Modeling the interaction between the hearing protector attenuation function and the hearing loss profile on sound detection in noise

Christian Giguère
Audiology/SLP Program, University of Ottawa, 451 Smyth Rd., Ottawa, Canada K1H 8M5.
Elliott H. Berger
Personal Safety Division, 3M, 7911 Zionsville Rd., Indianapolis, IN 46268, U.S.A.

Summary
Few studies document the exact conditions when flat/uniform hearing protectors can be beneficial in the noisy workplace. This modeling study reports on the interaction between the user's hearing loss profile and the shape and amount of the attenuation function on sound detection thresholds in noise. For normal-hearing users, detection thresholds are found to be hardly affected by use of hearing protectors, even in extreme conditions of low-frequency noise and steeply sloping attenuation functions. With aging and noise-induced hearing loss, sound detection above about 2000 Hz becomes progressively more sensitive to the slope of the attenuation function as well as to the overall protected level achieved. Shallower slopes may be warranted for users with hearing loss to limit the upward spread of masking in low-frequency noise, while controlling the total amount of attenuation at high frequencies prevents excessive elevation of absolute thresholds. Decisions regarding hearing protector selection also entail consideration of the principal auditory tasks that are anticipated and the important sounds to which a worker may need to attend.

PACS no. 43.50.Hg, 43.66.Vt

1. Introduction

Hearing protector devices (HPDs) with flat or nearly uniform attenuation across frequencies preserve the spectral balance of workplace sounds and are often recommended when, in addition to protection, good signal audibility, speech communication and auditory awareness are essential [1]. Such HPDs may be especially indicated for users with high-frequency hearing loss to maintain audibility at all frequencies. Still, few studies are available on the exact conditions when the intended benefits of flat/uniform devices would arise [2]. Furthermore, while flat/uniform HPDs are described in several acoustical standards and/or national documents [3-5], the definition of "flatness" is often unspecified or given broad tolerances.

In [5], a general criterion based on the slope of the linear regression of the mean attenuation values between 125 and 4000 Hz is specified. Based on prior research with road traffic and railway workers, HPDs with an attenuation slope less than 3.6 dB/octave are deemed to fulfill requirements for "signal audibility (general), speech intelligibility, and the perception of operative sounds." In a proposed revision to standard EN458:2004 [4], flat devices are defined more simply as HPDs with H minus L attenuation values less than or equal to 9 dB. In addition to flatness characteristics, the assumed protection value of a HPD is also an important parameter to considerer in some standards [3,4] in order to reduce the risks of overprotection. HPDs selected to achieve a protected level between 5 and 10 dBA below the national regulation level are deemed to achieve a good protection outcome.

It is unclear if such simple guidelines for flatness and protection level achieved can find general use given, among other factors, the wide range of spectral characteristics of workplace noises and the large spread of possible hearing profiles in the workforce. The goal of this modeling study is to gain more insight into the complex interaction between the hearing protector attenuation function, the noise spectrum, and the hearing status of the worker.

2. Methods

The psychoacoustic model described in [6] was used to compute masked detection thresholds for three workers with hypothetical hearing profiles under unprotected listening and when protected with HPDs controlled for the slope of the attenuation function and the protected level achieved.

2.1. Individuals

Absolute hearing thresholds for the three workers (W_1, W_2, W_3) are listed in Table I. Worker 1 is a normal-hearing individual. Worker 2 is a 40-year old male with 20 years of daily exposure at 90 dBA. Worker 3 is a 55-year old male with 35 years of daily exposure at the same level. Standard ISO 1999:2013 [7] was used to compute the combined effects of noise exposure and aging on hearing thresholds for Workers 2 and 3. The computation was performed at the 10th percentile of the statistical distribution for each worker to simulate worst case scenarios. Annex A in [7] was used to compute the aging component. Above about 2000 Hz, Worker 2 has mild hearing loss while Worker 3 has a moderate to moderately-severe loss.

