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Effect of wearing hearing protectors on the audibility of railway warning signals for hearing-impaired listeners – an experimental study

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ABSTRACT

In order to evaluate the effect of wearing hearing protector devices (HPDs) on the audibility of railway warning signals, masked thresholds measurements were performed in the laboratory with and without wearing the HPDs. Seven railway warning signals and two HPDs (custom molded earplugs and a passive earmuff) were tested on normal-hearing (NH, N=11) and hearing-impaired (HI, N=60) listeners 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). On the contrary, for HI subjects, the protected thresholds are higher than the unprotected thresholds and this detrimental effect of HPDs tends to increase with increasing hearing loss.

To guarantee the security of HI workers, it was considered that their protected thresholds should not be higher than the unprotected thresholds of the NH subjects. Based on this statement, the results show that the security of HI workers is guaranteed up to around 25 dB of hearing loss (dB HL), in average at 500, 1000 and 2000 Hz in the best ear.

Keywords: Hearing Protection, Warning Signals, Hearing Impaired
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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 Europe, HPDs must (respectively should) be worn when daily noise exposure levels exceed 85 dB(A) (respectively 80 dB(A)) [3]. However, article 11 states that derogations may be granted in exceptional conditions if the "use of individual hearing protectors would be likely to cause a greater risk to health or safety than not using such protectors".

Until 2009, the French National Railway Company (SNCF) was granted from such derogation (Article L4111-4 of the French Labour Code) because the risk of not hearing warning signals when wearing HPDs could result in fatal accidents. Since May 2009, the derogation was not granted anymore and SNCF therefore initiated listening tests to evaluate the influence of wearing HPDs on the perception of warning signals. In a previous experimental study only considering normal hearing (NH) listeners [4], 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 [5]. This more detrimental effect for HI listeners may be due to two distinctive phenomena : first, elevated absolute thresholds (referred as "Case 1 elevation" in [6]) and second, broadened auditory filters (referred as "Case 2 elevation" in [6]).

Therefore, the present experimental study was conducted to evaluate the effect of wearing HPDs on the detection of railroad warning signals for HI listeners.

2. METHOD

2.1 Participants

Seventy-five listeners aged from 18 to 81 years (mean age = 51.5 years; SD = 15.8 years) participated to the experiment. Fifteen listeners had normal hearing (no absolute thresholds greater than 20 dB HL at any of the audiometric frequencies from 125 to 8000 Hz and on both ears). The other listeners were grouped into four hearing classes according to their mean absolute threshold at 500, 1000 and 2000 Hz on their best ear (denoted PAM in this paper):

- 20 listeners are in the class $10<PAM\leq20$ dB HL (class HI1)
- 18 listeners are in the class $20<PAM\leq30$ dB HL (class HI2)
- 14 listeners are in the class $30<PAM\leq40$ dB HL (class HI3)
- 8 listeners are in the class $PAM>40$ dB HL (class HI4).

