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Audibility of warning signals: methods to evaluate the combined effects of hearing protectors and hearing impairment

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ABSTRACT

Workers exposed to high noise levels are generally required to wear hearing protection devices (HPDs). For security reasons, it is important to evaluate whether the audibility of warning signals in noise is impeded when using HPDs, especially for hearing-impaired workers. The typical method to assess the effect of HPDs is to perform subjective experiments which require large populations with various degrees of hearing impairment to get statistically significant results. To ease the evaluation of the combined effects of HPDs and hearing impairment, two alternative methods are proposed. First, sound simulations have been used to reproduce the combined effects of impairment and HPDs to perform listening tests on normal hearing listeners. Qualitatively, the effects are successfully simulated. Second, a detection model has been developed to predict masked thresholds of warning signals in presence of background noise. Even though it overestimates the detrimental effects of HPDs, the model is qualitatively in agreement with the experimental data.

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Overall, these results should help to produce general recommendations for security purpose at work.

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1. INTRODUCTION

In many workplaces, acoustic warning signals are often used to alert workers in case of dangerous situations. However, several factors may decrease the efficiency of these signals [1,2], notably the presence of background noise, the hearing status of the workers or the use of hearing protection devices (HPDs). As such, it is important to be able to assess the effect of HPDs on the workers' detection ability. The effect of HPDs is usually assessed by performing subjective experiments to measure the masked threshold of a signal, (i.e. the level at which the signal becomes audible in presence of a background noise) both with and without wearing a HPD [3]. The HPD is then considered as improving or deteriorating detection depending on whether the masked threshold while wearing the HPD is higher (deterioration) or lower (improvement) than the masked threshold without HPD. However, this method is time consuming and the recruitment of listeners is a major difficulty. Indeed, to yield statistically significant results, it is necessary to constitute a large population with various degrees of hearing impairment, with enough listeners for each degree of impairment. Because of this difficulty, two alternative methods to ease the evaluation of the effect of HPDs on audibility are presented hereafter.

These methods should take into account two hearing capabilities that govern the audibility of warning signals: the absolute thresholds and the width of the auditory filters. The elevated absolute thresholds of hearing-impaired listeners can deteriorate detection because the attenuations of HPDs add up to the absolute thresholds to the point where the signal becomes inaudible [2]. Another source of deterioration is the increase in the upward spread of masking [2]. Because the HPDs usually have higher attenuation in high frequencies than in low frequencies, the masking effect of a low frequency noise will almost not be changed while the high frequency components of a signal to be detected will be attenuated. Hearing-impaired listeners may be more affected as they already have a poorer frequency selectivity (their auditory filters are wider) when their absolute thresholds exceeds around 30 dB HL [4,5]. On the other hand, the non linear growth of masking with noise levels can also improve detection: when a noise level is attenuated by the HPDs, it leads to weaker masking effects which in turn allows for lower masked thresholds [3].

The first method to evaluate the effects of the HPDs combine to impairment consists in using sound simulations to reproduce the effects of hearing impairment and HPDs. By altering signals so they are perceived by normal hearing listeners as if they were hearing-impaired (and/or wearing HPD), listening tests can be performed on a limited number of normal hearing listeners (which are a lot easier to recruit than hearing-impaired listeners) and thus speed up the experiment.

The second method is a predictive model based on Glasberg and Moore's excitation pattern model [6]. The model is able to compute masked thresholds for pure and complex sounds while taking into account the sound attenuations of a HPD and the hearing status of the listeners (absolute thresholds and auditory filters).

In this paper, the results of these two methods are compared to the result of a previous subjective experiment held on hearing-impaired listener.

2. EXPERIMENT ON HEARING-IMPAIRED LISTENERS

The experiment on hearing-impaired listeners is only briefly presented here since it is presented in details in a companion paper proposed at Inter-noise 2019 [7].

2.1. Participants

Seventy-three listeners aged from 18 to 81 (mean age = 53.3 years; SD = 14.5 years) with various hearing status from normal to highly impaired participated in a detection experiment. Their hearing status were assessed by measuring the absolute thresholds at the 11 standard audiometric frequencies from 125 to 8000 Hz as well as the equivalent rectangular bandwidths (ERBs) of the auditory filters centered at 500, 1000, 2000 and 3000 Hz via a notched-noise experiment [8,9]. Four hearing groups were then considered using an average loss indicator named BIAP corresponding to the mean of the absolute thresholds at 500, 1000, 2000 and 4000 Hz on the best ear:

- NH group: normal hearing with BIAP≤20dB HL; 28 listeners
- group HI1: weak to medium impairment with 20<BIAP≤30; 16 listeners
- group HI2: medium to severe impairment with 30<BIAP≤40; 17 listeners
- group HI3: severe impairment with BIAP>40; 12 listeners

The average audiograms for each group are shown figure 1.

