Mechanical and Physical Risk Prevention

Studies and Research Projects

REPORT **R-833**

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Assessment of Three Types of Reverse Alarm

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PEER REVIEW

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SUMMARY

New technology for heavy vehicle reverse alarms has recently appeared on the market. According to the manufacturer, this technology, based on the use of a broadband signal (*shh…shh…shh* signal), is safer for workers and causes less noise pollution than the conventional tone alarm (*beep…beep…beep* signal). However, it is difficult to say whether this technology is better, because of the paucity of independent and rigorous scientific studies on the subject.

This study compared the new broadband alarm technology with conventional alarms from the standpoint of worker safety. Two sets of trials were carried out to make the comparisons. In the first, a field trial, the sound propagation fields generated by the alarms behind heavy vehicles were measured to study their uniformity under conditions similar to those found in the workplace. In the second, human participants carried out psychoacoustic tests in the laboratory. They performed tasks related to alarm perception (detection thresholds, equal loudness, perceived urgency and sound localization).

Through an analysis of the alarm signals, the broadband alarm was deemed compliant with the SAE J994 standard, which is the standard most commonly used to certify alarms installed on heavy vehicles. In addition, the overall results of both field and laboratory trials did not reveal any contraindications to the use of the broadband reverse alarm with respect to worker safety. This type of alarm provides a much more homogeneous sound field behind vehicles and is easier to locate spatially, particularly in the front/rear dimension. The potential advantages of a tonal alarm (better detection under noisy conditions and a slightly greater sense of urgency conveyed in certain situations), would probably not overcome the adverse effect of major spatial variations in sound levels found over short distances behind a vehicle with this alarm (on the order of 15 to 20 dB), which are noticeably more pronounced than those generated by the broadband alarm.

In this report, the effect of parameters such as ambient noise, the use of hearing protection devices (HPD), and the type of protectors worn (ear muffs versus earplugs) on psychoacoustic indicators is presented for both alarm types. Finally, recommendations have been formulated to ensure the optimal use of broadband alarms, and important aspects requiring more extensive investigation are identified.

1. INTRODUCTION

Given the high number of accidents every year involving reversing vehicles, it is critical to ensure that reverse alarms are optimally designed so that people working nearby are alerted promptly, while limiting noise annoyance for people farther away who are not at risk. Auditory warning sounds have an advantage over visual warnings because they usually capture people's attention no matter where they are looking. However, accidents can occur in the workplace when alarms are not well detected by workers, due to masking by noise, when hearing protection devices are worn, or when the auditory signal emitted is difficult to locate and thus does not prompt the worker to react adequately by moving in the right direction. Accidents also occur when alarms are ignored, particularly when they often go off without signalling any real danger or emergency, or when they are set at annoyingly loud levels such that people prefer to deactivate them.

The most commonly used reverse alarms in Québec and elsewhere have traditionally consisted of either a single pure tone (most popular) or a warble tone. However, various groups of researchers and workplace stakeholders have voiced concerns about the use of these types of tonal alarm with respect to both worker safety and noise pollution. A relatively recent reverse alarm technology using a broadband signal has been developed to overcome the main problems related to conventional tonal alarms. This technology has been marketed and a range of broadband reverse alarms is now available. The advent of this new technology raises an important question for workplaces: will the use of these alarms instead of conventional alarms significantly improve the detection and localization of reversing vehicles as well as creating a sufficient sense of perceived urgency to ensure safety, while limiting the annoyance factor? Already, some workplaces in Québec have expressed an interest in and a desire to implement this technology. However, it remains difficult to draw conclusions about its superiority over other types of alarms, as there are few independent and rigorous scientific studies demonstrating improved worker safety when using the broadband alarm.

This report presents the results of a two-part study comparing the new broadband alarm technology with that of conventional alarms. In the first part, the field trial, the sound propagation field generated by the alarms was measured behind heavy vehicles. In the second part, the laboratory trial, psychoacoustic measurements were carried out on human participants and targeted various aspects related to the perception of reverse alarms (detection thresholds, equal loudness, perceived degree of urgency and sound localization). The study focused primarily on workers' health and safety rather than on noise pollution. The following sections present a review of the literature, the objectives of the study, the methodology used and the results obtained. A discussion and conclusion wind up the report.

2. CURRENT SITUATION

2.1 Occupational Safety and Health (OSH) issues associated with heavy vehicle reversing

According to the motor vehicles subpart 1926.601(b)(4) in the US Occupational Safety and Health Administration's Safety and Health Regulations for Construction (OSHA, 2000), heavy truck drivers whose rear view is obstructed must operate with a functional reverse signal alarm that is audible above the surrounding noise level or must only back up the vehicle when an observer signals that it is safe to do so. In Québec, two sections in the Safety Code for the construction industry (updated on October 1, 2011) deal with warning devices. Section 3.10.5 states that a signalman is required when a vehicle is driven in reverse "if such a move may create a hazard for any person" or if the view of the driver is obstructed. Paragraph 2 of section 3.10.12 provides a list of vehicles that must have automatic warning horns for the reverse gear, with "a noise intensity that is superior to the noise of the equipment on which it is installed and have a distinct sound." In addition, "if the warning horn is electric, it must conform to SAE Standard J994b-1974 Performance, Test and Application Criteria for Electrically Operated Backup Alarm Devices."

Despite such guidelines, every year there are more accidents and mortalities involving heavy vehicles driving in reverse (Laroche et al., 1995; Murray et al, 1998; NIOSH, 2004; Blouin, 2005) in Québec and elsewhere. A recent accident (September 2, 2011), on a construction worksite for Highway 30, in which a surveyor was run over by a reversing truck, points to serious shortcomings in workplace safety. Despite clearly formulated guidelines by the Commission de la santé et de la sécurité au travail (CSST) following the accident, an investigation revealed that many reversing manoeuvres were still being carried out without a signal person and that some vehicles were not yet equipped with a reverse alarm (CSST, 2011).

Almost a quarter of all deaths involving work vehicles take place when the vehicle is reversing (HSE, 2001). Moreover, from accident reports published by OSHA from 1972 to 2001, Purswell and Purswell (2001) estimated that approximately 43% of the 150 reported accidents that involved vehicles occurred despite the reverse alarm being in good working order at the time. In Québec, Laroche and colleagues (Laroche et al, 1991, 1995; Laroche and Denis, 2000), using the CSST computerized data bank (www.centredoc.csst.qc.ca), identified 25 fatal accidents caused by reversing vehicles in Québec between 1975 and 1991, of which 15 occurred on construction sites. The construction industry therefore appears to be especially affected by this problem. According to the US Bureau of Labor Statistics, 6% of all fatal accidents (397 deaths) in the construction industry in 2002 were due to vehicles backing over workers (Seattle District Safety Gram, 2009). A summary table of the 19 backover fatalities that occurred on construction sites in the United States between 1992 and 2007 is presented in Appendix A. In most cases, the alarm was functional and operating during the accident and the vehicle was moving at speeds of less than 5 mph.

Accidents may occur in noisy work environments when audible warning devices do not attract attention, either because they are not heard or because they are ignored, for example, when an alarm often goes off without signalling any real danger or urgency (habituation phenomenon). In other cases, reverse alarms are so loud and irritating that they are deactivated. Additional factors that may contribute to the non-perception of reverse alarms include hearing loss, masking by ambient noise and inappropriate installation of the alarm on heavy vehicles (Laroche and Lefebvre, 1998), as well as the use of hearing protection devices (HPD).

Serious concerns about the effectiveness of conventional reverse alarms in conveying an appropriate sense of urgency in the critical zone behind heavy vehicles can therefore be raised. A number of factors can contribute to the effectiveness of alarms, including the alarm's frequency content, the workers' hearing status, masking by ambient noise, the habituation phenomenon, signal recognition, reaction times, the degree of urgency conveyed by the signal, the ability to localize the signal and the signal's sound propagation pattern (Morgan and Peppin, 2008). Alarms must convey information that will address three important questions (Catchpole et al, 2004): *What* is the danger? *Where* is the danger? *When* is it a danger?

In the literature, three major problems associated with conventional reverse alarms are noted: a difficulty in localizing the sound, the non-uniformity of the sound propagation pattern behind the vehicle, and noise pollution.

- Sound localization

The "beep, beep, beep" of a vehicle in reverse gear is familiar to everyone, but people are often uncertain as to where the sound is coming from. Emergency vehicle sirens are another convincing example of signals that are difficult to localize and that often cause confusion as to whether the vehicle is approaching from the front, behind, right or left. Despite the broad range of frequencies that humans can hear (from 20 to 20,000 Hz), important localization cues are found mainly in frequencies lower than 1500 Hz and higher than 3000 Hz. For sounds below 1500 Hz, the main cue for differentiating between sounds in the left/right dimension is the interaural time difference (ITD), while for sounds in ranges higher than 3000 Hz, it is the interaural intensity difference (IID) that matters. A final category of spectral cues making use of high frequency (> 5000 Hz) information enables sources in the front to be distinguished from those behind and to determine the degree of elevation of the source (Middlebrooks and Green, 1991; Carlile and King, 1993; Blauert, 1997; Hartmann, 1999).

In theory, broadband spectrum alarms are easier to localize because they provide a greater number of cues (ITD, IID, spectral cues) compared to tonal signals, where the frequency spectrum is limited, such as conventional emergency vehicle sirens and reverse alarms. Indeed, conventional reverse alarms typically have a dominant frequency between 1000 and 4000 Hz (Laroche and Lefebvre, 1998), a frequency region in which few localization cues are available.[1] Furthermore, the SAE J994 (2009) standard recommends a predominant frequency between 700 Hz and 2800 Hz for reverse alarms. Confusion in identifying the position of the sound source may lead to a delayed response from workers, when a timely reaction is often critical to avoid danger. Finally, from a workplace health and safety perspective, the effects of HPD must also be

[1] The spectral content of tonal and broadband alarms is presented in Figure 2.

taken into consideration, because they can further compromise the ability to localize sound (e.g., Tran Quoc and Hétu; Bolia et al 2001; Berger, 2003; Simpson et al, 2005).

- Sound propagation

Difficulties in detection and confusion as to the position of the source can also be attributed to abrupt spatial variations in the sound pressure levels of the alarm over very short distances behind heavy vehicles. This issue has been well documented with tonal reverse alarms (Laroche et al, 2006). The uneven pattern of sound propagation behind heavy vehicles due to sound wave interference (reflection and diffraction) can lead workers to underestimate or overestimate the distance and direction of a vehicle that is outside their field of vision. This issue has been identified as a probable contributing factor in a fatal accident on a highway construction site near Montréal in 2003 (Laroche, 2006). Figure 1, taken from work by Laroche et al (1995), illustrates the sound pressure levels of an alarm behind an immobile vehicle as a function of distance. At distances of less than 2 m from the vehicle, enormous fluctuations in sound pressure levels can be noted, and reach up to 15 dB over just a few cm. Furthermore, sound pressure levels do not decrease steadily with increasing distance.

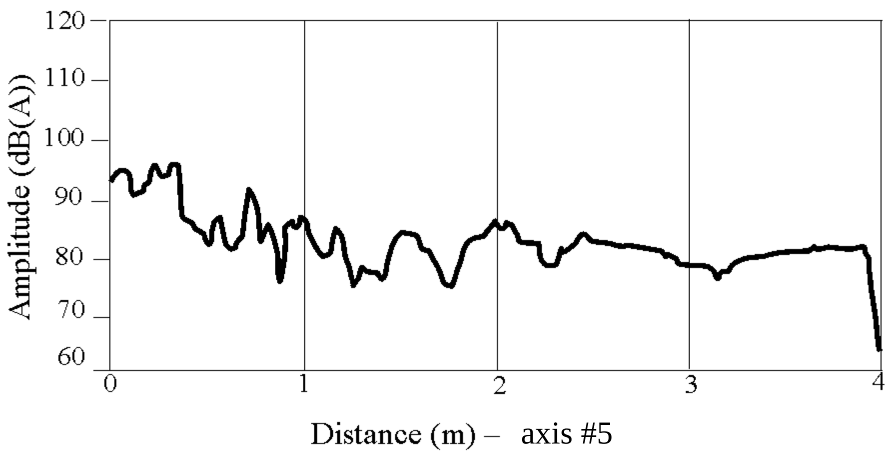

Figure 1: Example of sound pressure levels measured behind a heavy vehicle as a function of distance when a pure tone reverse alarm is in operation.

In addition to a non-uniform propagation pattern, the sound of tonal alarms can travel over large distances, well beyond the hazard zone immediately behind a heavy vehicle. A false alarm occurs when an alarm is heard outside of the hazard zone, and can lead to a dissociation between the alarm and the danger, thus affecting its efficacy (Morgan and Peppin, 2008; Bliss et al 1995; Bliss and Dunn, 2000; Holzman, 2011). In fact, Bliss et al (1995) have shown that the response rate to an alarm by people involved in a cognitive task closely mirrors the alarm's reliability rate. If the sound signal is associated with a high rate of false alarms, for example, 75% (the alarm directs attention to a real danger situation only 25% of the time), most people will respond to the signal only 25% of the time. Workplace safety may then become markedly jeopardized by perfectly audible signals that have lost their effectiveness in transmitting a danger warning because of the number of false alarms.

- Noise pollution

The sound of tonal reverse alarms in a neighbourhood can be heard over long distances by residents who have no need to respond. For them, alarms become an annoying and unnecessary nuisance (Burgess and McCarty, 2009), leading to great frustration and many complaints, even legal proceedings. In fact, it is often these complaints and the eventual legal remedies that motivate businesses to change their reverse alarms, much more than a concern for worker safety.

The unpredictable nature of reverse alarms and the lack of perceived control over this source of noise have a major impact on the immediate surroundings. In a report recently published by the National Academy of Engineering (Committee on Technology for a Quieter America, 2010), tonal alarms were cited as one of the top six noise sources that can cause behavioural and emotional consequences. They have also been identified as a major night-time construction noise nuisance in several US states (Federal Highway Administration, 2008). As previously mentioned, the annoyance caused by alarms not only affects nearby residents, but also workers (Burgess and McCarty, 2009), who often turn off or sabotage alarms deemedtoo loud and distracting (Haas and Edworthy, 1998).

A good reverse alarm should convey an appropriate degree of urgency that accurately reflects the dangerousness of the situation. While a number of parameters may influence the degree of urgency perceived (Hellier and Edworthy, 1989; Edworthy et al, 1991; Edworthy and Stanton, 1995; Haas and Casali, 1995; Haas and Edworthy, 1998), the predominant frequency, rhythm and frequency range are the most important. The SAE J994 standard specifies the predominant frequency, pulse rate and on/off interval duration (SAE J994, 2009) to be used for reverse alarms. Generally, high frequencies, a broad frequency spectrum and a rapid repetition rate are deemed to be urgent (Edworthy et al, 1991).

2.2 Broadband Sound Technology

The aim of broadband alarm technology, commonly referred to as BBS, developed at Leeds University (Withington, 2004) in the United Kingdom and marketed worldwide, is to reduce noise nuisance while increasing reverse alarm effectiveness through better sound propagation behind vehicles and sound localization. Although a number of documents, including a white paper and several advertising brochures from the manufacturer (Brigade Electronics) praise the merits of this technology (Leventhall, 2007; Morgan, 2007; Morgan and Peppin, 2008; Brigade Electronics, 2011), reporting its benefits with respect to safety, noise nuisance and health, the statements are not always supported by experimentally verified data and often rely on anecdotes and examples.

- Anticipated safety benefits

Because of its broad frequency spectrum, this warning signal may be easier to localize (larger number of available localization cues), generate a more uniform sound propagation pattern behind vehicles (less sound wave interference), be easier to detect (more frequency components in the most sensitive hearing range, i.e., between 2000 and 4000 Hz) and less likely to be masked by workplace noise. Better audibility for people with hearing loss and those wearing hearing protectors (low frequencies can penetrate physical obstacles more easily than high frequencies) has also been reported. According to a variety of documents, other safety benefits could include a higher response rate (fewer false alarms) and a reduction in intentional deactivation and sabotage of alarm devices.

While both alarm types meet the temporal characteristics necessary to indicate danger, as stipulated in the SAE J994 standard (SAE, 2009), the above-mentioned authors stipulate that the BBS may also be more easily recognized than the conventional tonal alarm by providing a clear and unambiguous message. According to them, the BBS signal is heard only in the hazard zone and its origin is easier to identify, thus limiting the possibility of confusing several sound sources. To support this assertion, they provide an anecdote related to an accident in which a worker was struck even after hearing the tonal alarm because he had assumed that the danger signal emanated from another truck that he could see reversing. As BBS propagation is more contained within the hazard area, it would not convey as many false danger warnings as pure tones, according to the manufacturer.

- Anticipated benefits with respect to noise pollution

According to the manufacturer (Brigade Electronics, 2009), a reduction in environmental impact could result from the fact that, at the same overall sound level in dBA, frequency-rich sounds seem louder than limited spectrum sounds. The BBS could thus be set at 5 dBA lower level than that of a tonal alarm to generate the same loudness, while at the same time reducing the sound energy emitted into the surrounding area. The more variable sound propagation of pure tones also comes into play because peak sound levels may be heard over a greater distance from the truck, again according to the manufacturer.

The directionality of broadband alarms is also cited as an advantage of this technology. Since high frequencies in the signal are more directional and more easily absorbed into air and ground, sound propagation would be largely confined to the hazard zone. Sound levels produced by the alarm would attenuate more rapidly with distance than those of a pure tone, leading to greater masking by ambient noise at a distance and thus less intrusion of the signal into the surrounding environment.

Moreover, at the same sound pressure level, tonal alarms are reportedly more strident and thus more annoying (invasive) then broadband alarms (Brigade Electronics, 2011). Some organizations suggest 3 to 7 dB penalties in the calculation of environmental noise nuisance in the case of sounds rich in tonal components (ISO 1996-1, 2003; Federal Aviation Administration, 2012).

If the BBS can be adjusted to lower levels (because it sounds louder) and if the signal spreads less outside of the hazard zone (more directional), its use on heavy vehicles would logically result in reduced community noise complaints and worker habituation. In fact, many examples of reductions in complaints from residents following the installation of broadband alarms can be found on the Internet and in Brigade Electronics' advertising material, and have also been anecdotally reported by members of the follow-up committee for this project.

- Anticipated health benefits

With respect to health benefits, Brigade Electronics (2009) claims a reduced risk of hearing damage because: 1) BBS energy is spread over a larger frequency range, so that even at the same overall level, the energy in a specific band would be less than that contained in the predominant band of a pure tone; 2) the low frequencies contained in the BBS would be less damaging than the frequencies typically found in tonal alarms, at the same SPL; and, 3) the reflection and diffraction possible with pure tones could contribute to higher sound levels. To support this claim, the authors cite the example of noise exposure levels for electric buggy drivers: "A health study by BAA involving noise exposure monitoring resulted in some very high noise readings. Originally thought to be due to faulty meters, a more detailed study identified that the tonal alarms on the passenger terminal electric buggies were being reflected so intensely they created a health problem. Following further studies and a safety review, BAA now specifies white sound alarms." (Brigade Electronics, 2009). It is also reported that BBS causes less of a "startle" (stress) reaction in workers (Brigade Electronics, 2009; Seattle District Safety Gram, 2009).

It is important to note that the benefits reported by the manufacturer of broadband alarms are not always supported by recognized theoretical foundations or controlled and independent scientific study data.

2.3 Examples of Use of BBS Technology

Despite the numerous advantages reported above, broadband reverse alarms are seldom used in Canada because of concerns that they may not be in compliance with the SAE J994 standard (2009), which states that the predominant frequency must be between 700 and 2800 Hz. In fact, the criteria in use for conventional reverse alarms do not appear to be directly applicable to BBS signals. Subjective measurements carried out by Leventhall (2007) suggest that BBS can be effective even when operating at a SNR below the 0 dB stipulated in the ISO 9533 (1989) standard, putting the validity of that adjustment criterion into doubt. It should be noted that no comparison with a conventional tonal alarm was made and that the subjective measurements were carried out while participants were performing tasks not requiring the same cognitive resources as those needed to effectively carry out job functions in a workplace environment.

There are, however, several examples of BBS technology being used in other countries (see Table 3 in Appendix B) and the results are generally positive, particularly with respect to reducing noise nuisance complaints. In 2005, the technology won an award of excellence from the Society of Automotive Engineers in the Noise Management Innovations category (SAE International, 2005). Broadband alarms are now included in regulations on construction noise in New York City, which requires quieter alarms to be used (white noise alarms or tonal alarms set at lower levels) after regular working hours and near sensitive areas such as schools, hospitals and seniors' residences (City of New York, 2007).

Most examples come from short documents, including promotional material published by the manufacturer, which are not subject to a rigorous peer review process. Various testimonials leave no doubt as to the superiority of this technology in reducing noise complaints. However, few published scientific studies have demonstrated the advantages and disadvantages of such a technology in ensuring worker safety (Homer, 2008; Burgess and McCarty, 2009). The following section discusses studies in which an attempt has been made to compare the performance of broadband alarms to that of tonal alarms, particularly with respect to the detection and audibility of the alarms and their sound localization.

2.4 Comparative Studies

2.4.1 Detection and Audibility

In order to reduce the noise pollution impact of train warning horns, a comparative study was carried out by the RRK Jones firm (2004). In the United Kingdom, horns must be clearly audible at 400 m in front of the train, even under adverse sound propagation and background noise conditions, and to listeners with significant hearing loss. The sound levels of two tonal alarms and the broadband alarm (with five loudness settings) were measured over distances of up to 400 m in front of the train. For the alarm to be considered “just clearly audible” in this study, its spectrum had to exceed the masking threshold by at least 15 dB within the same 1/3 octave band level, in addition to the sound level of three harmonics or three 1/3 octave band levels being greater than 10 dB above the masking threshold. Scenarios using hearing thresholds based on the ISO 7029 (2000) standard revealed that the BBS was not sufficiently audible under adverse listening conditions, but that an increase in level of approximately 3 dB could provide acceptable results. In addition to performing further testing to verify this assertion, the authors recommended conducting controlled listening tests under real ambient noise conditions and measuring the directionality of BBS, because the results were unsuccessful in demonstrating that the sound emission pattern of broadband alarms was superior to that of tonal alarms.

Promotional leaflets state that BBS is less susceptible to masking. However, measurements carried out at a mining site seem to contradict this assertion (Homer, 2008). According to ISO 9533, the difference between two sets of sound level measurements (set 1 = vehicle revving with no alarm; set 2 = vehicle in neutral with the alarm on) must be equal to or above 0 dB at seven measurement points behind the vehicle. The results of the study demonstrated that, for the tonal alarm, the 0 dB SNR criterion was met at all measurement points, with the exception of one, compared to only three for the broadband alarm. Moreover, the sound of the tonal alarm was projected over greater distances than that of the broadband alarm, covering an approximately 45% larger zone in a high noise environment. The alarm level measured just behind the vehicle exceeded the background noise by 9.6 dBA (114.0–104.4 dBA) with the tonal alarm and by 7.4 dBA (111.8–104.4 dBA) with the broadband alarm, which fails to respect the 15 dB audibility criterion prescribed by ISO 7731. As part of the analysis, each alarm’s spectrum was compared to that of the noise and, according to the author, the spectral similarities made the broadband alarm more likely to be masked than the pure tone in high-noise environments. It should, however, be noted that the maximum level of each alarm was different (111.8 versus 114.0 dBA) and that the study dealt essentially with sound levels, without regard to the alarms’ audibility thresholds, thereby limiting the scope of the results. Two alarms can reach similar audibility at quite different signal-to-noise ratios or, inversely, have quite different audibility at the same signal-to-noise ratio. No data on alarm audibility as such was presented, although it is precisely the kind of information that determines whether or not workers are able to hear an alarm.

Another comparative study examined sound propagation behind heavy vehicles. The study, carried out in Australia for the Department of Transport, Energy and Infrastructure, assessed the compliance of three alarms (a broadband alarm, a focused tonal alarm, and a "smart" tonal alarm with an automatically adjusting level) to the Australian AS 4742-2003 standard (equivalent to ISO 9533:1989). Results showed the broadband alarm and the focused tonal alarm to be compliant with the standard. While "smart" alarms were noncompliant, a slight change to the measurement protocol showed that they could self-adjust to levels 1 to 2 dB louder than the background noise of the machine. A comparison of levels measured directly behind (central point) and at 45° on one or the other side of the median line revealed that focused and broadband alarms display some sound directionality, unlike "smart" alarms, and that a broadband alarm would be preferable in situations where protruding components on a truck could obstruct noise propagation (Basset Consulting Engineers, 2009). In the same study, a telephone survey gathered the opinions of representatives from eight different companies following the use of broadband alarms. In general, the authors reported no safety issues, greater ability to identify the truck emitting the signal, increased attention to safety (novelty, but also a reduction in the habituation phenomenon), detection of the signal behind the vehicle equivalent to that of the conventional alarm, reduced fatigue in workers and operators of heavy machinery and a considerable reduction in noise complaints, particularly at night. Details regarding the methodology of the telephone survey were not documented, which raises questions as to the validity of the results and conclusions reported.

The use of hearing protection devices must be taken into account, as they have significant consequences on the audibility of warning signals. In general, for noises louder than 85 dBA, conventional HPD do not appear to interfere with sound detection and speech perception and can even improve those abilities in people with normal hearing (Casali et al, 2004). However, they reduce audibility at lower noise levels (Berger and Casali, 1997) and, in particular, can interfere with sound detection (Robinson and Casali, 1995) and speech perception (Giguère et al, 2010) in people with hearing loss if the signals are attenuated to levels lower than auditory thresholds.

Robinson and Casali (1995) demonstrated that a tonal alarm would remain audible in noise above 85 dBA at relatively low SNR (0 dB), even for individuals with significant hearing loss (45–50 dB HL), when passive earmuffs were worn. They concluded that workers with such a hearing impairment should be able to hear the alarm if the ISO 7731 standard were respected (if the level of the alarm was at least 15 dB louder than the ambient noise). Active protectors, which provide protection against high noise levels but allow weak signals to be transmitted, do not appear to significantly improve the masked threshold for alarms in people with normal hearing (Casali and Wright, 1995; Lovejoy, 2008) or with hearing loss (Lovejoy, 2008), compared to passive protectors.

Casali and colleagues (Casali et al, 2004; Erika V. Christian, 1999) also compared the performance of passive earmuffs and earplugs with those of HPD with active noise reduction in individuals with normal hearing asked to detect a conventional alarm while involved in another task and exposed to 85 and 100 dBA noises. Testing without HPD was also conducted at 85 dBA. At 100 dBA, masked thresholds were better with passive earplugs, and the active noise reduction (ANR) earmuffs provided an advantage over the passive earmuffs. At 85 dBA, no difference was noted among the various protectors, but an improvement in masked thresholds of approximately 2.6 to 4.3 dB was found compared to the condition without protection.

With respect to sound detection, to our knowledge, only one study compared the tonal alarm (Preco 6003 unit) to the broadband alarm (BBS-97 unit) while passive and active hearing protectors were being used (Alali, 2011). With outdoor background noise of approximately 52.3 dBA, the detection distance was assessed in 12 people with normal hearing in eight listening conditions (unprotected and with seven different types of protectors). The mean detection distance was less when passive earmuffs were worn (1132.2 ft.) and greater without protection (1652.3 ft.). Other than the passive earmuffs and one type of passive earplugs (with greater attenuation values), hearing protection did not appear to markedly increase the distance at which the alarm became audible. Results revealed an advantage in detection distance of 221.5 ft. for the tonal alarm (1600.9 ft.) compared to the broadband alarm (1379.4 ft.), which is interpreted by the author as a considerable advantage, in that it enables detection of the tonal alarm over a greater distance, thereby providing a longer reaction time. However, one must be careful not to jump to the conclusion that the tonal alarm is inherently safer. If an alarm is heard over a greater distance, but is ignored (because workers have become habituated to the sound or confuse its location with another truck that is reversing), or if workers perceive the truck to be moving away rather than approaching because sound wave interference is causing the alarm level to decrease as the truck is actually approaching (Laroche et al, 1995), the additional reaction time will have no impact and safety will be compromised. A number of factors must therefore be taken into consideration before determining which alarm is better with respect to safety.