Table I. Absolute hearing thresholds (dB HL) for three hypothetical workers (W_1, W_2, W_3).

Frequency (Hz)	W_1 (dBHL)	W_2 (dBHL)	W_3 (dBHL)
500	0	11	15
1000	0	11	17
2000	0	21	32
3000	0	32	48
4000	0	37	57
6000	0	36	59

Table II. Relative widths of auditory filters (broadening ratios) for three hypothetical workers (W_1, W_2, W_3).

Frequency (Hz)	W_1	W_2	W_3
500	1	1	1
1000	1	1	1
2000	1	1	1.5
3000	1	1.6	3.0
4000	1	1.9	3.5
6000	1	1.9	3.7

Hearing loss is also associated with poorer frequency selectivity, which affects masked detection thresholds. This is modeled in [6] by using larger auditory filters for Workers 2 and 3 than the normative values applicable for normal-hearing individuals. Table II reports the size of the broadening as the ratio of the auditory filter bandwidth for each worker to that of a normal-hearing individual. This ratio was computed according to [6] based on the original data in [8].

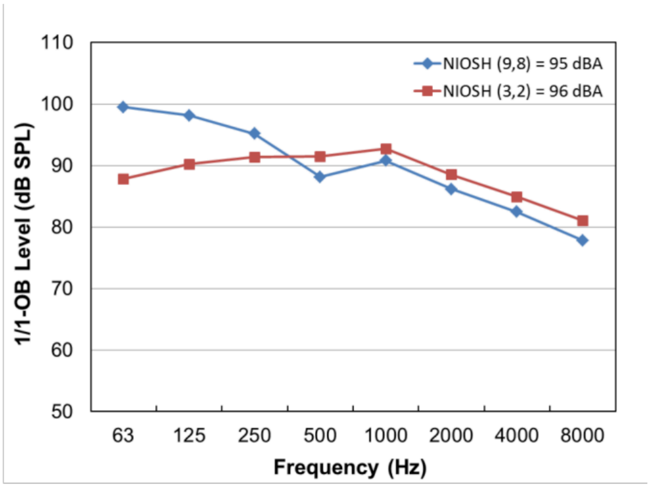

Figure 1. Noise spectra

2.2. Noises

Two noise prototypes were investigated to account for workplace spectra with either large or typical L_C-L_A values, as shown in Figure 1. NIOSH (9,8) and NIOSH (3,2) are the average of spectra in the NIOSH100 database [9] with L_C-L_A values falling between 8 and 9 dB, and 2 and 3 dB, respectively.

2.3. Hearing protectors

Various datasets of HPD attenuation functions were simulated; two are presented here.

Dataset 1 investigated the effect of a change in the slope of the attenuation function. For this purpose, a family of functions was generated sloping linearly from the 125 to the 4000 Hz octave band at a rate varying from 0 to 8 dB/octave. Below 125 Hz and above 4000 Hz, attenuation was held constant to avoid generating unrealistic functions. Each curve was calibrated to achieve a fixed protected level of 75 dBA in noise. Figure 2 shows the set of functions applicable to NIOSH (9,8). Functions for NIOSH (3,2) were similar.

Dataset 2 investigated the effect of the protected level achieved from 60 to 85 dBA at fixed a slope of 4 dB/octave. Figure 3 shows the family of functions applicable to NIOSH (9,8). Again, functions for NIOSH (3,2) were similar.