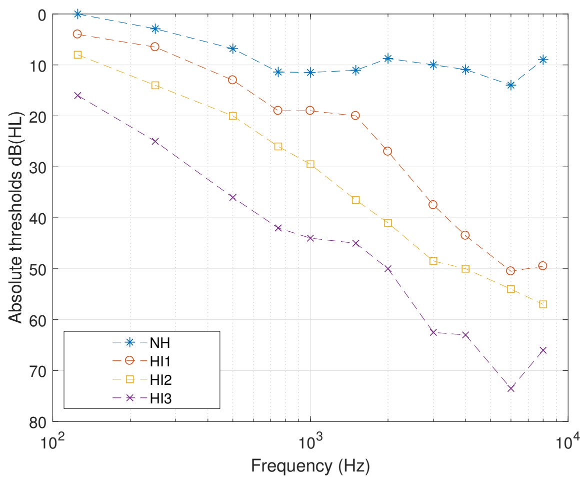

Figure 1: Averaged audiograms for the four hearing groups defined in section 2.1.

2.2. Detection task

Warning signals from the French National Railway Company (SNCF) were used in the detection task: seven warning signals and two background noises. The masked thresholds were estimated using a two interval forced choice (2IFC) procedure with a two-down one-up adaptive rule leading to a 70.7 % detection [10]. The levels of the background noises were fixed at 86 dB(A). The masked thresholds were estimated in three conditions: without HPD, with an earmuff and with custom-moulded earplugs. The experiment results for the four groups will be used as a basis for comparison with the two methods proposed.

3. SOUND SIMULATION

The principle of this method is to modify audio signals so they are perceived by normal hearing listeners as if they were hearing-impaired listeners and/or wearing HPDs.

3.1. Hearing impairment and HPD simulation

To simulate hearing impairment, the hearing loss simulator (HLS) developed by Grimault *et al* [11] was used. This simulator compensates the cochlear compression of the healthy ear to reproduce the in-out function of an impaired ear to simulates the impaired frequency selectivity as well as the elevated absolute thresholds. As input, it only requires the audiogram to be simulated.

The HPDs simulated were those tested in the experiment with hearing-impaired listeners (see section 2). The attenuations of the earmuff have been measured in narrowband on the listeners during the experiment each time they had to put it on, an average attenuation was then computed from the several attenuation measured. The attenuations of the earplugs have been measured in narrowband on an artificial head as it was too difficult to place a microphone in the ear of the subjects to measure the attenuation without altering the attenuations of the earplugs too much. The HPDs simulation is achieved by applying narrowband attenuation on the magnitude of the signals' spectrum, while preserving the phase.

Finally, the signals were first modified to simulate the HPDs, then they were modified by the HLS to simulate impairment.

3.2. Participants & simulated impairments

Eight young normal hearing listeners (absolute thresholds < 20 dB HL at all tested frequencies for both ears) performed the same experiment as the one described in section 2 except they were listening to the simulation signals of impairment and HPDs. The simulated hearing impairments correspond to the averaged audiograms of the three hearing-impaired groups (HI1, HI2 and HI3 as described in section 2.1) shown figure 1. Thus, each listener performed the detection task in four different conditions: with three different impairments simulated and with their own normal hearing status (no simulation of impairment). Results are shown in section 5.

4. PREDICTIVE MODEL

The proposed model is based on the excitation pattern model of Glasberg and Moore [6] upon which is applied the signal detection theory (SDT) [12].

In a detection task where the listener has to choose between two stimuli ("noise alone" and "noise + signal") which one contains the signal it is possible to compute a detectability index d':

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

This index d' informs on the difficulty of the detection task and yields the information of the targeted detection percentage; $\Delta\mu$ is linked to the levels of the stimuli and, at threshold, yields the level of the target signal. Finally, σ is the internal noise of the listener doing the task. The values of internal noise according to hearing status were evaluated from the thresholds without HPDs measured in the experiment presented in section 2.2. This evaluation is presented in another paper that shows that the values of σ increase with increasing impairment. 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 [13] (σ is considered equal in all bands):

$$d' = \sqrt{\sum_{i=1}^{Nb} d_i'^2} = \sqrt{\sum_{i=1}^{Nb} \frac{\Delta\mu_i^2}{\sigma_i^2}} = \frac{\sqrt{\sum_{i=1}^{Nb} \Delta\mu_i^2}}{\sigma} \tag{2}$$

with Nb the number of independent bands.