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

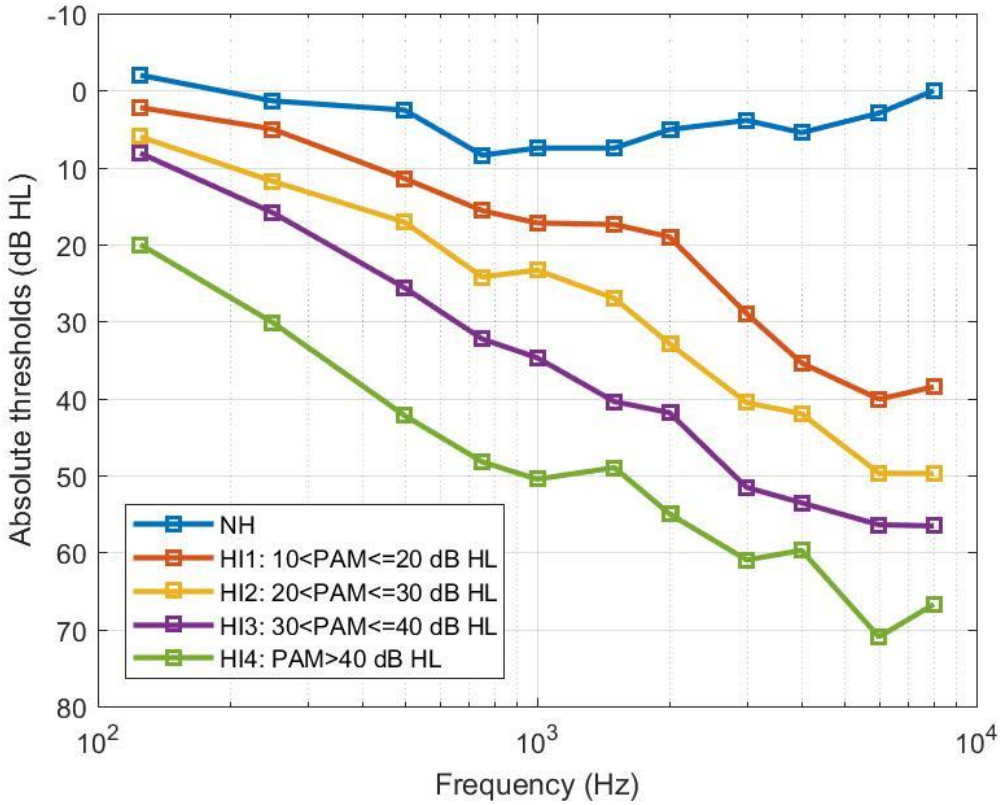

Figure 1: Mean audiograms for the five hearing classes. PAM is the mean absolute threshold at 500, 1000 and 2000 Hz on the best ear.

2.2 Warning signals, noises 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.

2.3 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 [7]. 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.

3. RESULTS

Figure 2 shows the box-and-whisker plots of the measured masked thresholds with and without wearing the HPDs. For the sake of conciseness, the thresholds have been averaged across the seven warning signals, leading to a rather large spread of the values.

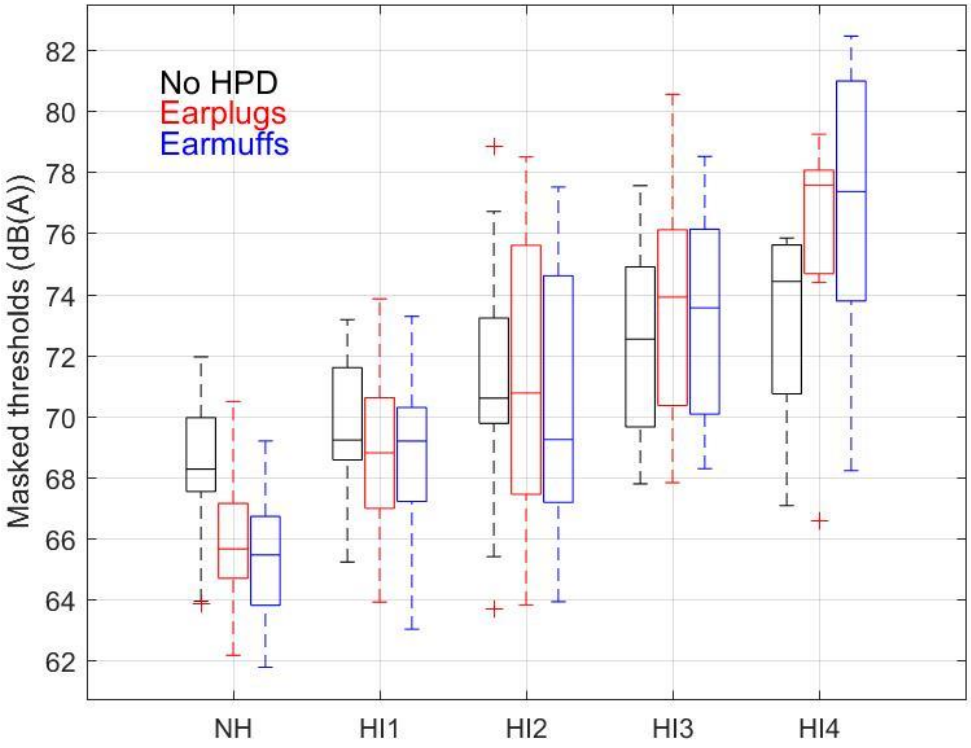

Figure 2: Masked thresholds measured for the five hearing classes considered and in three conditions: without HPDs, with the earplugs and with the earmuff. The results have been averaged across the seven warning signals tested.