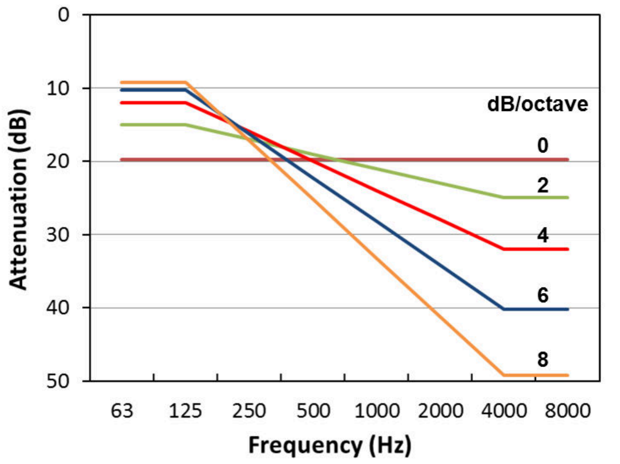

Figure 2. HPD Dataset 1: Attenuation functions for various slopes (dB/octave) at a fixed protected level of 75 dBA in NIOSH (9,8).

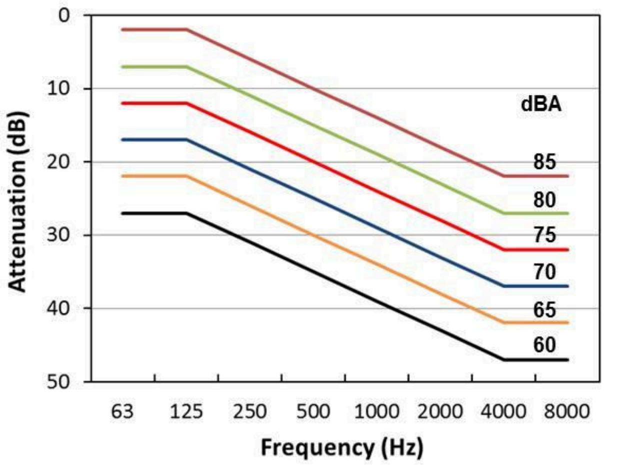

Figure 3. HPD Dataset 2: Attenuation functions for various protected levels (dBA) at a fixed slope of 4 dB/octave in NIOSH (9,8).

2.4. Simulation and data analysis

Pure-tone masked detection thresholds from 125 to 8000 Hz were computed in the two noises and for the three hypothetical workers using the algorithms specified in the psychoacoustic model in [6]. This was carried out both for unprotected listening and when protected according to the attenuation functions from the two HPD datasets.

Unprotected detection thresholds were then subtracted from protected detection thresholds to highlight cases of threshold elevation from the use of HPDs. Thus, the unprotected detection thresholds served as a baseline to quantify the effects of hearing protection for each individual worker and noise. Such a threshold elevation can occur due to an overly large loss of hearing sensitivity from the combined effects of the absolute hearing thresholds and the amount of HPD attenuation at one or more frequencies (referred to here as Case 1 elevation) and/or due to an increase in the upward spread of masking from the interaction between the noise spectrum, the broadening of the auditory filters and the shape of the HPD function (Case 2 elevation).

3. Results

Figure 4 shows the detection threshold elevation (dB) arising from the attenuation functions of the HPD Dataset 1, separately for the three workers. The results are for NIOSH (9,8), the noise with a large L_C-L_A. For Worker 1, the maximum threshold elevation was less than 2 dB across the entire range of frequencies and for all HPD attenuation slopes simulated. The maximum effect, occurring at 400 Hz, is related to a peculiarity in the NIOSH (9,8) spectrum which shows a sudden drop of noise energy near that frequency. This, in turn, led to some upward spread of masking from the lower frequency energy that passed more easily through the HPDs with the largest slopes of increasing attenuation with frequency (4-8 dB/octave).

For Worker 2, there were also minimal effects over the entire range of frequencies, but only up to a slope of about 4 dB/octave (Figure 4). At steeper slopes of 6 and 8 dB/octave, the detection thresholds progressively increased over unprotected thresholds for frequencies above 3000-4000 Hz. This was almost equally the result of Case 1 and Case 2 threshold elevation effects. For Worker 3, only the flat attenuation function of 0 dB/octave produced minimal effects over the entire range of frequencies. HPD Functions with slopes of 2 dB/octave or greater progressively incurred higher threshold elevations above 2000 Hz. Case 2 threshold elevation was the controlling factor for the two largest slopes.

