Advanced hearing protection and communication: progress and challenges

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INTRODUCTION

Noise remains a major problem in many industrial and military work environments. In addition to increasing the risk of permanent hearing loss, high noise levels can cause temporary hearing loss, and compromise speech communication and the perception of important signals from the environment. While the preferred method to mitigate the effects of noise is through engineering control measures at the source, this is not always technically possible or practical, and hearing protectors remain a mainstay of hearing loss prevention programs (Gerges & Casali 2007; Canetto 2009). Broadly speaking, hearing protectors can be classified as active or passive devices, whether or not powered electronic circuitry is incorporated into the design. Conventional protectors are of the passive type and are still the most commonly used. They provide a fixed attenuation irrespective of the noise level in all but the most extreme noise situations. Unfortunately, they also reduce speech and other important sounds from the environment, and a compromise in the amount of attenuation provided must be established for optimal protection, safety and work efficiency.

Some standards (CAN/CSA Z94.2-02 R2007; EN 458:2004) recommend selecting hearing protectors so that the protected level falls 5-10 dB below the occupational limit (typically 85 dBA), but this goal is difficult to achieve in practice. Firstly, the attenuation provided by hearing protectors varies widely across individuals depending on the ear geometry, fitting proficiency and motivation, among other factors, and the real-world attenuation is often far short and poorly related to current performance ratings and labelling of hearing protectors (Williams 2009). Secondly, even if the effective attenuation can be ascertained, workplace noise is rarely constant over time or uniform spatially. Thus, the protected level will vary in a given day with periods of overprotection and periods of insufficient protection. Workers generally view hearing protectors as an inconvenience and often perceive them as an impediment to information exchange and work performance, especially in the presence of a pre-existing condition of hearing loss (Abel 2008; Canetto 2009; Casali 2010).

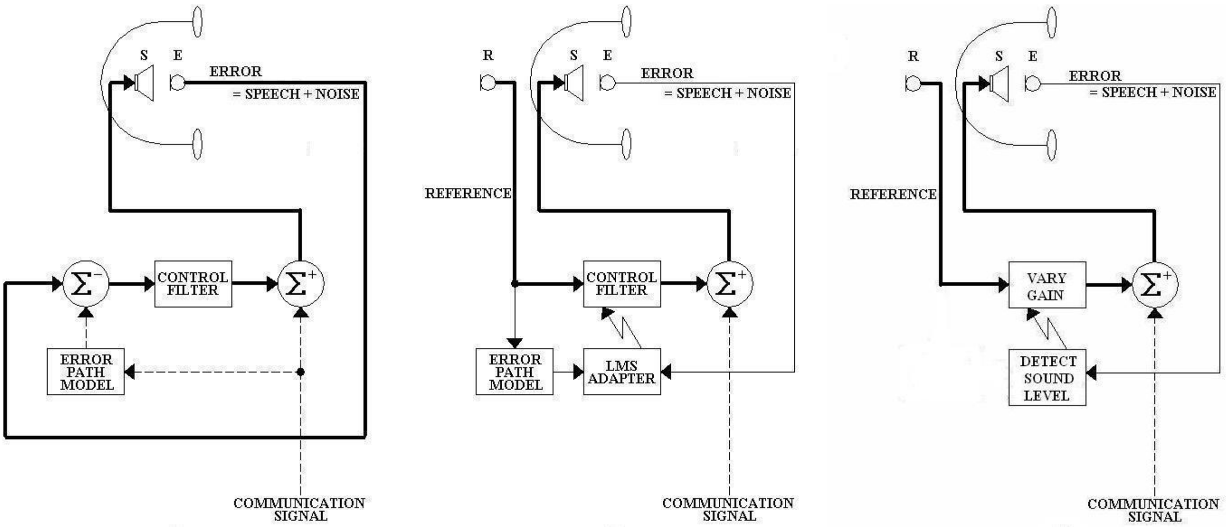
Advanced active hearing protection devices are rapidly being introduced into the marketplace with the dual purpose of providing effective protection against noise and enhancing communications. In some of the most challenging environments and work situations, the devices must protect hearing against hazardous continuous and impulse noise while maintaining good situational awareness (e.g. warning signal perception, sound localization, speech communication, detection of distant events) within the immediate surroundings and over radio communications. This paper provides an overview of recent developments, current approaches and issues in advanced active hearing protection and communication devices, and builds on the recent reviews by Brammer et al. (2008) and Casali (2010).