First, regarding the thresholds without HPDs, it can be observed that the median values of the five hearing classes considered increase with increasing hearing impairment. However, the differences on the medians are rather small: for instance, the median of the most hearing-impaired class (HI4) is just around 6 dB higher than the median of the NH class.

Secondly, regarding the thresholds obtained when wearing the HPDs, the differences between the hearing-impaired classes and the NH class tend to be greater (than without HPD): for instance, the HI4 class median is around 12 dB higher than the NH class median. This is true for the two HPDs tested. However, when looking at the NH class results, it appears that the thresholds with HPDs are lower than the thresholds without HPDs.

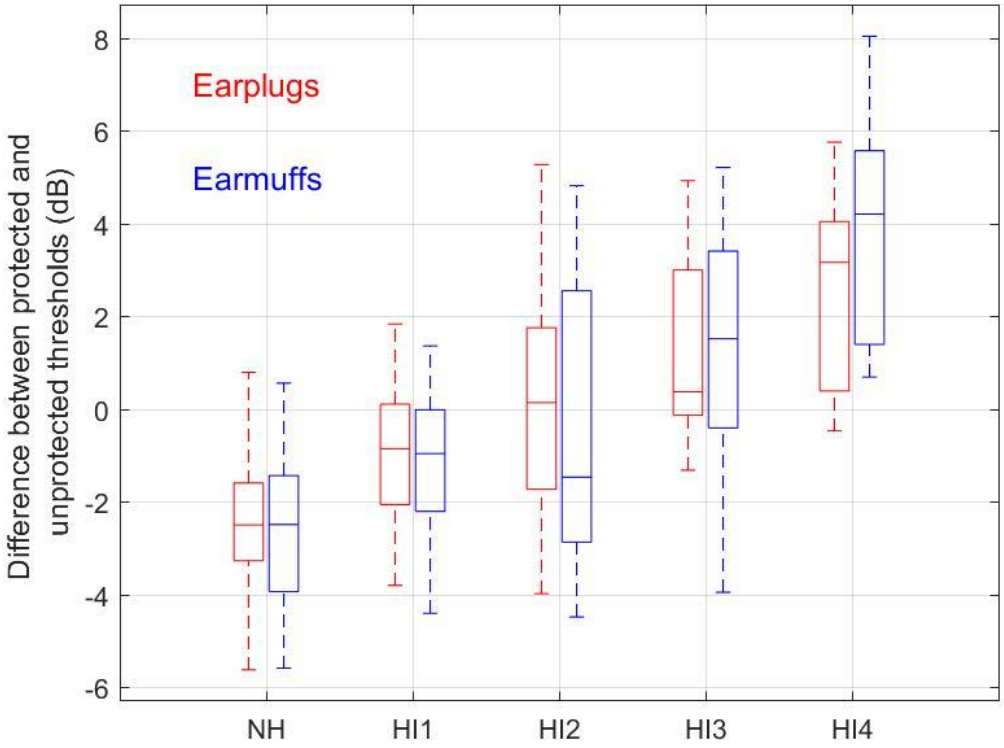

Figure 3: Differences Δ between masked thresholds with HPDs and masked thresholds without HPDs for the five hearing classes and the two HPDs tested. The results have been averaged across the seven warning signals tested.

To gain better insights into the influence of wearing HPDs as a function of hearing impairment, Figure 3 shows the differences Δ between the thresholds with HPDs and the thresholds without HPDs. For the NH class, these differences almost always have negative values (around -2 dB on the medians) so wearing the HPDs seems to improve the detection. The result that the perception is generally improved for NH listeners when wearing HPDs (as compared to no HPD) is consistent with the results of other studies [4, 5]. By contrast, for HI listeners, the Δ values tend to increase with increasing hearing impairment and become mostly positive from the HI3 class, indicating a deterioration of the perception.