Results for the NIOSH (3,2) noise with the HPD Dataset 1 (not shown) were similar to NIOSH (9,8), except that the lower L_C-L_A value and the less rich low frequency spectrum (Figure 1) produced somewhat less upward spread of masking. There were no threshold elevation effects at 400 Hz for any of the three workers with this noise.

Figure 5 shows the detection threshold elevation (dB) arising from the attenuation functions of the HPD Dataset 2 applied to noise

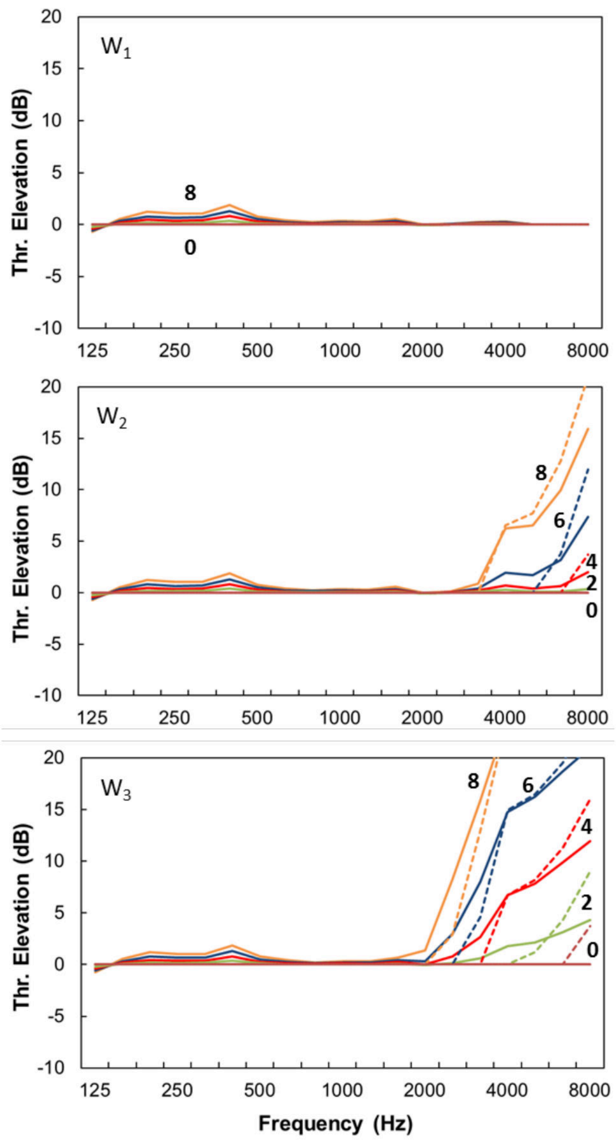

Figure 4. Detection threshold elevation in NIOSH (9,8) for HPDs from Dataset 1 for the three workers. Case 1 and 2 elevation shown in dashed and solid lines respectively for five attenuation slopes from 0 to 8 dB/octave at a fixed protected level of 75 dBA.

