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Effect of hearing protection and hearing loss on warning sound design

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ABSTRACT

Warning sound devices are commonly used in noisy workplaces to warn workers of potentially dangerous situations. Warning sound perception depends on many factors, including warning sound levels relative to the background noise, hearing protection and hearing status. Although national and international standards (i.e. ISO 7731) are available to guide the choice of warning sound devices, none appears to take into account all these factors within a comprehensive model. A software tool, Detectsound, was used to demonstrate the extent to which hearing protection can compromise the perception of warning sounds by workers with hearing loss. Detectsound yields desired target sound levels at different workstations for different workers using and for various conditions of hearing protection. Scenarios were constructed using a low-frequency noise spectrum from NIOSH database, different degrees of sensorineural hearing losses, and personal hearing protector attenuation measurements or estimates according to the manufacturer's data. Detailed analysis of realistic scenarios with Detectsound revealed that a flat and high frequency sensorineural hearing loss combined with hearing protection can compromise high frequency perception and lead to overprotection. Such realistic scenarios make it explicit that the configuration of warning devices can vary significantly depending on the hearing status of workers at a given workstation and the variability in attenuation provided by hearing protectors.

INTRODUCTION

In many workplaces, hearing protection is crucial to reduce noise exposure to within set regulatory limits. The use of hearing protection in industrial workplaces has been studied extensively [1] and is the object of national and international standards [2,3]. In Canada and Europe respectively, the CSA Z94.2-02 [2] and EN 458 [3] standards cover all aspects of physical and acoustical performance, selection, care and use of hearing protection devices in the workplace.

Sound attenuation must be adequately high to reduce at-ear effective noise exposure to levels below regulatory limits (85 or 90 dBA depending on the jurisdiction). Minimum attenuation requirements for a given situation therefore depend on the global level and spectral characteristics of the background noise prevailing within the work area. Overprotection caused by excessive attenuation is not recommended given the risk of isolating workers from their surroundings, thereby hindering communication amongst workers and the perception of warning sounds. Minimum attenuation requirements are hence crucial to avoid compromising safety in the workplace [4,5].

Along those lines, the CSA Z94.2-02 [2] and EN 458 [3] standards recommend reducing at-ear effective noise exposure to levels 5-10 dB below regulatory limits when hearing protection is used. If maximal noise exposure is set to 85 dBA, an "optimal" hearing protector would hence result in at-ear effective exposure levels ranging from 75 to 80 dBA. Less attenuation may not be adequate to minimize the hazardous effects of noise on hearing, whereas greater attenuation could result in overprotection. In general, this simple selection guideline offers adequate protection to workers, particularly those with normal hearing, without isolating them from their acoustic surroundings. Unfortunately, selection guidelines and standards do not specifically take into consideration the individual worker's hearing status.

Workers with age-related or noise-induced hearing loss present an even greater risk than their normal hearing counterparts of feeling isolated under hearing protection. The combined effect of hearing protection and elevated hearing thresholds can render inaudible acoustic signals such as warning sounds, particularly those rich in high-frequency spectral components [1,4-7]. Hearing loss also affects frequency selectivity, the ability to detect signals in background noise [8]. Hence, workers with hearing loss require a generally greater signal-to-noise ratio than workers with normal hearing to reach similar performances. As demonstrated in a recent study [9], the installation of auditory warning devices in noisy settings is particularly difficult when workers with various hearing profiles occupy a common work area. A given warning sound can indeed be too loud for some workers and too soft for others. In light of the complex interaction between noise characteristics, hearing protector attenuation and worker hearing status, the identification and implementation of reliable and verifiable solutions for acoustic warning devices in noisy workplaces is almost impossible, without a detailed analysis [9,10].