2.4.2 Sound Localization

In general, it is easier to localize a frequency-rich signal than a signal with limited spectral content (see, for example, Butler and Planert, 1976; Butler, 1986; Trahiotis and Stern, 1989; Butler and Humanski, 1992; Hofman and Van Opstal, 1998; Racanzone et al, 1998). Deborah Withington, inventor of the broadband reverse alarm, demonstrated the advantage of broadband signals over conventional sirens on emergency vehicles (Withington, 1996, 1999, 2000; Withington and Paterson, 1998).

For reverse alarms, the results of a survey involving 1477 vehicles (of which 313 were equipped with broadband alarms) revealed that while both alarm types are recognized as effective danger warning signals, the broadband alarm is easier to localize and causes less noise nuisance than the tonal alarm. In fact, 80% of those surveyed stated that they could always correctly identify a reversing truck equipped with a broadband alarm, compared to only 10% for one equipped with a tonal alarm, and all reported that the broadband alarm was less annoying (Withington, 2004).

In 2005, the National Institute for Occupational Safety and Health (NIOSH) funded a study on alarm localization under controlled conditions at Washington State University (Lakatos and Miller, 2009). Two experiments were carried out in the laboratory, with human participants using headphones to listen to binaural recordings of alarm signals made during two simulations of a reversing vehicle approaching, with “direct hit” or “near miss” trajectories. The results did not reveal any conclusive advantage of either a tonal alarm or a broadband signal. A significant limitation of this study was the use of generic head-related transfer functions (KEMAR mannequin) rather than those specific to each individual, which required the elimination of trials in which there was front/back confusion, the most critical from a safety standpoint.

To ensure optimal safety and to take advantage of the benefits of tonal and noise-based alarms, Catchpole et al. (2004) studied different signals combining the characteristics of both alarm types. In a first localization task, eight participants with normal hearing were to indicate whether the signal (white noise, notched white noise from 1000 to 3000 Hz, notched white noise from 1000 to 10,000 Hz, 2000 Hz pure tone, ascending frequency sweep from 1000 to 3000 Hz, and descending frequency sweep from 3000 to 1000 Hz) was coming from the right or the left. Localization was more accurate and rapid with noise-based signals than the tonal signals, with performances being more accurate for white noise and less accurate for the 2000 Hz pure tone. In a second task, the same participants were to identify the signal heard while carrying out the localization task. Six stimuli were used, i.e., the three tonal signals individually and each in combination with the notched white noise (1000–3000 Hz). Localization was more accurate and rapid for the combined signals than for tonal stimuli, suggesting that it is possible to increase the effectiveness of a tonal alarm by adding noise. Finally, in the third part of the study, 18 participants rated, on a scale of 0 to 100, the degree of urgency evoked by three stimuli (noise + ascending frequency sweep, noise + descending frequency sweep, and noise + five harmonic complex tonal signal). In general, the ascending frequency sweep was deemed more urgent than the descending frequency sweep, which was in turn deemed more urgent than the complex tonal signal. While adding noise bands to a tonal signal could improve safety behind heavy vehicles compared to tonal alarms (at least for sound localization), the noise annoyance factor would not necessarily be reduced. This duality between safety and noise annoyance is the crux of the problem.

Hearing protection is also an important consideration in sound localization, with passive protectors being generally detrimental (Berger, 2003; Berger and Casali, 1997; Nixon and Berger, 1998; Noble et al, 1990; Atherley and Noble, 1970; Abel and Hey, 1996; Noble and Russell, 1972; Simpson et al, 2005; Bolia et al, 2001). To our knowledge, only a few studies have specifically examined the effect of hearing protectors on the localization of conventional reverse alarms compared to spectrally modified alarms (Alali and Casali, 2011; Casali and Alali, 2010; Alali, 2011).

In a first study, Alali and Casali (2011) examined the effect of seven hearing protection devices on the ability of individuals with normal hearing to localize a conventional alarm and a modified alarm (with additional components at 400 and 4000 Hz) in two levels (60 and 90 dBA) of pink noise. The alarms were routed through eight hidden loudspeakers, covering 360°, in eight hearing protection conditions, i.e., without HPD, with four types of earplugs (two passive and two augmented) and three types of earmuffs (one passive, one active dichotic and one active diotic). The participants were asked to identify the perceived position of the source, to the nearest degree. Head movements were allowed and the alarm's level was increased within each trial to simulate the sound of a vehicle approaching at a speed of 10 mph. For each of the dependent variables, only the performance with the diotic earmuffs was significantly different than all the other listening conditions, with and without hearing protection, a result that can be explained by the loss of interaural localization cues due to the device's single-microphone design. Overall, localization was better in the left/right plane compared to the front/rear plane, and more accurate in the low noise environment than the high noise environment, with a notable increase in front/rear confusion in the latter. The results showed some advantages of the modified alarm over the conventional alarm in the high noise environment, i.e.: (1) an approximately 5% reduction in angular error (up to 10% with some HPD and 5% without protection); (2) an approximately 10% reduction in left/right errors with some HPD and 4% without protection; (3) an approximately 3.5% reduction in front/rear errors; (4) an approximately 10% improvement in localization with some HPD and 3% without protection. Based on this study, it would seem that new hearing protection technologies do not improve localization compared to conventional passive protectors. Localization with and without hearing protection (with the exception of the diotic earmuffs) was relatively good (correct localization = 64.6–83.9%; left/right errors = 2.4–9.0%; front/rear errors = 4.0–12.7%; absolute deviation = 11.8–28.1%). It would have been interesting to quantify the contribution of head movements since Noble (1981), for example, demonstrated that horizontal localization of a narrowband noise centred on 1000 Hz with an HPD could be improved by head movements (24% without movement; 50% with movement), while an almost perfect performance (95%) was noted without protection when participants could move their heads. Similar results were obtained by the same researchers in a follow-up study comparing the performance of electronic earplugs with performance without hearing protection in another group of participants (Casali and Alali, 2010).

3. STUDY OBJECTIVES

The literature review revealed no clear consensus as to whether the new broadband alarm technology is better than conventional tonal alarms for ensuring the safety of people working in proximity to reversing vehicles. The overall objective of this study is to determine if the recent broadband reverse alarm technology can improve worker safety, whether or not hearing protection is being used. The study focuses solely on worker health and safety, not on noise pollution.

More specifically, the study addresses the following objectives:

1. To determine whether broadband alarms comply with the SAE J994 (2009) standard;

2. To determine whether the phenomenon of sound wave interference noted with conventional tonal reverse alarms also exists with the new broadband technology, by measuring sound imission patterns behind heavy vehicles according to the ISO 9533 standard (fixed receiver locations) and by using microphone sweeps (mapping) in various work environments;

3. To compare the performance of three reverse alarms: conventional tonal (single pure tone), multi-tone (three pure tones) and broadband (noise) using psychoacoustic tasks (sound detection thresholds, equal loudness, perceived urgency and sound localization) performed by people with normal hearing, with or without HPD, in background noises typically encountered in work environments where vehicles are reversing;

4. To make recommendations on the use of broadband reverse alarms if it is demonstrated that they are more advantageous.

4. METHOD

Both objective and subjective measurements were carried out in this study to compare the three selected alarms. In the first part, microphone measurements were used to describe sound field propagation uniformity of each alarm behind a given vehicle. These objective measurements were carried out in the field, using vehicles and terrain configurations representative of actual operating conditions. In the second part of the study "subjective" measurements were performed in the laboratory using normally hearing individuals, and included psychoacoustic tasks related to sound detection, equal loudness, perceived urgency and sound localization. The following sections describe the choice of reverse alarms and the methods used for the objective and subjective measurements.

4.1 Selection of Reverse Alarms

The spectral content[2] of each of the selected alarms (tonal, multi-tone and broadband) is shown in Figure 2, while their main characteristics are presented in Appendix C, particularly their temporal aspects and directivity pattern, as measured in a semi-anechoic environment.

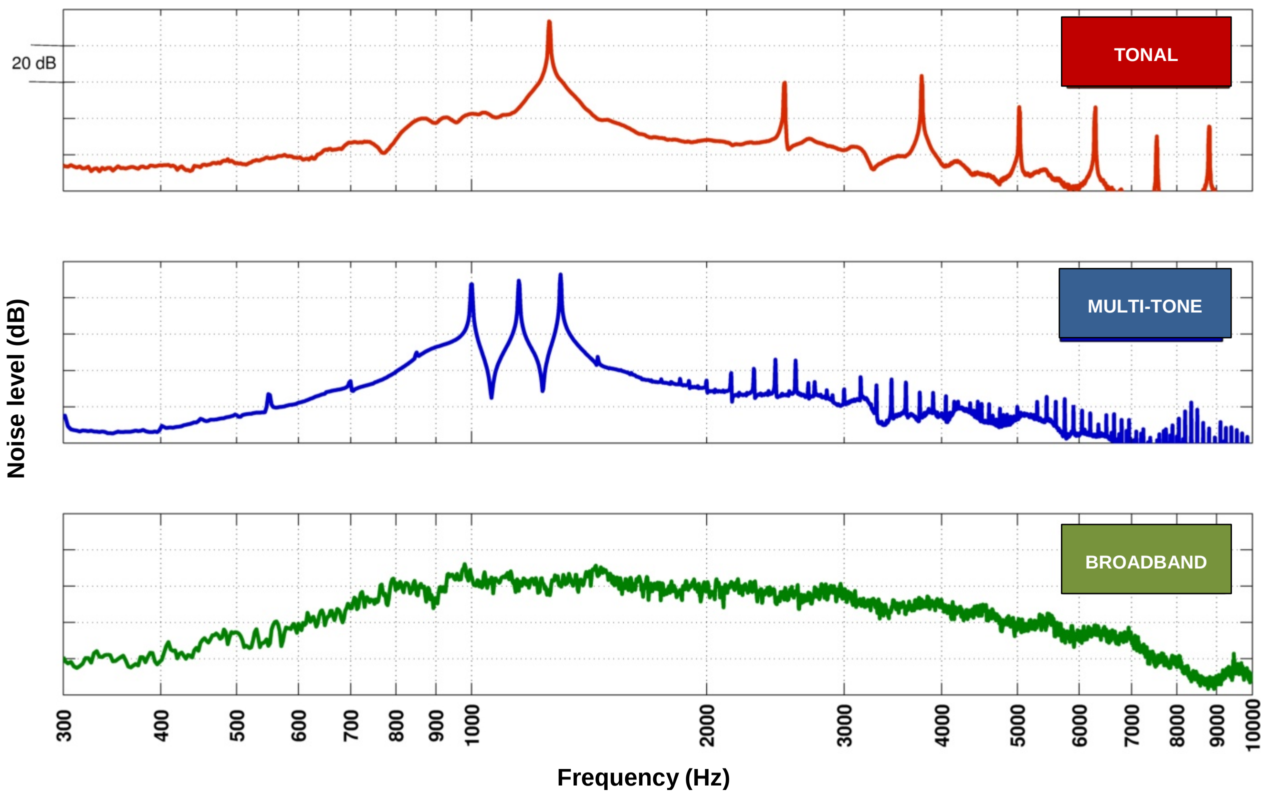

Figure 2: Spectral content of the alarms

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[2] The alarm levels were obtained using a 20-sec. microphone recording at approximately 1 m behind a stationary vehicle, with the alarm in operation.

4.1.1 Tonal Alarm

The tonal alarm, model 73030 manufactured by Grote (Grote 2011), consists mainly of a 1264 Hz pure tone and much weaker higher frequency harmonics, and is easily recognized as the well-known "beep-beep" alarm signal found on most vehicles. Each alarm cycle has a nominal duration of 990 ms. (a 500-ms. "beep" and a 490-ms. pause).

4.1.2 Multi-tone Alarm

The multi-tone alarm, a three-frequency (1000, 1150 and 1300 Hz) pulsed signal, is not commercially available. It was, however, determined by Laroche (1995) to be the most audible alarm signal during a study on the optimal acoustic characteristics of reverse alarms, and was therefore included in this study for comparative purposes. The multi-tone signal was digitally synthesized and generated using the 73030 Grote alarm device, by replacing the tonal signal of the unit with an externally simulated three-frequency (1000, 1150 and 1300 Hz) signal. The time trace of the multi-tone alarm is identical to that of the tonal alarm.

4.1.3 Broadband Alarm (BBS)

The broadband alarm, a BBS-107 Heavy Duty marketed by Brigade Electronics (Brigade Electronics 2011), produces a "shh-shh" sound rather than the "beep-beep" of conventional alarms. Its acoustic energy is spread over a larger spectrum, mainly from 700 Hz to 4000 Hz. Each alarm cycle has a nominal duration of 770 ms. (400-ms "shh" and 370-ms pause).

4.2 Objective Measurements: Sound Propagation Behind Vehicles

Few standardized protocols exist for the field evaluation of reverse alarms. The ISO 9533 (1989) standard prescribes an acoustic testing method and establishes criteria necessary to assess the acoustical performance of warning devices mounted on earth-moving machinery meant to warn workers of potential danger in the vicinity of moving machinery. Measurement trials are performed for a specific vehicle and alarm combination, using a stationary vehicle. To test various alarms on different vehicles, and to make the method more instructive and flexible, the ISO 9533 approach was slightly modified. The resulting measurement series adopted for this study are presented in the following two sections.

4.2.1 Series 1: Alarm Level Adjustments

In this measurement series, seven microphones were placed behind a stationary heavy vehicle equipped with a reverse alarm, as described in ISO 9533 and Appendix D. In the first step, the vehicle motor was operating at maximum governor engine speed, or high idle (transmission in neutral, engine revving). The sound pressure levels[3] were measured at each of the seven microphone positions. The engine was then switched off, the alarm was activated and its level was manually adjusted in such a way that the SPL at all the microphones was at least equal to or greater than the levels originally recorded (motor revving, alarm off). In other words, an attempt

[3] L_{FMAX}, fast integration time weighting, *A* frequency weighting, duration of measurement: 20 sec.

was made to adjust the alarm level to obtain a signal-to-noise ratio (SNR) greater than or equal to 0 dB at all the microphones. The operation was repeated for each alarm; thus enabling a comparison of the SNR obtained at all the microphones for each alarm, and a determination as to whether or not some alarms generate greater SPL variations in their sound propagation behind heavy vehicles.[4]

Two alarm mounting scenarios were considered. In the "realistic" scenario, measurements were made with the alarm device mounted "as is" on the vehicle (without any modification), while in the "ideal" scenario the alarm device was centred on the vehicle, unobstructed, and facing outward. Figure 3 shows examples of both mounting scenarios.

(a) (b) (c)

Figure 3: Examples of alarm devices mounted on a heavy vehicle: (a) Grote alarm in the "realistic" scenario; (b) Grote alarm in the "ideal" scenario; (c) BBS in the "ideal" scenario.

4.2.2 Series 2: Sound Field Uniformity

To document in greater detail the alarm's sound field uniformity behind heavy vehicles, a second set of measurements was carried out, with the alarm operational, using a microphone to continuously record sound pressure levels along various axes. As illustrated in Appendix D, a 30-40 second sweep was performed at a steady pace along nine straight lines (numbered from 1 to 9) and two curvilinear arches, each situated at 2 and 4 m from the vehicle.[5] Sweep time was longer for the two curvilinear arches than for the straight lines (30-40 seconds). During these measurements, each alarm was set to its original level (as per the first set of measurements described in 4.2.1). Recordings were analyzed using MATLAB calculation routines yielding L_{eq} values for every second, thus representing alarm levels at various positions in the area directly behind the vehicle. An interpolation algorithm was then used to produce sound pressure level contour maps, and the entire process was repeated for each alarm. Results allowed direct comparisons across the three alarms of sound field uniformity behind a given heavy vehicle.

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[4] Unlike what is proposed here, ISO 9533 dictates that the signal-to-noise ratio must be recorded with the alarm set at the regular volume (at installation and during normal use). This SNR must be equal to or above 0 dB for the alarm to be deemed in compliance with the standard.

[5] The sweep was carried out manually by a member of the research team, using a pole-mounted microphone and maintaining as constant a speed as possible while walking slowly with the pole.

4.2.3 Selection of Measurement Locations

Members of the follow-up committee were helpful in identifying locations for field testing, with the objective of carrying out measurements in various noisy environments, using various types of vehicle and terrain configurations. Two companies granted the research team access to their facilities, and measurements were performed in three different vehicle/terrain configurations, as described in Appendix E. Industry type is also provided for informational purposes.

4.2.4 Selection of Noisy Environments

Recordings of various background noises were also carried out in the field for use in laboratory psychoacoustic trials (subjective testing), with the objective of recreating background noises closely mirroring real work environments. As such, four different noisy backgrounds covering a range of levels, frequency content and temporal characteristics were chosen. Their frequency content is illustrated in Figure 4, while a brief description is provided in Appendix E.

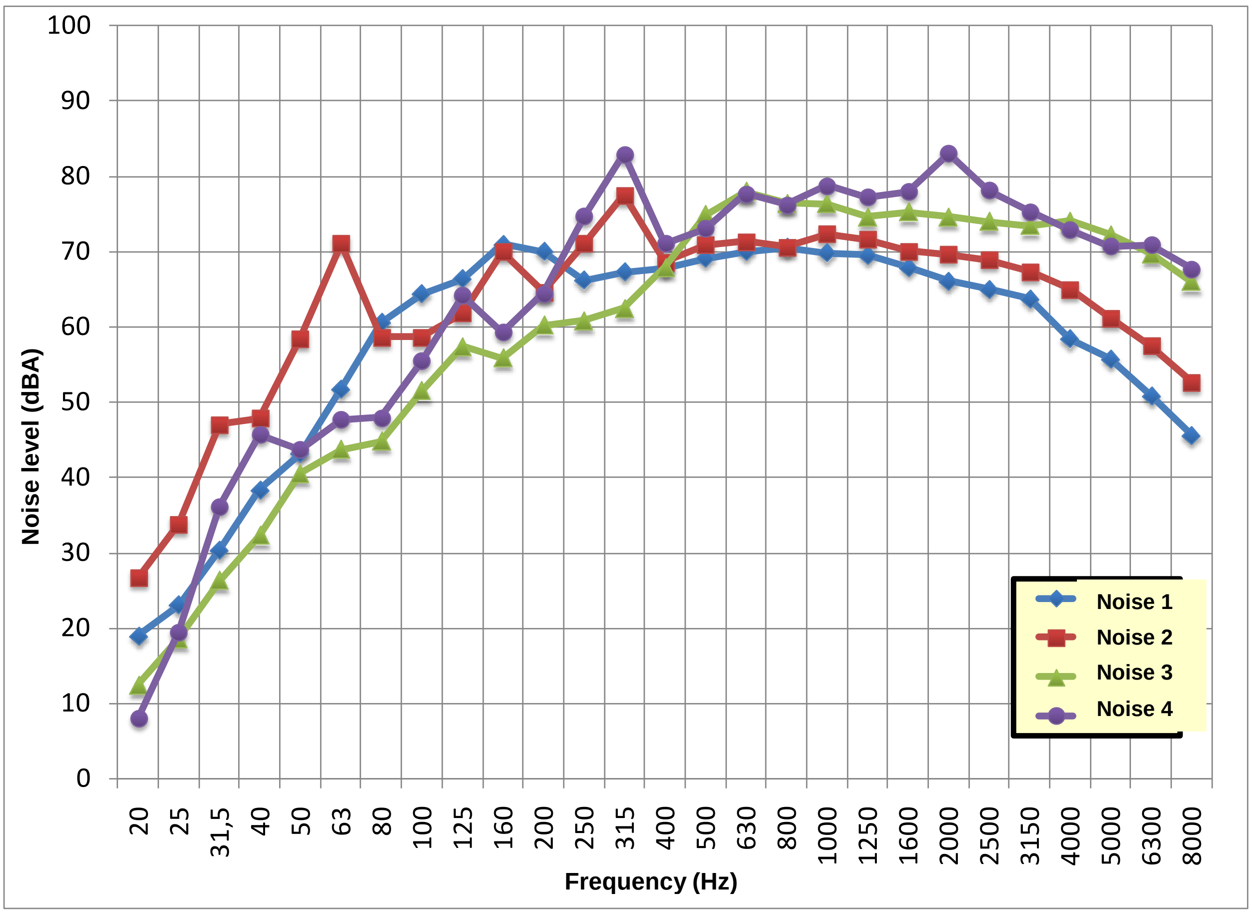

Figure 4: Spectral content of the four selected noises. Overall sound pressure levels: Noise 1 – 80.5 dBA; Noise 2 – 83.3 dBA; Noise 3 – 85.9 dBA; Noise 4 – 89.6 dBA

4.3 Subjective Measurements: Psychoacoustic Testing

4.3.1 Participants

Twenty-four young adults, aged from 22 to 31 (mean = 25; standard deviation = 2.3), participated in the psychoacoustic trials carried out in the laboratory. All the participants met the following selection criteria: (1) normal hearing in both ears, as defined by pure tone detection thresholds via air conduction equal to or below 25 dB HL (from 250 to 8000 Hz), (2) a negative otological history, and (3) a normal tympanogram (static compliance = 0.30 to 1.70 cm^3; external auditory canal volume = 0.9 to 2.0 cm^3; gradient = 51 to 114 daPa; pressure = -150 to +50 daPa) [as per Martin and Clark, 2003].

4.3.2 Auditory Screening

Before taking part in the study, participants were required to read an information letter, sign a consent form and fill out an auditory history questionnaire. Participant recruitment and testing were carried out in accordance to the ethical policies in effect at the University of Ottawa's Office of Research Ethics and Integrity (Certificate H 12-09-0). To ensure that the participants met the selection criteria, a Welch Allyn otoscope was used to examine the external auditory canals and eardrums, while a GSI 38 tympanometer was used to assess middle ear integrity. Auditory screening was also carried out using a clinical audiometer (Inter-acoustics AC 40) coupled with Telephonics TDH-39P headphones, during which participants were required to press a button upon hearing pure tones of different frequencies (between 250 and 8000 Hz). Individuals who satisfied all the selection criteria were then invited to take part in the listening tests described in the following paragraphs.

4.3.3 Experimental Conditions in the Laboratory

During the laboratory measurements, the participants took part in four listening tasks (detection thresholds, equal loudness, perceived degree of urgency, and sound localization), all performed with and without hearing protection devices. Two test sessions lasting 90 to 120 minutes were required, with detection thresholds, equal loudness and perceived urgency being assessed in the first session and sound localization in the second. An earmuff-type protector (PELTOR Optime 95; NRR[6] = 21 dB) was randomly assigned to half the participants, while an earplug-type protector (EAR Ultrafit; NRR = 25 dB) was used for the remaining 12. The measurements were carried out in audiometric booths at the Hearing Research Laboratory of the University of Ottawa. A description of all measurements and instrumentation is presented in Appendix F.

4.3.4 Detection Thresholds

Detection thresholds are defined as the sound pressure level at which an individual correctly perceives the target signal 50% of the time. To familiarize the participants with the signals used, the three alarms and four noises were initially presented in the sound field. Afterward, a formal familiarization step was undertaken in quiet. Using a tablet computer, the participants were

[6] NRR = Noise Reduction Rating.

required to adjust (by selecting the "+" and "-" symbols) the level of the first alarm by using 2 dB steps, until the alarm was just barely audible in an ascending excursion. When satisfied with their response, the participants repeated the procedure with the two other alarms, and then pressed the "end" key to save the results and proceeded to the next trial. Each trial included three threshold measurements, one per alarm type. After familiarization, the procedure was repeated in quiet and in each of the four background noises, with the presentation order of the noises and alarms having been previously determined for each participant so as to ensure adequate counterbalance. The initial alarm level varied across alarms and trials, but was always greater than that of the expected threshold. Each condition was also repeated to determine threshold measurement reliability using this approach. In total, 20 trials consisting of 60 thresholds were performed; 30 thresholds each with and without HPD.

4.3.5 Equal Loudness

Loudness refers to the subjective appraisal of a sound's intensity. Loudness depends not only on actual sound pressure levels, but also on other acoustic characteristics of the signal, such as the frequency content and duration, and the characteristics of the noise. An equal loudness paradigm was used, with the reference signal always being the conventional alarm presented in a SNR of 0 dB in each of the four noises (thus at 81 dBA, 83 dBA, 86 dBA and 89 dBA for noises 1, 2, 3 and 4, respectively). Using a tablet computer, the participants were required to activate and listen to the conventional alarm. Then, they had to activate the next alarm and adjust its level (using the "+" and "-" keys) until it was judged to be equally loud as the conventional alarm. The same was done with the final alarm. Participants were encouraged to repeat the procedure several times, until they were satisfied with their responses, and then press the "end" key to save the results. Each trial thus consisted of two comparisons, by adjusting the level of two alarms (multi-tone and broadband) to achieve a level of loudness equivalent to that of the reference signal (conventional tonal alarm). A practice run was carried out in one of the four noises to familiarize participants with the task at hand. The procedure was then repeated four times (one trial per noise) without and four times with hearing protection (earmuffs or earplugs), for a total of 16 comparisons. The presentation order for the noises and alarms was counterbalanced across the participants.

4.3.6 Perceived Urgency

Two sounds of equal loudness do not necessarily convey the same degree of urgency. Like loudness, the urgency evoked by a signal depends not only on the sound level, but also on several other acoustic characteristics of the signal (Hellier and Edworthy, 1989; Edworthy et al, 1991; Edworthy and Stanton, 1995; Haas and Casali, 1995; Haas and Edworthy, 1998), including its frequency content, temporal characteristics and familiarity as a warning sound. Participants were asked to rate the urgency of the three alarms presented randomly at different SNR (-6 dB, 0 dB and 6 dB), using a sliding scale of 0 to 100, with 0 indicating that the alarm evoked little to no sense of urgency and 100 representing a very urgent situation. During each trial, in one given background noise, nine urgency ratings were required (one rating per alarm x three alarms x three SNR) After each rating, participants pressed the "next" key to hear the following signal. An initial familiarization consisted of nine ratings in one of the background noises. The procedure was then repeated for each of the four noises, with and without hearing protection (earmuffs or earplugs), for a total of 72 ratings (9 ratings × 4 noises × 2 hearing protection conditions). The presentation order of the noises, alarms and SNR was randomly selected by the testing software.

4.3.7 Sound Localization

Sound localization was tested in a single noise condition (noise 2 adjusted to 80 dBA), by presenting a three-second alarm signal through 12 loudspeakers arrayed in a 180° arc, with a 15° separation between each loudspeaker. Since the repetition cycle of the broadband alarm is shorter than that of the tonal and multi-tone alarms, four cycles (“shh, shh, shh, shh”) of the broadband alarm were heard, compared to only three cycles (“beep, beep, beep”) for the other two alarms. In addition, to simulate an approaching truck reversing at a speed of 10 mph (4.4 m/sec.), the sound pressure level was increased for each successive cycle of the alarm according to the spherical spreading rule (+6 dB for each halving of distance), culminating in 80 dBA at the end of the alarm signal, thus a 0-dB SNR two seconds (8.8 m) before the presumed impact. The two-second interval was chosen based on the SAE J1741 standard (1999) and corresponds to the delay in reaction time upon hearing a warning sound.

While holding a sheet illustrating the loudspeaker array, participants were required to identify, by calling out a number from 1 to 12, the loudspeaker thought to have emitted the signal. To assess the performance in the most difficult situations and to avoid potential ceiling effects, which could limit the comparisons of results across the different alarms, head movements were not allowed. Sound localization was measured in the left/right horizontal plane (individuals with their back toward the middle of the loudspeaker array, or speakers 6 and 7)) and in the front/back horizontal plane (individuals facing either the “0°” or the “180°” position), thus taking into account the two types of localization error that are possible in the horizontal plane (right/left and front/back confusions). Familiarization consisted of presenting the alarm stimulus from each of the loudspeakers in a sequential manner (1 to 12 sweep), with the loudspeakers placed behind. In each of the three experimental conditions (loudspeakers placed behind, to the right and to the left), each alarm was presented randomly through each of the loudspeakers, with and without hearing protection, for a total of 432 presentations (216 without hearing protection and 216 with either earmuffs or earplugs). To limit changes in participants’ position, each alarm was presented in turn in a given condition before proceeding to the next. The presentation order of the conditions and alarms within each condition was counterbalanced across participants.

