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Research on Modelling the Effects of Personal Hearing Protection and Communications Devices on Speech Intelligibility in Noise

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DRDC Toronto CR 2011-101
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In conducting the research described in this report, the investigators adhered to the policies and procedures set out in the Tri-Council Policy Statement: Ethical conduct for research involving humans, National Council on Ethics in Human Research, Ottawa, 1998 as issued jointly by the Canadian Institutes of Health Research, the Natural Sciences and Engineering Research Council of Canada and the Social Sciences and Humanities Research Council of Canada.

Abstract

The effects of two advanced level-dependent communication devices on face-to-face speech intelligibility in military noises were investigated. Devices were the NACRE QuietPro and the PELTOR Powercom Plus. Noises from the LAVIII and Bison light-artillery vehicles were reproduced in a noise simulation room at 80-95 dBA. Over 45 subjects covering a wide range of hearing profiles from normal hearing to severe hearing loss were tested using sentences from the Hearing-In-Noise Test (HINT). When used as passive devices with the electronics powered off, the two devices performed as expected from conventional hearing protectors having the same amount of attenuation. In this mode, there were large performance differences among subject groups in terms of the effects of wearing the devices compared to unprotected listening. However, when used in active talk-through (or surround) mode, both devices showed large speech intelligibility benefits over the passive mode and demonstrated a level of performance often exceeding that in unprotected listening. The subject group with the most impaired hearing benefitted the most from the active mode. The findings indicate that the current technology of high-end tactical communication devices could provide substantial benefits in situational awareness during noisy military operations for all hearing grades.

Résumé

Deux appareils de communication haute gamme avec isolation acoustique dépendante du niveau sonore ont été évalués lors d'essai de reconnaissance de la parole en situation bruyante face à face. Il s'agit des appareils NACRE QuietPro et PELTOR Powercom Plus. Des bruits militaires en provenance de véhicules blindés légers de type LAVIII et Bison ont été reproduits dans une salle d'écoute à des niveaux sonores de 80-95 dBA. Un total de 45 sujets couvrant un large éventail de profils auditifs de normal à perte sévère ont été testés à l'aide des phrases du test de parole « Hearing-In-Noise Test (HINT)». Lors de tests d'écoute en mode passif avec circuits électroniques non alimentés, les deux appareils ont procuré des résultats similaires à ceux attendus par des protecteurs contre le bruit conventionnels possédant un même niveau d'isolation acoustique. De grandes différences de performance ont été observées entre les différents groupes de sujets en ce qui a trait à l'effet du mode d'utilisation passif comparativement à l'écoute sans protection. Par contre, lors de tests d'écoute en mode actif avec amplification des sons extérieurs, les deux appareils ont procuré un bénéfice important en reconnaissance de la parole par rapport au mode passif et démontré un niveau de performance souvent au-delà des résultats sans protection auditive. Le groupe de sujets présentant la perte auditive la plus sévère a bénéficié le plus du mode actif. Ces résultats semblent indiquer que la présente technologie d'appareils de communication tactique haute gamme puisse offrir une présence situationnelle rehaussée lors d'opérations militaires bruyantes pour toutes les catégories d'audition.

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Executive Summary

Research on Modelling the Effects of Personal Hearing Protection and Communications Devices on Speech Intelligibility in Noise

Christian Giguère, Chantal Laroche, Véronique Vaillancourt; DRDC Toronto CR 2011-101; Audiology Research Laboratory, University of Ottawa; June 2011.

Background:
Noise and hearing loss are two major problems affecting operational efficiency and safety in the military. In addition to causing permanent or temporary hearing loss, excessive noise impacts aural communication tasks. As well, hearing loss from all sources interacts with noise and protective equipment and may produce suboptimal conditions in the field. The advent of advanced tactical communication devices with hearing protection capabilities holds the promise of superior field performance compared with conventional hearing protectors. However, these devices are very complex and they can be set over a wide range of different control settings. Yet, very little empirical data is available on their efficacy with human subjects, especially for users with hearing loss.

Methodology:
Speech intelligibility tasks were carried out over a group of 45 subjects in two military noise environments reproduced in a noise simulation room at 80-95 dBA. The hearing status of subjects covered a wide range of profiles from normal hearing to severe hearing loss. Two level-dependent active communication devices were tested: the NACRE QuietPro insert device and the PELTOR Powercom Plus earmuff. Each device was tested in three different modes: a mode with electronics turned OFF to simulate a conventional passive hearing protector, and two active modes where the device passed through external sounds at a low (-4 dB) or high (+10 dB) gain. Subjects were also tested without devices to analyse the impact of wearing the device on speech perception in noise.