From further analyses made individually for each warning signal, it appears that the effect of the HPDs greatly depends on the frequency content of the warning signals. The signals that are less affected by hearing impairment are those who have a fundamental frequency that dominates in low frequency (f<500 Hz). This is certainly due to the fact that the absolute thresholds are generally moderate at these low frequencies (see Figure 1) and that the HPDs tested also have rather low attenuation values below 500 Hz; hence these signals are not or little affected by the elevation of absolute thresholds (see "Case 1 elevation" in [6]). By opposition, the non-harmonic warning signal composed by two pure tones in high frequencies (3430 and 4084 Hz) is greatly affected by the hearing impairment: the median value of the deterioration reaches up to 10 dB for the earplugs and 13 dB for the earmuffs for the HI4 class. This is certainly due to the fact that both the absolute thresholds values and the attenuation values of the HPDs are large at these frequencies (see "Case 1 elevation" in [6]). This signal, which has no energy below

1500 Hz, is not in accordance to the ISO 7731 standard [8] since the standard requires sufficient energy below 1500 Hz when HPDs are worn.

4. DISCUSSION

To guarantee the security of HI workers, it was considered that their protected thresholds should not be higher than the unprotected thresholds of the NH subjects. Based on this statement, statistical analyses (Wilcoxon rank sum tests) performed individually for each warning signal showed that the security is not guaranteed for the two most impaired classes considered (i.e. from PAM > 30 dB HL) and for the two HPDs tested ($p<0.05$). For the HI2 class ($20 < PAM \leq 30$ dB HL), the security is guaranteed only for four warning signals (out of the seven signals tested). However, additional analysis showed that the security is guaranteed for the whole seven signals as soon as the unprotected thresholds of the NH subjects are majored by 2 dB (i.e. the protected thresholds of the HI2 are not higher than the unprotected thresholds of the NH subjects majored by 2 dB). This discrepancy of 2 dB seems rather small compared to the variations of the signal levels observed in the field and due to the variations of the position of the workers respective to the positions(s) of the alarm device(s). Thus, if this 2 dB difference can be tolerated, the audibility of the HI listeners when wearing the earplugs or the earmuffs is not statistically different from the audibility of the NH class without HPD up to the hearing class HI2 ($20 < PAM \leq 30$ dB HL). Moreover, by considering another hearing class such as $15 < PAM \leq 25$ dB HL (N=20), results show that the protected thresholds for this class are not statistically different from the unprotected thresholds of the NH group. Overall, these results suggest that the security of HI workers is guaranteed up to around 25 dB of hearing loss (dB HL), in average at 500, 1000 and 2000 Hz in the best ear.

Furthermore, for security purposes, this laboratory study should be complemented by other listening tests in the field. Indeed, this study only evaluated the influence of HPDs by comparisons between the thresholds with and without wearing the HPDs. It did not evaluate the influence of HPDs on other aspects such as the localization of the warning signal or the perceived urgency of the warning signals [9].

Another limitation of this experimental study is that it is not possible to evaluate, for each warning signal, which phenomenon among absolute thresholds or broadened auditory filters (see [6]) is mainly responsible for the degradation of the audibility. To do so, a predictive model is currently being developed and is presented in a companion paper at Inter-Noise 2019 [10].

4. CONCLUSION

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

To guarantee the security of HI workers, it was considered that their protected thresholds should not be higher than the unprotected thresholds of the NH subjects. Based on this statement, the results show that the security of HI workers is guaranteed up to around 25 dB of hearing loss (dB HL), in average at 500, 1000 and 2000 Hz in the best ear.

Besides, to gain better insights into which phenomenon (among elevated absolute thresholds or broadened auditory filters) is responsible for the degradation of the

audibility, a predictive model of masked thresholds is currently under development. Such a model should ease the evaluation of the influence of HPDs by multiplying the scenarios of background noises, warning signals, attenuations of HPDs and hearing impairments to guarantee the security of the workers.

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