5. RESULTS

5.1 Compliance with the SAE J994 Standard

To be in compliance with the SAE J994 standard (2009) a reverse alarm must meet a set of performance requirements. Acoustical testing performed in the laboratory is described in the standard, and consists of measuring alarm levels using a microphone placed 1.2 m in front of the device, with an acoustical barrier on the ground, placed between the microphone and the device, to limit reflections.

Paragraph 6.1 of the standard states: "The predominant sound frequency of the alarm shall be defined as a frequency that produces the highest A-weighted sound pressure level. The acceptable frequency range is 700 to 2800 Hz."

Based on their spectrum (Figure 2), it is clear that both tonal and multi-tone alarms meet this requirement, with a maximum sound pressure level in the vicinity of 1000-2000 Hz. The rather imprecise definition of "predominant sound frequency" in the standard may, however, pose greater challenge in determining compliance for broadband alarms, with energy spread over a larger frequency span. There is indeed no one recognizable predominant frequency, since no peaks are clearly apparent in the spectrum.[7] However, if the technical specifications of the standard are applied literally ("the frequency that produces the highest A-weighted sound pressure level"), a maximum sound pressure level can easily be identified between 700 and 2800 Hz, as prescribed by the standard.

5.2 Objective Measurements: Sound Propagation Behind Vehicles

5.2.1 Series 1: Alarm Level Adjustments

Table 1 presents the results of the level adjustment procedure described in section 4.2.1. The means and standard deviations of the signal-to-noise ratio (expressed in dB) at the seven microphone positions are presented, as is the level (in dB(A)) measured at 1 m (reference microphone).

[7] The SAE J994 standard was initially drafted at a time when only tonal alarms were used. The proposed definition of "predominant sound frequency" was therefore probably suitable at the time and did not cause any real interpretation issues.

Table 1: SNR (dB) means and standard deviation values and reference microphone levels (dB(A))

“Ideal” mounting						
Alarm type	**Site 1**		**Site 2**		**Site 3**	
	Mean (standard deviation)	Level at 1 m	Mean (standard deviation)	Level at 1 m	Mean (standard deviation)	Level at 1 m
Tonal	6.9 (4.2)	107.2	8.0 (5.9)	112.0	3.2 (2.9)	106.0
Multi-tone	3.9 (2.3)	99.4	5.4 (4.0)	105.2	4.9 (3.1)	102.8
Broadband	1.9 (1.2)	99.3	3.1 (2.9)	104.9	1.0 (0.7)	102.1
“Realistic” mounting						
Alarm type	**Site 1**		**Site 2**		**Site 3**	
	Mean (standard deviation)	Level at 1 m	Mean (standard deviation)	Level at 1 m	Mean (standard deviation)	Level at 1 m
Tonal	6.4 (4.7)	109.0	5.4 (3.9)	108.6	3.9 (2.4)	97.1
Multi-tone	3.5 (2.5)	98.5	3.9 (3.4)	99.7	3.0 (2.8)	104.7
Broadband	1.7 (1.6)	97.4	2.3 (2.0)	103.8	2.1 (1.3)	101.4

With the exception of the “realistic” position at site 3, sound pressure levels at 1 m are higher with the tonal alarm to satisfy the SNR≥0 dB criterion at all microphones. The lower level of the tonal alarm at 1 m could, in this case, be attributed to the microphone being placed in an area of weaker sound pressure levels, given the significant spatial variations reported in Table 1 and illustrated in Appendix G. Moreover, the SNR means and standard deviations are noticeably weaker for the broadband alarm than for the tonal and multi-tone alarms.

5.2.2 Series 2: Sound Field Uniformity

The results of the microphone sweep described in section 4.2.2 are illustrated in Figure 5 for site 1 and in Appendix G for sites 2 and 3, and consist of sound pressure level contour maps (also called “imission patterns”) behind the vehicle, where overall alarm levels (Leq in dB(A)) are represented by different colours. Each change in colour corresponds to a 3-dB variation in overall level. A map was generated for each combination of alarm/site/mounting condition, for a total of 18 maps. From these maps, it is also possible to extract the evolution of sound pressure levels along specific axes, as illustrated in Figure 6 for the axis directly behind the vehicle (axis 5 in Figure 14, Appendix D).

Unsurprisingly, the broadband signal produces a much more uniform sound field, not only directly behind the vehicle, both further away and laterally. Sound pressure levels for the broadband signal also decrease in a consistent manner with distance, unlike tonal alarms that display significant level variations due to acoustic interference. In some cases (e.g., figures 6 and 18 in Appendix G), abrupt variations of 15 to 20 dB are observed for the tonal alarm over distances of less than a metre. Level variations are much smaller (up to 7 or 8 dB) for the multi-tone alarm, suggesting that sound field uniformity can be appreciably improved by additional tonal components.

Finally, it can be seen from the imission patterns that the alarms emit sound slightly more towards the centre than to the sides, a finding consistent with the measured directivity patterns presented in Figure 12 (section C.5 of Appendix C).

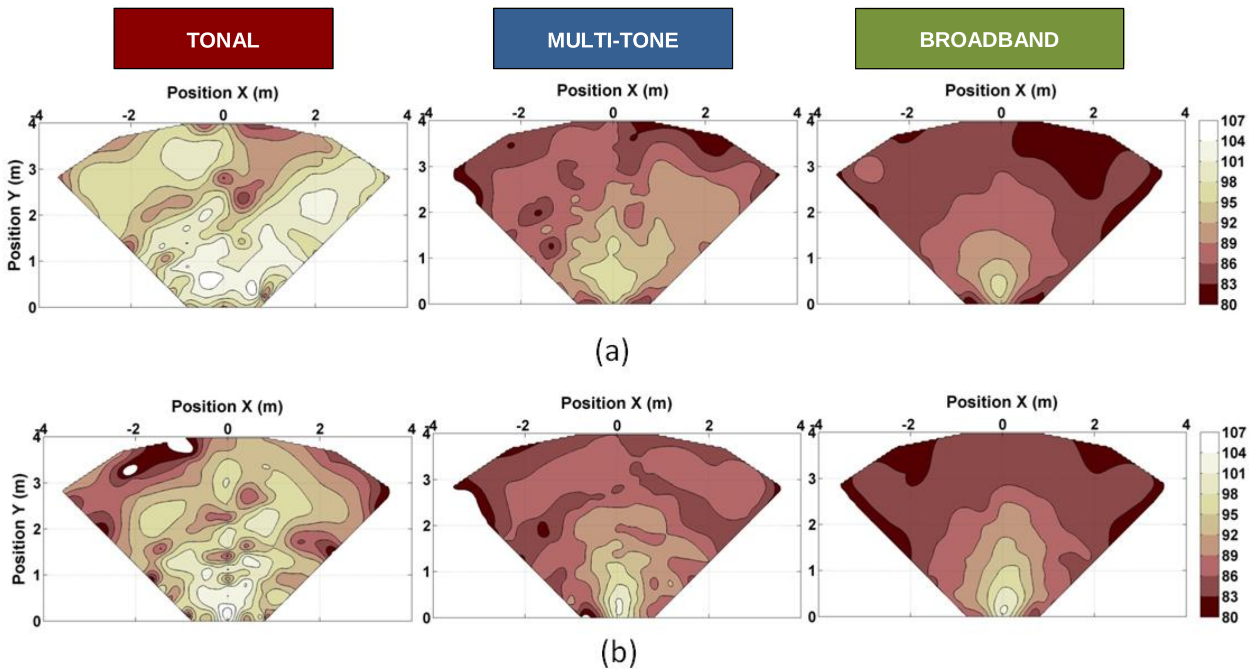

Figure 5: Alarm levels (Leq: dB(A)) behind the vehicle at Site 1: (a) alarm in “realistic” position; (b) alarm in “ideal” position

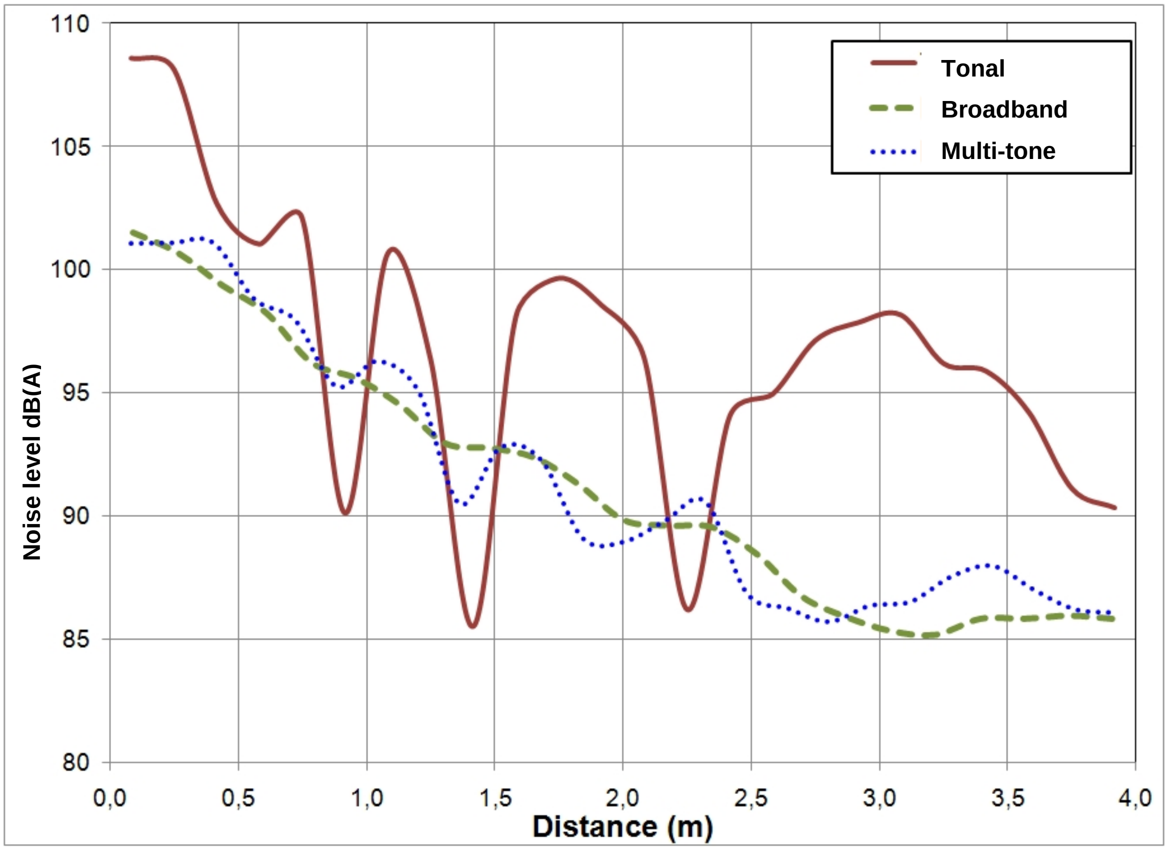

Figure 6: Alarm levels (Leq: dB(A)) along axis 5 from Figure 14 (site 1, alarm in "ideal" position)

5.3 Subjective Measurements: Psychoacoustic Testing

5.3.1 Detection Thresholds

Mean detection thresholds in noise are provided in Figure 7 for the three alarms, with and without protection (upper panel = earmuff group; lower panel = earplug group). Detection thresholds are expressed as a signal-to-noise ratio (dB SNR), by subtracting the noise level (81 dBA, 83 dBA, 86 dBA or 89 dBA for noises 1 to 4, respectively) from each threshold measured in dBA.[8] As threshold measurements were repeated, individual thresholds were obtained by averaging both thresholds in a given listening condition, for each subject.

[8] It is important to note that for all the psychoacoustic trials, the alarms' reported sound level is that of the active portion ("on") of the signal, or 3 dB above the mean level measured over several cycles with a sound level meter.

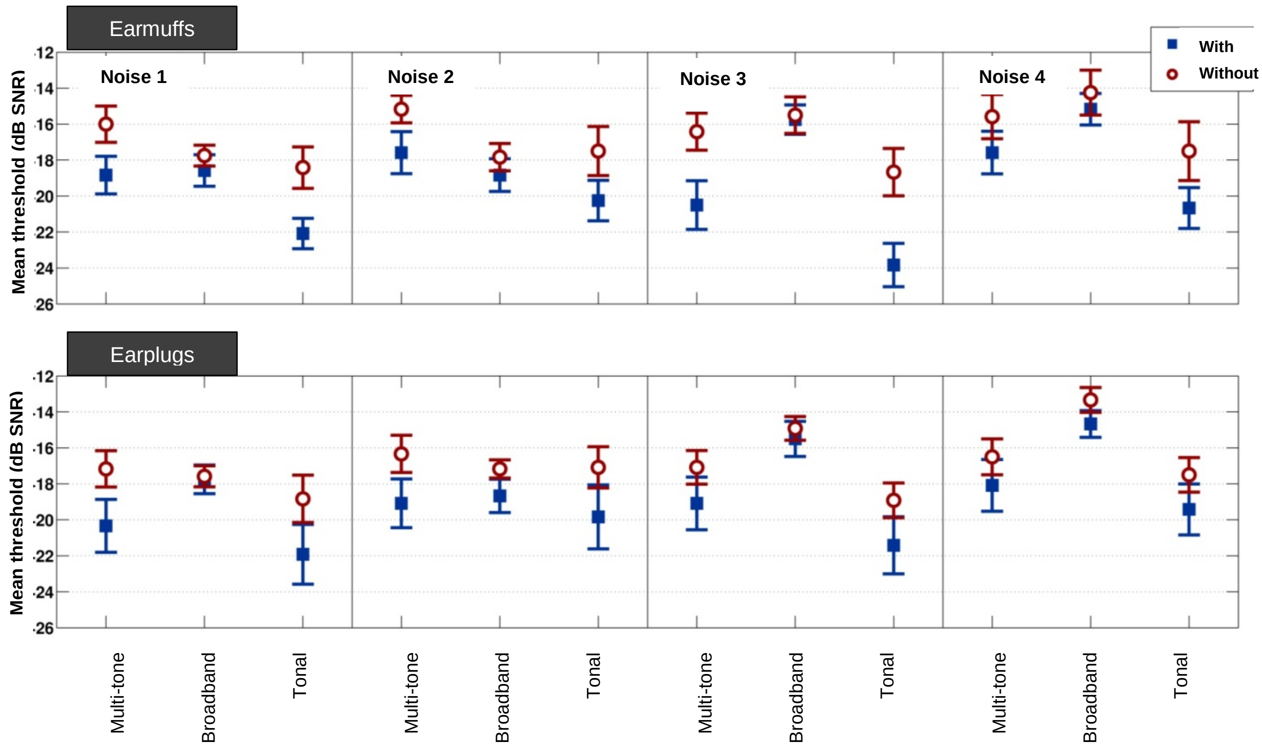

Figure 7: Mean detection thresholds for the reverse alarms in four noisy environments, with and without hearing protectors. The error bars represent +/- 1 standard error of the mean.

It can be noted in Figure 7 that error bars with and without hearing protection often intersect, particularly in the case of earplugs, suggesting similar detection thresholds in both listening conditions. Differences between unprotected and protected thresholds are however more frequent with earmuffs. Alarm and noise type also appear to be influential, and detection data seems to follow similar trends in both groups (earmuffs and earplugs). To verify this observation and confirm the existence of main effects and interactions among factors, statistical analyses were performed.

Results of the statistical analyses are found in Appendix H.1 and reveal significant main effects for the three intra-subject factors (alarm type, noise, and HPD use) and significant interactions among the factors of alarm type and noise, alarm type and HPD use, as well as among the three intra-subject factors. On the other hand, HPD type (inter-subject factor) does not seem to significantly impact on detection thresholds.

5.3.2 Equal Loudness

The participants were required to adjust the level of the multi-tone and broadband alarms to achieve loudness (perception of sound intensity) identical to that of the reference tonal alarm presented at 0 dB SNR in each of the four selected noises (81 dBA for noise 1, 83 dBA for noise 2, 86 dBA for noise 3 and 89 dBA for noise 4). Data express differences in alarm levels relative to the tonal alarm, a positive (or negative) difference indicating that the alarm was adjusted to a sound pressure level higher (or lower) than the tonal alarm to reach the same loudness. Results are summarized in Figure 8 for the two alarms compared to the tonal alarm, with and without protection, in the four background noises (left panel = earmuff group; right panel = earplug group).

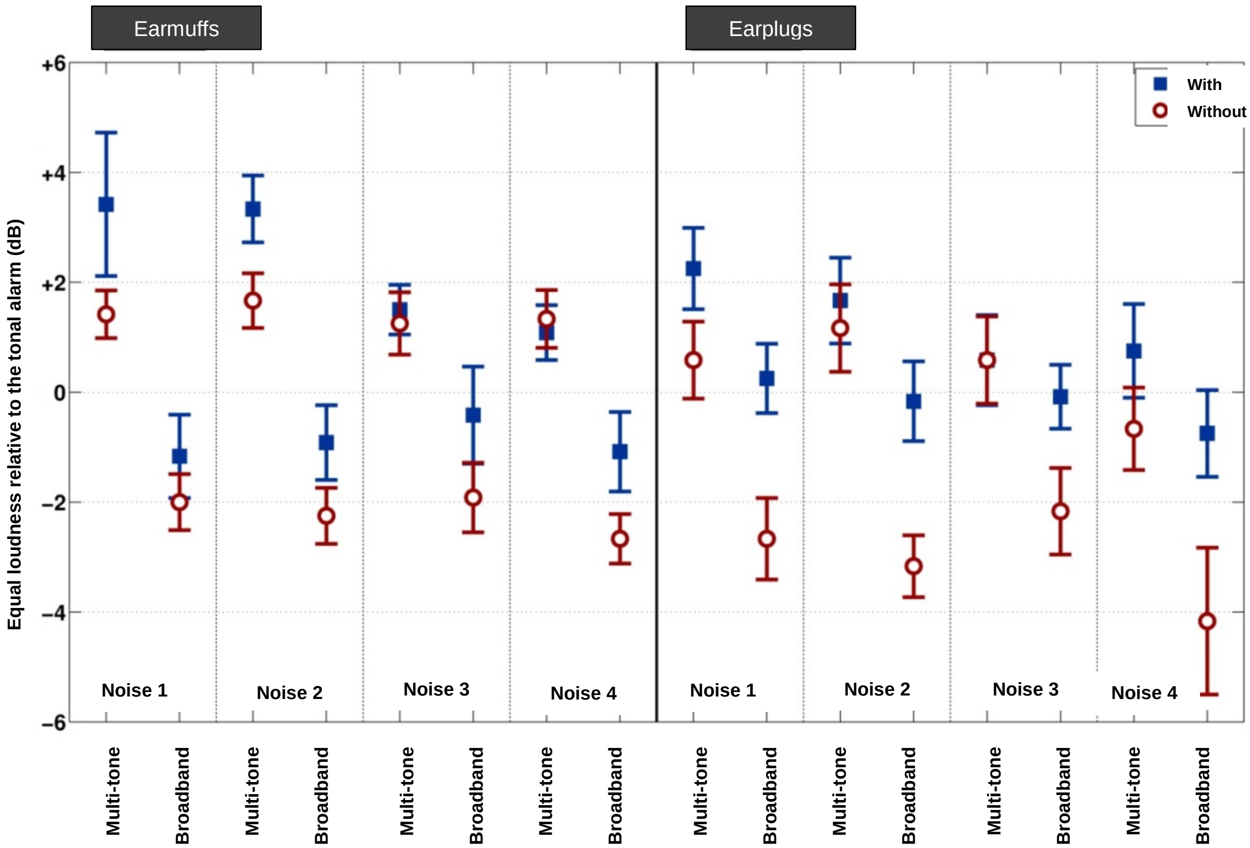

Figure 8: Equal loudness relative to the tonal alarm in four noisy environments, with and without hearing protectors. The error bars represent +/- 1 standard error of the mean.

Although the error bars for data with and without HPD intersect in many cases, suggesting similar results in both listening conditions, several data points comparing protected and unprotected performances are clearly distinct, especially for the broadband alarm in the group of participants using earplugs. Indeed, the alarm factor seems to play a particularly important role in judging loudness. To verify these observations and confirm the existence of main effects and interactions among factors, statistical analyses were performed.

The results of the statistical analyses are found in Appendix H.2 and reveal significant main effects for the three intra-subject factors (alarm type, noise and HPD use) and significant interactions between alarm type and noise, and between alarm type and HPD use. However, HPD type (inter-subject factor) does not seem to have a significant effect on results.

5.3.3 Perceived Urgency

Figure 9 presents mean perceived urgency, on a scale of 0 to 100, evoked by the three alarms presented at three SNR, with and without protection, in each of the four noises (upper panel = earmuff group; lower panel = earplug group).

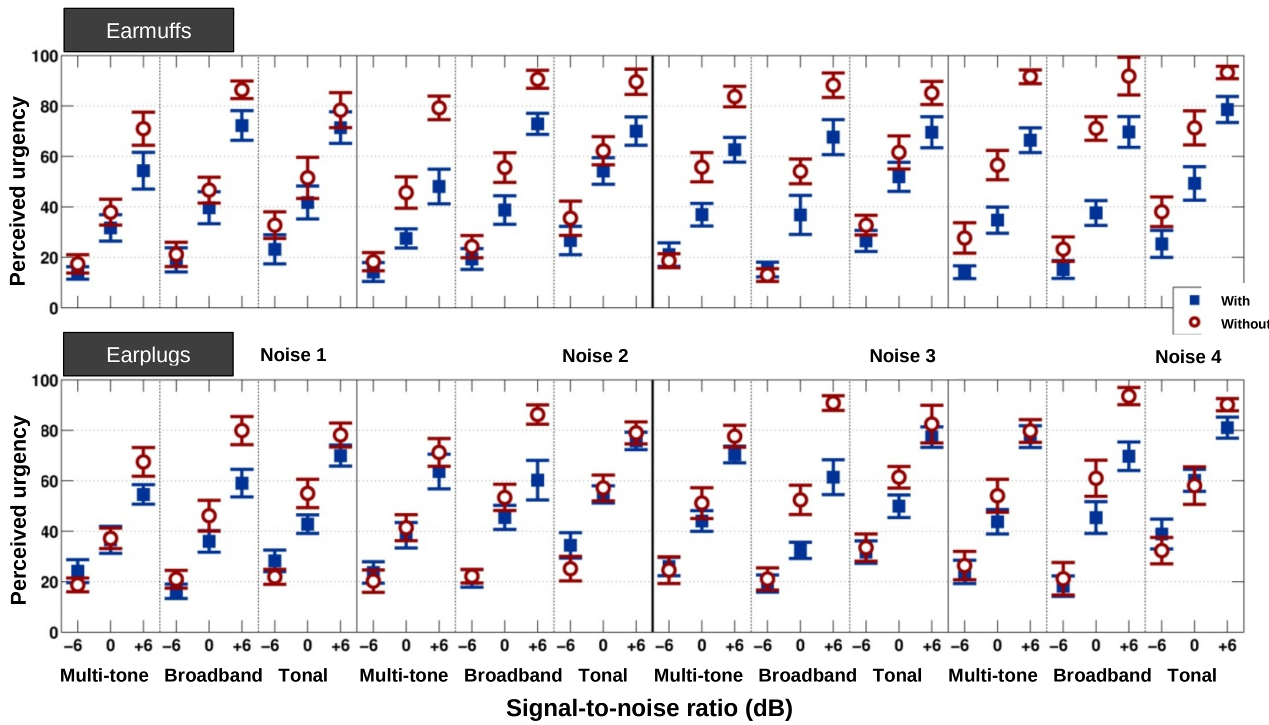

Figure 9: Degree of perceived urgency (scale of 0 to 100) evoked by the three alarms presented in four noisy environments at three different signal-to-noise ratios, with and without hearing protectors. The error bars represent +/- 1 standard error of the mean.

HPD use appears to have a significant effect on perceived urgency, since differences in unprotected and protected results are often observed (no intersecting error bars) with earmuffs and earplugs It is also clear that, irrespective of alarm and noise type, the SNR plays a crucial role in urgency ratings, with urgency increasing with presentation level for all alarms and conditions tested. The types of alarm and noise factors also appear to influence the degree of urgency perceived. To verify these observations and confirm the existence of main effects and interactions among factors, statistical analyses were performed.

The complete statistical analysis of the results is found in Appendix H.3. The earmuffs and earplugs were analyzed separately. For the earmuffs, significant main effects for the four intra-subject factors (alarm type, noise, HPD use and presentation level), second-order interactions between alarm type and noise, between alarm type and presentation level, and a significant third-order interaction among alarm type, HPD use and presentation level were noted. In the case of earplugs, the number of significant effects and interactions was lower, with significant main effects for noise, HPD use and presentation level, as well as a significant second-order interaction between alarm type and HPD use.

5.3.4 Sound Localization

Two dependent variables (angular error and percent of left/right confusions for loudspeakers behind or front/back confusions for loudspeakers on either side) were measured during the sound localization tasks. In quantifying angular error, confusion between two adjacent loudspeakers consists of a 15° error, independently of the direction of the error, while confusion between positions separated by two loudspeakers corresponds to a 30° error, and so on. Individual angular error is the arithmetic mean, in degrees, of errors made over all 24 presentations.

Left/right and front/back confusion occurs when participants identify the sound source as coming from a quadrant opposite to the actual stimulus. As illustrated in Appendix F.2, the experimental set-up forms two 90° quadrants, delimited by loudspeakers 1 to 6 and loudspeakers 7 to 12. It should be noted that confusion between loudspeakers 6 and 7 is considered a left/right confusion when the loudspeakers are behind, but not a front/back confusion when loudspeakers are placed on either side. In fact, data from a previous study (Vaillancourt et al, 2011) using these same experimental conditions with normally-hearing listeners revealed, for loudspeakers to the side, a mean angular error (11°) similar to the 15° separation found between adjacent loudspeakers. Front/back confusions therefore do not include errors in distinguishing loudspeakers 6 and 7, because such an error could potentially be attributed to difficulties in distinguishing adjacent loudspeakers, rather than front and back per se. With loudspeakers placed behind, the mean angular error in individuals with normal hearing is only 6° (Vaillancourt et al, 2011), which is clearly less than the 15° separation between loudspeakers 6 and 7, and confusion between the two could thus be considered a true left/right error. For each listening condition, individual confusion percentages were calculated by dividing the number of times there was confusion by 24 (number of presentations) and then multiplying by 100.

Sound localization results for the three alarms are summarized in Figure 10, with and without hearing protection, in the three loudspeaker arrangement conditions (upper left panel = mean angular error with earmuffs; upper right panel = mean angular error with earplugs; lower left panel = confusion percentage with earmuffs; lower right panel = confusion percentage with earplugs).

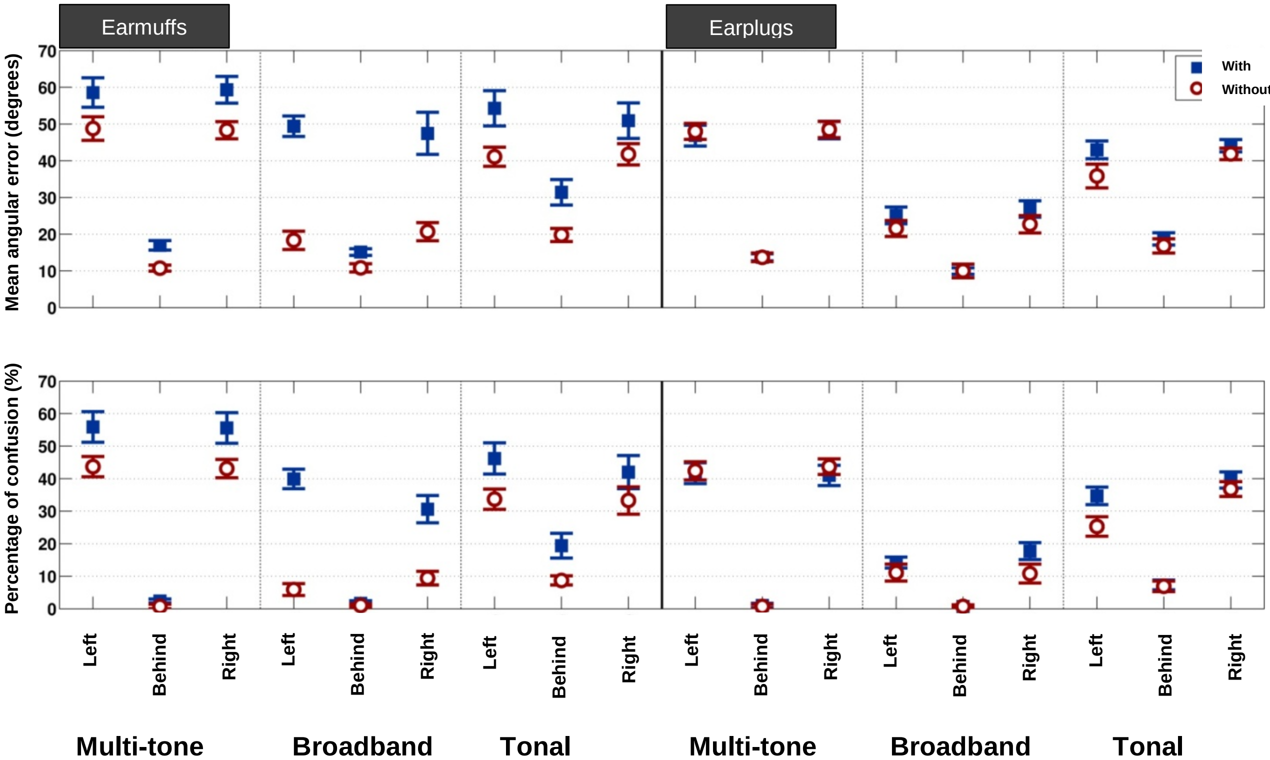

Figure 10: Mean angular error (upper panel) and percentage of confusion (lower panel), with and without hearing protectors. The error bars represent +/-1 standard error of the mean.