Results:
The speech intelligibility data collected with the two communication devices in passive mode closely paralleled those expected from conventional hearing protectors with the same amount of attenuation. However, when used in the two active modes, the communication devices tested provided superior performance and large benefits for all groups of subjects. Not only was performance in active mode superior to the passive mode, it produced performance at or beyond unprotected performance in many cases. Electroacoustic testing revealed that the devices have output limitation circuitry that would likely maintain user's exposure below the regulatory limit in continuous noise environments up to at least 100 dBA.

Significance and future plans:

The current technology of high-end tactical communication devices appears to provide very substantial benefits over conventional hearing protection devices for speech perception in noisy face-to-face communication situations, especially for users with a pre-existing condition of hearing loss. This should impact very positively on situational awareness in the field for military personal in all hearing grades. Additional research on the effects of these devices on speech production in noise and over radio communication tasks is warranted, as well as their protective performance against impulse noise.

Sommaire

Recherche sur la modélisation des effets de la protection auditive individuelle et des appareils de communication sur la reconnaissance de la parole dans le bruit

Christian Giguère, Chantal Laroche, Véronique Vaillancourt; RDDC Toronto CR 2011-101; Laboratoire de recherche en Audiologie, Université d'Ottawa; juin 2011.

Introduction:
Le bruit et la perte auditive sont deux facteurs importants pouvant compromettre l'efficacité opérationnelle et la sécurité lors d'opérations militaires. En plus d'entraîner une perte auditive temporaire ou permanente, le bruit excessif peut nuire aux tâches nécessitant une communication orale. De plus, peu importe sa cause, une perte auditive peut interagir avec le bruit environnemental et la protection auditive et ainsi créer des conditions terrains sous-optimales. L'avènement d'appareils de communication avancés avec protection auditive intégrée est prometteur d'une performance terrain supérieure à celle des protecteurs auditifs conventionnels. Toutefois, ces appareils sont à la fois très complexes et ils peuvent être ajustés selon divers paramètres. Très peu de données empiriques sont disponibles concernant leur efficacité avec sujets humains, tout particulièrement pour les utilisateurs ayant une perte auditive.

Méthodologie:
Quarante-cinq individus ont participé à des essais de perception de la parole dans deux environnements sonores militaires recréés dans une salle de simulation sonore à des niveaux entre 80 et 95 dBA. Le statut auditif des participants couvrait un large éventail de profils, allant d'une audition normale à une perte auditive de degré sévère. Deux appareils de communication actifs avec atténuation variable en fonction du niveau sonore ont été évalués, un bouchon intra-auriculaire NACRE QuietPro et une coquille PELTOR Powercom Plus, dans trois différents modes d'utilisation : un mode dans lequel le circuit électronique était éteint (mode passif) afin de simuler un protecteur auditif conventionnel, ainsi que deux modes actifs laissant passer les sons externes tout en appliquant un gain faible (-4 dB) ou élevé (+10 dB). Des essais sans appareil de communication (oreilles non-obstruées) ont également été effectués afin d'évaluer l'effet du port d'appareil sur la perception de la parole dans le bruit.

Résultats:
Les données recueillies en mode passif pour les deux appareils étaient très similaires aux performances attendues par des protecteurs auditifs conventionnels offrant un même niveau d'isolation acoustique. Toutefois, lorsqu'utilisés en mode actif, les deux appareils de communication évalués ont démontré une performance supérieure et des bénéfices

importants pour tous les profils auditifs. Non seulement la performance dans le mode actif était nettement supérieure à celle du mode passif, elle égalait ou surpassait même la performance sans protection dans plusieurs cas. Tel que démontré par des mesures électroacoustiques, les deux appareils sont dotés d'un circuit à sortie limitée qui devrait permettre de maintenir l'exposition des utilisateurs à des niveaux inférieurs à la limite réglementaire dans des bruits continus pouvant atteindre au moins 100 dBA.