DESIGN CONSIDERATIONS

Rapid advances in electronics and dedicated digital signal processors in the past few years have led to a resurgence of interest in hearing protectors containing microphones, earphones and other electronic components. Typically, these devices aim to achieve one or more of the following objectives: increase the protection afforded over the passive attenuation of the device by means of active noise reduction (ANR) or phase-cancellation technology, enhance awareness of sounds in the surrounding environment through level-dependent attenuation, and incorporate radio channel capabilities for remote communications.

Active noise reduction

Figures 1a and 1b contrast the control structure of the traditional analog feedback ANR to that of the feedforward approach more commonly found in digital devices. The ear cup and cushion are shown in cross sectional view. The ear cup contains a miniature earphone (S) and one or more microphones (E and R). The thick lines show the path taken by the environmental noise.



a b c

Figure 1: Three basic schemes found in advanced hearing protectors as applied to an earmuff design: (a) feedback ANR, (b) feedforward ANR, and (c) level-dependent circuitry

In the feedback configuration (Figure 1a), a control filter acts to cancel the sound pressure at E. The main elements of this process are the transformation of the electrical signal to sound by the earphone S, the propagation of sound from S to E and the transformation of sound into an electrical signal by the microphone E. These transformations define the transfer function from S to E, which is termed the error path. In essence, microphone E detects the "error" in the cancellation of the environmental noise. Feeding back the output of the error microphone to the input of the control filter ensures that there is a continually updated correction to the performance of the control system. Owing to the delay for sound to propagate from S to E and the requirement to maintain stability, the maximum frequency for which active reduction can be achieved is typically limited to about 1,000 Hz for earmuffs and 2,000 Hz for earplugs (Brammer et al. 2008).

In the feedforward configuration (Figure 1b), a reference microphone R is used to sense the noise just outside the ear cup. An adjustable filter controls the intensity of the reference signal R. The control system accounts for the transmission of sound through the device, by using microphone E to sense the residual noise within the ear cup. In practical applications, sound cancellation is implemented digitally by an adaptive filter, the coefficients of which are commonly derived through a Least Mean Square (LMS) algorithm or its variants. Such an algorithm is most effective when it includes a model to represent the transmission of sound from S to E, which is termed the error path model. The time available for processing the reference noise signal cannot exceed the time taken for sound to propagate from R to S, typically about 150 µs. This constraint ultimately limits the complexity of algorithms that may be employed. Within this limitation, environmental noise may be reduced at frequencies typically below about 800 Hz, for earmuffs. The addition of a high-frequency active noise control system, operating in the range from about 800 to 1,600 Hz, is also possible to broaden the effective ANR bandwidth. Feedforward systems can also be effective to reduce tonal components and band-limited environmental noise in the range as high as 2,000-3,000 Hz (Casali 2010).

Level-dependent attenuation

In contrast to the ANR schemes, the pass-through structure is designed to amplify sounds reaching the ear by an amount varying according to the surrounding sound level. Devices employing such structure are often termed level-dependent hearing protectors. Figure 1c illustrates the similarities and differences with the feedforward concept (Figure 1b). A level-dependent hearing protector employs the same electro-acoustic components (microphones E and R, earphone S) as a feedforward device. However, the processing blocks have different functions. Provided that the sound level at E is below a maximum based on established limits for occupational noise exposure, the environmental sounds sensed by microphone R are amplified, and then fed to the earphone S to improve their audibility. This processing may involve analog or digital electronics. In simple designs, both speech and environmental noise are amplified usually with a preference for frequencies in which speech sounds are to be expected (e.g. frequencies > 125 Hz). This processing can improve audibility for environmental sounds that decrease in intensity with increasing frequency.

In Figure 1c, a detector continuously monitors the sound level under the ear cup at E. When the sound level exceeds a predetermined value, the gain from S to E is immediately reduced. In simple designs, the gain is kept constant, and the device behaves as a linear amplifier, when the sound level under the ear cup is below the upper limit. Other systems incorporate automatic gain control (AGC) to achieve a more gradual gain reduction over the range of external sound levels. Even more advanced designs employ complex algorithms that attempt to preferentially amplify the speech of a talker in front of the user. It is important to note that the gain block in Figure 1c is not only under direct control of the detector, but the user may manually vary the base gain through a volume control, typically over a range of 12-18 dB but sometimes more, or turn the amplifier off to achieve passive-only protection. Depending on the location of the volume control within the AGC circuitry, input- or output-sensitive compression functions akin to hearing aids can be realized.