With the use of earmuffs, little intersection in the error bars is noted for data with and without hearing protection, suggesting significantly different performances; while unprotected and protected results share greater similarities in the group using earplugs. As anticipated, unprotected performances also appear similar in both groups. However, sound localization seems more accurate with earplugs than with earmuffs, and other factors such as alarm type and loudspeaker arrangement also seem to contribute significantly to performance. To verify these observations and confirm existence of main effects and interactions among factors, statistical analyses were performed.

The complete statistical analysis of the results is found in Appendix H.4. As a significant effect of hearing protector type (inter-subject factor) was noted, statistical analyses had to be carried out separately for both groups. In the case of earmuffs, significant main effects for the three intra-subject factors (alarm type, loudspeaker arrangement and HPD use) were noted, as were significant interactions among the factors of alarm type and loudspeaker arrangement, alarm type and HPD use, loudspeaker arrangement and HPD use, and among the three intra-subject factors. For earplug use, significant main effects were also noted for the factors of alarm type and loudspeaker arrangement, but not for HPD use, with similar angular errors and percentages of confusion obtained with and without earplugs. Furthermore, for this group (earplugs), the only significant interaction noted is between the factors of alarm type and loudspeaker arrangement.

6. DISCUSSION

6.1 Compliance with the SAE J994 Standard

In North America, the SAE J994 standard is the most often cited in occupational health and safety regulations dealing with reverse alarms. As previously stated, the standard was drafted at a time when only tonal alarms were commercially available. With the advent of broadband technology, it is important to determine whether broadband alarms meet the requirements set out in the standard, which appears to be the case when section 6.1 is applied to the letter. However, what constitutes a "predominant sound frequency" and the definition of the alarm's sound level are vague and imprecise when applied to broadband alarms, and are therefore open to interpretation. Section 6 of the standard, which lays out the operational specifications of alarms, should be entirely reviewed to allow its application to a wider range of commercial reverse alarms, and should specify, in particular, the various analysis parameters (e.g., bandwidth of analysis filters, application of weighting windows, method for calculating sound levels, etc.).

6.2 Objective Measurements: Sound Propagation Behind Vehicles

To meet the ISO 9533 requirement for a SNR $\geq$ 0 dB measured at all seven microphone positions, the tonal alarm's sound level at 1 m behind vehicles must be 4 to 8 dB higher than those of the broadband alarm in an ideal mounting condition, and 5 to 10 dB higher in a realistic mounting condition. This can be explained by greater variations in sound levels from one microphone to the next for the tonal alarm (see Table 1), leading to a necessary increase in sound power to obtain a SNR of at least 0 dB at all the microphones.

When analyzing sound level maps behind vehicles, significant acoustic variations (see figures 5 and 6 and Appendix G) are evident for the tonal alarm, and can reach 15 to 20 dB over distances of less than 1 m. Variations of 7 to 8 dB are noted with the multi-tone alarm, while the sound field behind vehicles is more uniform for the broadband alarm and follows a more natural decrease with increasing distance. Similar findings have been reported in the literature for tonal alarms (Laroche et al, 1995), and could result in negative consequences for worker safety and in noise pollution.

Where safety is concerned, workers expect an alarm's sound level to increase when a reversing vehicle is approaching them. However, abrupt fluctuations may actually lead to decreasing tonal alarm levels as the vehicle is approaching, which workers may interpret as a reduction in associated danger by believing that the vehicle is moving away, or by underestimating its actual distance. The level may even drop to the point that workers are no longer able to detect the alarm or to tell whether the situation is urgent enough for them to get out of the way, especially if when performing another task (see the example of a fatal accident in Laroche, 2006). In addition, excessively high tonal alarm levels in some workplaces may lead to undesirable behaviour, such as disconnecting or modifying alarms, which could further compromise safety.

The need to increase the tonal alarm's sound power relative to that of the multi-tone alarm, and even more specifically, the broadband alarm, may also increase the nuisance factor for neighbours and workers outside of the danger zone, thereby leading to increased worker habituation behaviours.

As expected, the objective measurements show advantages of the broadband alarm over tonal and multi-tone alarms because of its more uniform propagation behind heavy vehicles.

6.3 Subjective Measurements: Psychoacoustic Testing

6.3.1 Detection

Mean detection thresholds were -13 to -24 dB SNR across all the experimental conditions, indicating that alarms may remain barely audible even when adjusted to levels considerably lower than the ambient noise. Therefore, reverse alarms should be clearly audible when adjusted in accordance to ISO 9533 recommendations (SNR ≥ 0 dB). In fact, the general criteria proposed for the optimal adjustment of acoustic warning devices (Tran Quoc and Hétu, 1996; Zheng et al, 2007) state that they must be set 12 to 25 dB above the masked threshold under noisy conditions. Lower levels may not attract attention, while higher levels could induce startle reactions.

The ISO 7731 standard is also often referenced when adjusting acoustic warning devices, including reverse alarms. Using Method *a* described in the standard, which consists in adjusting the overall sound pressure level of a warning device 15 dB above the ambient noise in the reception area, would result in alarm levels of up to 39 dB above detection thresholds using data from the current study. Method *a* thus yields excessive adjustment level values for reverse alarms. Despite their more complex acoustic analysis using frequency bands, methods *b* and *c* described in ISO 7731 are therefore encouraged, if additional verifications are also carried out in compliance with ISO 9533.

During measurements, the alarms had to be adjusted to levels between 97 and 109 dBA at 1 m (Table 1) to meet the ISO 9533 requirements, corresponding to type B and C alarms described in the SAE J994 standard and mainly used in noisy work environments. In the ISO 9533 standard, alarm levels are assessed using a single ambient noise scenario (that of a running vehicle at high idle). In practice, however, the vehicle could be running at different speeds, with additional ambient noise sources operating in proximity to workers, thereby requiring lower or higher alarm levels than those specified in ISO 9533 for different operating conditions. In such cases, self-adjusting alarms may be warranted, and the standard should cover the characteristics of the algorithm used to adjust alarm levels based on that of the reigning background noise.

As for the choice of alarm, results show better detection for the tonal alarm than for the broadband signal, with performance for the multi-tone alarm falling somewhere in between. A 5-7 dB improvement in protected thresholds was noted for the tonal alarm compared to the broadband signal in high-frequency rich noises (noises 3 and 4), with the tonal alarm's advantage reaching a maximum of 3-4 dB across all other combinations of noise and hearing protection conditions. Finally, hearing protector type (earplugs versus earmuffs) had no significant effect on detection thresholds.

From a practical standpoint, the above-noted advantage of the tonal alarm for detection must be interpreted in light of its less uniform propagation behind vehicles, with sound level variations reaching up to 15-20 dB over short distances. The more uniform sound propagation of the broadband signal would therefore make the above-noted advantage during laboratory measurements irrelevant in ensuring alarm detection by workers in the field.

6.3.2 Loudness and Urgency

The broadband alarm can be adjusted to levels 2-4 dB lower without hearing protection, and 1 dB lower with hearing protection, for its loudness to be judged equal to that of the tonal alarm. The broadband alarm would hence appear louder than the tonal alarm when adjusted to identical levels, while the multi-tone alarm would appear softer (see Figure 8). These findings are consistent with those reported in the literature on the comparative loudness of pure tones and broadband noises (Scharf and Fishken, 1970). Even if the broadband alarm is detected at higher sound levels than the tonal alarm in some noisy conditions, its loudness grows more rapidly with increasing levels given its broader frequency bandwidth.

The most influential factor on perceived urgency is the alarms' presentation level (see Figure 26, Appendix H). Using the results reported in tables 7 and 8 in Appendix G, the slope of the function relating urgency (on a scale of 0 to 100 units) and presentation level (SNR ratio in dB) can be determined, and is approximately 5 units/dB unprotected and approximately 4 units/dB with hearing protection. Under equivalent experimental conditions, the tonal alarm evokes greater urgency than the multi-tone alarm, with differences ranging from 1 to 27 units in mean degree of perceived urgency. The tonal alarm is also deemed more urgent than the broadband alarm in 19 of the 24 possible comparisons between the two alarms (of which only two comparisons reached statistical significance at lower presentation levels in noise 3), with differences ranging from 0 to 20 units. Due to the large variability in results, most of these differences are however not statistically significant. As for the significance of such differences in the actual field, the estimated slopes can be used to determine the adjustment in alarm level required to counteract a given difference across alarms in perceived urgency. The largest advantage of the tonal alarm over the broadband alarm found in this study was 20 units of perceived urgency, which corresponds to an advantage in presentation level of about 4 dB. In other words, the tonal alarm's level could be reduced by a maximum of 4 dB to convey the same urgency as the broadband alarm.

As with alarm detection, the advantage of the tonal alarm over the broadband alarm in conveying greater urgency in some situations must be interpreted while taking into account its level variations during propagation behind vehicles, which can reach 15 to 20 dB. The tonal alarm's maximum gain of 4 dB over the broadband alarm in conveying urgency in laboratory simulations certainly cannot overshadow its more significant sound pressure level variations in the actual field, and would therefore not constitute any real advantage.

It should be noted that this study dealt only with some acoustic characteristics known to influence perceived urgency conveyed by the alarms. Despite not being exposed to any real danger situations (laboratory measures only), participants were well informed of the study's context, and as such could not misinterpret the signals' meaning, even in the case of less familiar warning sounds such as the broadband alarm. That being said, the study did not reflect actual urgency evoked by a new alarm signal used in the field, where workers must not only perceive the signal, but also quickly recognize its meaning. When asked to comment on particular factors influencing their urgency ratings, many participants reported greater urgency ratings with the tonal alarm, as it is a more familiar warning sound than the broadband alarm. Based on previous studies on the perceived urgency of warning sounds, familiarization with the broadband alarm prior to its use in the field could have a significant impact on its perceived urgency (Guillaume et al, 2003; Burt et al, 1995; Petocz et al, 2008).

Finally, because the broadband alarm is easier to localize than the tonal alarm, particularly in the front/back dimension, it could facilitate learned associations between the warning sound and the actual source of danger in workers.

6.3.3 Localization

Overall, better localization performances are obtained with the broadband alarm, compared to the tonal and multi-tone alarms. The factor “alarm-type” is clearly evident under some conditions, and often interacts with other factors.

Localization is also considerably better in the left/right (loudspeakers behind) than in the front/back (loudspeakers to the side) dimension, a result congruent with the literature (Vaillancourt et al, 2011). For left/right localization, both the mean angular error and percentage of confusions are generally low, with maximum (worse) values obtained for the tonal alarm under earmuffs (approximately 30° angular error and 20% confusion).

As expected, the greatest disparity among alarm types is noted in the front/back dimension. For tonal and multi-tone alarms, participants confused front and back one in three times (33%) to every second time (50%), corresponding, in the latter case, to chance performance (random guessing). Using the broadband alarm, front/back confusion was much less frequent, both without protection (approximately 10%) and with earplugs (approximately 18%), but significantly increased with earmuffs (40%). A similar trend is noted for the angular error, highlighting the hindering effect of earmuffs on sound localization compared to without hearing protection or with earplugs. Again, such results are supported by the literature on better front/back sound localization when spectral energy extends to high frequencies (Butler, 1986; Makous and Middlebrooks, 1990).

It should be noted that head movements were not allowed during the localization tasks, thereby representing the most challenging situation, but also limiting ceiling effects which could have nullified differences in performance across alarms. From a practical standpoint, head movements help to resolve front/back confusion (Moore, 1982), but other factors, such as acoustic reflection and diffraction, temporal, spectral and spatial variations in ambient noise, the worker’s hearing status, and reaction time available to allow for head movements, should also not be neglected when evaluating safety concerns. Further work is needed to quantify the impact of head movements in ensuring worker safety in the proximity of moving heavy vehicles.

7. CONCLUSION

Although the SAE J994 standard needs revision, the broadband alarm nonetheless appears to be compliant. Objective measurements of sound pressure levels behind heavy vehicles showed a considerably more uniform sound field for the broadband alarm than the tonal and multi-tone alarms. Indeed, abrupt variations in sound pressure levels of 15 to 20 dB over short distances (less than 1 m) were noted with the tonal alarm. Thus, auditory perception of the broadband alarm in the proximity of a heavy vehicle should also prove more uniform. Measured sound pressure levels behind vehicles revealed that the SNR ≥ 0 dB criterion specified in ISO 9533 seems adequate for the scenario proposed in the standard, that of a vehicle operating at high idle. In practice, however, many other scenarios may be encountered in which the alarm may prove too loud or too soft, and may warrant consideration for the use of alarms that self-adjust on the basis of ambient noise levels.

Laboratory psychoacoustic testing revealed better detection in noise of the tonal alarm compared to the broadband alarm, with an advantage of 5 to 7 dB with hearing protection in background noises rich in high-frequency content. Moreover, the tonal alarm conveys slightly greater urgency in background noises than the broadband alarm, a warning signal with which individuals are less familiar, equalling a maximum advantage of approximately 4 dB at low presentations levels unprotected. Advantages in laboratory conditions cannot, however, overcome the negative effect of significant variations in alarm levels behind vehicles, which are considerably greater for the tonal alarm (up to 15-20 dB) in comparison to the more uniform sound field obtained with the broadband signal.

Despite laboratory findings showing some advantages of the tonal alarm, the broadband alarm may ultimately prove superior for detection and perceived urgency in the actual work environment given its more uniform sound propagation behind vehicles, free of abrupt drops in sound pressure levels which could compromise worker safety. Moreover, the 2 to 4 dB advantage in loudness of the broadband alarm over the tonal alarm noted in laboratory conditions should hold true in the field. Front/back sound localization is also best with the broadband alarm compared to the tonal and multi-tone alarms, a finding critical for worker safety given that front/back confusions can lead workers to move or to focus their attention towards the wrong direction. It should however be noted that hearing protection, particularly passive earmuffs, can further increase front/back confusions. Overall, the experimental psychoacoustic data did not reveal any advantage of the multi-tone alarm over tonal and broadband alarms. Finally, caution is warranted in interpreting the data since findings may not generalize to more reverberant work environments (e.g., factory or warehouse interiors) in which reflective surfaces could potentially affect sound field uniformity and sound localization ability.

Overall, no contraindication to the use of broadband reverse alarms was identified during objective and subjective measurements. To ensure their optimal use, however, and to clarify regulations, some recommendations are well advised:

1) Revise the SAE J994 standard to specifically include broadband alarms;
2) Use alarms that can self-adjust based on ambient noise levels and determine the optimal characteristics of adjustment algorithms to ensure adequate audibility in a variety of background noise scenarios;

3) Determine optimal mounting positions on heavy vehicles that will provide the most uniform sound propagation;
4) Use earplugs instead of earmuffs for better sound localization;
5) Familiarize workers with the broadband alarm before it is used in work environments, in the hope of increasing perceived urgency for this warning signal in the field.

Further work is required to provide more specific and in-depth recommendations for the use of broadband reverse alarms. Documentation of the perception and localization of broadband-type alarms in individuals with hearing loss, under various conditions of hearing protection, is recommended; as is studying the effect of head movements on detection and localization of broadband alarms under more realistic working conditions (with and without hearing protection), and documenting the effect of signal familiarity on perceived urgency. Active headsets (with amplification at low levels and gradual attenuation with increasing sound level) should also be explored to determine their potential advantages over passive hearing protection in the performance of various psychoacoustic tasks. Finally, before self-adjusting alarms can be recommended for use in real work environments, the algorithms used for adjusting alarm levels based on ambient noise levels must be validated and their potential impact on noise pollution should be assessed.

The members of the follow-up committee highlighted the importance of measuring sound pressure levels inside both the truck cab and other vehicles in close proximity, thereby ensuring that alarm signals remain audible to all drivers in the danger area to avoid potential accidents. Alarm perception and propagation in enclosed spaces (e.g., indoor industrial yards, warehouses) have also been identified and merit further documentation (effect of sound wave reflections on sound propagation behind vehicles and on sound localization ability). Other research avenues were also discussed with the follow-up committee, and stem from issues dealing with: (1) the use of an often excessive SNR in adjusting alarms; (2) the poorly documented performance characteristics of self-adjusting alarms by manufacturers and the lack of clear understanding of these characteristics on the part of stakeholders; (3) the poorly documented effect of incorrect alarm mounting on heavy vehicles; (4) the effect of simultaneously operating alarms on sound localization; (5) the effect on alarm perception of worker attention being focused on a work task; and (6) the effect of hearing protectors on alarm perception.

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Appendix A FATAL ACCIDENTS IN THE UNITED STATES BETWEEN 1992 AND 2007

Table 2 summarizes 19 runover fatalities involving a reversing vehicle on construction sites in the United States between 1992 and 2007 (data retrieved from the NIOSH electronic databank, available at http://www.workzonesafety.org/runover_backover/case_studies).

Table 2: Summary of fatal accidents in the United States between 1992 and 2007 (source: NIOSH electronic databank)

Case #	Year	Worker	Vehicle type	Reverse alarm	Noise levels
00CA005	2000	Inspector	10-wheel dump truck carrying asphalt	Operational and functioning properly	Not specified
00CA006	2000	Construction flag person	10-wheel tractor-trailer side dump truck	Operational and functioning properly	Not specified
01CA004	2001	Traffic controller	10-wheel dump truck	Not specified	Not specified
01CA008	2001	Construction surveyor	Grader	Operational and functioning properly	Not specified, but noise factor mentioned
00WI074	2000	Laborer	Dump truck	Operational reverse alarm and lights	Not specified
07CA001	2007	Laborer	Dump truck	Operational and functioning properly	Not specified
96IA055	1996	Road construction worker	Asphalt roller	Operational and functioning properly	Not specified
00-MA-61-01	2002	Police officer	10-wheel dump truck carrying asphalt	Missing	Not specified, but noise as a contributing factor (did not hear people yelling)
01-MA-039-01	2001	Police officer	Dump truck carrying asphalt	Operational and functioning properly	Not specified
95MA039	1995	Construction laborer	18-wheel tractor-trailer filled with asphalt	Missing	Not specified
MN9207	1992	Construction worker - paving	Dump truck	Operational and functioning properly	Noisy construction site
97MN047	1997	Construction worker - paving	Caterpillar	Not functioning	Not specified
98MN030	1998	Road construction worker	Front-end loader	Not functioning	Not specified
96MO012	1996	Highway department supervisor	Dump truck	Operational and functioning properly	Multi-lane road repair
04NE007	2004	Engineering technician	Dump truck	Audible reverse alarm (heard by witness) and reverse lights	Not specified
04NE040	2004	Concrete finisher	Dump truck	Audible reverse alarm (heard by witnesses) and reverse lights	Not specified
03OK04701	2003	Road construction worker	Dump truck carrying asphalt	Fully operational (97 dB) and heard by at least one other person	Not specified
00WA041	2000	2 victims: city worker and project superintendent	Dump truck	Operational and functioning properly (superintendent did not remember hearing the alarm; worker was on cell phone)	Not specified
99WA07001	1999	Flagger	Dump truck	Operational and functioning properly	Not specified

Appendix B BBS ALARMS: EXAMPLES OF USE

Table 3: Examples of broadband alarm applications. All listed sources were accessible online on September 25, 2011.

Company/ Organization/ Project	Reported or anticipated benefits	Source	Website
2012 Olympics Code of Construction Practice (UK)	Reduced noise complaints/ pollution	Olympic Delivery Authority (2007). Code of Construction Practice, December 2007; Burgess & McCarty, 2009	www.london2012.com/documents/oda-health-and-safety/code-of-construction-practice-final-low-res.pdf; http://www.environment.nsw.gov.au/resources/noise/beeperalarm.pdf
Arizona Materials (USA)	Reduced noise complaints/ pollution	Brigade Electronics Inc. (2006). The noiseless back-up alarm. November 2006 Newsletter	http://www.noisefree.org/brigade_electronics-newsletter.pdf
ASDA (UK)	Reduced noise complaints/ pollution	Brigade Electronics Inc. Vehicle Safety Solutions. Bbs-tek White Sound Warning Alarms. Brochure	http://www.brigade-inc.com/sites/default/files/bbs-tek%20brochure.pdf
British Airports Authority (BAA)	Health (reduced exposure levels)	Brigade Electronics Inc. Vehicle Safety Solutions. Bbs-tek White Sound Warning Alarms. Brochure	http://www.brigade-inc.com/sites/default/files/bbs-tek%20brochure.pdf
Burlington Slate Ltd (UK)	Reduced noise complaints/ pollution	UK trade journal Mining and Quarry World (Sept/Oct 2002) in Burgess M. & McCarty M. (2009). Review of alternatives to 'beeper' alarms for construction equipment. Report for the Department of Environment and Climate Change NSW Government, 8 May 2009, 69 pages	http://www.environment.nsw.gov.au/resources/noise/beeperalarm.pdf
Day Group (UK)	Reduced noise complaints/ pollution	Safety and Health Practitioner (2002). Reversing alarm. (Products & Services). The Safety & Health Practitioner, December 1, 2002; Burgess & McCarty	http://www.accessmylibrary.com/article-1G1-95829275/reversing-alarm-products-services.html; http://www.environment.nsw.gov.au/resources/noise/beeperalarm.pdf
Grace Pacific Corporation (USA)	Reduced noise complaints/ pollution	Morgan H. (2007). Back-up Safety Alarms Minimize Environmental Noise Exposure and Focus Warning Signals. Sound and Vibration, February 2007; Burgess & McCarty, 2009	http://findarticles.com/p/articles/mi_qa4075/is_200702/ai_n19198181/; http://www.environment.nsw.gov.au/resources/noise/beeperalarm.pdf
Greater London Authority (UK)	Reduced noise complaints/ pollution	Greater London Authority (2005). New reversing alarms cut noise pollution. Press release, 27 October 2005	http://www.london.gov.uk/media/press_releases_mayoral/new-reversing-alarms-cut-noise-pollution
Hanson Aggregates (USA)	Increased safety and reduced noise complaints/ pollution	Brigade Electronics Inc. (2006). The noiseless back-up alarm. November 2006 Newsletter	http://www.noisefree.org/brigade_electronics-newsletter.pdf
		Brigade Electronics PLC (2009). Broadband Sound. The safer and noiseless back-up alarm. A Brigade white paper, March 2009, 16 pages.	http://www.brigade-inc.com/sites/default/files/whitepaper.UK_.pdf
Ibstock Brick (UK)	Health (reduced exposure levels) and reduced noise complaints/ pollution	Brigade Electronics PLC (2009). Broadband Sound. The safer and noiseless back-up alarm. A Brigade white paper, March 2009, 16 pages.	http://www.brigade-electronics.com/sites/default/files/whitepaper.UK_.pdf
		www.ibstock.com	http://www.ibstock.com/sustainability.asp

Memphis Stone & Gravel Company (USA)	Increased safety and reduced noise complaints/ pollution	Parks AJ (2008). Broadband Alarms: A Tangible Part of Memphis Stone & Gravel Company's Noise Reduction Strategy. Special Report, Missouri University of Science and Technology, Department of Mining Engineering, January 3, 2008, 14 pages; Burgess & McCarty, 2009	http://www.msgravel.com/assets/1312/Broadband_Noise_Strategy.pdf; http://www.environment.nsw.gov.au/resources/noise/beeperalarm.pdf
Middleborough Road Rail Separation Project (Victoria, Australia)	Increased safety and reduced noise complaints/ pollution	Vic Worksite Safety Update No 59 in Burgess M. & McCarty M. (2009). Review of alternatives to 'beeper' alarms for construction equipment. Report for the Department of Environment and Climate Change NSW Government, 8 May 2009, 69 pages	http://www.environment.nsw.gov.au/resources/noise/beeperalarm.pdf
New York Department of sanitation	Reduced noise complaints/ pollution	Brigade Electronics Inc. (2006). The noiseless back-up alarm. November 2006 Newsletter	http://www.noisefree.org/brigade_electronics-newsletter.pdf
Quarries National Joint Advisory Committee (UK)	Increased safety	Brigade Electronics Inc. (2006). The noiseless back-up alarm. November 2006 Newsletter	http://www.noisefree.org/brigade_electronics-newsletter.pdf
Sainsbury's Superstore (UK)	Reduced noise complaints/ pollution	The Noise Abatement Society (2010). QDDS IVB Site Assessment, November 5, 2010, 8 pages.	http://www.ttr-ltd.com/information/QDDS/Reports/Annex4/Sainsburys_Bournemouth.pdf
Scottish Environment Protection Agency (UK)	Reduced noise complaints/ pollution	Scottish Environment Protection Agency. Environmental Best Practice Guidance Note – noise emissions from vehicle reversing alarms.	www.sepa.org.uk/air/pollution_prevention.../idoc.ashx?...1
Seattle Noise Variance (USA)	Reduced noise complaints/ pollution	OE Parts, LLC. (2009). Finally! A Safe Solution to the Annoying Beep-Beep Sound. Technology News, April 2009 Government Edition.	http://www.teamsters155.org/pdf/GOV_Tech_News_3_2009.pdf
South Australia Department of Transport, Energy and Infrastructure (Australia)	Reduced noise complaints/ pollution, and improved vehicle localization	Bassett Consulting Engineers (2009). Broadband Auditory Warning Alarms, report for SA Department for Transport, Energy and Infrastructure, doc AA0981-A9B01RP in Burgess M. & McCarty M. (2009). Review of alternatives to 'beeper' alarms for construction equipment. Report for the Department of Environment and Climate Change NSW Government, 8 May 2009, 69 pages	http://www.environment.nsw.gov.au/resources/noise/beeperalarm.pdf
State of Massachusetts - Department of Conservation and Recreation (USA)	Reduced noise complaints/ pollution	Department of Conservation and Recreation (2009). Boston University Bridge Rehabilitation Project. State of Massachusetts Department of Conservation and Recreation, June 30, 2009.	http://www.mass.gov/dcr/news/publicmeetings/materials/bubridge7-30-09.pdf
Tarmac (UK)	Increased safety and reduced noise complaints/ pollution	HUB Magazine (2007). Ringing Endorsements for Broadband Reversing, 22 March 2007	http://www.hub-4.com/news/461/ringing-endorsements-for-broadband-reversing
The Noise Abatement Society (UK)	Reduced noise complaints/ pollution	Brigade Electronics Inc. Vehicle Safety Solutions. Bbs-tek White Sound Warning Alarms. Brochure; Burgess & McCarty, 2009	http://www.brigade-inc.com/sites/default/files/bbs-tek%20brochure.pdf; http://www.environment.nsw.gov.au/resources/noise/beeperalarm.pdf
The Pentagon (USA)	Reduced noise complaints/ pollution	Brigade Electronics Inc. (2006). The noiseless back-up alarm. November 2006 Newsletter	http://www.noisefree.org/brigade_electronics-newsletter.pdf

The Sims Group (UK)	Increased safety	Health and Safety Executive (HSE). Waste management and recycling case studies; Burgess & McCarty, 2009	www.hse.gov.uk/waste/casestudies.htm; http://www.environment.nsw.gov.au/resources/noise/beeperalarm.pdf
Travis Perkins (UK)	Reduced noise complaints/ pollution	Forkliftaction.com (2002). Brigade reversing alarms solve noise pollution problems. Newsletter #085, 27 November 2002	http://www.forkliftaction.com/news/newsdisplay.aspx?nwid=724
UK Olympic Development Authority (UK)	Reduced noise complaints/ pollution	OE Parts, LLC. (2009). Finally! A Safe Solution to the Annoying Beep-Beep Sound. Technology News, April 2009 Government Edition.	http://www.teamsters155.org/pdf/GOV_Tech_News_3_2009.pdf
		Burgess M. & McCarty M. (2009). Review of alternatives to 'beeper' alarms for construction equipment. Report for the Department of Environment and Climate Change NSW Government, 8 May 2009, 69 pages	http://www.environment.nsw.gov.au/resources/noise/beeperalarm.pdf
Washington State Department of Transportation (USA)	Reduced noise complaints/ pollution	OE Parts, LLC. (2009). Finally! A Safe Solution to the Annoying Beep-Beep Sound. Technology News, April 2009 Government Edition.	http://www.teamsters155.org/pdf/GOV_Tech_News_3_2009.pdf
Waste Management Republic - Port of Houston (USA)	Reduced noise complaints/ pollution	Brigade Case Studies. Port of Houston to curb noise nuisance	http://www.brigade-electronics.com/industries/case-studies/port-houston-curb-noise-nuisance
		Burgess M. & McCarty M. (2009). Review of alternatives to 'beeper' alarms for construction equipment. Report for the Department of Environment and Climate Change NSW Government, 8 May 2009, 69 pages	http://www.environment.nsw.gov.au/resources/noise/beeperalarm.pdf
		Brigade Electronics Inc. (2006). The noiseless back-up alarm. November 2006 Newsletter	http://www.noisefree.org/brigade_electronics-newsletter.pdf
WBB Minerals (UK)	Reduced noise complaints/ pollution	UK trade journal Mining and Quarry World (Jul/Aug 2002) ins Burgess M. & McCarty M. (2009). Review of alternatives to 'beeper' alarms for construction equipment. Report for the Department of Environment and Climate Change NSW Government, 8 May 2009, 69 pages	http://www.environment.nsw.gov.au/resources/noise/beeperalarm.pdf

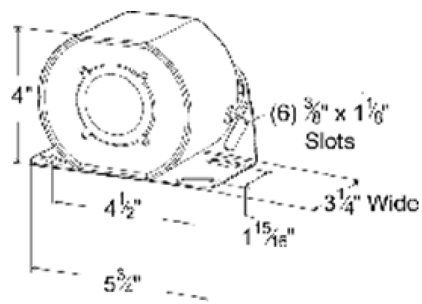
Appendix C ALARM TECHNICAL SPECIFICATIONS

C.1 TONAL ALARM

Grote 73030 field-selectable backup alarm (information retrieved from Grote's website)

Catalog search page > Hazard and Warning Devices > product sheet

Field-Selectable Backup Alarm



↖ Enlarge image ↖ Enlarge image

PRODUCT NUMBER
73030 - 107 or 112 Selectable Decibels

FEATURES & BENEFITS
- Electronics sealed in epoxy for protection against dust, vibration and moisture
- Adjusts to SAE type A or B for medium to high noise
- 12- to 36- volts
- Selectable volume control, 107 or 112 decibels by reversing the leads
- Universal mount

TECHNICAL SPECIFICATIONS
Material: Steel
FMVSS:
SAE J994 Type A or B
Finish: Blue
Voltage Amp: 12V - 36V / .6A at 12V

C.2 MULTI-TONE ALARM

The multi-tone signal was digitally synthesized (.wav file) and generated using the Grote 73030 alarm device, by replacing the tonal signal of the unit with an externally simulated 3-frequency (1000, 1150 and 1300 Hz) signal. The time trace of the multi-tone alarm is identical to that of the tonal alarm.