Importance et recherches futures:

La présente technologie d'appareils de communication de haute gamme semble offrir des bénéfices importants par rapport aux protecteurs auditifs conventionnels pour des tâches de perception de la parole dans des situations de communication face-à-face dans le bruit, particulièrement pour les utilisateurs atteints d'une perte auditive. Ces appareils pourraient donc avoir un impact positif sur la présence situationnelle sur le terrain pour tout le personnel militaire, peu importe la catégorie auditive. L'effet de tels appareils sur la production de la parole dans le bruit et lors de tâches de communication par radio devraient faire l'objet de recherches ultérieures, tout comme l'évaluation de leur niveau de protection contre les sons impulsifs.

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The authors wish to thank Dr. Sharon Abel (Defence Scientist, Diagnosis & Prevention Group, Individual Behaviour and Performance Section, DRDC Toronto) who acted as scientific authority on this contract and provided valuable expertise and feedback throughout this project. The authors would also like to thank the many participants for their contribution to the advancement of knowledge in the field of speech perception in noise with advanced hearing protective devices.

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1.0 Preamble

Defence Research and Development Canada (DRDC) Toronto has a requirement for *Research on modelling the effects of hearing protection and communications devices on speech perception in noise*, with a particular focus on field applications. The work is staged over three fiscal/reporting periods as follows:

Stage I (ending March 31st 2009): Design a Study
Stage II (ending March 31st 2010): Test Human Subjects; Conduct Preliminary Analysis of Data; Begin Modelling
Stage III (ending March 31st 2011): Complete Analysis and Modelling
Final report (due not later than June 30th, 2011)

This final report documents the work accomplished between February 23rd 2009 and June 30th 2011 under PWGSC Contract No. W7711-088145/001/TOR. It presents the study design and methods devised in Stage I, subjective and objective data collected in Stage II, and data analysis and results from Stage III.

2.0 Introduction

2.1 Background

Military personnel regularly face a wide range of very noisy situations during field operations (Gasaway, 1994). A hearing conservation program has been in place in the Canadian Forces (CF) since the 1950's (Neely, 1959) and undergoes periodic reviews and assessments (e.g. Forshaw, 1970; Rylands and Forshaw, 1988, Pelausa et al., 1995; Giguère and Laroche, 2005). Nonetheless, the prevalence of hearing loss among members in active duty progresses significantly with age, and the proportion of individuals over 45 years of age with hearing thresholds exceeding 40 dB HL is at least twice the proportion that is expected from published norms for otologically normal persons (Abel, 2005) as defined in ISO 7029:2000. There is also a wide susceptibility to noise among members, and hearing status ranges broadly from normal to severe hearing loss (Abel, 2005).

At the same time, functional hearing abilities such as speech communication and warning sound perception are of utmost importance in field operations. These tasks often require use of hearing protection or communication devices and must be carried out despite the presence of noise-induced hearing loss among members. Unfortunately, the hearing protection gear provided is sometimes incompatible with other protective equipment and/or often judged to be uncomfortable or impeding communications (Abel, 2008).

Adequate hearing loss prevention practices in the military not only require general periodic training on noise hazard and use of hearing protection devices, but also tailored interventions based on individual communication needs, task demands and constraints in the field. One difficulty in providing tailored solutions is the complex interaction between the hearing status of the member, the spectral and temporal nature of the noise field, the effects of the protective device on signal transmission and noise attenuation, and the characteristics of the communication task itself (e.g. distance from the talker, vocal effort, speech material, etc.). Computational tools and predictive models of speech intelligibility in noise are needed to take all the relevant factors into consideration. There is a pressing need to develop tools or guidelines to assist in the selection of hearing protection equipment for field applications.

2.2 Previous work

Recently, progress has been made towards the development of predictive models of speech intelligibility in noise applicable for individuals with normal hearing or with hearing loss while wearing conventional hearing protective devices (HPDs), as described in Giguère et al., 2008a). Accurate prediction of speech intelligibility was found to require consideration of both the audibility and the distortion components of a hearing loss, in addition to the attenuation of the device and the characteristics of the noise field. A summary of this work is found below.

2.2.1 Methodology

A set of two speech perception studies was carried out in eight representative military noises in a simulation room (Giguère et al., 2008a). The first experiment with a group of 32 normal hearing subjects was used to develop a general model of the psychometric function for speech intelligibility that can be tuned to the specific characteristics of the noise field under study. The second experiment conducted with an additional group of 35 subjects was used to validate the general model for use with listeners with a wide range of hearing profiles (up to severe hearing loss) and wearing HPDs (E-A-R Combat Arms earplugs, 3M, St. Paul, MN; and Peltor H10A earmuffs, 3M, St. Paul, MN).