Figure 2 shows the at-ear sound levels produced by an active level-dependent earplug on an acoustic manikin as a function of the incident free field sound level for a frontal speech-spectrum noise stimulus. Each curve represents a different talk-through gain setting, except for the curve with open diamonds which represents the open-ear function (no device fitted). Data points above (or below) the open-ear curve indicate that the device amplifies (or reduces) external sounds. In Figure 2, manikin levels increase with stimulus levels for all gain settings up to an upper limit. As expected, at-ear levels are higher with increasing gain settings at low-to-moderate stimulus levels (< 70 dBA). The shape of the curves for gain settings 6 and above shows that the device incorporates output-sensitive gain control set to a maximum at-ear level of around 92 dBA [Note that difference between open-ear and free-field levels is 8 dB, so that this upper limit corresponds to an equivalent free-field level of about 84 dBA]. Other features include input-sensitive compression characteristics at a free-field threshold of 80 dBA with a compression ratio of about 4:1.

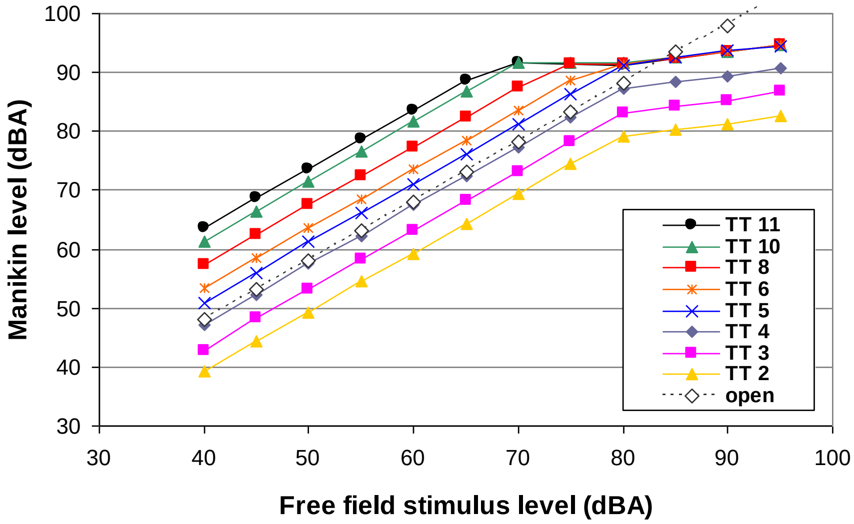


Figure 2: Level functions for a level-dependent communication earplug for different talk-through (TT) settings. Open diamonds represent the open-ear function. Frontal speech-spectrum noise stimulus

Finally, combination of the basic schemes in Figure 1 is possible, e.g. feedback ANR with level-dependent attenuation. Many ANR and level-dependent devices are also equipped with a communication channel (shown by dashed lines in Figure 1). This signal is fed to the same earphone through a summation unit (Σ^+).

FACTORS AFFECTING AUDITORY PERCEPTION

Table 1 lists some of the factors involved in the performance of auditory tasks from the perspective of a listener wearing hearing protection equipment. Common auditory tasks include signal detection (e.g. warning sound, distant audible cue), discrimination (e.g. machinery defect, different talkers) and recognition (e.g. speech understanding, source identification) as well as spatial localization of these sounds.

Table 1: Some factors involved in auditory perception and communication performance

Tasks	**Talker**	**Source factors**	**Environment**	**Listener**
Detection	Gender	Power	Distance	Hearing protectors
Recognition	Vocal effort	Directivity	Reverberation	Binaural effects
Localization	Lombard effects	Spectrum	Noise field	Fluency
	Fluency/accent	Temporal char.	Competing sounds	Hearing status
	Orientation			Cognitive abilities

Factors affecting speech production for a talker in the surrounding environment include gender and vocal effort (including the Lombard effect of naturally raising one's voice in noise), language fluency and accent, and the orientation of the talker with respect to the listener. Factors related to non-speech sources include the acoustic power and directivity of the sound radiated, and its spectral and temporal characteristics. The sound reaching the listener is modified by the transmission characteristics of the surrounding environment including distance, reverberation and other room acoustic effects, and may be degraded due to interfering noise sources or competing sounds. Factors affecting auditory perception include the use of hearing protectors and their performance characteristics, binaural effects related to the spatial distribution signal and noise, the signal-to noise ratio and the overall intensity, and the fluency, hearing status and cognitive abilities of the listener.

Communications carried over radio are affected by most of the factors above, but also include the characteristics and features of the pickup microphone at the talker's end, the quality of the radio transmission (especially distortions), and the acoustical characteristics of the communication signals presented to the listener in interaction with the environmental sounds passing through the passive or active hearing protection headset.