C.3 BROADBAND ALARM

BBS-107/Heavy Duty/107 dB (information retrieved from Brigade Electronics' website)

BBS-107 - Heavy Duty - 107 Decibels

Alternative models

BBS-102 - Heavy Duty - 102 Decibels

Learn more about:

Alarms-White Sound

The safest alarms in the world due to their instant locatability and directional sound. The multi-frequency alarms are only heard in the danger zone, thus eliminating noise nuisance for local residents.

Read more

Description

Heavy duty, market leading, white sound reversing alarm, ideal for vehicles working in high ambient noise levels. The safest reversing alarm on the market.

Decibel ratings: **102dB or 107dB**.

Information

Product code: 0899
Volts: 12-24Vdc
IP Rating: 68
Size (WxHxD): 172 x 79 x 95mm
Warranty: Life

Features | Power | Durability & Standards

Mechanical vibration: 10G
Operating temperature: -40 to +85°C
CE Marked: ✔
EMC Approved: e
SAE J994: ✔

C.4 ALARM TIME TRACE

Figure 11 displays the time trace of the three selected alarms. Over a three-second period, three “on-off” cycles are noted for the tonal and multi-tone alarms, compared to four for the broadband alarm.

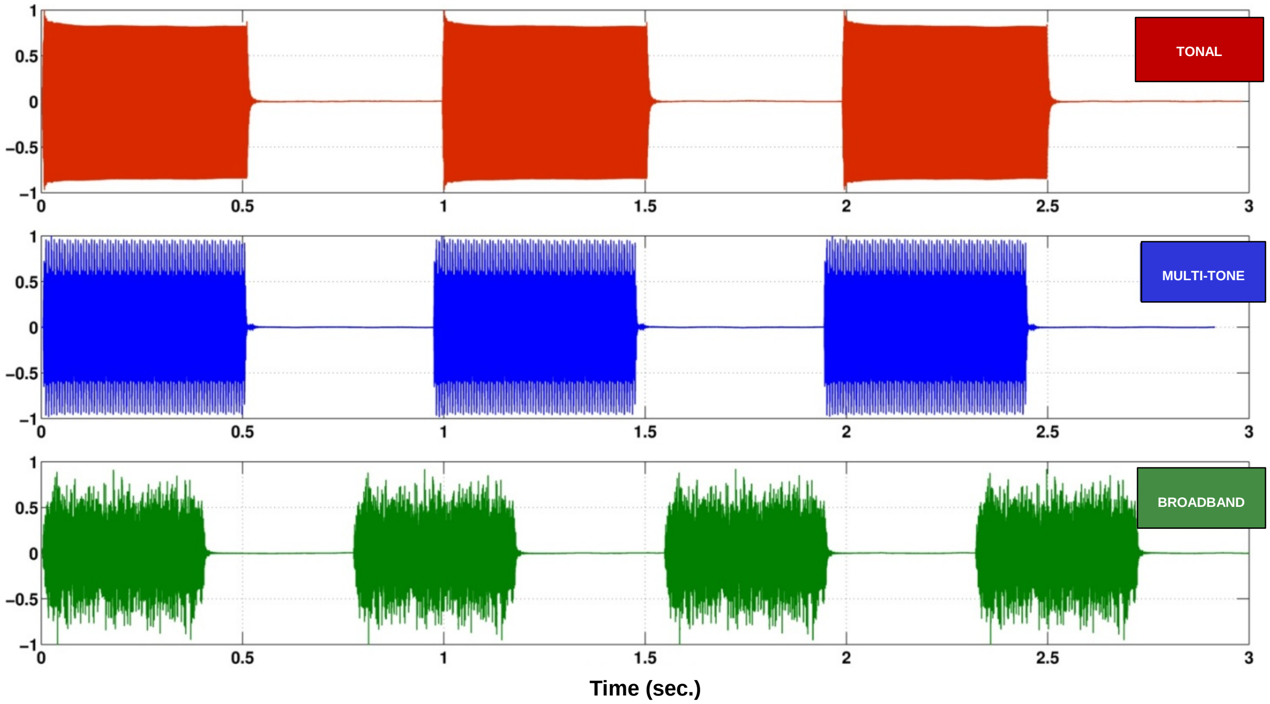


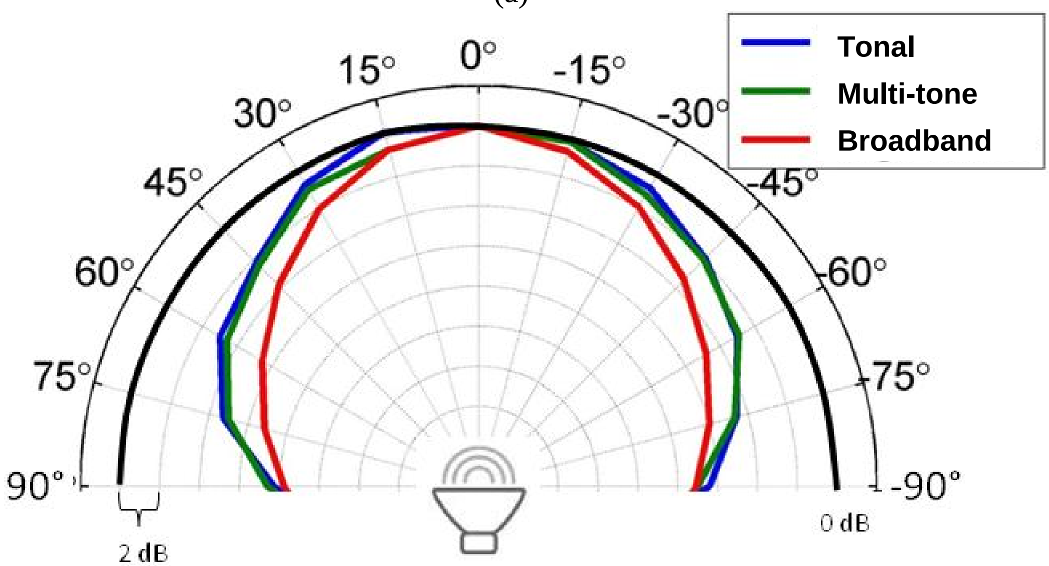
Figure 11: Time trace of the three selected alarms over a three second period

C.5 ALARM DIRECTIVITY IN A SEMI-ANECHOIC ENVIRONMENT

Directivity patterns were determined independently for each alarm in a semi-anechoic chamber by measuring sound pressure levels at about 1m from the device, using a single microphone varying in position (15° increments) in the horizontal plane (Figure 12a).[9] Level deviations from the reference position (θ = 0°) in dB, are presented in figure 12b, and show that the alarms are not entirely omni-directional, with 4 to 5 dB level differences obtained at positions greater than 45° on either side. These differences are slightly greater for the broadband alarm than the tonal and multi-tone alarms.

[9] It should be noted that the methods used to measure directivity did not follow any particular standard.

(a)



(b)

Figure 12: Alarm directivity patterns: (a) experimental set-up; (b) level differences relative to reference position (θ = 0°)

Appendix D MICROPHONE POSITIONS FOR FIELD MEASUREMENTS

D.1 MICROPHONE POSITIONS ACCORDING TO ISO 9533 SPECIFICATIONS

Figure 13 and Table 4 identify the microphone positions and coordinates used during the first series of objective measurements (alarm level adjustments), as specified in ISO 9533 (1989). While additional microphone positions are described in a more recent version of the standard (2010), the updated version was not available when field testing was performed.

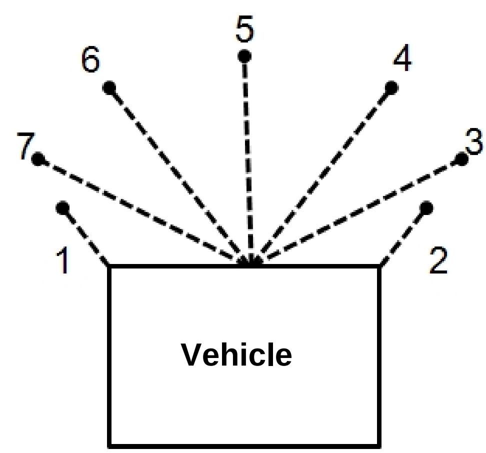


Figure 13: Microphone positions described in ISO 9533

Table 4: Microphone position coordinates specified in ISO 9533

Microphone	Distance (m) and direction	
1	0.7 left	0.7 rear
2	0.7 right	0.7 rear
3	4.9 right	4.9 rear
4	2.7 right	6.5 rear
5	0	7.0 rear
6	2.7 left	6.5 rear
7	4.9 left	4.9 rear

D.2 SCANNING LINES FOR MICROPHONE SWEEPS

The scanning lines used to determine sound field uniformity are displayed in Figure 14, with nine straight lines extending from the back of the vehicle and two curvilinear arches at 2 m and 4 m.

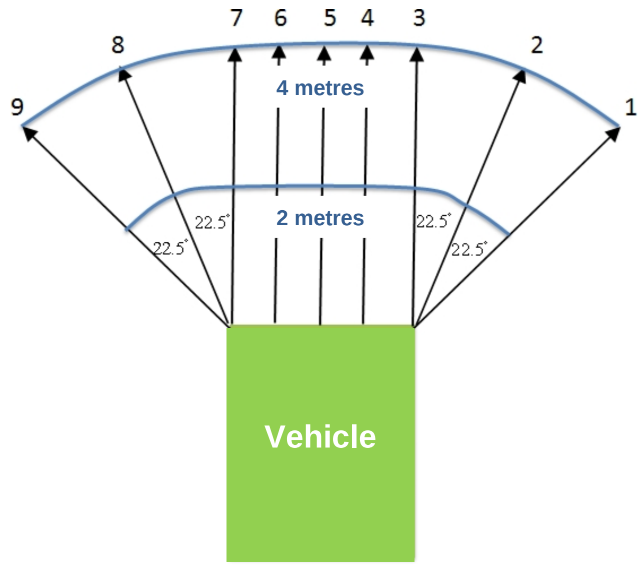


Figure 14: Scanning lines used for sound field measurements behind a vehicle

Appendix E SELECTED WORK ENVIRONMENTS, VEHICLES AND BACKGROUND NOISES

Table 5 summarizes the work environments and vehicles used during the sound propagation field tests.

Table 5: Work environments and vehicles used during field testing

Company	Terrain	Vehicle
A – Mineral products	Gravel, rocks and hard earth	
A – Mineral products	Packed earth, dust and gravel	
B – Wood products	Packed earth	

Background Noises

Four different background noises (see Figure 4, section 4.2.4 for frequency content), sampled in the environments displayed in Figure 15, were selected for the subjective (laboratory) measurements. Noise 1 (quarry) consists of a low-frequency buzzing noise with an overall sound pressure level of approximately 80.5 dBA. Noise 2 (quarry), at 83.3 dBA, also consists of a relatively stable buzzing noise. Noise 3 (sawmill) is characterized by the flapping, humming and crackling sounds of the wood chipping process, with an overall sound pressure level of 85.9 dBA. Noise 4 (sawmill) could be described as an 89.6 dBA buzzing noise composed of engine noise and lower high-frequency sounds.

Noise 1

Noise 2

Noise 3

Noise 4

Figure 15: Work environments used for sampling background noises

Appendix F LABORATORY SPACE AND EQUIPMENT

This appendix describes the audiometric booths and equipment used during psychoacoustic testing at the Hearing Research Laboratory of the University of Ottawa.

F.1 DETECTION, EQUAL LOUDNESS AND PERCEIVED URGENCY

Sound detection, equal loudness, and perceived urgency were assessed in a versatile acoustic chamber (Eckel Industries) with reversible wall and ceiling panels. Reflective surfaces on one side of the panels and absorbent material on the other side allow re-creating a host of sound environments by changing the configuration of the panels to vary the acoustic properties of the room (see Figure 16 for room layout and loudspeakers). A loudspeaker (S7) positioned 1 m in front of the participants transmitted the alarms, while five additional loudspeakers (S1 to S5) and a subwoofer (S6) were used to re-create the background noises, which were reproduced at levels measured in the field (81 dBA for Noise 1, 83 dBA for Noise 2, 86 dBA for Noise 3 and 89 dBA for Noise 4). Two computers were required to run the testing software specifically designed for this project (Laferrière, 2010). A standard computer was used by the investigator to present the alarms and noises and to set their acoustic parameters (level of initial presentation, step size, etc.), while participants adjusted the alarm levels and rated perceived urgency using a tablet computer.

F.2 SOUND LOCALIZATION

Sound localization testing was performed in an IAC double-walled soundproof booth using SELA (*Système d'évaluation de la localisation auditive*—sound localization assessment system, Dufour et al, 2005). Twelve Realistic Minimus loudspeakers with a similar frequency response, mounted on a 0–180° localization arc (Figure 17), were used to play the alarms, while background noise (Noise 2) emanated from a ceiling-mounted loudspeaker directly above the participants' head. The first loudspeaker on the arc was positioned at 7.5°, with a 15° spacing between adjacent loudspeakers. An external amplifier (Techron 5507) enabled the level of the background noises and alarms to be adjusted, and the noise file was played using a CD reader (Max dVP-6100).

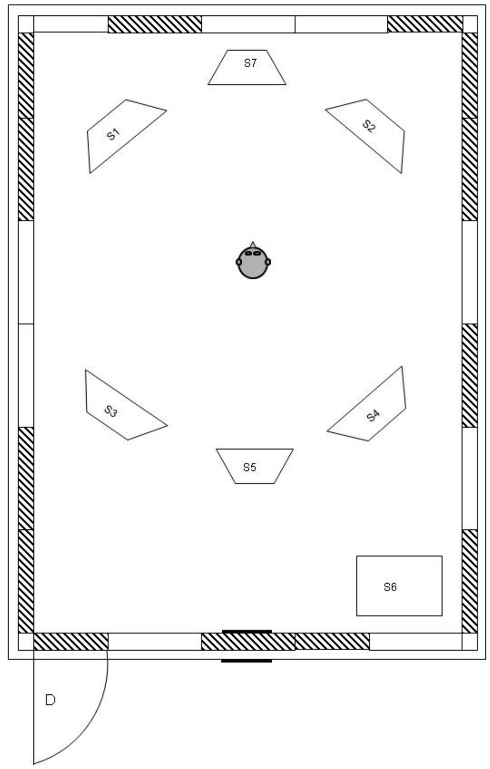


Figure 16: Room layout for detection, equal loudness and perceived urgency testing

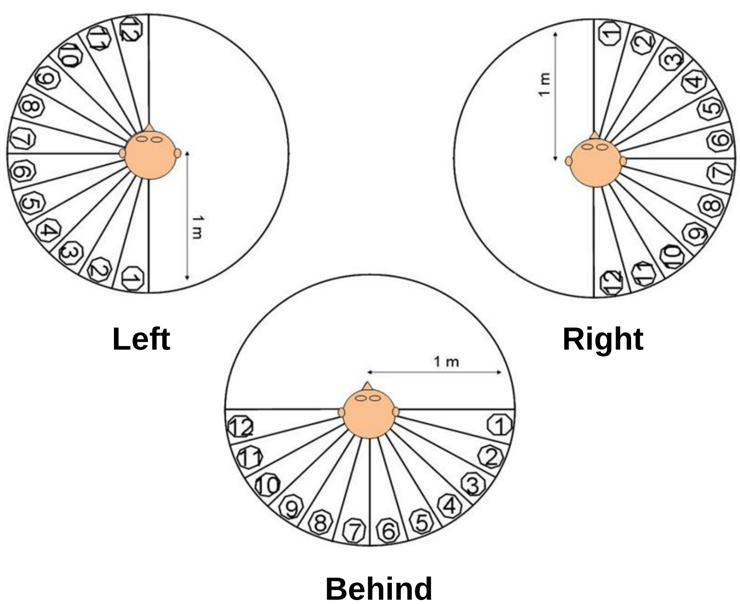


Figure 17: Loudspeaker positions for the sound localization testing

Appendix G RESULTS – SOUND PROPAGATION BEHIND VEHICLES

Figures 18 and 19 present a map of the alarm levels measured behind a vehicle using the microphone sweep method at sites 2 and 3 (results for site 1 are presented in section 5.2.2). Overall alarm levels (Leq expressed in dB(A)) are posted, with each change in colour corresponding to a 3 dB variation in overall level.

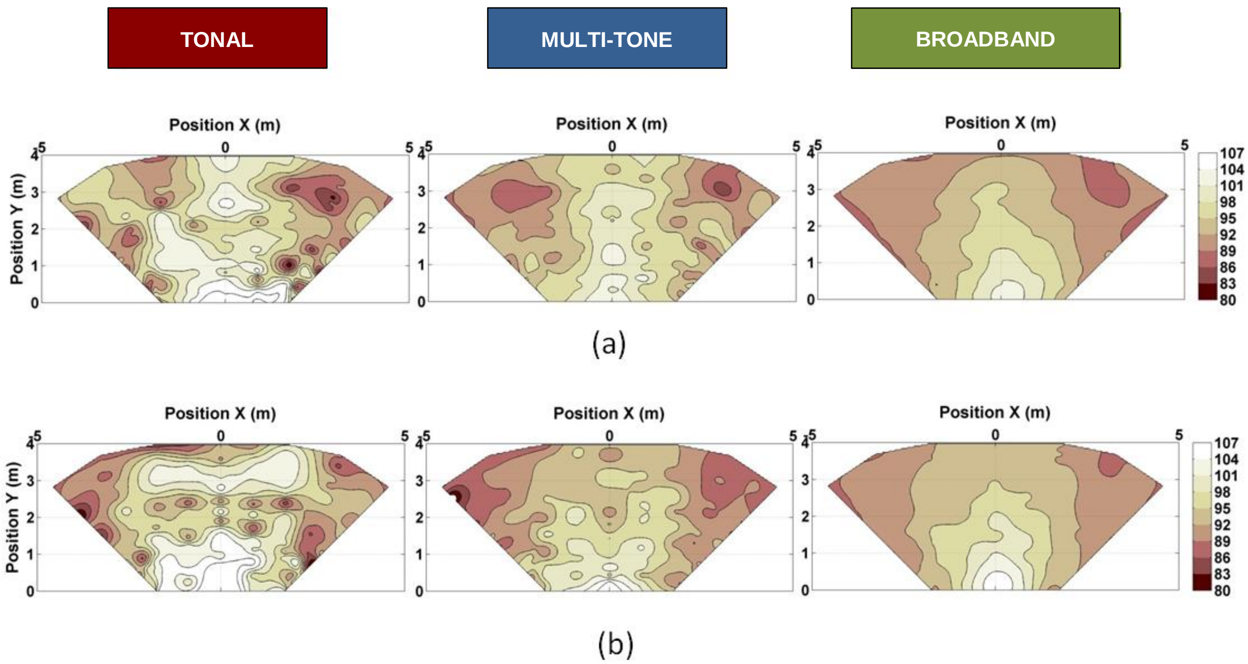


Figure 18: Alarm levels (Leq: dB(A)) behind the vehicle at site 2: (a) alarm in "realistic" position; (b) alarm in "ideal" position

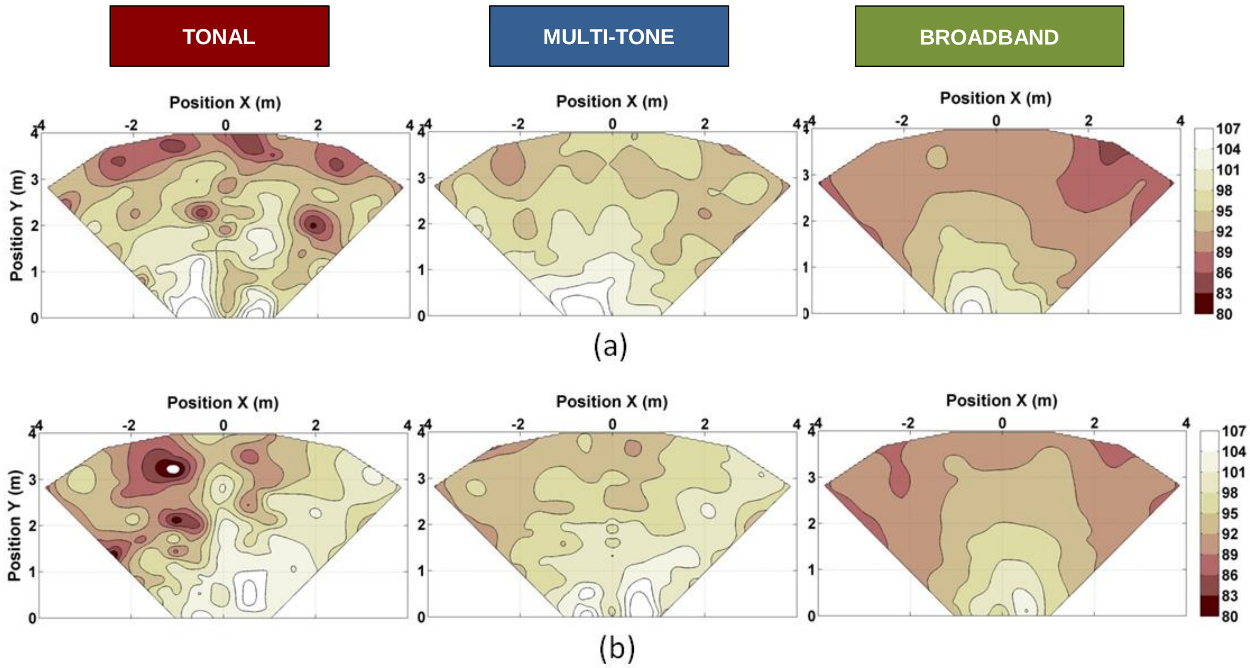


Figure 19: Alarm levels (Leq: dB(A)) behind the vehicle at Site 3: (a) alarm in "realistic" position; (b) alarm in "ideal" position

Appendix H RESULTS – PSYCHOACOUSTIC TESTING

This appendix describes the detailed statistical analyses performed on data from the psychoacoustic measurements of detection thresholds, equal loudness, perceived urgency, and sound localization. The data did not satisfy the assumption of sphericity required for performing univariate statistical analyses. Furthermore, a mixed linear model with an unstructured covariance matric could not be used since the data are highly dimensional. Multivariate methods of analysis based on an ANOVA-type statistic proposed by Ahmad et al (2008) were therefore used as needed, which represent a modification of Box's approximation (1954) for highly dimensional data (number of measurements per participant greater than number of participants). Statistical Analysis System (SAS) version 9.2 was used to perform the analyses in conjunction with Interactive Matrix Language (IML) programming by a statistician.

H.1 DETECTION THRESHOLDS OF BACKUP ALARMS

H.1.1 Experimental Plan

The experimental plan consists of a mixed design with one inter-subject factor (HPD type– earmuffs or earplugs) and repeated measurements on three intra-subject factors: (1) type of alarm (tonal, multi-tone and broadband alarms); (2) noise (four noises); and (3) HPD use (with and without). The subject factor was also considered in the analysis, with each participant being modelled as a vector of 24 measurements.

H.1.2 Effect of Protector Type (inter-subject factor)

A comparison of the variance-covariance matrix of both groups (earmuffs vs. earplugs) revealed similar total variances (344.6 with Box ϵ of 0.115 for earmuffs and 383.8 with Box ϵ of 0.094 for earplugs) (Box, 1953; Strivastava, 2005). Using Dempster's (1960) statistic adjusted for non-sphericity, no significant effect on detection thresholds was found for the inter-subject factor of HPD type [F (2.33; 55.92) = 0.736]. Data from both groups were therefore combined to carry out the remaining analyses based on ANOVA-type statistics with an unstructured covariance matrix.

H.1.3 Main Effects and Interactions (intra-subject factors)

For intra-subject factors, overall significant main effects were found [χ^2 (3.054) = 10.913, p<0.001], particularly significant main effects for alarm type [χ^2 (1.431) = 12.978, p<0.001], noise [χ^2 (1.481) = 14.277, p<0.001] and HPD use [χ^2 (1) = 11.347, p=0.001], as well as significant interactions between alarm type and noise [χ^2 (2.083) = 14.408, p<0.001], alarm type and HPD use [χ^2 (1.683) = 5.331, p=0.008], and between all three intra-subject factors [χ^2 (5.583) = 2.385, p=0.03], at α = 0,05.

Since an interaction among the three intra-subject factors exists, the levels of the two other factors in the description of each main effect had to be adjusted.