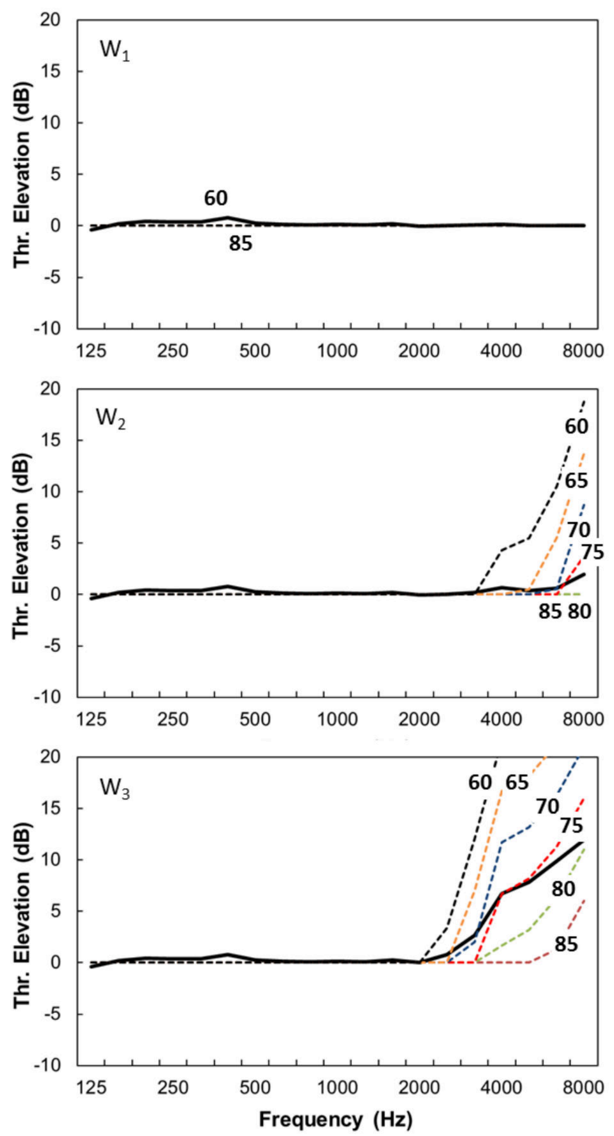

Figure 5. Detection threshold elevation in NIOH (9,8) for HPDs from Dataset 2 for the three workers. Case 1 and 2 elevation shown in dashed and solid lines respectively for six protected levels from 60 to 85 dBA at a fixed attenuation slope of 4 dB/octave.

NIOSH (9,8). Of note, the upward spread of masking effects, when they occurred, were independent of the protected level achieved with this dataset since no change was being made to the shape of attenuation curve across conditions (Figure 3). For Worker 1, the maximum threshold elevation was less than 1 dB across the entire range of frequencies and for all protected levels simulated. For Worker 2, there were also minimal effects over the entire range of frequencies, but only down to a protected level of about 75 dBA (Figure 5). At lower protected levels, the threshold elevation progressively increased with increasing amounts of attenuation, for frequencies above 3000-4000 Hz. This increase was entirely the result of Case 1 threshold elevation effects. For Worker 3, only the higher protected level of 85 dBA produced minimal effects, and only up to 6000 Hz. Lower protected levels (i.e. more attenuation) progressively incurred higher threshold elevation above 2000 Hz. Case 1 elevation was the origin of the effect for protected levels below 75 dBA, whereas Case 2 elevation was the basis for the effect above 75 dBA.

Again, results for the NIOSH (3,2) noise with the HPD Dataset 2 (not shown) were similar to NIOSH (9,8), but with a lesser amount of upward spread of masking.

4. Discussion and conclusions

This computational study highlights the complex nature of the interaction between the hearing loss profile of the user, the HPD attenuation function on sound detection in noise, and to some extent the noise spectrum.

For normal-hearing users, the maximum effect was less than 2 dB even under the most extreme condition investigated of a low-frequency noise (large L_C-L_A value between 8-9 dB) and use of a HPD with a very steep attenuation curve (8 dB/octave). Furthermore, sound detection in noise appears quite insensitive to the overall protected level achieved for normal-hearing users, down to at least 60 dBA. These results indicate that, for sound detection in noise, there may be little value in placing restrictions on attenuation slope and protected level achieved for this class of user. Such a finding corroborates earlier reports that auditory perception in noise is hardly affected by use of HPDs for normal-hearing users [1].

