Optimal installation of audible warning systems in the noisy workplace

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INTRODUCTION

Warning sounds are necessary to promptly alert workers of events that can compromise safety. A wide range of strategies, including verbal and non-verbal signals have been used in different environments (Edworthy & Adams 1996; Haas & Edworthy 2006; Edworthy & Hellier 2006). Unfortunately, the use of warning signals in industry is often submitted to intuitive installation practices with little regard to the many factors contributing to an efficient and safe use (Tran Quoc & Hétu 1996). There may also be a mismatch between auditory demands and capabilities in the workplace (Hétu 1994). Failure to react to alarms can increase the risk of accidents.

The installation of warning devices in a noisy workplace poses particular challenges for optimal detection and recognition of acoustic signals, such as the use of adequate sound levels (ISO 7731). Factors affecting the audibility of warning sounds include the noise field in the work area (level, spectrum, and type), the hearing status of the population of workers, the use of hearing protectors, and the acoustical properties of the work area (size, reverberation, distance between warning devices and workstations). All workers must be able to hear audible signals, in the presence of background noise, warning them of an emergency, the presence of hazardous events or other circumstances requiring their immediate attention. A too soft warning sound can be easily masked by the background noise and draw little attention, while excessively loud warning sounds may be uncomfortable and impede verbal communication in the critical moments following the onset of the alarm or cause hearing damage in extreme cases.

Proper analysis of all interacting factors is difficult without detailed models and computerized tools. Methods to optimize the level of warning sounds are typically based on the concept of masked threshold (ISO 7731; Robinson & Casali 2000; Zheng et al. 2007). The latter is the signal level which is just detectable in the presence of an interfering masker (e.g. the workplace noise). Warning sounds need to be adjusted at a certain level above the masked threshold to ensure they attract attention and are recognizable. In practice, a level of 10 to 15 dB above the masked threshold has been proposed (Patterson & Milroy 1980; Wilkins & Martin 1978; Laroche et al. 1991; ISO 7731). An upper limit is also warranted to prevent overly loud warning signals, typically 25 dB above the masked threshold for each frequency component of the warning signal (Coleman et al. 1984; Laroche et al. 1991).

Acoustic warning devices are normally installed on walls or on the ceiling in the work area at a certain distance from the targeted workstations. Therefore, in addition to a detailed psychoacoustic analysis of warning sound requirements at each workstation, the sound transmission path from the warning devices to the workstations must also be considered (Nanthavanij & Yenrades 1999).

This paper presents a general framework to deal both with the psychoacoustical and the acoustical constraints in the work area. An implementation using two integrated modeling tools, Detectsound and AlarmLocator, is described. The final solution is provided in a format that can be easily used in the field; i.e. the number of warning devices needed in the work area, their optimal location on walls, and their sound power level specifications by frequency. The method allows investigating the effects of noise-induced hearing loss and use of hearing protectors on warning sound perception in a systematic way.

MODELING FRAMEWORK

The general framework proposed for the installation of warning devices is illustrated in Figure 1 and consists of two main modeling blocks: AlarmLocator and Detectsound. Detectsound (Giguère et al. 2003; Zheng et al. 2007) analyzes the noise field in the industrial room and specifies the target acoustical characteristics of warning signals (optimal sound level range by frequency) at each workstation in the room. The analysis can be adapted to the needs of specific workers or populations of workers. Detectsound requires four input parameters:

(1) Noise field at each workstation (L_p);
(2) Hearing protector attenuation (*if used by worker(s)*);
(3) Absolute hearing thresholds of the worker(s);
(4) Frequency selectivity characteristics of the worker(s).

The last 2 inputs can be obtained through clinical measurements or predicted through ISO 1999 based on age, gender and lifetime occupational noise exposure.

The output of Detectsound is the predicted optimal range (or design window) of warning signal levels at each workstation. Lower (TL_{low}) and upper (TL_{up}) target levels are specified, consisting of levels 12 and 25 dB above masked detection thresholds (THR) for warning sound perception in the given noise field, over a range of signal frequencies (125-3150 Hz). A 105-dB SPL maximum limit is also imposed. During the installation of warning devices, warning levels between TL_{low} and TL_{up} are targeted and, ideally, at least 4 frequency components should fall within the design window (Tran Quoc & Hétu 1996). Figure 2 shows an example design window at a workstation and a warning signal for which 4 of the 5 frequency components meet the requirements set by Detectsound.