From Eq. 2, once the internal noise values are known, it is then possible to choose a detection percentage, expressed through d', and to compute the level of the target signal (expressed through $\Delta\mu_i$).

To take into account hearing impairment, the excitation pattern model [6] is modified in two ways. First, since hearing-impaired listeners may have wider auditory filters [4,5], the average ERBs of the different impaired group are used to compute the equivalent widths of the filters used by Glasberg & Moore's model to compute the excitation pattern. The measured ERBs are also used to define the frequency bands used in Eq.2; which are fewer but larger for hearing-impaireds. 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 $\Delta\mu_i$ is equal to 0 in this band. In short, the average ERBs are first used to modify the way the excitation pattern is computed, then the average absolute hearing thresholds are used to correct the values of $\Delta\mu_i$ in each band.

The average audiograms and ERBs of the 4 groups (NH, HI1, HI2 and HI3) have been used as input to predict the thresholds for the signals used in the experiment presented section 2, targeting the same detection percentage (70.7%), which implies $d' = 0.78$ [14]. Results for this method are shown in section 5.

5. RESULTS & DISCUSSION

Figures 2 and 3 show the boxplot distribution of the HPDs effects (averaged on the 7 alarms) on the different groups computed as the difference between the masked thresholds with hearing protectors and the masked thresholds without hearing protectors. The results are presented for the three methods considered:

- Experiment on hearing-impaired listeners (that serves as a reference, see section 2)
- Sound simulation (see section 3)
- Predictive model (see section 4).

The results from the experiment on hearing-impaired listeners show that the perception is improved for NH and HI1 groups, whereas it is deteriorated for HI2 and HI3 groups.

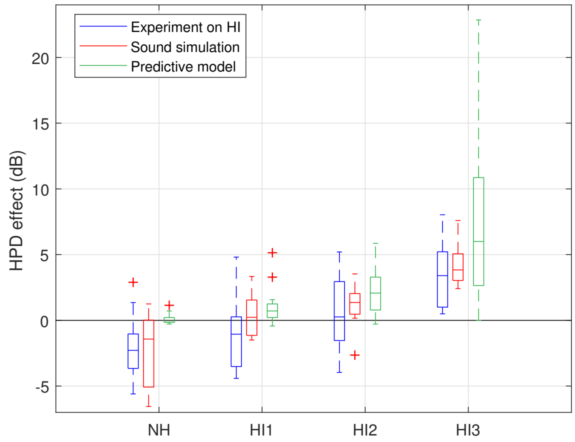

Figure 2: Effects of the earmuff, assessed by the three different methods as the difference between the masked thresholds with and without HPD.

The sound simulation method yields fairly good results as it is able to properly reproduce the effect of a HPD observed from the experiment on hearing-impaired listeners: the higher the hearing loss, the higher the deterioration due to the HPD. The sound simulation method was compared to the experiment on HI listeners through Wilcoxon rank sum tests. The tests show no significant difference between the two methods ($p>0.05$ for all groups and for both HPDs). The remaining discrepancies between these two methods are relatively small. These discrepancies could be explained by the fact that each HPD was simulated using a unique set of attenuation values (see section 3.1) whereas in the experiment with hearing-impaired listeners, the attenuations experienced by each listener may vary. Because the sound simulation results tend to overestimate the detrimental effect of HPD for hearing-impaired listeners (the median value of the effect of the HPD are higher), it can be hypothesised that the attenuations experienced by several listeners were lower than those simulated.

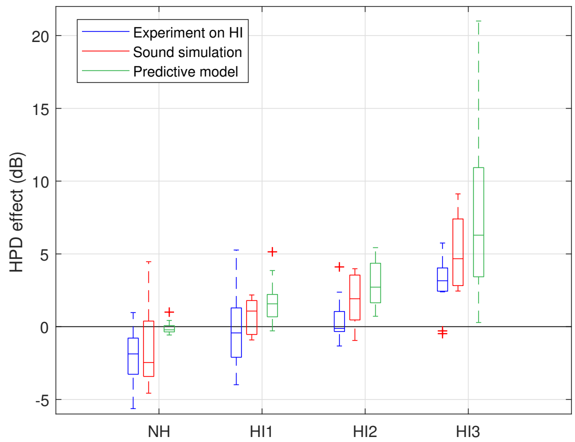

Figure 3: Effects of the earplugs, assessed by the three different methods as the difference between the masked thresholds with and without HPD.