Detectsound [9], a psychoacoustic model, allows predicting one's ability to detect warning signals taking into account the hearing status of the target population or of individual workers, the background noise level in the workplace and the use of hearing protectors. The model is used to establish acoustic target levels at different workstations within a given industrial setting. Depending on the worker's hearing status and the hearing protection selected, the target levels range from 12 to 25 dB above absolute or masked hearing thresholds at the various workstations.

In the current study, Detectsound is used to systematically analyze constraints associated with the installation of warning devices when workers with diverse hearing status operate within the same work environment and wear earplug type hearing protectors for which attenuation has been measured or predicted. Results demonstrate how hearing loss and overprotection further exacerbate installation constraints.

FRAMEWORK

The general modeling framework guiding the optimal installation of acoustic warning devices is found in Figure 1 and consists in the integration of two computerized models, Detectsound and AlarmLocator. Detectsound [9] is based on an analysis of the prevailing background noise and allows identification of the optimal acoustical characteristics of warning signals (sound pressure level of each frequency component) for each workstation, taking into account the specific needs of a worker or group of workers. The input to Detectsound consists of the following four parameters:

- The spectral distribution of the noise at the workstation;
- Hearing protector attenuation (if used);
- Absolute hearing thresholds;
- Frequency selectivity characteristics of the worker.

The last two parameters can be either measured clinically or predicted by Detectsound [9] taking into account the age and gender of the worker, in addition to previous noise exposure. Detectsound's output is a design window or range of target warning sound levels at different frequencies (between 125 and 3150 Hz), for each workstation studied. Lower (TL_{low}) and upper (TL_{up}) limits of the target sound levels defining the design window range from 12 to 25 dB above the predicted detection thresholds and depend on the noise, the hearing status of workers, and the use of hearing protection. An absolute upper limit of 105 dB SPL is also imposed within each third-octave band. During installation practices, sound pressure levels between TL_{low} and TL_{up} are targeted. Ideally, at least 4 frequency components of the warning signal should fall within the design window [9]. Figure 2 provides an example of a design window for a workstation in which 4 of the 5 signal components meet the requirements specified by Detectsound.

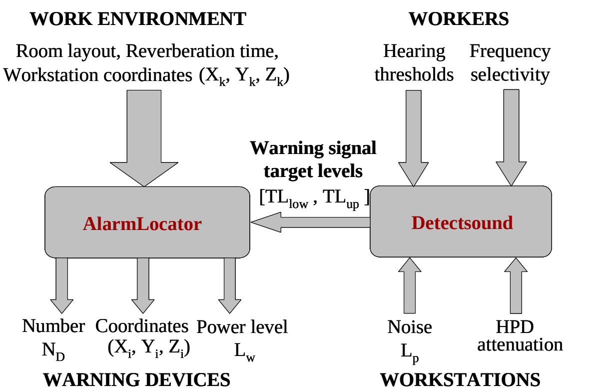

Figure 1. General framework for the installation of acoustic warning devices in noisy workplaces integrating a psychoacoustic model of sound detection (Detectsound) and a model for sound propagation in industrial settings (AlarmLocator).

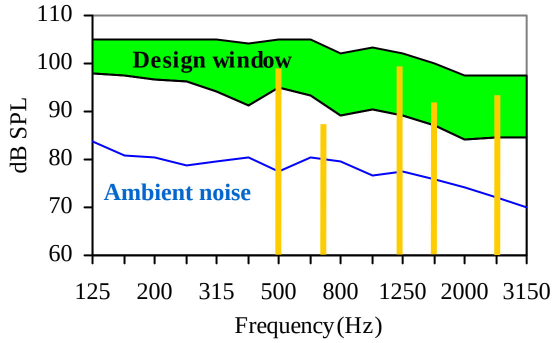

Figure 2. Example of design window generated by Detectsound. The frequency components of the warning sound (vertical lines) must fall within the shaded area. Third-octave band levels of the noise at the workstation are also identified (lower portion of the figure).