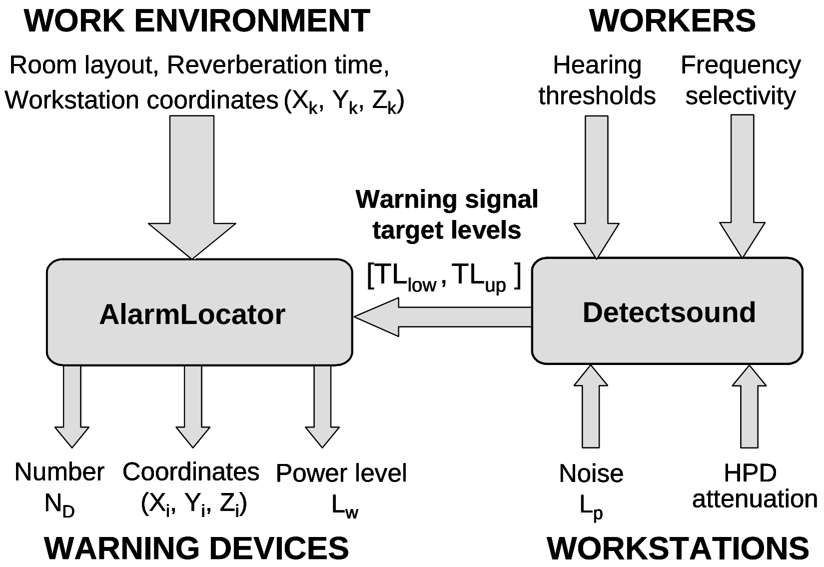


Figure 1: Modeling framework for guiding the installation of audible warning devices

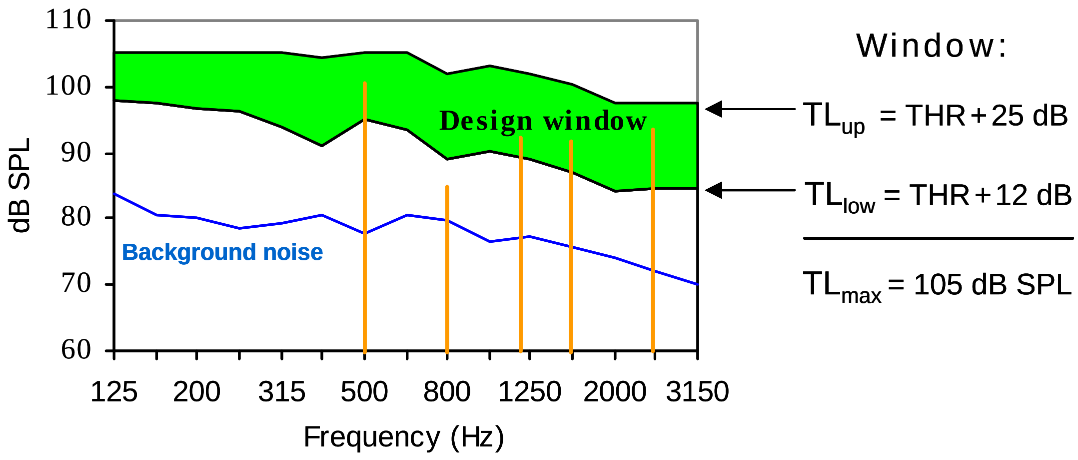


Figure 2: Example of a Detectsound warning signal design window (shaded area) generated by Detectsound. The lower horizontal curve is the background noise at the workstation under study. The received level of the warning signal components (vertical bars) must fall within the design range. Four of the five components meet the specifications in this example.

The AlarmLocator model deals with the sound propagation of warning signals from the physical device location (on walls or ceiling) to the position of individual workers or workstations (Al Osman et al. 2006). The model takes into account the direct field from the warning devices and the reverberant field due to wall, ceiling, floor and other reflections. A hybrid computational method is used combining the mirror-image technique for the direct wave and early reflections (up to three orders of room reflections) and the statistical room acoustics theory for the residual reverberation (Al Osman 2007). AlarmLocator requires the following inputs:

(1) The target warning sound levels [TL_{low},TL_{up}] at each workstation, as determined by Detectsound;

(2) The physical and acoustical characteristics of the work area (room layout, reverberation time or average sound absorption, and location of workstations in the room).