2.2.2 Model description

Figure 1 below depicts the general method used to predict speech perception in noise with hearing protectors for a given individual, with or without hearing loss. Essentially, it combines a method previously used by the authors (Laroche et al., 2005; Giguère et al., 2008b) to account for supra threshold distortion deficits in speech perception together with the use of the Speech Intelligibility Index (SII) (ANSI S3.5-1997 R2007) to account for possible audibility effects when HPDs are worn. The prediction is based on the individual's Hearing-In-Noise-Test (HINT) (Nilsson et al., 1994) score and audiogram, the hearing protector attenuation, the external noise spectrum and signal-to-noise ratio (SNR), and a generalized model of speech perception in noises for normal listeners with open ears.

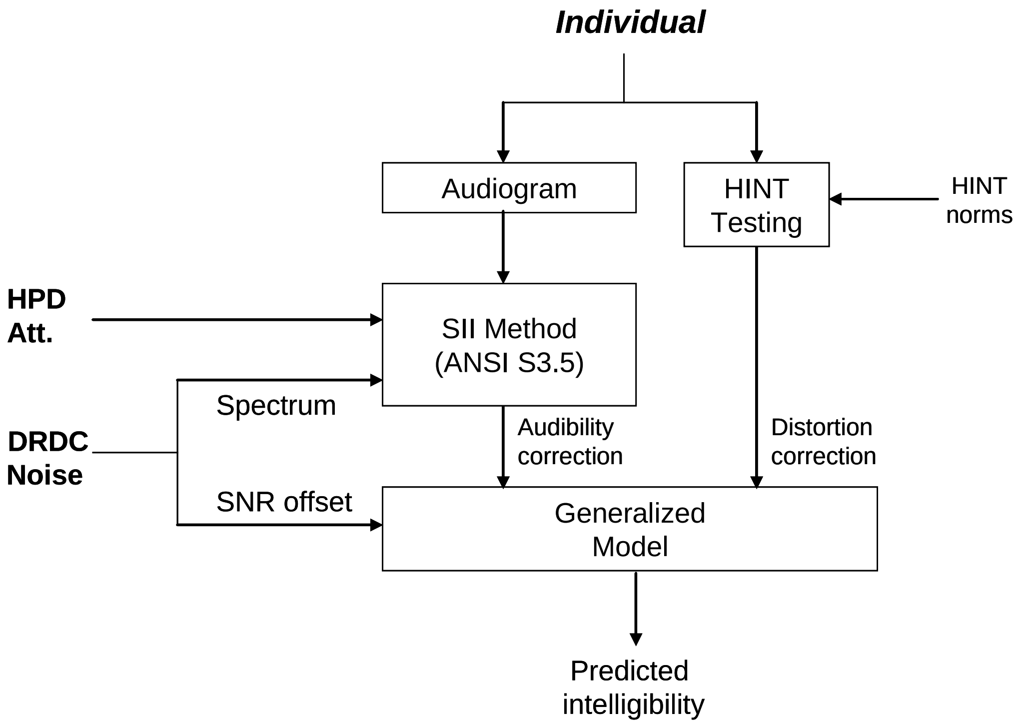

Figure 1: General method to predict speech perception with hearing protectors.

2.2.3 Results

The collected data provided new insight into the complex interaction between hearing status and HPD attenuation on speech intelligibility in noise. Figure 2 contrasts protected speech intelligibility scores (vertical) against unprotected scores (horizontal) for four categories of hearing profiles among subjects: Normal hearing, Slight/Mild hearing loss, Mild/Moderate hearing loss and Moderate/Severe hearing loss. If hearing protectors were not influencing speech intelligibility, data points would fall near the diagonal line across all panels on this figure. Instead, a decrease of 15.6% (SD = 23.9) was noted, on average, across all subjects, noises and hearing protectors. Moreover, the HPD effect (protected minus unprotected scores) was highly influenced by hearing profile as shown in Figure 3.