In Figure 1, the sound propagation model (AlarmLocator) [11] actively browses through various warning device configurations that potentially meet the requirements set forth by Detectsound. The analysis is performed simultaneously for all workstations. Together, these various elements provide a complete and user-friendly solution to the installation of warning devices in the workplace.

In this study, various scenarios were analyzed to demonstrate the need to take into consideration such factors as hearing loss and hearing protector attenuation in the process of selecting adequate warning sounds. Only the psychoacoustic model Detectsound was used in the following simulations.

SIMULATIONS

Workstation characteristics

The presumed noise spectrum at the workstation is the NIOSH #12 noise from ANSI 12.68-2007 [12] at 96-dBA global sound level. The noise spectrum available in one-octave band was mapped into third-octave band levels for use with Detectsound, as shown in Figure 3. The noise is rich in low frequencies (around 250 Hz), it levels off with a slope of 5-10 dB/octave starting at around 400 Hz.. Spread of masking can be important for this type of noise, particularly in individuals with high-frequency hearing loss.

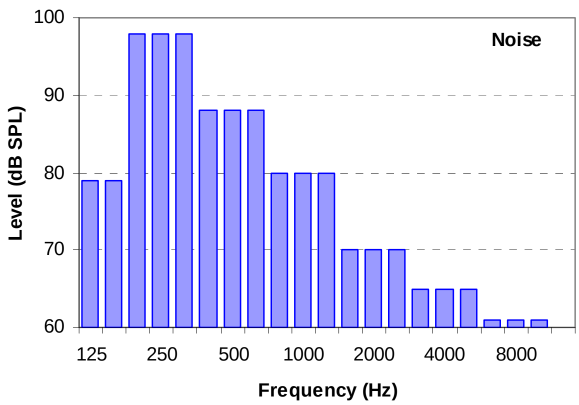

Figure 3. Spectral distribution of NIOSH #12 noise at the workstation (96 dBA) in third-octave bands (dB SPL).

Worker characteristics

Data from three individuals (Indiv$_1$, Indiv$_2$, Indiv$_3$) in the database of subjects at the Hearing Research Laboratory of the University of Ottawa were selected for the analyses on the basis of different hearing status and measured attenuation for earplug-type EAR Combat AeroSafety hearing protectors. Individual 1 has normal hearing, Individual 2 has moderate to severe hearing loss in the high frequencies, and Individual 3 has flat hearing loss of moderate degree. Hearing thresholds for these individuals are found in Table 1. Personal attenuation values measured according to the psychophysical procedure at threshold and Method A (trained-subject fit) in ANSI 12.6-2008 [13] are reported in Table 2 for each individual together with the available manufacturer's group data from ANSI S3.19-1974 [14] (experimenter fit).

Table 1. Hearing thresholds of the three workers: Indiv$_1$ (normal hearing), Indiv$_2$ (moderate-severe high-frequency hearing loss), Indiv$_3$ (moderate flat hearing loss).

Frequency (Hz)	Indiv$_1$ (dBHL)	Indiv$_2$ (dBHL)	Indiv$_3$ (dBHL)
500	5	20	40
1000	10	35	45
2000	5	55	50
3000	5	65	50
4000	10	65	50
6000	10	70	55

Table 2. Personal attenuation and manufacturer's data (average ± s.d.) for EAR Combat AearoSafety earplugs.

Frequency (Hz)	Indiv$_1$ (dB)	Indiv$_2$ (dB)	Indiv$_3$ (dB)	Manufacturer (average ± s.d.)
125	25	31	6	32.7 ± 5.9
250	25	31	6	31.8 ± 6.1
500	27	33	3	33 ± 6.5
1000	31	40	15	32 ± 5.5
2000	21	46	17	34.5 ± 4.1
3150	29	42	13	37.3 ± 5.3
4000	36	37	9	38.9 ± 6.1
6000	36	37	10	43.8 ± 6.7
8000	36	37	10	43.3 ± 6.9

Effect of hearing loss and hearing protection at a given workstation

Detectsound can help demonstrate how the optimal design window for auditory warnings at a workstation depends on the worker's hearing loss and the hearing protector attenuation characteristics. Analyses were perfomed using personal attenuation ratings for each individual as well as with manufacturer's data using ± 2 standard deviations from average attenuation. The latter was used to estimate the effects of the hearing protector on warning sound design over a wide range of possible attenuation ratings.