AlarmLocator actively searches for warning device configurations that satisfy the Detectsound warning sound level specifications jointly at all workstations in the work area, and specifically identifies:

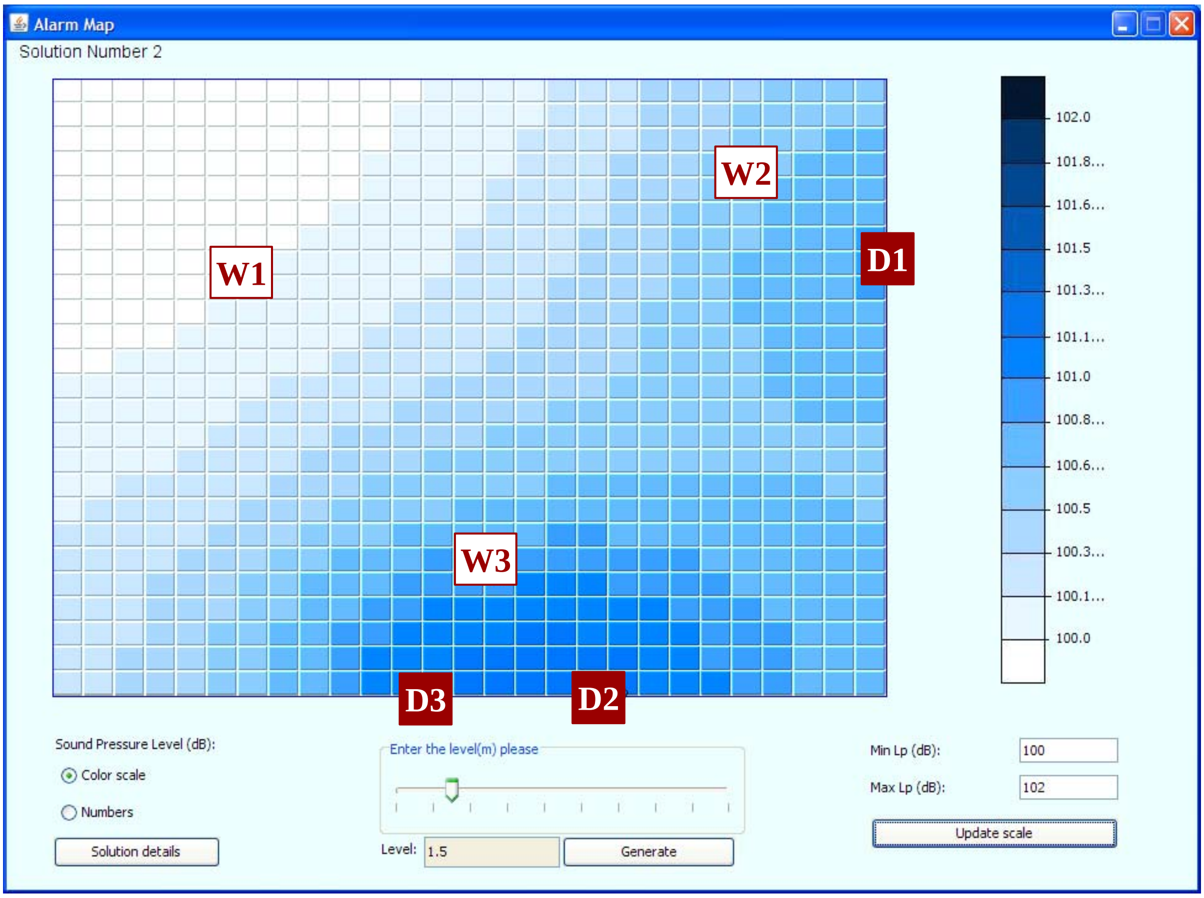
(1) The minimum number of warning devices required N_D;

(2) The optimal spatial coordinates of the warning devices in the room;

(3) The required sound power level L_w of each warning device.

Together, these three outputs form a complete solution to the problem of installing acoustic warning devices that can be easily understood and used in the workplace. The minimum number of devices and optimal power level specifications are required for procurement purposes, whereas the optimal location of devices on walls and ceilings is required during installation.

Figure 3 shows an example for an industrial room with three workstations (W_1-W_3). In this case, three warning devices (D_1-D_3) are required to ensure optimal audibility of warning sounds at all workstations by all workers. The actual solution depends on the noise field in the room, the location of the workstations and the hearing status of workers, among other factors.