REVIEW OF RECENT STUDIES

Most reports on advanced active hearing protectors have focussed on attenuation characteristics. Relatively few, independent, field and laboratory studies have been conducted to assess their benefits or drawbacks on auditory tasks and operational performance compared to conventional hearing protection or unprotected listening.

Sound detection

Signal detection in quiet is generally superior with level-dependent hearing protectors than conventional hearing protectors, as expected due to their lower attenuation at low levels. When used at high amplification settings, they may even result in improved hearing thresholds compared to unprotected listening for hearing-impaired listeners, a benefit somewhat limited by the amount of audible masking hum from the device electronics for normal hearing listeners (Abel & Giguère 1997). Casali et al. (2009) showed that, in at least one active communication earplug with pass-through gain of 36 dB, the auditory detection distance improved by 80 % compared to unprotected listening, demonstrating the potential benefits in quiet of level-dependent hearing protection in tactical operations.

With regards to the detection of backup alarms in noise, data from Casali et al. (2004) indicate that hearing protectors with superior low-frequency attenuation, such as typically provided by ANR devices, may provide an advantage over conventional hearing protectors in some situations of intense low-frequency noise for normal hearing subjects. Such a benefit appears related to a reduction in the upward spread of masking into the signal frequency range (Casali et al. 2004; Brammer et al. 2008). Recent data collected in one of our laboratories (University of Connecticut) with a level-dependent earmuff indicate that the direction of the signal with respect to the user may be an issue for the detection of an alarm in noise. In some situations, near-perfect alarm detection can be achieved for frontal incidence while chance performance is obtained for signals from the back in the same diffuse noise field. This may be related to the directional characteristics or position of the external microphones on the ear cups.

Sound localization

Differences were noted across studies concerning the benefits of advanced hearing protection devices for sound localization in quiet. Abel et al. (2007) found that two advanced communication systems (earplug and earmuff) were less detrimental than passive protectors in an 8-speaker identification task in the horizontal plane using broadband noise stimuli. The decrement in performance compared to unprotected listening were largely due to front-back reversal errors. In a follow-up study with the active earplug device in interaction with various military helmet configurations (Abel et al. 2009), the degradation in localization performance with respect to unprotected listening was relatively smaller, especially with helmet use, and related to fine front-back confusions between sources close to the interaural axis, which are less likely to impact on operational performance. However, in another study by Brungart et al. (2007), use of hearing protectors with level-dependent characteristics resulted in poorer localization performance than conventional hearing protectors for broadband noise stimuli, and even poorer performance compared to unprotected listening in a 3D sound localization task. However, the authors note that their results were much worse than those obtained for a different set of level-dependent hearing protectors in a previous study in their laboratory.

In a sound localization study carried out in traffic noise, Carmichel et al. (2007) evaluated three different active level-dependent earmuffs. Results indicated that the devices did not preserve localization abilities under most stimulus conditions, and reaction times were longer for familiar broadband stimuli with the active devices than unprotected listening. Alali & Casali (2011) investigated the sound localization of back-up alarms in pink noise for a range of seven active and passive earplugs and earmuffs. Overall, a dichotic level-dependent earmuff tested did not show an advantage for sound localization over a passive counterpart, and performed slightly worse than some passive earplugs in high noise levels. The difference was related to larger front-back errors.

Speech recognition

Dolan and O'Loughin (2005) investigated the impact of one passive and three active level-dependent earmuffs on sentence recognition for listeners with sensorineural hearing loss. Speech recognition thresholds in 85 dBA industrial noise (speech and noise at frontal incidence) did not improve nor degrade by use of the passive device or the active devices set at the listener's preferred gain setting, despite greatly different gain characteristics across devices, compared to unprotected listening.

The impact of hearing protectors, active and passive, depend on the experimental conditions investigated. Recent data collected at the University of Ottawa is illustrative. Word recognition scores were obtained for frontal speech incidence in two military noises presented in a diffuse field at 80-95 dBA. The difference between protected scores with an active level-dependent earmuff under three different pass-through gain settings (off, low, high) and unprotected scores for four groups of subjects with different degrees of hearing loss is shown in Figure 3a. A positive difference indicates a benefit over unprotected listening. Normal-hearing subjects were unaffected by the device when used in the off position, which results in about 30 dB of passive attenuation, but subjects with hearing loss were negatively affected by an amount dependent on the degree of the loss, in agreement with previous studies on the impact of passive protection. In the low position, which provided about -4dB pass-through gain, a large benefit was obtained compared to the off position in the order of 25-60 % across subject groups. In the high position, which provided about +10 dB of pass-through gain, all subject groups showed an improvement of about 20-30 % with respect to unprotected listening, a very encouraging outcome.