H.1.3.1 Main Effect of Alarm Type

Figure 20 summarizes the findings for eight possible groups of comparisons across alarms, taking into account combinations of the two other interacting factors (noise and HPD use).

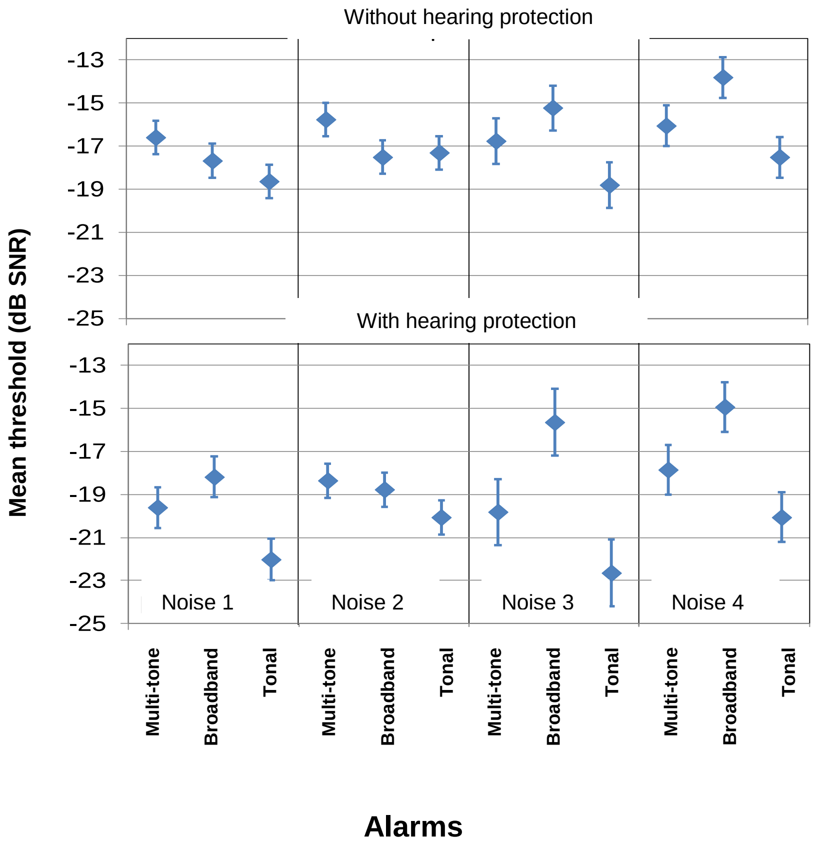


Figure 20: Comparison of mean detection thresholds across alarms when adjusting the levels of the factors of noise and HPD use (with/without hearing protection). The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

For Noise 1, without hearing protection the mean detection threshold is significantly higher for the multi-tone alarm than for the tonal alarm, while that of the broadband alarm is comparable to the other two alarms. With hearing protection, similar thresholds are obtained for the multi-tone and broadband alarms, while that of the tonal alarm is significantly better (lower).

In Noise 2, without hearing protection, the mean detection threshold is significantly higher for the multi-tone alarm than for the broadband alarm, while that of the tonal alarm is comparable to the other two alarms. With hearing protection, the mean detection threshold is significantly higher for the multi-tone alarm than for the tonal alarm, while that of the broadband alarm is comparable to the other two alarms.

For noises 3 and 4, similar results are obtained for the multi-tone and tonal alarms, and the mean detection threshold is significantly higher for the broadband alarm than for the tonal alarm, both with and without hearing protection. Apart from the unprotected condition in Noise 3, the mean detection threshold is also significantly higher for the broadband alarm compared to the multi-tone alarm.

It should be noted that the significant differences found in noises 1 and 2 are relatively small, about 1 to 3.8 dB (measurement step = 2 dB), while those obtained in noises 3 and 4 can reach 7 dB (2.3 to 7 dB).

H.1.3.2 Main Effect of Noise

Figure 21 summarizes the findings for six possible groups of comparisons across noises, taking into account combinations of the two other interacting factors (alarm type and HPD use).

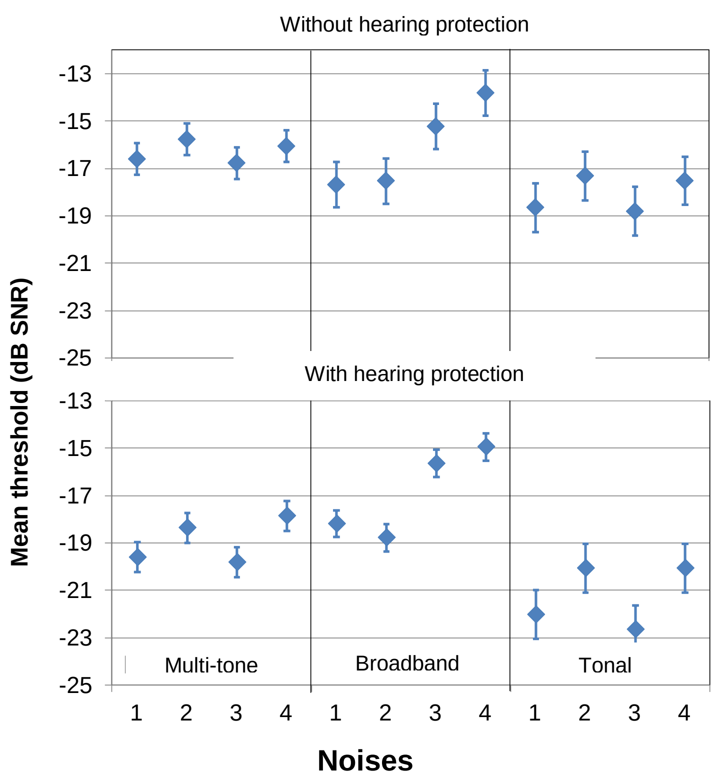


Figure 21: Comparison of mean detection thresholds across noises when adjusting the levels of the factors of alarm type and HPD use (with/without hearing protection). The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

For the multi-tone alarm, no significant difference is noted in the mean thresholds obtained in each of the noises, when hearing protection is not used. In contrast, with hearing protection the mean detection threshold is significantly higher in Noise 4 than in noises 1 and 3, and in Noise 2 compared to Noise 3.

For the broadband alarm, similar trends are noted with and without hearing protection. The mean thresholds are similar in noises 1 and 2 and in noises 3 and 4, with thresholds being significantly higher in noises 3 and 4 than in noises 1 and 2.

Similar mean detection thresholds for the tonal alarm are obtained across all noises without hearing protection. With hearing protection, however, the mean detection threshold is considerably higher in Noise 2 than in Noise 3 and in Noise 4 compared to Noise 3.

H.1.3.3 Main Effect of HPD Use

Figure 22 summarizes the findings for twelve possible groups of comparisons across HPD use, taking into account combinations of the two other interacting factors (alarm type and noise).

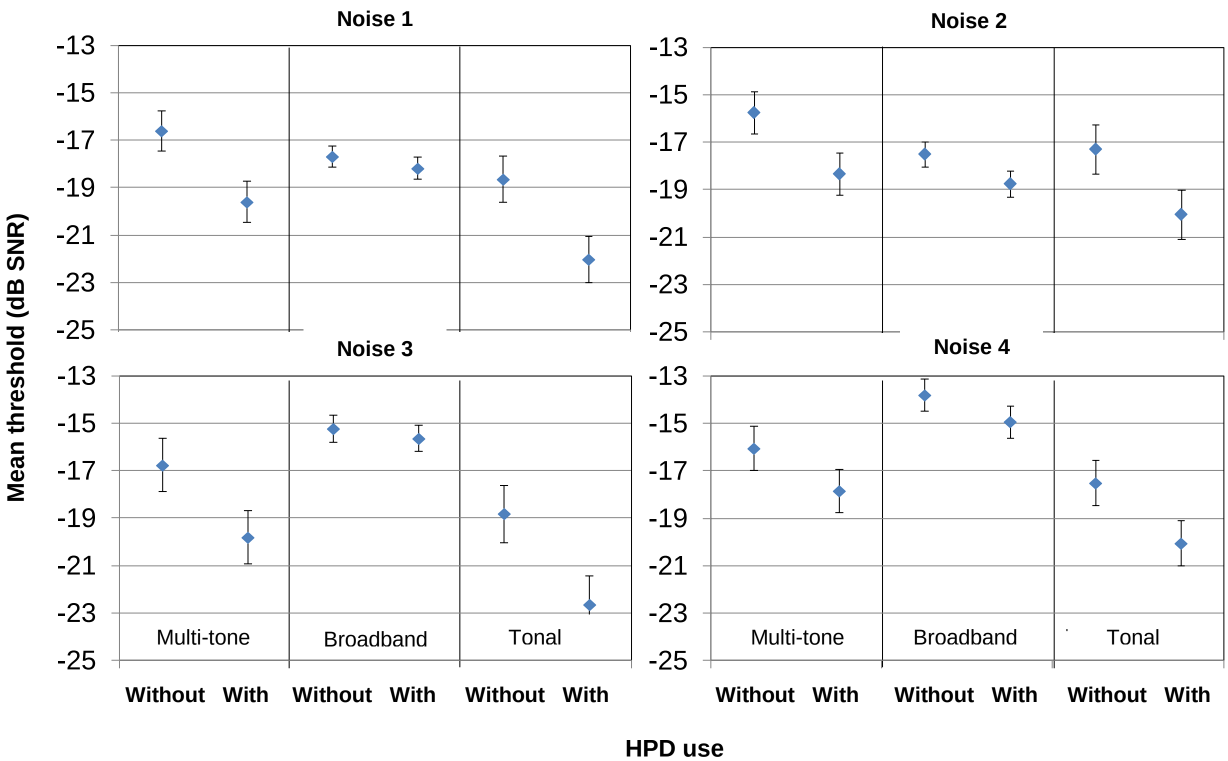


Figure 22: Comparison of mean detection thresholds with and without hearing protection when adjusting the levels of the factors of alarm type and noise. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

The mean detection threshold for the multi-tone alarm is generally significantly lower with protectors than without, apart from Noise 4 in which case thresholds are similar with and without hearing protection. Detection of the broadband alarm seems to be similar with and without hearing protection, apart from a significantly higher (1.3 dB difference) mean detection threshold with hearing protection compared to without protection in Noise 2. It should however be noted that this difference is smaller than the step size used for threshold measurements. Finally, in all the noises, the mean detection threshold for the tonal alarm is much lower with hearing protection compared to without protection.

H.2 EQUAL LOUDNESS

H.2.1 Experimental Plan

The experimental plan consists of a mixed design with one inter-subject factor (HPD type: earmuffs or earplugs) and repeated measurements of three intra-subject factors: (1) type of alarm (tonal, multi-tone and broadband alarms); (2) noise (four noises); and (3) HPD use (with and without). The subject factor was also considered in the analysis, with each participant being modelled as a vector of 24 measurements. The dependant variable in this case is the difference in level between the tonal alarm (reference) and the alarm under study being adjusted by participants.

H.2.2 Effect of Protector Type (inter-subject factor)

A comparison of the variance-covariance matrix of both groups (earmuffs vs. earplugs) revealed similar total variances (84.2 with Box ϵ of 0.525 for earmuffs and 120.5 with Box ϵ of 0.417 for earplugs) (Box, 1953; Strivastava, 2005).

A multivariate analysis of variance was first used to compare the 16 average data points obtained in both groups of HPD users (earmuffs vs. earplugs), and no effect of HPD type was noted [χ^2 (7.788) = 7.710, p=0.440]. Data from both groups were therefore combined to carry out the remaining analyses.

H.2.3 Main Effects and Interactions (intra-subject factors)

For intra-subject factors, overall significant effects were found [χ^2 (3.417) = 36.157, p<0.001], particularly significant main effects of alarm type [χ^2 (1.0) = 18.424, p<0.001], noise [χ^2 (2.536) = 11.771, p=0.005] and HPD use [χ^2 (1.0) = 11.451, p=0.001], and significant interactions between alarm type and noise [χ^2 (3.160) = 11.726, p=0.010] and alarm type and HPD use [χ^2 (1.0) = 4.102, p=0.043], at $\alpha = 0.05$. No interaction was revealed between all three intra-subject factors.

H.2.3.1 Main Effect of Alarm Type

Because alarm type significantly interacts independently with each of the other two intra-subject factors, the levels of both these factors (noise and HPD use) must be adjusted when interpreting the main effect of alarm type. Figure 23 summarizes the findings for eight possible comparisons between the multi-tone and broadband alarms.

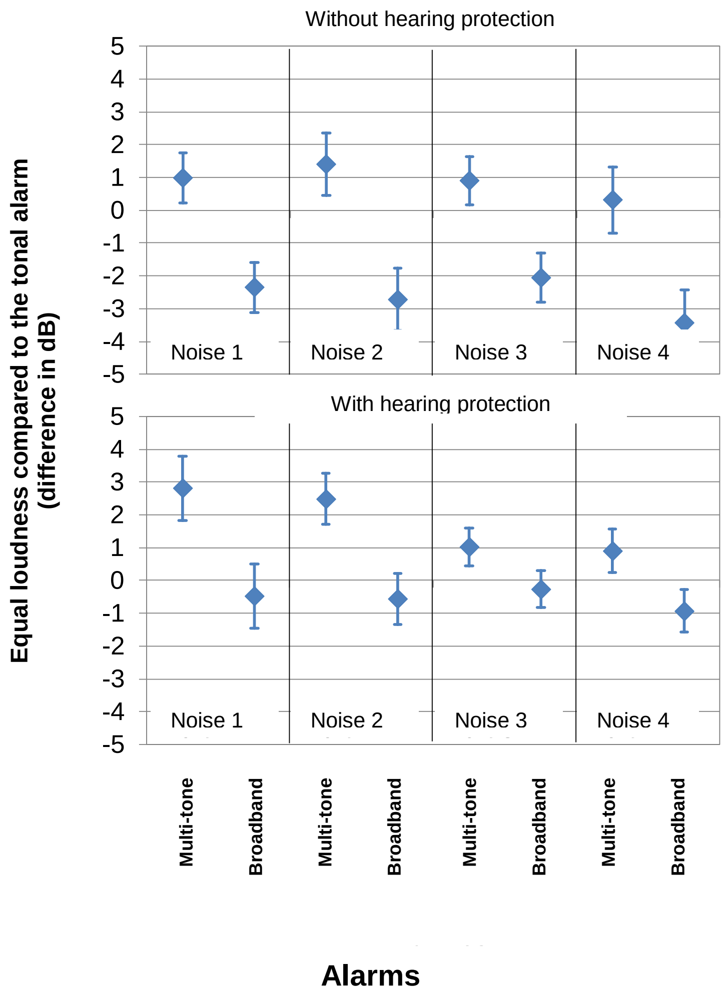


Figure 23: Equal loudness for multi-tone and broadband alarms compared to the tonal alarm: interpretation of alarm-type factor. The vertical axis represents the difference in sound pressure level between the alarm under study (multi-tone or broadband alarm) and the reference (tonal) alarm. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

As can be seen, the difference in level relative to the tonal alarm is always positive for the multi-tone alarm and negative for the broadband alarm, across all conditions of noise and HPD use Thus, to reach a sensation of loudness equivalent to that of the tonal alarm, the level of the multi-tone alarm must be higher relative to the tonal alarm, while the level of the broadband alarm must be lower. In other words, when adjusted to equal sound pressure levels, the broadband alarm appears louder than the tonal alarm, which in turn seems louder than the multi-tone alarm. For equal loudness perception, the multi-tone alarm must be adjusted to levels 0.3 to 1.4 dB higher than the tonal alarm when hearing protection is not used and 0.9 to 2.8 dB higher when hearing protection is used. Broadband alarms, on the other hand, can be adjusted to levels 2.0 to 3.4 dB lower than the tonal alarm when hearing protection is not used and 0.2 to 0.9 dB lower when hearing protection is used for equal loudness perception.

As the dependant variable is the difference in levels between the tonal alarm and either the multi-tone or broadband alarm, confidence intervals were determined based on an ANOVA-type statistic used for the mean of the difference while controlling for the levels of all three factors. The Bonferroni adjustment was also used to ensure a confidence level of 95%. A significant difference in level relative to the tonal alarm was found in two out of eight conditions for the multi-tone alarm (in Noises 1 and 2 with hearing protection) and in four out of eight conditions for the broadband alarm (unprotected in all four noises). The advantage in loudness of the broadband alarm over the tonal alarm therefore seems to disappear with hearing protection, when both alarms tend to be judged similarly at equal levels.

Figure 23 also shows that the two alarms (multi-tone and broadband) behave differently under all conditions, when their differences are examined. In fact, in each of the different figure panels, no interaction between errors bars is noted.

H.2.3.2 Main Effect of Noise

Noise and alarm type interact with each other; there are thus two comparison groups (Figure 24) in which a total of six different comparisons are possible (noises 1-2, 1-3, 1-4, 2-3, 2-4, 3-4). These comparisons are illustrated in Figure 24.

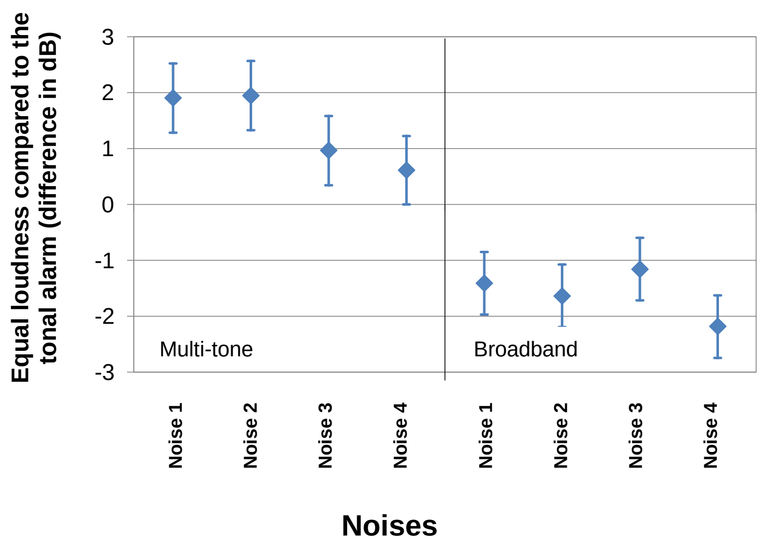


Figure 24: Equal loudness for multi-tone and broadband alarms compared to the tonal alarm: interpretation of the noise factor. The vertical axis represents the difference in sound pressure level between the alarm under study (multi-tone or broadband alarm) and the reference (tonal) alarm. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

Again, irrespective of the type of noise, the broadband alarm can clearly be adjusted to lower levels than the tonal alarm for equal loudness perception, whereas the multi-tone alarm must be adjusted to higher levels. For the multi-tone alarm, a significant difference is noted between noises 1 and 4 and between noises 2 and 4, with a smaller difference in sound level in Noise 4 than in noises 1 and 2. For the broadband alarm, no significant differences are noted across the various noises.

H.2.3.3 Main Effect of HPD Use

The interaction between HPD use and alarm type yields two comparison groups (Figure 25) in which level differences for each alarm relative to the tonal alarm can be compared with and without hearing protection.

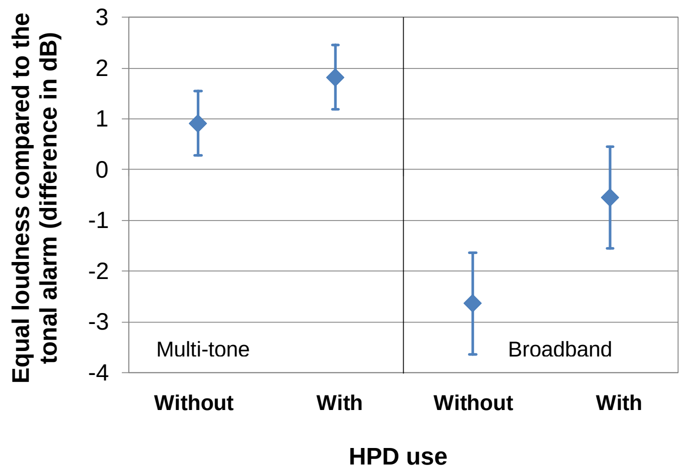


Figure 25: Equal loudness for multi-tone and broadband alarms compared to the tonal alarm: interpretation of the HPD factor. The vertical axis represents the difference in sound pressure level between the alarm under study (multi-tone or broadband alarm) and the reference (tonal) alarm. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

No significant effect of HPD use was noted for the multi-tone alarm, whereas the level difference of the broadband alarm relative to the tonal alarm is significantly greater without hearing protection than with it. As previously stated, the advantage in loudness of the broadband alarm over the tonal alarm seems to disappear when hearing protection is used.

H.3 PERCEIVED URGENCY

H.3.1 Experimental Plan

The experimental plan consists of a mixed design with one inter-subject factor (HPD type: earmuffs or earplugs) and repeated measurements on four intra-subject factors: (1) type of alarm (tonal, multi-tone and broadband alarms); (2) noise (four noises); (3) presentation level of alarms (SNR of -6, 0 and +6); and (4) HPD use (with and without). The subject factor was also considered in the analysis, with each participant being modelled as a vector of 72 measurements.

H.3.2 Effect of Protector Type (inter-subject factor)

The total variances of the variance-covariance matrices were found to be different in both groups (24 244.4 with Box ϵ of 0.095 for earplugs and 20 745.1 with Box ϵ of 0.293 for earmuffs) (Box, 1953; Strivastava, 2005), supporting the need to perform separate statistical analyses for each group. Moreover, Strivastava's (2005) sphericity test for highly dimensional data with a Helmert transformation suggests a lack of sphericity in the orthogonal components ($1/\epsilon = 2.08$, $p<0.001$

for earmuffs and $1/\epsilon = 2.62$, $p<0.001$ for earplugs). Since the requirements for a univariate ANOVA-type analysis could not be met, analyses based on the ANOVA-type statistic for highly dimensional data (Ahmad et al, 2008) were used.

To compare the means of both groups (earplugs and earmuffs), the ANOVA-type statistic that does not require matrix equality was used, with results revealing no significant difference between earmuffs and earplugs [$\chi 2$ (12.257) = 10.864, p=0.562]. However, in light of extensive variability in data and unequal variance-covariance matrices, separate analyses were performed for the earmuffs and for the earplugs.

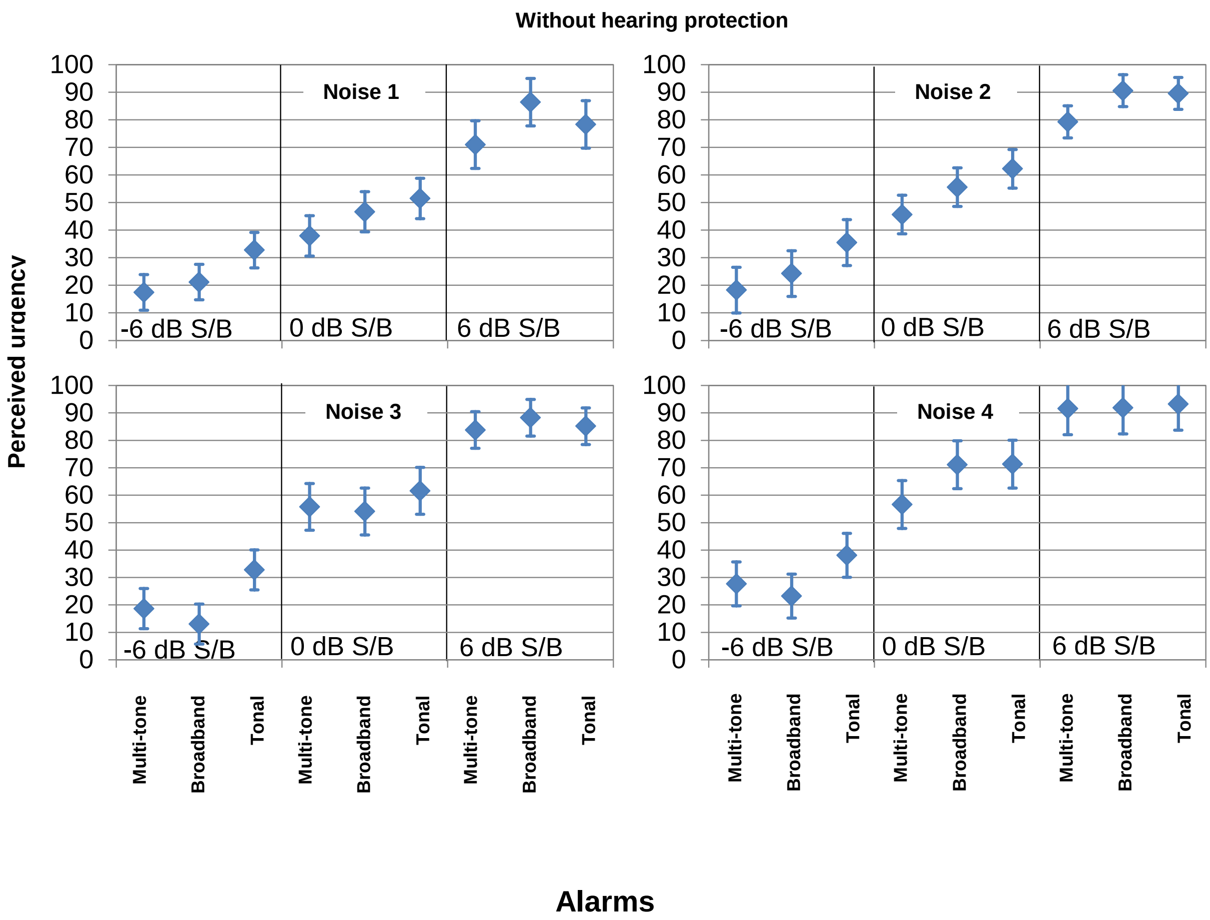
H.3.3 Main Effects and Interactions (intra-subject factors)

In describing significant effects, Kimball's inequality was used to control independent test errors. In the following analyses, second and third order interactions were therefore considered statistically significant for p values lower than 0.0085 and 0.017, respectively.

In the group using earmuffs, overall significant effects were found [χ^2 (1.757) = 15.880, p<0.001], particularly significant main effects of alarm type [χ^2 (2.071) = 13.025, p=0.002], noise [χ^2 (2.360) = 10.535, p=0.008], HPD use [χ^2 (1.0) = 10.053, p=0.002] and presentation level [χ^2 (1.026) = 11.725, p=0.001], significant second-order interactions between alarm type and noise [χ^2 (5.327) = 20.389, p=0.001], alarm type and presentation level [χ^2 (3.550) = 15.900, p=0.002], HPD use and presentation level [χ^2 (1.999) = 11.705, p=0.003], and a third-order interaction between alarm type, HPD use and presentation levels [χ^2 (5.065) = 14.442, p=0.014].
In the group using earplugs, overall significant effects were found χ^2 (2,124) = 17,423, p<0,001], particularly significant main effects of noise [χ^2 (1.951) = 11.961, p=0.002], HPD use [χ^2 (1.0) = 7.393, p=0.007] and presentation level [χ^2 (1.017) = 11.466, p=0.001], and a significant 2nd order interaction between alarm type and HPD use [χ^2 (1.689) = 9.026, p=0.008]. The interaction between HPD use and presentation levels [χ^2 (1.438) = 8.156, p=0.009] was also taken into consideration since the p value was very close to the adjusted value of 0.0085 to establish statistical significance.

H.3.3.1 Main Effect of Alarm Type: Earmuffs

Since multiple interactions exist among the various intra-subject factors for results obtained in the group using earmuffs, the levels of other factors had to be adjusted when describing the main effect of the alarm type. Twenty-four comparison groups are therefore possible (Figure 26: upper panel = unprotected; lower panel = with earmuffs) in which the alarms are compared (multi-tone vs. broadband, multi-tone vs. tonal, and broadband vs. tonal), for a total of 72 comparisons.