Figures 4, 5 and 6 provide Detectsound analysis results for the three individuals in the selected noise environment. For each individual, optimal design windows (upper and lower targets) are provided for four different scenarios of hearing protection use (no protection, personal attenuation, manufacturer's data + 2 s.d., and manufacturer's data – 2 s.d.).

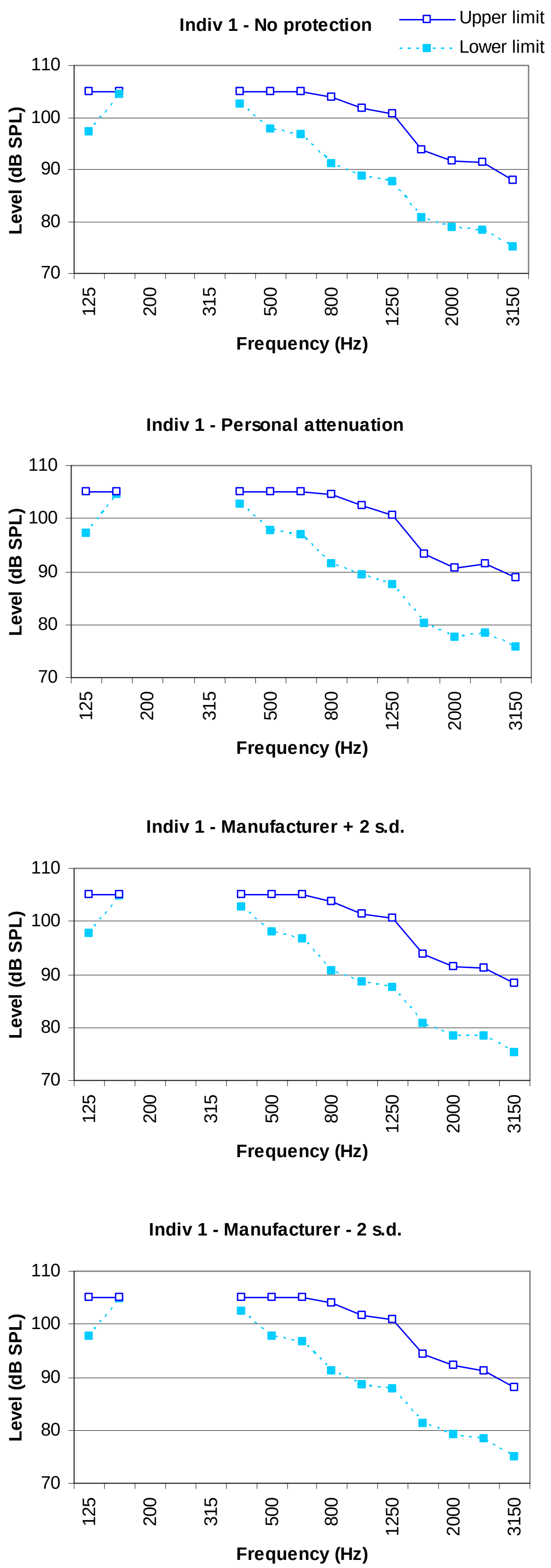

Figure 4. Optimal design windows (lower and upper targets) for Indiv$_1$ (normal hearing) for various scenarios of hearing protection (no protection, personal attenuation, manufacturer's data ± 2 s.d.).

