is generally improved for NH listeners whereas it tends to be deteriorated for HI listeners and the deterioration increases with increasing absolute hearing thresholds.

The proposed predictive model yields qualitatively good results (i.e. masked thresholds increase with increasing absolute thresholds) but for HI listeners, it strongly overestimates the detrimental effect of the HPD observed from the measurements. This overestimation can be explained by the fact that the unique set of attenuations used in the model are larger than those experienced by several of the hearing-impaired listeners. Another explanation could be that the sharpening of the filters due to the reduction of the sound levels for the listeners who performed the tests is larger than the sharpening used in the model.

Furthermore, one drawback of the approach is that the predictions for the seven warning signals use as input the values of internal noise that were evaluated from the measured masked thresholds without HPDs on the same seven signals. In the future, it will be intended to evaluate these internal noise values from other types of measurements (like frequency selectivity measurements) and possibly to consider internal noise values that vary with frequency (instead of considering a unique internal noise value for the entire frequency range).

Overall, the proposed predictive model can be used to easily predict masked thresholds of warning signals for different hearing profiles, detection percentages of the target signal and attenuation profiles of HPDs.

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