Without hearing protection
Perceived urgency
Noise 1
Noise 2
Noise 3
Noise 4
-6 dB S/B
0 dB S/B
6 dB S/B
Multi-tone
Broadband
Tonal
Alarms

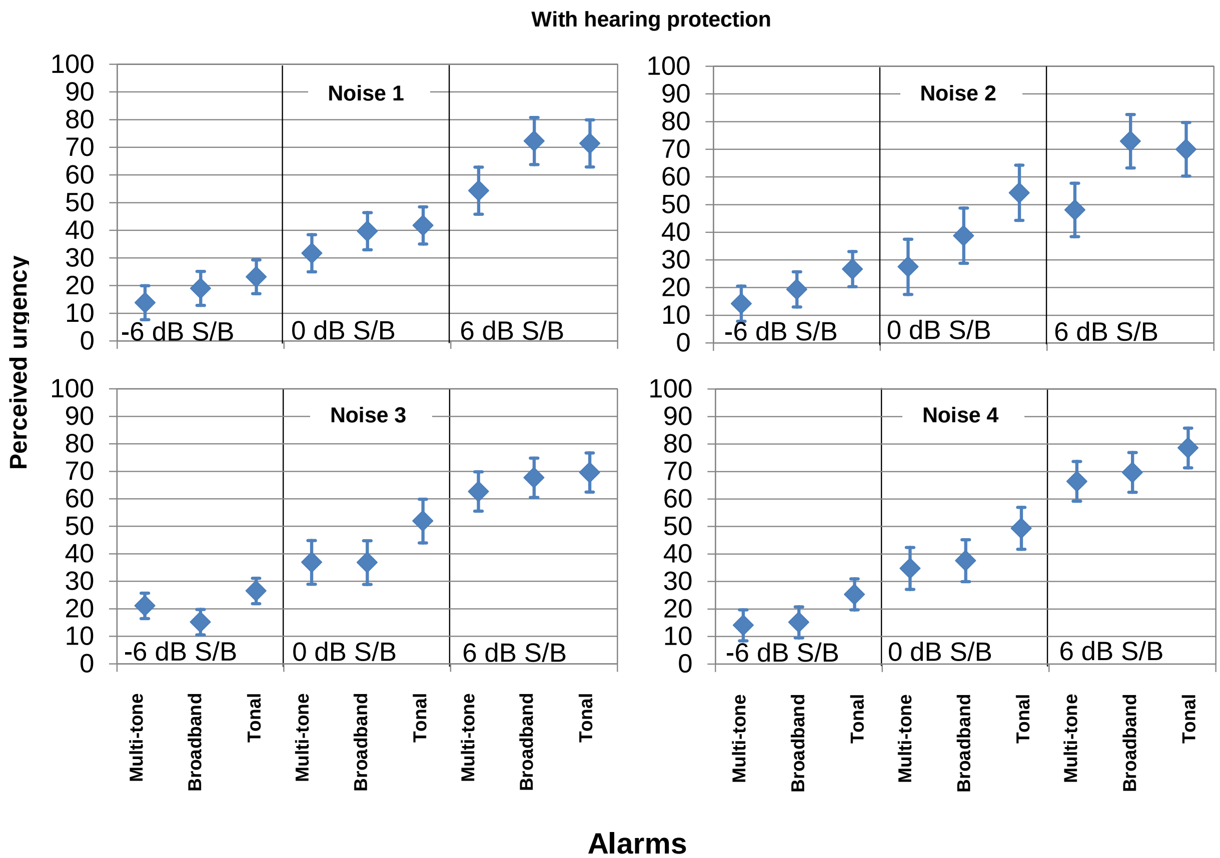


Figure 26: Comparison of mean perceived urgency for the three reverse alarms in the group of participants using earmuffs, by adjusting the HPD factor levels. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel). Upper panel = unprotected; lower panel = with earmuffs (S/B should be SNR in the figure).

As expected, in light of the significant impact of sound pressure levels on urgency ratings, the data show increased perceived urgency with increasing presentation level, an effect that will be explored later in this report. In interpreting the alarm-type factor, each alarm was compared to the other two alarms a total of 24 times. Overall, under equivalent experimental conditions, the tonal alarm was always deemed more urgent than the multi-tonal alarm, with differences ranging from 1.4 to 26.8 units of mean perceived urgency, and evoked greater urgency than the broadband alarm in 19 out of the possible 24 comparisons between these two alarms, with differences ranging from 0.3 to 19.8 units. The broadband alarm evokes greater urgency than the multi-tone alarm in 19 out of the possible 24 comparisons, with differences ranging from 0.1 to 24.8 units.

It should however be noted that most of these differences across alarms are not statistically significant. Indeed, data variability is so high that in several cases the maximum error within a comparison group is substantially larger than the actual differences in perceived urgency across alarms. Despite this observation, some differences reached the threshold for statistical significance (Table 6).

Table 6: Statistically significant differences in mean perceived urgency across reverse alarms

Noise	Protection condition	Presentation level	Alarms compared	Difference
Noise 1	Without earmuffs	-6 dB SNR	Tonal > Multi-tone	15.3
	With earmuffs	6 dB SNR	Tonal > Multi-tone	17.1
			Broadband > Multi-tone	17.9
Noise 2	Without earmuffs	-6 dB SNR	Tonal > Multi-tone	17.3
		0 dB SNR	Tonal > Multi-tone	16.6
	With earmuffs	0 dB SNR	Tonal > Multi-tone	26.8
		6 dB SNR	Tonal > Multi-tone	21.9
		6 dB SNR	Broadband > Multi-tone	24.8
Noise 3	Without earmuffs	-6 dB SNR	Tonal > Broadband	19.8
	With earmuffs	-6 dB SNR	Tonal > Broadband	11.3

While only 10 out of the 72 possible comparisons were found to be statistically significant, half of which were obtained in Noise 2, significant differences generally reveal greater mean perceived urgency for the tonal alarm over the multi-tone alarm (6 out of 10 significant differences), for the broadband alarm over the multi-tone alarm, and for the tonal alarm compared to the broadband alarm. While all comparisons did not reach statistical significance, the data are consistent with the trends reported in Table 6.

H.3.3.2 Effect of Alarm Type: Earplugs

As alarm type interacts with HPD use, two comparison groups (Figure 27) are required to explore the effect of alarm type on perceived urgency. Again due to large data variability, no comparison reached statistical significance as the maximum error within each comparison group was substantially larger than the actual differences in perceived urgency across alarms (ranging from 2.1 to 13.4 units) and none of the 6 possible comparisons reached the statistical significance threshold.

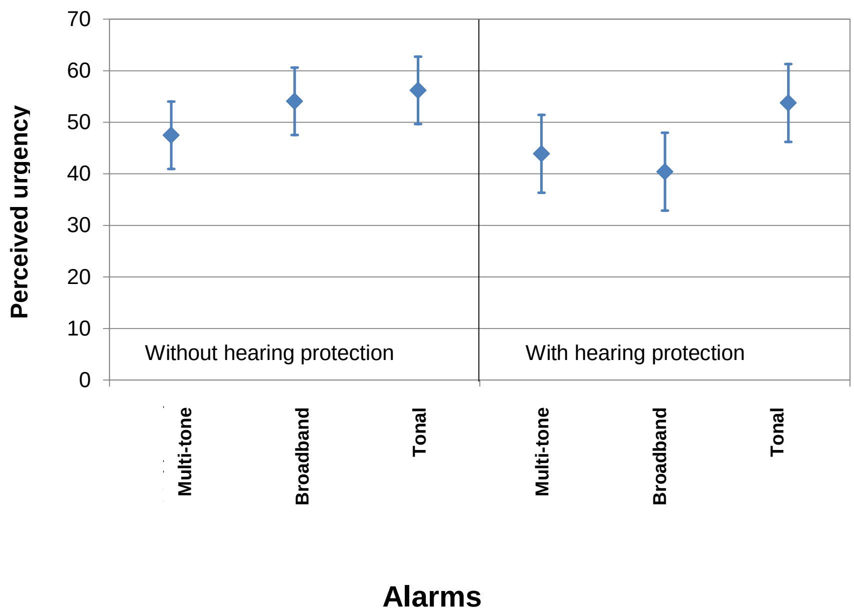


Figure 27: Comparison of mean perceived urgency for the three reverse alarms in the group of participants using earplugs, by adjusting the HPD factor levels. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

H.3.3.3 Effect of Noise: Earmuffs

In the group using earmuffs, noise and alarm type interact with each other; hence there are three comparison groups (Figure 28) in which six different comparisons are possible (noises 1-2, 1-3, 1-4, 2-3, 2-4, 3-4), for a total of 18 comparisons.

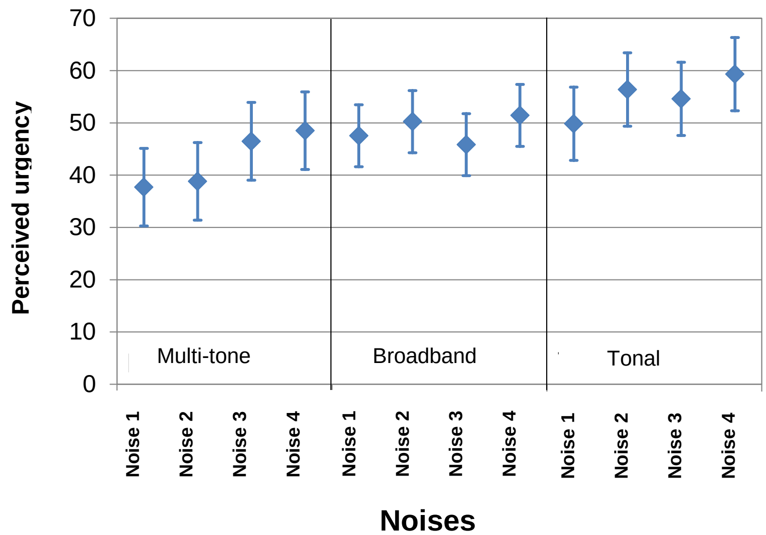


Figure 28: Comparison of mean perceived alarm urgency obtained in the four noises in the group of participants using earmuffs, by adjusting the levels of the alarm-type factor. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

For each of the alarms, no significant difference in perceived urgency is noted across the four noises. Once again, high data variability precludes finding significant differences as the maximum error within each comparison group clearly exceeds the measured differences in perceived urgency across noises. Overall, differences ranging from 1.8 to 9.5 units were obtained for the tonal alarm, while those for the multi-tone alarm ranged from 1.1 to 10.8 units. For both alarms, the greatest difference occurred between noises 1 and 4, although the difference was not statistically significant. Mean perceived urgency seemed to vary less across noises for the broadband alarm (differences = 1.2 to 5.6 units).

H.3.3.4 Effect of Noise: Earplugs

In the group using earplugs, the noise factor does not interact with other intra-subject factors. As such only one comparison group exists (Figure 29), with six possible comparisons across the various noises.

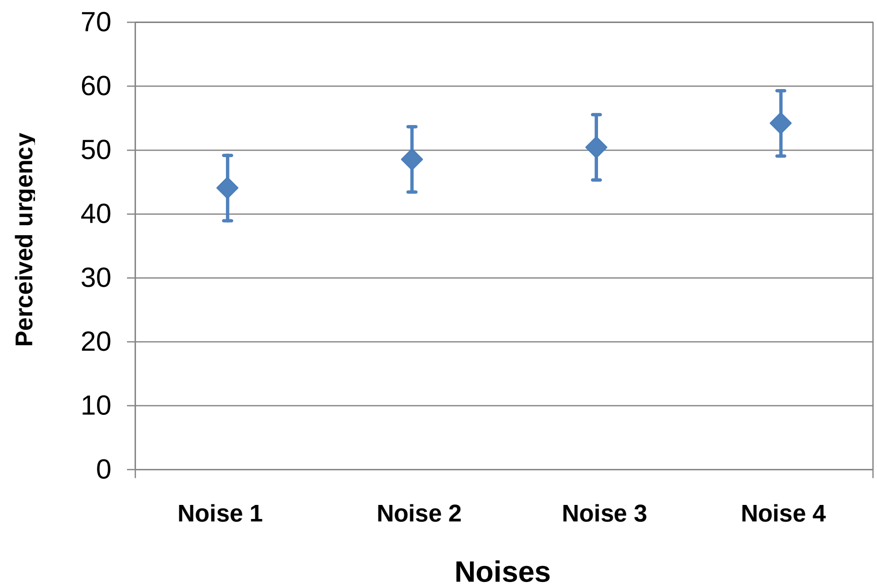


Figure 29: Comparison of mean perceived alarm urgency in the four noises in the group of participants using earplugs. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within the comparison group.

Despite a significant main effect of noise on perceived urgency in the group of individuals wearing earplugs, the differences noted across the various noises were relatively small, ranging from 1.9 to 10.1 units in all six possible comparisons, and failed to reach statistical significance at the 95% confidence level. This can in part be explained by high data variability. Using a less stringent confidence level (90%), mean perceived urgency is significantly higher in Noise 4 compared to Noise 1, with a difference of 10.1 units.

H.3.3.5 Effect of HPD Use

In both groups (earmuffs and earplugs), HPD use interacted with alarm type and presentation level, thereby yielding nine comparison groups in which mean urgency can be compared with and without HPDs (Figure 30 for earmuffs and Figure 31 for earplugs).

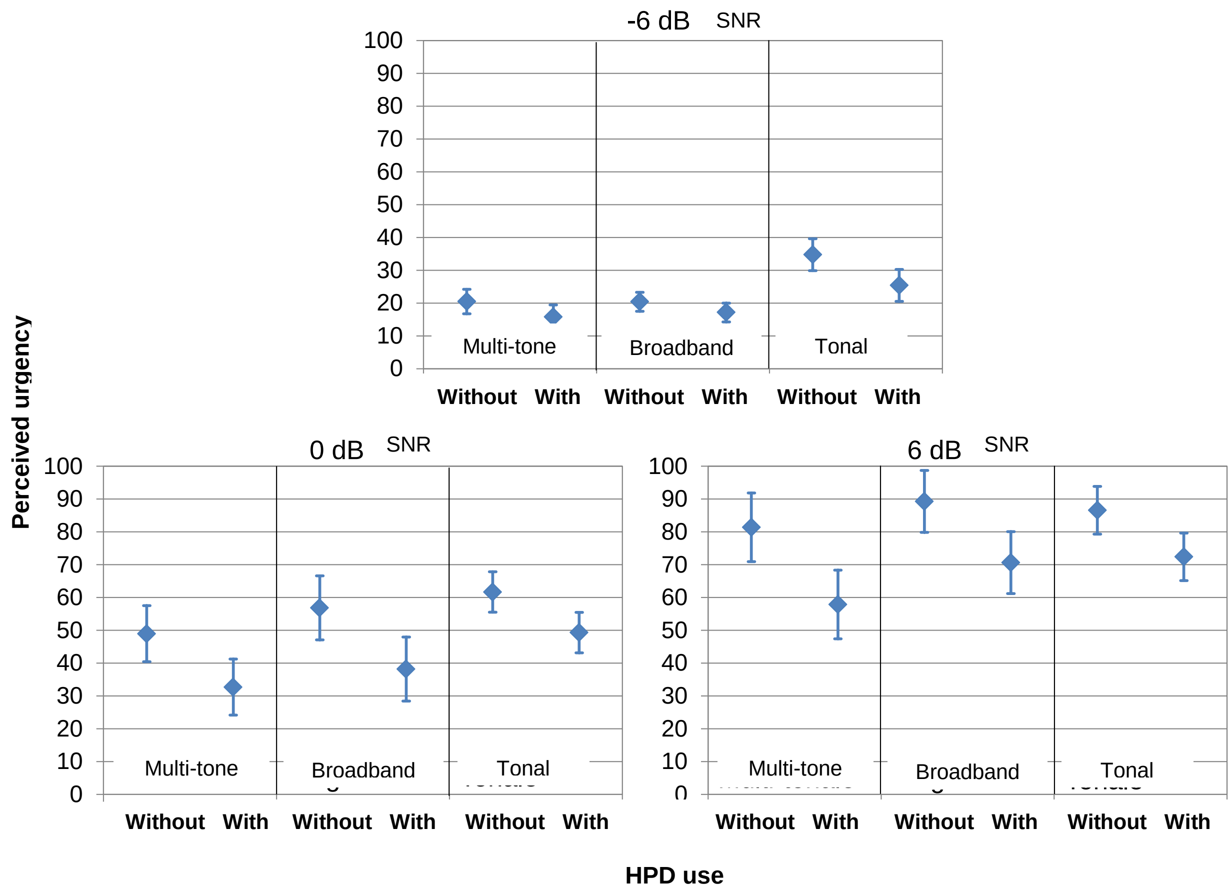


Figure 30: Comparison of mean perceived alarm urgency with and without earmuffs, by adjusting for the alarm type and presentation level factors. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

In the group of participants using earmuffs, differences in mean perceived urgency with and without hearing protection ranges from 3.3 to 23.5 units, with greater urgency perceived without earmuffs than with them in all nine comparisons. Despite this trend, only two differences were found to be statistically significant: (1) tonal alarm at 0 dB SNR (middle level) and (2) multi-tone alarm at -6 dB SNR (lower level). It should, however, be noted that the p value is fairly close to 0.05 (from 0.056 to 0.07) in five other comparisons.

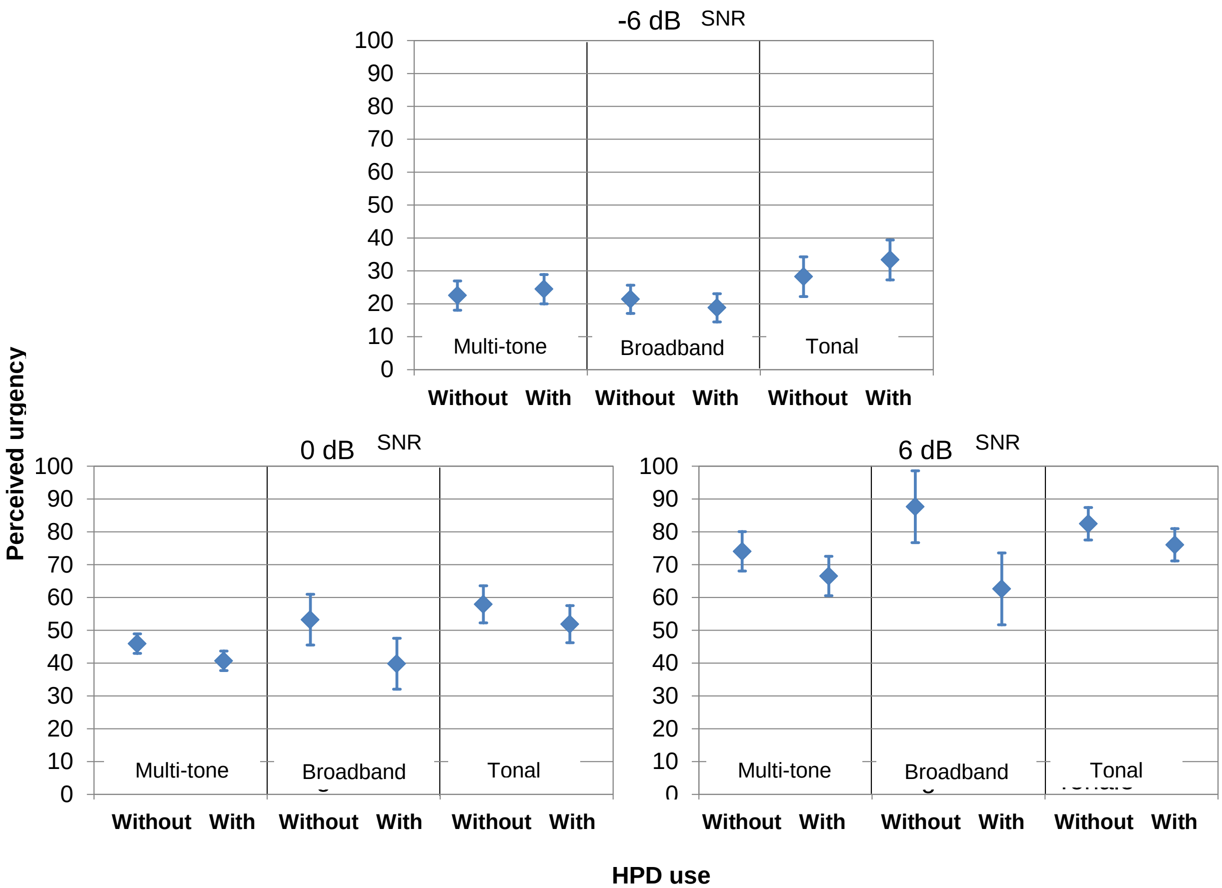


Figure 31: Comparison of mean perceived alarm urgency with and without earplugs, by adjusting for the alarm type and presentation level factors. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

In the group of participants using earplugs, only one statistically significant difference in perceived urgency was found, with greater urgency perceived without earplugs than with them for the broadband alarm at the highest presentation level (6 dB SNR). As with other analyses involving perceived urgency, high data variability renders the finding of statistical differences unlikely. Using a more descriptive approach, it can be noted that differences in perceived urgency with and without earplugs range from 1.9 to 25.0 units, with greater urgency perceived without earplugs than with them in seven of the nine possible comparisons.

H.3.3.6 Effect of Presentation Level: Earmuffs

In the group of participants using earmuffs, presentation level interacts with alarm type and HPD use, thereby yielding six comparison groups (Figure 32) in which perceived urgency across the three presentation levels can be compared.

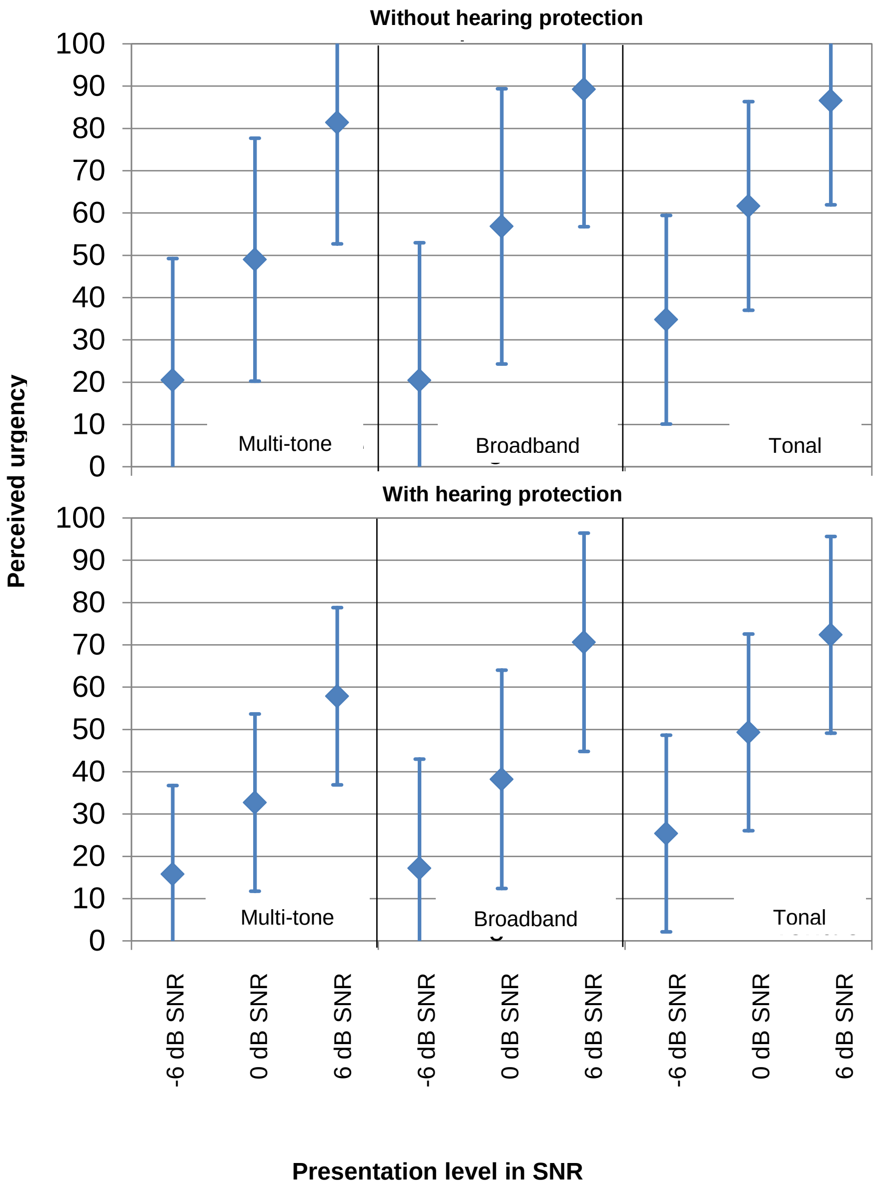


Figure 32: Comparison of mean perceived urgency at three presentation levels in the group of participants wearing earmuffs, by adjusting for the HPD use factor. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

Irrespective of alarm type, mean perceived urgency seems to increase with increasing presentation level, with and without earmuffs. However, as data variability is high, only differences in perceived urgency between the two extreme presentation levels (-6 dB SNR and 6 dB SNR), ranging from 42.1 to 68.9 units, were found to be statistically different in the six comparison groups. Overall, perceived urgency increases by approximately 25 to 35 units without protection, and by 17 to 30 units with earmuffs, for each 6 dB increase in SNR. Moreover, urgency often increases more rapidly with level for the broadband alarm compared to the other two alarms (Table 7). While this statement was not statistically verified, the differences arising from such comparisons would likely fail to reach statistical significance due to high data variability.

Table 7: Increase in perceived urgency with increasing presentation levels in the group of participants using earmuffs.

Alarm	Without earmuffs		With earmuffs	
	Difference between -6 and 0 dB SNR	Difference between 0 and 6 dB SNR	Difference between -6 and 0 dB SNR	Difference between 0 and 6 dB SNR
Multi-tone	28.5	32.4	16.9	25.2
Broadband	36.4	32.4	21.0	32.4
Tonal	26.9	24.9	23.9	23.1

H.3.3.7 Effect of Presentation Level: Earplugs

In the group of participants using earplugs, presentation level interacts only with HPD use. Therefore, only two comparison groups were formed (Figure 33) in which perceived urgency across the three presentation levels can be compared (-6 vs. 0 dB SNR, -6 vs. 6 dB SNR, and 0 vs. 6 dB SNR).

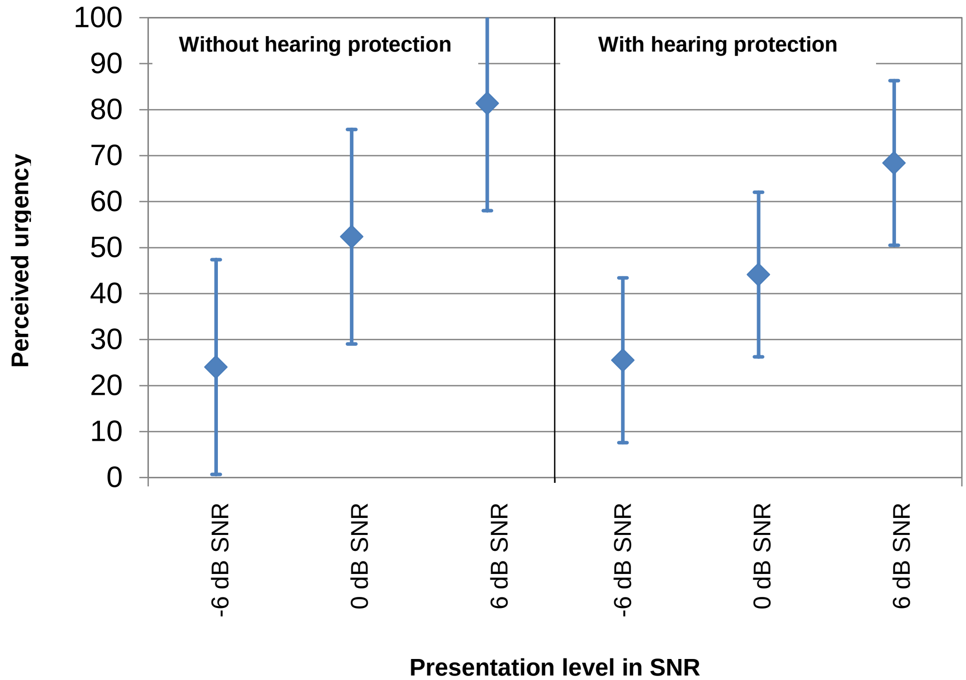


Figure 33: Comparison of mean perceived urgency for three presentation levels in the group of participants wearing earplugs, by adjusting for the HPD use factor. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

As expected, both with and without earplugs, perceived urgency increases with increasing presentation levels. Again, because of high data variability, only differences in perceived urgency between the two extreme presentation levels (-6 dB S/N and 6 dB S/N), about 57.4 units unprotected and 42.9 units with earplugs, were found to be statistically significant. Overall, perceived urgency increases by approximately 30 units without HPD and by approximately 20 units with earmuffs (about 18.6 units from low to medium levels, and 24.3 units from medium to high levels), for each 6-dB increase in SNR (Table 8).