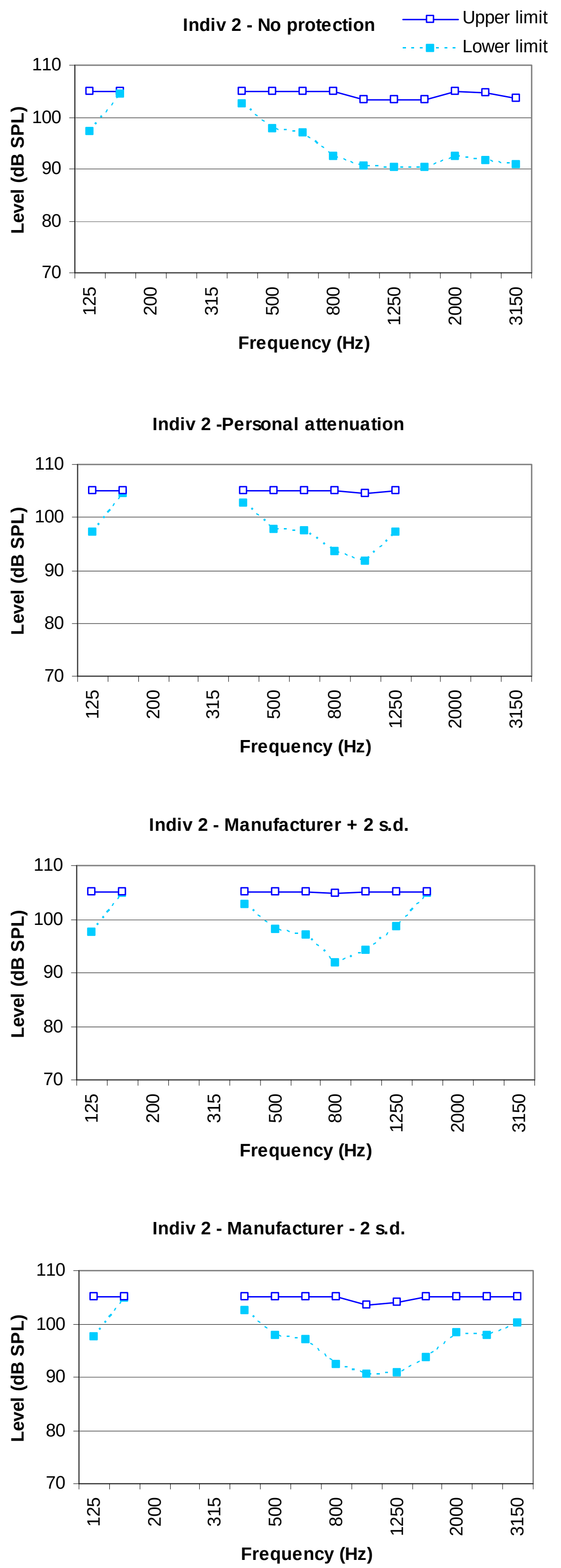

Figure 5. Optimal design windows (lower and upper targets) for Indiv$_2$ (moderate-severe high-frequency hearing loss) for various scenarios of hearing protection (no protection, personal attenuattion, manufacturer's data ± 2 s.d.).