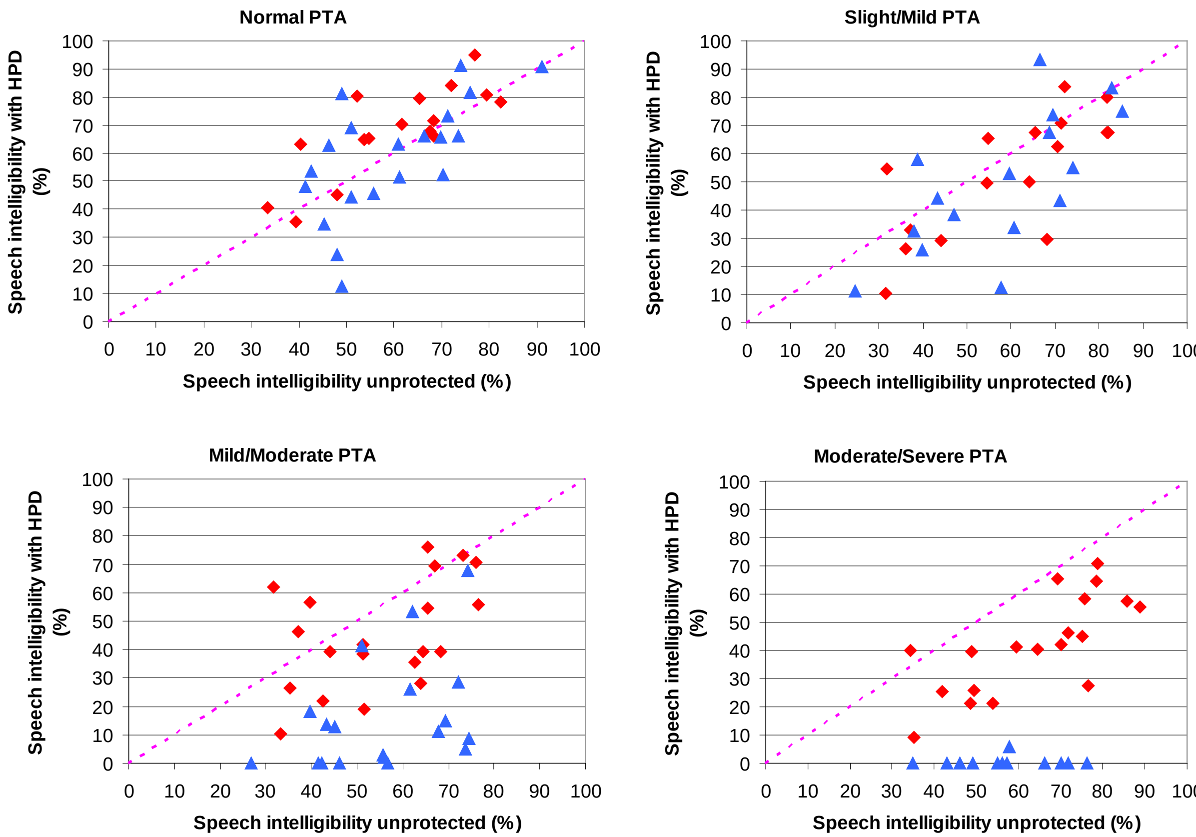

Figure 2: Unprotected and protected speech intelligibility scores across all noise environments for individuals with various hearing profiles.

For individuals with hearing thresholds within normal limits, hearing protectors did not seem to significantly hinder speech intelligibility in the majority of cases (Figure 2). In some cases, speech intelligibility even improved, especially when using a hearing protector which provided less attenuation, such as the E-A-R Combat Arms earplugs. In contrast, the Peltor H10A earmuffs did not, on average, increase nor decrease speech intelligibility for this group (Figure 3). For all remaining profiles in which hearing loss was present, hearing protectors generally reduced speech intelligibility, an effect which increased rapidly with the degree of hearing impairment (Figures 2 and 3). As hearing loss increased, audibility became a crucial contributing factor in explaining the reduction in speech intelligibility when hearing protectors were used, and differences in the effects of both hearing protectors also became evident. For the Mild/Moderate and Moderate/Severe hearing categories, the Peltor earmuffs appeared to yield greater decreases in speech intelligibility compared to the AOSafety earplugs. Indeed, for the most severe impairments, intelligibility dropped to zero or near-zero values for all subjects wearing the Peltor earmuffs while some speech intelligibility remained with the AOSafety, as indicated in the bottom-right panel of Figure 2. Altogether, these data illustrate the problem of overprotection in some cases and demonstrate the need to account for audibility effects in predictive models of speech intelligibility for individuals wearing hearing protectors, especially if hearing loss is present. As clearly shown in Figure 2, speech cues can sometimes be rendered inaudible by wearing hearing protectors.