Table 8: Increase in perceived urgency with increasing presentation levels in the group of participants using earplugs

Without earplugs		With earplugs	
Difference between -6 and 0 dB SNR	Difference between 0 and 6 dB SNR	Difference between -6 and 0 dB SNR	Difference between 0 and 6 dB SNR
28.3	29.0	18.6	24.3

H.4 SOUND LOCALIZATION

H.4.1 Experimental Plan

The experimental plan consists of a mixed design with one inter-subject factor (HPD type: earmuffs or earplugs) and repeated measurements of three intra-subject factors: (1) type of alarm (conventional tonal, three component and broadband alarms); (2) listening condition (loudspeakers at the back, right and left); and (3) HPD use (with and without). The subject factor was also considered in the analysis, with each participant being modelled as a vector of 18 measurements.

H.4.2 Effect of Protector Type (inter-subject factor)

The total variances of the variance-covariance matrices were found to be different in both groups (percentage of confusion: 22.8 with Box ϵ of 0.616 for earmuffs and 11.1 with Box ϵ of 0.956 for earplugs; angular error: 2150.2 with Box ϵ of 0.587 for earmuffs and 943.41 with Box ϵ of 0.931 for earplugs) (Box, 1953; Strivastava, 2005), supporting the need to perform separate statistical analyses for each group. To compare the means of both groups (earmuffs and earplugs), the ANOVA-type statistic that does not require matrix equality was used, with results supporting the presence of a significant effect of hearing protector type on the percentage of confusion [χ^2 (5.821) = 24.175, $p<0.001$] and on the angular error [χ^2 (4.899) = 22.068, $p<0.001$]. Therefore, separate analyses were performed for the earmuffs and for the earplugs.

The ANOVA-type statistic was used to compare the 18 intra-subject means obtained in the group using earmuffs with those of the group using earplugs. Since estimates are not precise enough in this case to describe significant differences using two-by-two comparison groups, 18 Student's t-tests for the equality of means were used. Without hearing protection, the data revealed no significant difference between the earmuff and earplug groups, apart from two conditions for the percentage of confusion and one condition for the angular error: (1) broadband alarm with loudspeakers on the left (difference = 5.2%); (2) tonal alarm with loudspeakers on the left (difference = 8.3%) and; (3) multi-tone alarm with loudspeakers behind (difference = 3°).

Similarity in performance across both groups for most unprotected testing conditions was anticipated and showed that both groups of 12 participants lead to similar performance in almost all experimental conditions. With hearing protection, significant differences across earplugs and earmuffs were found in all experimental conditions, apart from: (1) the percentage of confusion obtained for the broadband alarm with loudspeakers behind and (2) both the percentage of confusion and the angular error obtained for the tonal alarm with loudspeakers on the right. Apart from these exceptions, the percentage of confusion and the angular error in localizing reverse alarms with hearing protection were always higher (poorer performances) with earmuffs than with earplugs.

Since the 18 intra-subject means of both groups were shown to be different, separate statistical analyses were performed for the earmuffs and for the earplugs.

H.4.3 Main Effects and Interactions (intra-subject factors)

In the group using earmuffs, overall significant effects were found [χ^2 (1.584) = 14.938, p<0.001 for the percentage of confusion and χ^2 (1.693) = 15.116, p<0.001 for the angular error], particularly significant main effects of alarm type [χ^2 (1.190) = 11.752, p=0.001; χ^2 (1.311) = 12.202, p=0.001], listening condition [χ^2 (1.112) = 12.295, p=0.001; χ^2 (1.185) = 12.598, p=0.001] and HPD use [χ^2 (1.0) = 9.001, p=0.003; χ^2 (1.0) = 8.684, p=0.003], significant second-order interactions between alarm type and listening condition [χ^2 (2.295) = 16.016, p=0<001; χ^2 (2.724) = 16.081, p=0.001], alarm type and HPD use [χ^2 (2.315) = 8.536, p=0.020; χ^2 (1.980) = 11.017, p=0.004], and listening condition and HPD use [χ^2 (1.976) = 8.922, p=0.011; χ^2 (2.001) = 6.338, p=0.042], and a third-order interaction between alarm type, listening condition and HPD use [χ^2 (2.217) = 15.081, p=0.001; χ^2 (3.605) = 18.809, p=0.001], at $\alpha = 0.05$.

In the group using earplugs, overall significant effects were found [χ^2 (1.438) = 14.486, p<0,001 for the percentage of confusion and χ^2 (1.493) = 14.682, p<0,001 for the angular error], particularly significant main effects of alarm type [χ^2 (1.162) = 12.221, p=0.001; χ^2 (1.109) = 12.143, p=0.001] and listening condition [χ^2 (1.055) = 12.293, p<0.001; χ^2 (1.069) = 12.197, p=0.001] and a significant second-order interaction between alarm type and listening condition [χ^2 (1.743) = 14.955, p<0.001; χ^2 (2.080) = 15.099, p=0.001], at $\alpha = 0.05$. Of interest, no significant main effect of HPD use (with and without) was found in earplug users [χ^2 (1.0) = 3.540, p=0.06; χ^2 (1.0) = 2.600, p=0.104], indicating similar confusion percentages and angular errors with and without earplugs.

H.4.3.1 Main Effect of Alarm Type: Earmuffs

In the group of participants using earmuffs, a third-order interaction between alarm type, listening condition and HPD use was found. When exploring the main effect of alarm type, levels of the two other factors (listening condition and HPD use) must therefore be adjusted, yielding 6 possible comparison groups in which the various alarms can be compared (Figure 34). Again, the Ahmad et al (2008) ANOVA-type statistic was used to estimate differences between the mean percentages or angular error, together with a Bonferroni adjustment to control the confidence level for the six comparison groups.

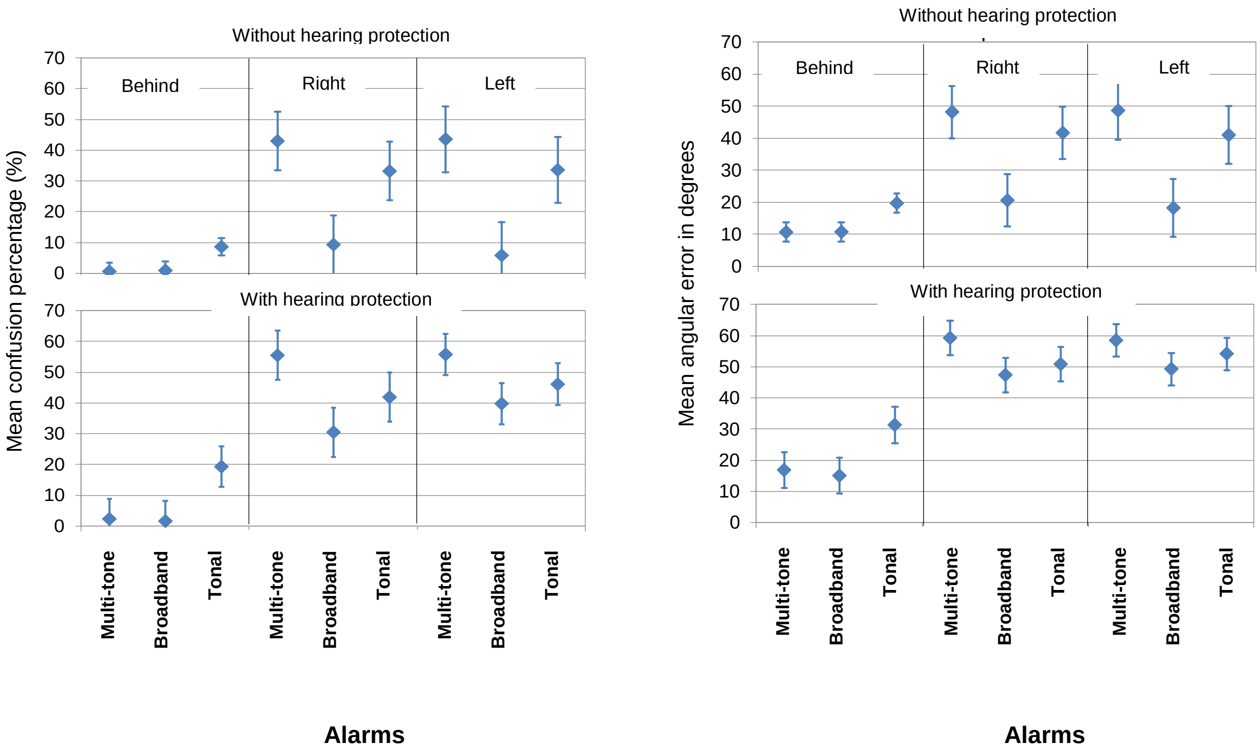


Figure 34: Comparison of mean confusion percentage (left) and mean angular error (right) for the three alarms in the group of participants using earmuffs, by adjusting the levels of the listening condition and HPD use. Error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

With loudspeakers behind, the left/right confusion percentage and the angular error are significantly higher for the tonal alarm than for the multi-tone and broadband alarms (by approximately 8% and 9° in both cases), while both dependant variables were found to be similar for the multi-tone and broadband alarms.

With loudspeakers on the side without earmuffs, the mean front/back confusion percentage and the mean angular error are significantly lower (better performances) for the broadband alarm than for the tonal and multi-tone alarms, with similar results for the latter two. The differences between the broadband and the tonal alarms range from 24.0 to 27.8% and from 21.1 to 22.8°, while the differences between the broadband and multi-tone alarms are about 33.7 to 37.8% and 27.6 to 30.4°. With earmuffs, the front/back confusion percentage is significantly higher for the multi-tone alarm than for the broadband and tonal alarms, with similar results obtained for the latter two. The mean angular error is also significantly higher for the multi-tone alarm than for the broadband and tonal alarms (which produce similar results), but only when the loudspeakers are on the right. With loudspeakers on the left, the mean angular error is similar for the three alarm types.

H.4.3.2 Main Effect of the Listening Condition: Earmuffs

Since a third-order interaction between alarm type, listening condition and HPD use was found in the group using earmuffs, the factors alarm type and HPD use must be adjusted when determining the main effect of listening condition, thereby yielding 6 possible comparison groups in which performance across the three listening conditions (loudspeaker configurations) can be compared (Figure 35).

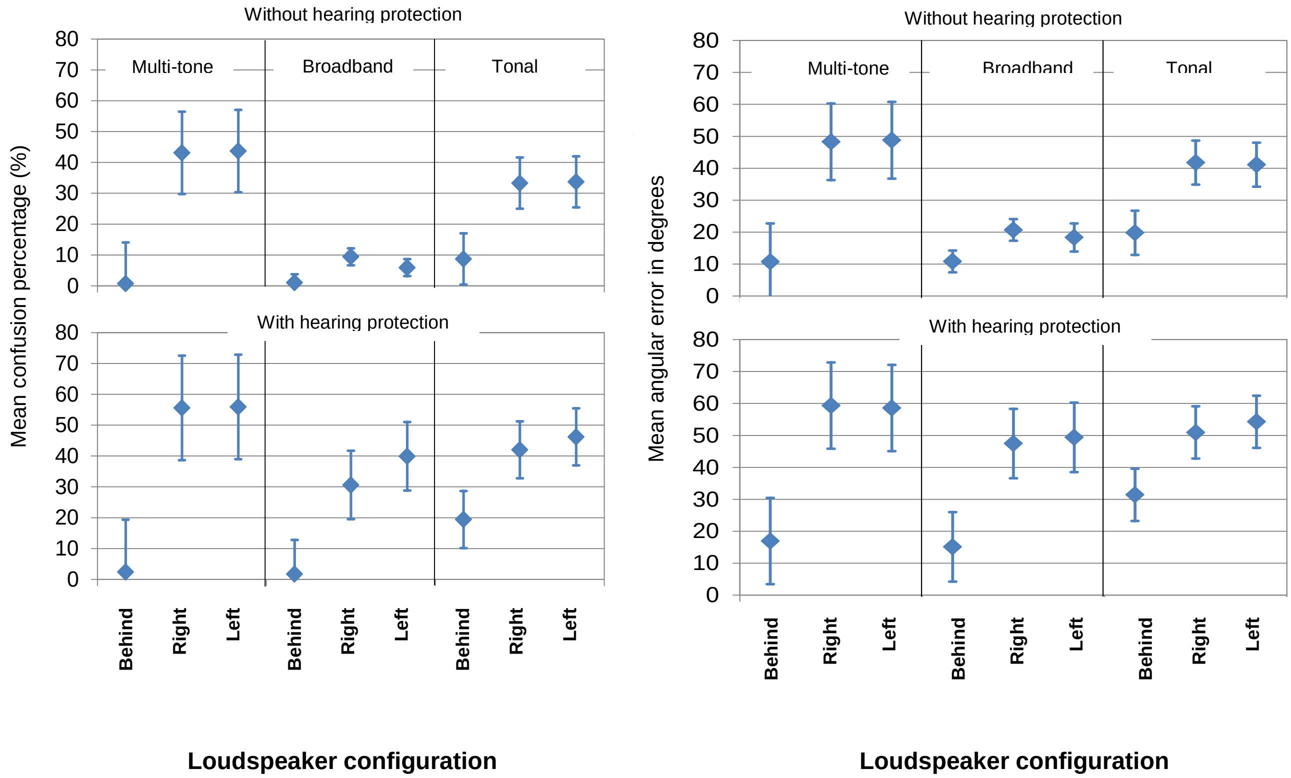
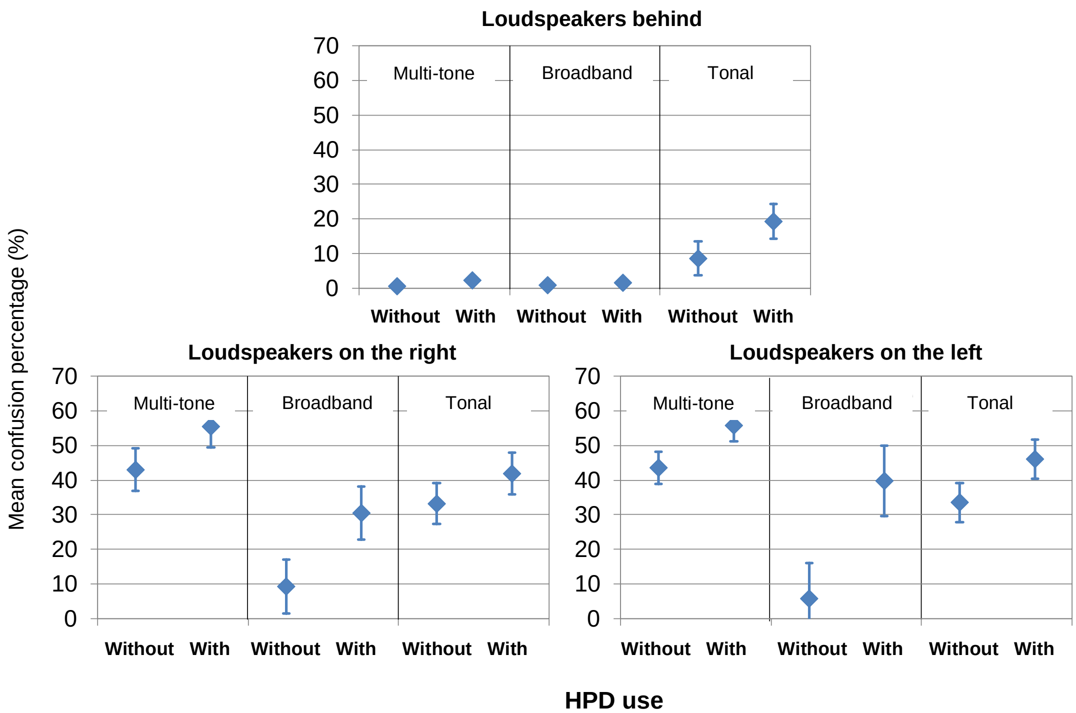


Figure 35: Comparison of mean confusion percentage (left) and mean angular error (right) for the various listening conditions (loudspeaker configurations), by adjusting the levels of the alarm type and HPD use factors. The error bars are based on the maximum error (+/- half of the maximum error) of the difference in each group of comparisons (each panel).

With and without earmuffs, the confusion percentage and angular error are similar for the conditions when loudspeakers are on the right and the left, which are considerably higher than the percentage of confusion (differences between 22.6 and 53.5%) and angular error (differences between 7.5 and 42.4°) obtained in the condition with the loudspeakers behind, irrespective of alarm type. A single exception is noted for the percentage of confusion without earmuffs with the broadband alarm, in which case only the conditions with loudspeakers behind and on the right differ significantly, although the mean confusion percentage is extremely low in all three loudspeaker configurations (less than 10%).

H.4.3.3 Main Effect of HPD Use: Earmuffs

When adjusting the levels of the alarm type and listening condition factors, nine comparison groups are obtained to examine the main effect of HPD use (Figure 36; top = mean confusion percentage; bottom = mean angular error).



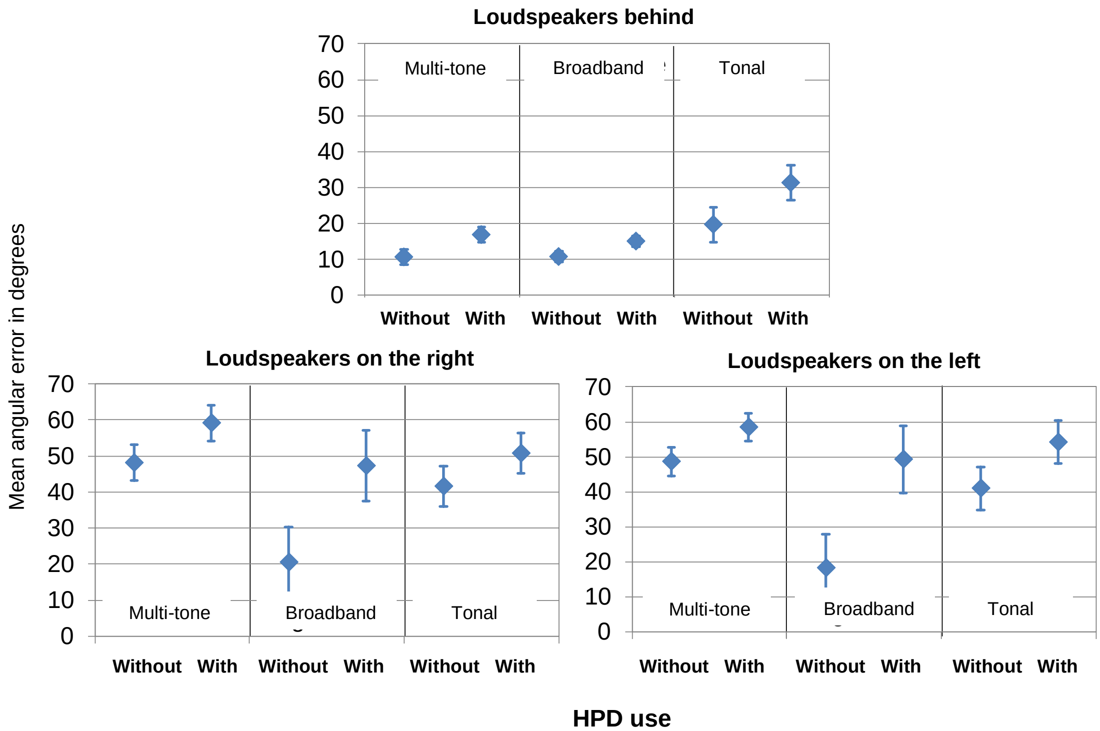


Figure 36: Comparison of mean confusion percentage (top) and mean angular error (bottom) for each HPD condition, by adjusting the levels of the alarm type and listening condition factors. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

When the loudspeakers are behind, the percentage of left/right confusion seems unaffected by the use of earmuffs compared to without hearing protection, except for the tonal alarm, in which case left/right confusions are more frequent (by 10.8%) with earmuffs than without hearing protection.

Overall, confusion percentages are generally higher with the loudspeakers on either side, and except for the tonal alarm when the loudspeakers are on the right, front/back confusion percentages are lower without earmuffs than with them (by about 13% for the tonal and multi-tone alarms and 21-34% for the broadband alarm).

With the exception of the condition involving the tonal alarm and the loudspeakers on the right, the mean angular error is always significantly higher with earmuffs than without them, by 9.8 to 31.1° for loudspeakers on the side and by 4.3 to 13.2° for loudspeakers behind.

H.4.3.4 Main Effect of Alarm Type: Earplugs

Because a significant second-order interaction exists between the alarm type and listening condition factors in the group of participants wearing earplugs, 3 possible comparison groups (Figure 37) must be taken into account when describing the main effect of alarm type, one for each listening condition (loudspeakers behind, to the right and to the left). Again, the Ahmad et al (2008) ANOVA type statistic was used to estimate the differences between the mean percentages while using a Bonferroni adjustment to control the confidence level in the three comparison groups.

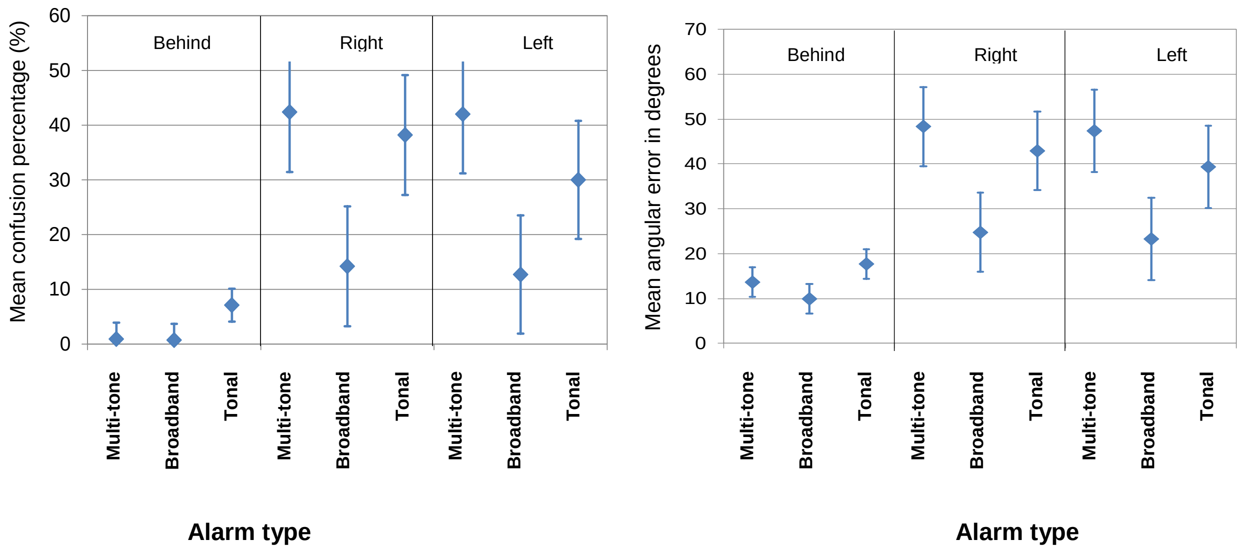


Figure 37: Comparison of mean confusion percentage (left) and mean angular error (right) of the alarms, by adjusting the levels of the listening condition factor. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

With loudspeakers behind, the left/right confusion percentage and the angular error are significantly higher for the tonal alarm than for the broadband alarm (by approximately 6% and 8°). The mean left/right confusion percentage is also 6% higher for the tonal alarm than for the multi-tone alarm, while both the multi-tone and broadband alarms share similar percentages.

With the loudspeakers on the right, the front/back confusion percentage and the mean angular error are significantly lower (better performances) for the broadband alarm than for the tonal and multi-tone alarms, with similar results for the latter two. Between the broadband alarm and the tonal alarm, there is a 24.0% difference in confusion percentage and a difference of 18.2° for angular error, while for the broadband alarm and the multi-tone alarm, the differences in confusion percentage and angular error are 28.1% and 23.6°, respectively.

With the loudspeakers on the left, the front/back confusion percentage and the mean angular error are significantly higher for the multi-tone alarm than for the broadband alarm (by 29.3% and 24.1°), indicating poorer localization performances, while similar performances were found for the broadband and tonal alarms.

H.4.3.5 Main Effect of the Listening Condition: Earplugs

When examining the main effect of the listening condition in the group of participants wearing earplugs, the levels of the alarm-type factor must be adjusted, yielding 3 possible comparison groups (Figure 38).

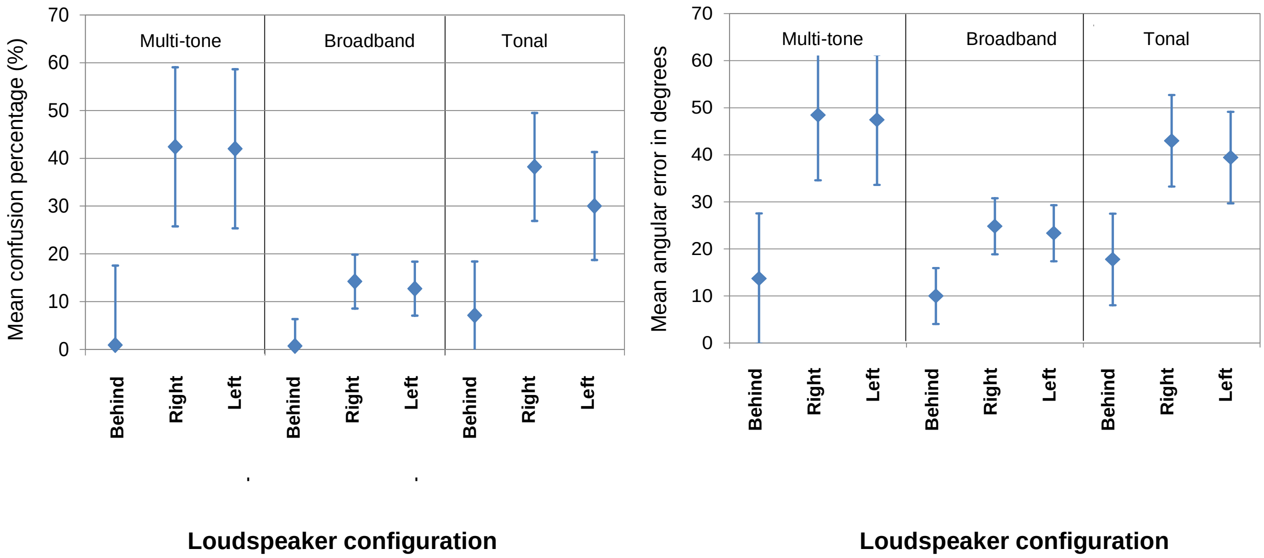


Figure 38: Comparison of mean confusion percentage (left) and mean angular error (right) across the various listening conditions (loudspeaker configurations), by adjusting the levels of the alarm-type factor. The error bars are calculated based on the maximum error (+/- half of the maximum error) of the difference obtained within each comparison group (each individual panel).

For all the alarms, the mean confusion percentage and the mean angular error are similar with loudspeakers on the right and on the left, as expected, and are significantly higher in both of these conditions than those obtained with loudspeakers behind. The differences are, however, smaller for the broadband alarm (12.0 to 13.5% and 13.3 to 14.8°) than for the tonal (22.9 to 31.1% and 21.6 to 25.2°) and multi-tone alarms (41.1 to 41.5% and 33.7 to 34.7°).

H.4.3.6 Main Effect of HPD Use: Earplugs

Finally, as mentioned previously, no significant effect was noted for HPD use, with similar mean confusion percentages and mean angular errors with and without earplugs (19.8% and 28.8° without HPD compared to 22.0% and 30.7° with HPD). It should however be noted that the p value for the mean confusion percentage (0.06) was close to reaching significance (0.05). Overall, earplugs do not seem to negatively impact sound localization, in contrast to earmuffs which particularly hinder front/back localization (loudspeakers on either side).