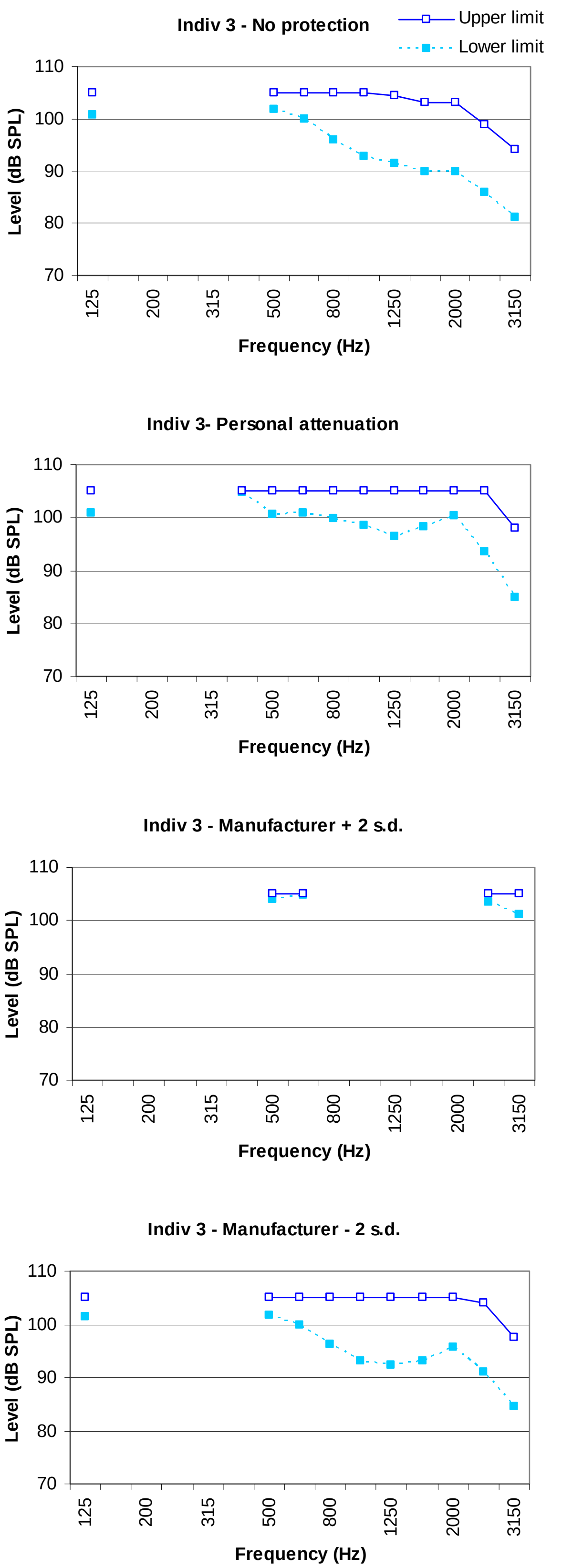

Figure 6. Optimal design windows (lower and upper targets) for Indiv$_3$ (moderate flat hearing loss) for various scenarios of hearing protection (no protection, personal attenuation, manufacturer's data ± 2 s.d.).

Lower and upper target values of the design windows for Indiv1 (normal hearing) remain relatively unchanged following the use of hearing protection, regardless of attenuation. For this worker, the use of individual (personal attenuation) or manufacturer's data (± 2 s.d.) does not seem to alter the design of auditory warning signals at the workstation, and a solution for acoustic warning signals without protection would be equally adequate when wearing the selected hearing protector. Hence, perception of warning signals will be very little affected by the different sources of variability in the real attenuation provided by the hearing protector in the field for this individual.

For $Indiv_2$ (high-frequency hearing loss), it can be noted in Figure 6 that upper and lower target values of the design window without hearing protection are elevated compared to those of $Indiv_1$. The difference is about 1-3 dB from 800 to 1250 Hz, but reaches 10-15 dB between 1600 and 3150 Hz. This increased difference in higher frequencies is attributable to the effect of a widening of auditory filters on masked thresholds in noise associated to the high-frequency hearing loss. For this worker, measured personal attenuation greatly restricts the design window as no possible solution is identified beyond 1250 Hz due to overprotection. In this range, detection of sounds is limited by absolute hearing thresholds and warning sounds must overcome the combined effects of the elevated hearing thresholds and the protector attenuation. Predictions based on manufacturer's data with + 2 s.d. are similar, but the design window is extended to 1600 Hz. When manufacturer's data - 2 s.d. are used, the design window extends to 3150; however, lower limit target values are increased by 3-10 dB between 1600 and 3150 Hz when compared to the no protection scenario. For this individual, results with the personal attenuation closely mirror results using using manufacturer's data + 2 s.d. Above 1600 Hz, the design window is very sensitive to the assumed attenuation values.