By contrast, for users with hearing loss, detection thresholds in some noise situations may be affected by use of hearing protectors with steeply sloped attenuation functions and/or excessive attenuation. The negative effect may be due to elevated absolute hearing thresholds arising from a too-large HPD attenuation in the high frequencies in conjunction with the hearing loss (Case 1 elevation) and/or from an upward spread of masking due to steep HPD attenuation functions in the presence of either broadened auditory filters or low-frequency noise (Case 2 elevation).

From Figures 4 and 5, the effects of HPDs on sound detection in noise are found to be quite dependent on the user's hearing profile and the signal frequency. This finding presents a special challenge when setting general guidelines for HPD selection applicable to all users, as shown below. Assuming the maximum detection threshold elevation in noise to be not larger than 5 dB at 4000 Hz, to minimize adverse effects on the speech frequency range for example, then a fairly wide prescription consisting of an attenuation slope of no more than 6-7 dB/octave and a protected level not lower than 60-65 dBA may be suitable for a user with mild hearing loss (W_2). Using the same criterion, a more stringent prescription consisting of a slope not exceeding 3-4 dB/octave and a protected level not less than 75 dBA may be required for a user with moderate-severe high frequency hearing loss (W_3). On the other hand, if good sound detection is required at frequencies greater than 4000 Hz, more stringent requirements may be needed for HPD selection. It is also important to note that workers W_2 and W_3 specified in this study are only two of a myriad of possible case studies. In general, there are much wider variations in hearing profiles across users than variations in attenuation across available HPD products, which greatly compounds to the problem of setting general selection guidelines.

Simulations were also carried out with two additional datasets of HPD functions, as reported in [10]. To investigate the effects of purposely-flat real products, the mean attenuation values of the Etymotic® Musicians Earplugs™ and the 3M™ HiFi™ Earplug were considered. The devices have mean slopes varying from -0.3 to 1.4 dB/octave in the range from 125 to 4000 Hz and, when applied to NIOSH (9,8) and NIOSH (3,2), yield protected values in the range 71-85 dBA. Not surprisingly, these products led to reduced threshold-elevation effects that were comparable to the shallowest slopes investigated in Figure 4. Even for the worker with the most hearing loss (W_3), the maximum predicted threshold elevation was 5 dB or less up to 5000 Hz for all products in both NIOSH (9,8) and NIOSH (3,2) noises. Simulations were also carried out using the average attenuation curves reported in [5] for groups of real hearing protectors fulfilling and not fulfilling the German criterion of a mean slope of less than 3.6 dB/octave. Note that these curves were found to possess mean slopes of about 2.3 dB/octave (fulfill) and 4.7 dB/octave (not fulfill). For the normal-hearing worker (W_1), the maximum predicted threshold elevation was less than 2 dB up to 8000 Hz for both groups of protectors in either noises, similar to results for Datasets 1 and 2 (Figures 4-5), and the difference between the two groups was at most 1 dB. For worker 3, the threshold elevation due to the upward spread of masking (Case 2) was consistent with that presented in Figure 4 for each group of protectors at comparable slopes, and thus favored the group fulfilling the criterion. However, the controlling factor for the threshold elevation was the loss of hearing sensitivity (Case 1) and, owing to the nearly equal amounts of attenuation they provide at mid-to-high frequencies, both groups of protectors led to the same outcome above 3000 Hz.

In practice, decisions regarding HPD selection for hearing-impaired users will entail some knowledge about the principal auditory tasks to carry out in the given workplace. Proper consideration of the characteristics of acoustic signals to attend to is also important. With regards to the perception and design of audible danger signals, for example, ISO 7731:2003 [11] specifies that "*in the case of persons wearing hearing protection or having a hearing loss, sufficient signal energy should be present in the frequency range below 1500 Hz*." Such a recommendation is clearly in line with the results of this computational study. Below 2000 Hz, sound detection in noise was found to be quite insensitive to the HPD attenuation function over a wide range of noise conditions and types of users from normal hearing to moderate-severe hearing losses due to aging and noise (Figures 4 and 5). Thus, warning signal perception may be little affected by HPDs for a wide range of users when proper consideration is first given to the design of warning sounds in the workplace. On the other hand, there are many instances of incidental sounds over which we have little or no control, such a malfunctioning machine or parts falling from a conveyor belt [1]. In these cases, hearing-impaired users may benefit from shallower attenuation slopes and reduced amounts of attenuation, especially in cases where such sounds are likely to generate mostly high-frequency acoustic energy.