Data collected at the University of Connecticut for normal hearing subjects in diffuse field low-pass pink noise show the effect of talker position for two active level-dependent earmuffs (Figure 3b). There is a 10-15 % word recognition benefit with respect to passive protection when the speech is frontally incident, but the converse occurs when speech is incident from the back. This again may be related to the directional characteristics or position of external microphones on the ear cups.

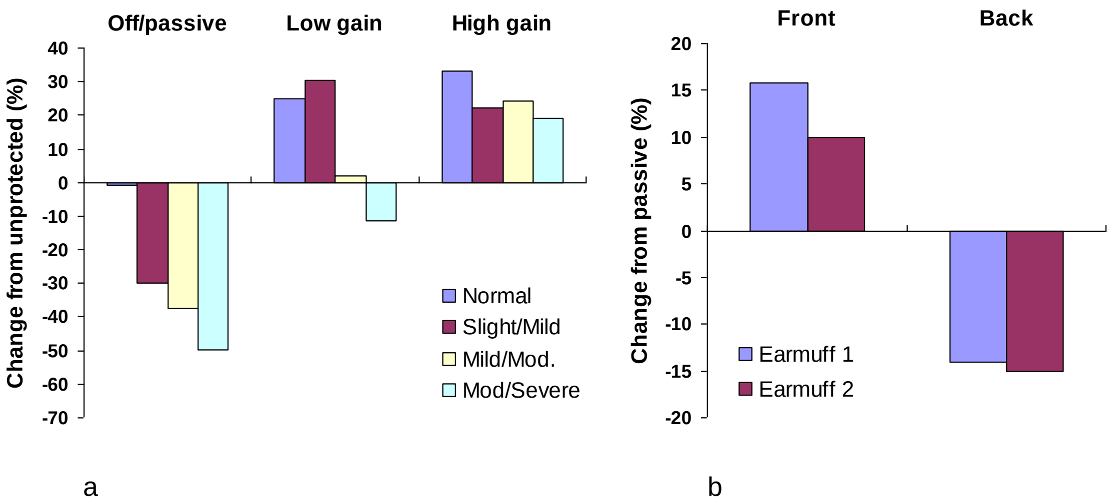


Figure 3: Speech recognition with two active earmuffs
(a) Data for Earmuff 1 for frontal speech as a function of pass-through gain and hearing loss
(b) Data for front and back incidence for both devices

Casali et al. (2007) investigated speech intelligibility and operational performance while using three ANR headsets and one passive device in a flight simulation experiment carried out over the communication channel. In adverse conditions, the three ANR devices led to less command repetitions than the passive headset and, in three of four measures of flight control, one ANR device led to better performance than the other devices. Also, subjects' ratings of workload was lower with the ANR headsets than the passive device. Further work is needed to uncover which specific design parameters of the headset are critical to flight performance.

CONCLUSIONS

To our knowledge, as yet there is no device sufficiently engineered to restore reliably the situational awareness to that in the absence of a hearing protector in all situations but, as described above, progress is being made in a number of areas. Subjective impression by users is generally favorable to active level-dependent and ANR devices over passive protectors (Casali et al. 2007; Williams 2011; Tufts et al. 2011). However, only a limited subset of the factors listed in Table 1 has been investigated thus far, often for very specific listening situations or work occupations, and it has been difficult to generalize outcomes over different or even similar test conditions.

One impediment to future progress is the sparse and widely disparate disclosure of electro-acoustic technical data by manufacturers of advanced active hearing protectors, in sharp contrast to hearing aid manufacturers. Some progress is expected since the promulgation of standard ANSI/ASA S12.42 (2010); however, this new standard only focuses on the noise attenuation characteristics of the devices. Important parameters for situational awareness, such as the directional characteristics of microphones, compression parameters, internal noise, and harmonic distortion of pass-through and communication channels, are not addressed. Hence, it remains difficult to associate outcomes to specific technical parameters of the devices. This is needed to develop predictive models and tools to assist in the selection of the most appropriate device for specific situations as may be done, for example, for conventional hearing protectors (Giguère et al. 2010).

[Work funded by the Natural Science and Engineering Research Council of Canada, Defence R&D Canada, and the National Institute for Occupational Safety and Health]

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