In the case of Indiv3 (flat hearing loss), the design window is practically inexistent at 125 and 160 Hz. Despite limited measured personal attenuation for this worker (Table 2), the combined effect of attenuation and hearing loss significantly affects the design window: lower target levels are increased by 5-6 dB at 1000 and 1250 Hz, 7-10 dB between 1600 and 2500 Hz, and by 4 dB at 3150 Hz. The situation is made worse when manufacturer's data + 2 s.d. are used, in which case the design window almost entirely disappears and essentially no solutions can be identified, despite the fact that a usable design window is available in Figure 6 according to the personal attenuation data.

Workers presenting with various profiles of hearing at a common workstation

In industrial settings, workstations are often shared by many workers, either jointly or sequentially. In such cases, a given solution for acoustic warning signals must meet the specific needs of all workers operating at the workstation. Warning sound levels must therefore meet the constraints identified by the design windows of all workers. A common window for all workers consists of the highest lower target value and the lowest upper target value at each frequency, thereby limiting discomfort in workers with good hearing while ensuring adequate levels for those with hearing loss.

Design windows valid for all three individuals are found in Figure 7, for the workstation described earlier. Again, the following scenarios are included: no protection, measured personal attenuation and predicted attenuation (manufacturer's data ± 2 s.d.).

Results indicate that no warning signal components greater than 2000 Hz should be used in the absence of hearing protection, the design window being too restricted in width or altogether absent. Indeed, beyond 2000 Hz lower target values for $Indiv_2$ (high-frequency hearing loss) are greater than upper target values for $Indiv_1$ (normal hearing). Hence, warning signal components in this frequency region cannot satisfy the needs of both workers.