Finally, it is important to note that the present study assumed continuous noises in the 95-96 dBA range. In practice, workplace noises may fluctuate in level over the course of the day. In quieter periods, the effect of HPDs may be more pronounced. Also, due to medical conditions and other reasons, some workers may have hearing loss configurations that depart from the typical profiles due to aging and noise-induced hearing loss investigated in the present study. Sound detection in noise is also only one of many possible auditory dimensions where flat/uniform hearing protectors may have an impact. A recent computational study also showed that speech perception may also be little affected by the HPD attenuation function over a wide range of situations, except for users with a substantial amount of hearing loss [12]. Still, flat/uniform hearing protectors preserve the spectral balance of sounds and they may provide substantial benefits in terms of user acceptance resulting from improved sound quality and auditory situational awareness such as the recognition, interpretation, or in the case of entertainment-sounds such as music, the enjoyment of important sounds in one's environment. Further work is needed in this area.

References

[1] E.H. Berger: Hearing protection devices. Chapter 10 In: E.H. Berger, L.H. Royster, J.D. Royster, D.P. Driscoll and M. Layne (eds.). The Noise Manual, Fifth Edition, American Industrial Hygiene Association, Fairfax VA, 2003, 379-453.

[2] J.G. Casali: Passive augmentations in hearing protection technology circa 2010 including flat-attenuatin, passive level-dependent, passive wave resonance, passive adjustable attenuation, adjustable-fit devices: Review of design, testing and research. *International Journal of Sound and Vibration* 15 (2010) 187-195.

[3] CSA Z94.2-14: Hearing protection devices - Performance, selection, care, and use. Canadian Standards Association, 2014.

[4] EN 458: Hearing protectors - Recommendations for selection, use, care and maintenance – Guidance document. European Standard, 2004.

[5] M. Liedkte: Specifying a general criterion for hearing protectors with the aim of ensuring good acoustic perception. *International Journal of Occupational Safety and Ergonomics* 15 (2009) 163-174.

[6] Y. Zheng, C. Giguère, C. Laroche, C. Sabourin, A. Gagné, M. Elyea: A psychoacoustic model for specifying the level and spectrum of acoustic warning signals in the workplace. *Journal of Occupational and Environmental Hygiene* 4 (2007) 87-98.

[7] ISO 1999: Acoustics – Estimation of noise-induced hearing loss. International Organization for Standardization, 2013.

[8] C. Laroche, B. Josserand, H. Tran Quoc, R. Hétu, B.R. Glasberg: Frequency selectivity in workers with noise-induced hearing loss. *Hearing Research* 64 (1992) 61-72.

[9] ANSI/ASA S12.68: Methods of Estimating Effective A-Weighted Sound Pressure Levels When Hearing Protectors are Worn. Acoustical Society of America, 2007 (R2012).

[10] C. Giguère, E.H. Berger: Exploration of flat hearing protector attenuation and sound detection in noise. *168th Meeting of the Acoustical Society of America*, Indianapolis IN, 27-31 October 2014.

[11] ISO 7731: Ergonomics — Danger signals for public and work areas — Auditory danger signals. International Organization for Standardization, 2003.

[12] C. Giguère, E.H. Berger: Investigation of Hearing Protector Attenuation Function on Sound Detection and Speech Recognition in Noise. *40th Annual Conference of the National Hearing Conservation Association*, New Orleans LA, 19-21 February 2015.