Alarm Map

Solution Number 2

Sound Pressure Level (dB):

● Color scale

○ Numbers

Enter the level(m) please

Level: 1.5

Min Lp (dB): 100

Max Lp (dB): 102

Figure 3: Warning sound level distribution (dB SPL) generated by AlarmLocator in an example industrial room illustrating a possible solution to the installation of warning devices (W: workstation number; D: warning device number).

FIELD VALIDATION

Methods

The proposed modeling framework was tested in a real workshop. The objectives were: (1) to verify, through listening tests with a group of subjects, that Detectsound provides valid design windows for warning sound levels at specific workstations, and (2) to verify, using sound measurement equipment, that AlarmLocator accurately predicts the sound level produced by warning devices over a group of workstations in a real room.

The workshop is a rectangular work area (8.77m × 14.75m × 6.62m) with reverberation times ranging from 0.62 to 0.91 s over the frequency span from 125 to 8000 Hz. Three simulated workstations were set-up in the room as well as two noise sources to generate a controlled noise field. Two noise types were investigated: continuous white noise and impact noise consisting of 10-ms bursts of white noise at a rate of 12 per second.

Psychoacoustic validation of Detectsound

Two experiments were carried out to determine the validity of Detectsound: (1) the measurement of masked thresholds for human subjects in the noisy workshop compared to Detectsound masked threshold predictions, and (2) the subjective judgment of optimal warning level by human subjects compared to the Detectsound design window. Five normal hearing subjects were used for this pilot study.

In the first experiment, subjects were seated at one of the three workstations in the noisy workshop and listened to a warning sound. Using an ascending/descending adaptive threshold search method, individual masked thresholds were determined in continuous and impact noise for pulsed pure tone warning sounds at 500, 1000 and 2000 Hz. The continuous noise condition was also carried out with Peltor H9 hearing protectors. The subjective masked threshold measurements are reported in Table 1 and compared with Detectsound masked threshold predictions (which are the lower bound of the design window minus 12 dB). These predictions were based on the measured noise field at the workstation where subjects were seated. Over all 9 test conditions (frequency, noise, hearing protection), the mean prediction error is 0.0 dB and the standard deviation is 1.4 dB, thereby indicating very good predictive validity for Detectsound. The greatest difference between the subjective data and Detectsound predictions is a 2.5 dB overestimate at 2000 Hz using the Impact noise without protection. By noise type, there is a tendency for Detectsound to slightly underestimate subjective data for the continuous noise by 0.6 dB on average over the three frequencies, and to slightly overestimate the subjective data for the Impact noise by 0.6 dB. Detectsound predictions for the condition with hearing protection indicate no evidence of overestimation or underestimation and are all within 1.0 dB of the subjective data.

Table 1: Mean subjective masked thresholds with and without hearing protectors and comparison to Detectsound predictions at one workstation

Condition	Noise	Freq. (Hz)	Measured masked thresholds		Detectsound predictions TL_{low} (dB SPL)	Error (dB)
			mean (dB SPL)	s.d. (dB)		
No hearing protection	Continuous noise	500	67.2	1.4	66.1	-1.1
		1000	63.1	2.4	61.1	-2.0
		2000	60.5	2.4	61.7	1.2
	Impact noise	500	61.4	1.8	61.9	0.5
		1000	58.0	1.2	56.8	-1.2
		2000	55.0	0.9	57.5	2.5
Hearing protection	Continuous noise	500	66.4	1.7	66.1	-0.3
		1000	61.6	2.6	61.1	-0.5
		2000	60.9	1.4	61.7	0.8

In the second experiment, subjects were asked to optimally adjust the level of a three-component warning sound (500, 1000, 2000 Hz) to a preferred listening level ensuring clear audibility while maintaining comfort. The warning sound complex signal was so designed that each frequency component reached threshold synchronously. The results in Table 2 show that preferred listening levels are very close to the middle (18.5 dB) of the Detectsound design window (12 to 25 dB above masked thresholds). The mean preferred listening levels ranged from 15.5 dB to 21.7 dB above the masked thresholds. Over all conditions, the mean adjustment is 18.3 dB above masked thresholds. From these data, it appears that with hearing protection, individuals prefer levels slightly higher than what would be predicted from their masked thresholds. It is important to note that the background noise levels used in this experiment (73-77 dBA) were less than what would typically be found in many occupational settings and that loudness judgments are dependent on background noise levels. Caution must therefore be exerted in the interpretation of these results and measures should be repeated in more realistic background noise levels, using a greater number of subjects.