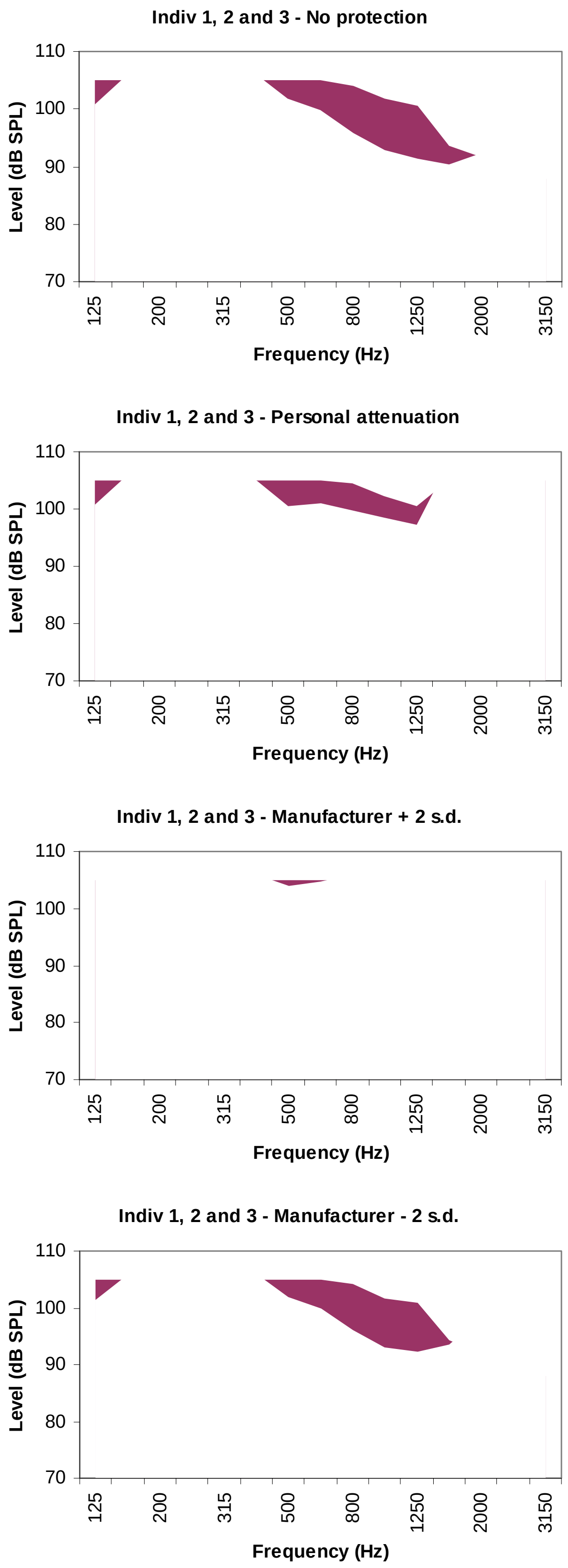

Figure 7. Common design window for all three workers ($Indiv_1$–$Indiv_3$) in each hearing protection scenario.

When using personal attenuation data, the window is considerably reduced compared to the situation without protection depletion occurs, and no solution is available beyond 1250 Hz. Using the upper end of the manufacturer's data (+ 2 s.d.), no valid common window exists for all three workers. Finally, the common design window does not extend beyond 1600 Hz when the manufacturer's data - 2 s.d. are used.

CONCLUSIONS

In this study, a detailed example was used to reveal warning sound design constraints, particularly those stemming from the combined influence of hearing loss and hearing protection. A workplace scenario was simulated to include a representation workplace noise predominantly rich in low-frequency components, as well as workers presenting different hearing profiles (normal hearing, high-frequency hearing loss and flat hearing loss). Results show that hearing protector attenuation, either measured or predicted, affects very little the perception of warning sounds in workers with normal hearing, the identified solutions being almost identical with and without hearing protection. However, for workers with high-frequency or flat hearing loss, attenuation can significantly hinder perception of warning signals. In such cases, a solution based on a given hearing protector is no longer adequate if real attenuation in the field differs significantly from presumed attenuation, and identifying optimal warning signal components becomes difficult.

The situation is further complicated when workers with various profiles of hearing occupy a common workstation, even when hearing protectors are carefully selected using current selection standards to avoid overprotection. In such cases, warning signal components in the high frequencies do not seem adequate. The simulations also reveal constraints associated with using frequency components in the very low frequency range when noise is moderately rich in low frequencies. In such cases, target levels quickly reach the 105 dB SPL ceiling imposed by Detectsound to limit startle and communication problems upon alarm activation [15].

Results of the current study are congruent with ISO 7731 [10], which recommends dominant warning signal components between 500 and 2500 Hz, and below 1500 Hz when workers have hearing loss or wear hearing protectors. Overgeneralization to all noisy workplaces must however be avoided. For example, industrial noise rich in high frequencies could yield likely different conclusions. Using available tools like Detectsound [9] or the ISO 7731 standard [10] is crucial to insure the validity of a given solution.

Overall, a solution for warning signals in the workplace is more reliable if attenuation is known precisely. Unfortunately, considerable deviation from manufacturer's attenuation data is often noted in the field [1], often in excess of 10-20 dB deviations with some hearing protectors, particularly earplug-type devices. As seen in this study, such differences can significantly affect the design window, particularly for workers with hearing loss. Recent innovations in tools used to estimate real attenuation in the field for different workers [16,17] should allow a more realistic definition of the design window for warning signals than the use of statistical data measured in the laboratory.

Moreover, any variability in estimating noise levels at different workstations and the parameters of workers' hearing status must be taken into account to ensure a reliable solution, free of error. It should also be noted that any modification to the acoustical environment within the work area, such as the addition or removal of machines, workstation reorganization or at-source noise control measures, can potentially modify needs associated with the use of warning devices. Following modifications to the work area, solutions previously implemented must be revalidated to ensure worker safety. Detectsound, or a similar tool, could help ensure that such modifications are quickly taken into consideration.

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