Considering the predictive model method, it does predict higher deterioration for higher impairments but the detrimental effect of the HPD is clearly overestimated (as compared to the experiment on hearing-impaired listeners). Indeed, the amelioration observed for groups NH and HI1 (from the experiment on hearing-impaired listeners) is not reproduced by the model while the deterioration effect for groups HI2 and HI3 is greatly overestimated. When comparing the effects of the earmuff evaluated by the model and the experiment on HI listeners, Wilcoxon tests show no significant difference ($p>0.05$) for groups HI2 and HI3 while there is significant differences between methods for groups NH and HI1 ($p<0.05$). For the earplugs, the Wilcoxon tests show significant differences between the model and the experiment on HI listeners ($p< 0.05$) for all groups. As already mentioned for the sound simulation method, this overestimation could be explained by the fact that the unique set of attenuations values used in the predictive model are larger than those experienced by several listeners.

Another possible explanation could be that the variation of the width of the auditory filters with sound level is not properly taken into account. Indeed, the beneficial effect of a HPD on normal hearing listeners comes from an improved frequency selectivity (i.e. sharper auditory filters) thanks to the reduced sound levels under the HPD which lead to less masking effects. The lack of beneficial effect observed for the NH group with the predictive model method (see figures 2 and 3) suggests that the sharpening of the filters due to the reduction of the sound level is underestimated in the model. This aspect deserves further work.

6. CONCLUSIONS

As an alternative to subjective tests on hearing-impaired listeners which require the recruitment of large populations with various degrees of hearing impairment, two methods have been proposed to evaluate the effects of HPDs on the audibility of warning signals. The sound simulation method yields satisfactory results as the effects of HPD observed from the experiment on hearing-impaired listeners are well reproduced. The next step would be to test different sets of attenuation values to evaluate how sensitive detection is to these attenuations. More generally, this method is also an interesting prevention tool as it allows workers to experiment what an impaired audition sounds like, thus encouraging them to properly protect their hearing.

The predictive model method also yields qualitatively good results but it strongly overestimates the detrimental effect of the HPD observed from the experiment on hearing-impaired listeners. 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. Overall, the proposed predictive model could be used to easily predict masked thresholds of warning signals for different detection percentages of the target signal.

7. REFERENCES

[1] P.A. Wilkins. A field study to assess the effects of wearing hearing protectors on the perception of warning sounds in an industrial environment. *Applied Acoustics*,

17(6):413–437, 1984.

[2] Jean-Pierre Arz, Jean-Pierre Gettliffe, and Philippe Delattre. Effect of wearing hearing protectors on the audibility of railway warning signals – an experimental study. *International Journal of Occupational Safety and Ergonomics*, 24(1):149–159, January 2018.

[3] P. Wilkins and A.M. Martin. Hearing protection and warning sounds in industry—a review. *Applied Acoustics*, 21(4):267–293, 1987.

[4] Mary Florentine, Søren Buus, Bertram Scharf, and Eberhard Zwicker. Frequency selectivity in normally-hearing and hearing-impaired observers. *Journal of Speech, Language, and Hearing Research*, 23(3):646–669, 1980.

[5] Brian C. J. Moore. *Cochlear hearing loss: physiological, psychological and technical issues*. Wiley series in human communication science. Wiley, Chichester, 2nd. ed edition, 2007. OCLC: 863078597.

[6] Brian R Glasberg and Brian C.J Moore. Derivation of auditory filter shapes from notched-noise data. *Hearing Research*, 47(1-2):103–138, August 1990.

[7] Jean-Pierre Arz, Nicolas Grimault, and Ossen El Sawaf. Effect of wearing hearing protectors on the audibility of railway warning signals for hearing-impaired listeners – an experimental study. Madrid, June 2019.

[8] Roy D. Patterson. Auditory filter shapes derived with noise stimuli. *The Journal of the Acoustical Society of America*, 59(3):640–654, March 1976.

[9] R. D. Patterson and Brian C. J. Moore. Auditory filters and excitation patterns as representations of frequency resolution. *Frequency selectivity in hearing*, pages 123–177, 1986.

[10] H. Levitt. Transformed up-down methods in psychoacoustics. *J. Acoust. Soc. Am.*, 49(2):Suppl 2:467+, February 1971.

[11] Nicolas Grimault, Toshio Irino, Samar Dimachki, Alexandra Corneyllie, Roy D. Patterson, and Samuel Garcia. A real time hearing loss simulator. *Acta Acustica united with Acustica*, 104:904–908, 09 2018.

[12] David M. Green and John A. Swets. *Signal detection theory and psychophysics*. Peninsula Publ, Los Altos Hills, Calif, repr. ed edition, 1988. OCLC: 837792861.

[13] David M. Green. Detection of Multiple Component Signals in Noise. *The Journal of the Acoustical Society of America*, 30(10):904–911, October 1958.

[14] J.A. Swets. *Signal detection and recognition by human observers: contemporary readings*. John Wiley, 1964.