Table 2: Mean preferred listening level of a 3-frequency component warning signal to ensure clear audibility and comfort at one workstation

Condition	**Noise**	**Preferred listening level relative to masked thresholds**	
		Mean	**s.d.**
No hearing protection	Continuous noise	17.6	0.9
	Impact noise	15.5	1.8
Hearing protection	Continuous noise	21.7	2.2

Acoustic validation of AlarmLocator

The acoustic validation of AlarmLocator was carried out using sound measurement equipment to verify that it could provide realistic predictions of the sound pressure level L_p in the workshop produced by omnidirectional warning sound devices located along the room walls, given the sound power L_W of the devices. This was evaluated independently for three source positions S_1-S_3 (fixed along two lateral walls and at one wall intersection), three simulated workstations W_1-W_3 and three octave bands of noise.

Table 3 shows the difference between the sound level measurements for the 27 conditions (3 sources by 3 receiving workstations by 3 octave bands) and the predictions by AlarmLocator. Over all measurements, the prediction error varies between -2.1 dB (S_1-W_1 at 500 Hz) and +1.7 dB (S_2-W_3 at 500 Hz). Averaged over workstations, the prediction error varies between -0.1 dB (W_1) and 0.3 dB (W_3). Averaged over source locations, the prediction error varies between -0.1 dB (S_1) and 0.2 dB (S_2). Averaged over octave bands, the prediction error varies between -0.2 dB (500 Hz) and 0.4 dB (2000 Hz). Altogether, there is no indication of any systematic error over workstation, source location or frequency. Moreover, these errors are very small for all practical purposes when compared to the size of the Detectsound design window (13 dB). Thus, the estimation error is unlikely to affect the decision outcome for Detectsound.

Table 3: Sound pressure level prediction error (dB) for 3 source positions, 3 workstations and 3 octave bands. Positive numbers indicate an overestimation

	1/1Oct	**W_1**	**W_2**	**W_3**
S_1	500 Hz	-2.1	0.3	-1.4
	1000 Hz	-0.9	1.5	0.2
	2000 Hz	0.8	0.1	0.8
S_2	500 Hz	1.4	0.1	1.7
	1000 Hz	-0.7	-0.6	0.6
	2000 Hz	-0.2	-0.8	0.6
S_3	500 Hz	-0.3	-0.6	-0.9
	1000 Hz	0.1	0.5	0.4
	2000 Hz	1.2	0.3	0.9

DISCUSSION AND CONCLUSIONS

This research contributes to the advancement of scientifically-based practical tools to guide the design and generation of warning sounds in industrial work areas. This is achieved through the use of two modeling tools: Detectsound and AlarmLocator. The first tool is a psychoacoustic model that takes into account the noise field, the use of hearing protectors and the hearing status of worker(s) to determine the optimal characteristics of warning sounds (level, frequency components) at each workstation in the work area. The second tool is a model for the acoustic propagation of warning sounds from the physical device source location to the receiving stations in the work area. The final solution is provided in a format that can be easily used in the field; i.e. the number of warning devices needed in the work area, their optimal location on walls, and their sound power level specifications by frequency. The method allows investigating the effects of noise-induced hearing loss and use of hearing protectors on warning sound perception in the workplace in a very systematic way (Giguère et al. 2007).

In practice, use of the tools developed in this research would follow the general procedure detailed below (Figure 1):

(1) Specify the floor layout and location of the workstations;
(2) Measure the noise level L_p at each workstation under realistic work conditions and the reverberation time in the room;
(4) Identify the specific workers or the general characteristics of the population of workers at each workstation (age, gender, and years of occupational noise exposure);
(5) Measure the hearing status of the identified workers or estimate hearing thresholds and frequency selectivity based on age, gender and years of exposure (e.g. ISO 1999);
(6) Determine if hearing protectors are required in the work area and specify the attenuation of the devices;
(7) Using Detectsound, determine the optimum target warning sound levels TL_{low} and TL_{up} at each workstation;
(8) Using AlarmLocator, determine the number of warning devices required N_D, their location on walls and their sound power L_w;
(9) Install the warning devices in the work area as per AlarmLocator specifications;
(10) Verify that the devices produce warning sound levels within the Detectsound window specifications at each workstation using a sound level meter. A minimum of four frequency components within the Detectsound window are recommended.

The method is aimed at stakeholders in occupational health and safety to help them make informed decisions regarding the procurement and installation of warning devices in the workplace. It is hoped that this work could also contribute to new knowledge and insight into the optimal design and operation of warning devices in the workplace, which would be directly relevant to industrial hygienists and engineers, device manufacturers and standardization organizations.

Finally, the method strictly deals with the audibility of warning sounds in the workplace. It does not specifically address other important factors such as the distinctiveness and sense of urgency conveyed by the warning sounds, and the cognitive load or demands associated with the workers' tasks (Edworthy & Adams, 1996; Smith, 2003).

REFERENCES

Al Osman R (2007). Development of “AlarmLocator”: A computerized model for predicting the optimum number, location, and power level of acoustic warning devices in noisy work plants. Systems Science Master’s Thesis, University of Ottawa.

Al Osman R, Giguère, C, Laroche C (2006). ALARMLOCATOR: A software tool to facilitate the installation of acoustic warning devices in noisy workplants. Can Acoust 34(3): 20-21.

Coleman CJ, Graves RJ, Collier SG, Golding D, Nicholl AG, Simpson GC, Sweetland KF, Talbot CF (1984). Communications in noisy environments. Final Report on CEC Contract 7206/00/8/09. Edinburgh: Institute of Occupational Medicine.

Edworthy J, Adams A (eds.) (1996). Warning design: a research perspective. London: Taylor & Francis.

Edworthy J, Hellier E (2006). Complex nonverbal and auditory signals and speech warnings. In: Wogaltier MS (ed.): Handbook of warnings (pp 199-220). Mahwah NJ: Lawrence Erlbaum Associates.

Giguère C, Laroche C, Zheng Y, Sabourin C (2003). A warning sound perception model software. International Congress on Noise as a Public Health Problem (pp 80-81). Rotterdam, June 29-July 3.

Giguère C, Laroche C, Al Osman R, Zheng Y (2007). Influence de la perte auditive et du port de protecteurs auditifs sur l’installation d’avertisseurs sonores en milieux bruyants. Congrès international sur l’ingénierie des risques industriels (pp 29-43). Montréal, 17-19 Décembre.

Haas E, Edworthy J (2006). An introduction to auditory warnings and alarms. In: Wogalter MS (ed.): Handbook of warnings (pp 189-198). Mahwah NJ: Lawrence Erlbaum Associates.

Hétu R (1994). Mismatches between auditory demands and capabilities in the industrial work environment. Audiology 33: 1-14.

ISO 1999 (1990). Acoustics – Determination of occupational noise exposure and estimation of noise-induced hearing impairment. Geneva: International Organization for Standardization.

ISO 7731 (2003). Danger signals for work places – Auditory danger signals. Geneva: International Organization for Standardization.

Laroche C, Tran Quoc H, Hétu R, McDuff S (1991). Detectsound: A computerized model for predicting the detectability of warning signals in noisy workplaces. Appl Acoust 32: 193-214.

Nanthavanij S, Yenrades P (1999). Predicting the optimum number, location, and signal sound level of auditory warning devices for manufacturing facilities. Int J Ind Ergon 24: 569-578.

Patterson RD, Milroy R (1980). The appropriate sound level for auditory warnings on civil aircraft. J Acoust Soc Am 67: S58.

Robinson GS, Casali JG (2000). Speech communications and signal detection in noise. In: Berger EH, Royster LH, Royster JD, Driscoll DP, Layne M (eds.): The Noise manual (pp 567-600). Fairfax VA: American Industrial Hygiene Association.

Smith AP (2003). “Noise, accidents, minor injuries and cognitive failures.” Proceedings of the 8th International Congress on Noise as a Public Health Problem, pp 140-144.

Tran Quoc H, Hétu R (1996). La planification de la signalisation acoustique en milieu industriel: critères de conception des avertisseurs sonores de danger. Can Acoust 24(2): 3-17.

Wilkins P, Martin AM (1978). Hearing protection and warning sounds in industry - a review. Appl Acoust 21: 267-293.

Zheng Y, Giguère C, Laroche C, Sabourin C, Gagné A, Elyea M (2007). A psychoacoustic model for specifying the level and spectrum of acoustic warning signals in the workplace. J Occup Environ Hyg 4: 87-98.