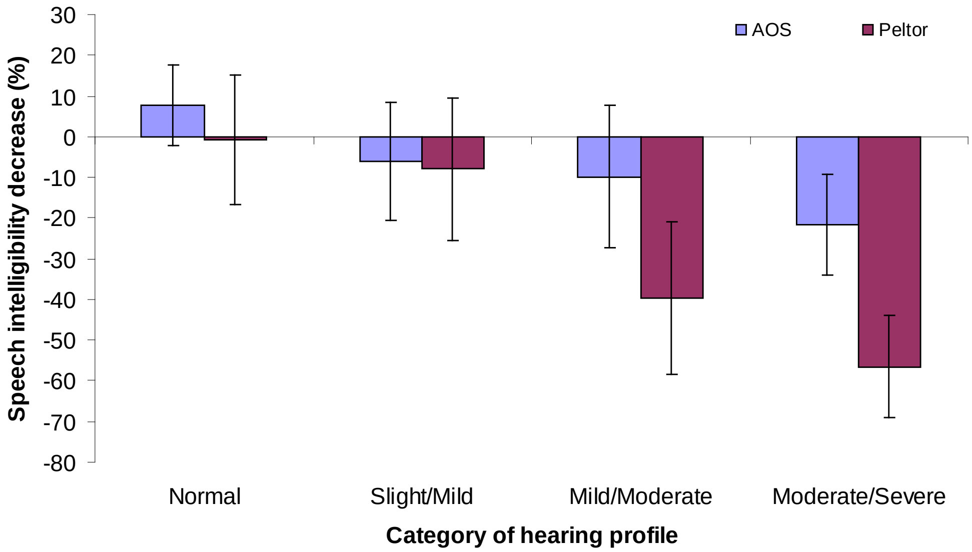

Figure 3: Overall effect of hearing protectors on speech intelligibility as a function of hearing profile. Error bars represent ± 1 standard deviation.

The method illustrated in Figure 1 was used to predict speech intelligibility scores in protected and unprotected conditions. The starting point is a generalized model of speech intelligibility in noise applicable for normal hearing individuals in open-ear conditions (reference case). For individuals with hearing loss and/or wearing hearing protectors, the generalized model is adjusted by deriving correction factors for audibility (absolute threshold) and distortion (supra threshold) effects to yield the effective decrement in SNR compared to the reference case. The audibility correction factor is a value in dB calculated from the SII procedure (ANSI S3.5-1997 R2007) by matching the proportion of speech cues reaching the listener under test (hearing loss, with or without HPD) compared to the reference case (0 dB HL, open ear) in each listening situation. The distortion correction expresses the "SNR loss" of the individual under test in dB and is derived for each listener as the difference between the speech recognition threshold (SRT) measured with the HINT screening test and the HINT normative value. Finally, in each listening situation, the generalized PI function and noise-specific offset were used to make an intelligibility prediction at an effective SNR corresponding to the physical stimulus SNR minus the audibility and distortion corrections.

Table 1 summarizes speech intelligibility predictions for both the protected and unprotected conditions using the model in Figure 1. A total of 140 data points were obtained under unprotected listening conditions and 153 under protected listening conditions. Across all conditions (n=293), the addition of audibility and distortion correction factors significantly improved the predictive ability of the model, from a mean prediction error of 25.7% (no correction factors) down to 15.8% (audibility correction only), 14.8% (distortion correction only) to –0.1% (both corrections). The standard deviation of the prediction error was also smallest when both correction factors were used.

Table 1: Mean prediction error (%) and standard deviation for the four approaches used to predict speech intelligibility.

Conditions	Number of data points	Parameter	Audibility and distortion correction (HINT + SII)	Distortion correction (HINT)	Audibility correction (SII)	No correction (original model)
All conditions	293	Mean	-0.1	14.2	15.8	25.7
		SD	14.6	23.5	17.8	24
Unprotected	140	Mean	-2	5.2	13.5	18.4
		SD	13.3	11.9	13.9	15.5
Protected	153	Mean	1.7	22.4	18	32.4
		SD	15.5	28.1	20.6	28.1

When attempting to predict unprotected speech intelligibility, the addition of an audibility correction did not significantly improve the prediction power when the model had already been corrected for distortion (Table 1). The mean prediction error decreased from 5.2 to -2% but the standard deviation increased from 11.9 to 13.3%. Indeed, taking into account the HINT deviation score (distortion correction) in the generalized model has previously been demonstrated to be quite effective in predicting speech intelligibility in unprotected conditions (Laroche et al., 2005; Giguère et al., 2008b). However, when hearing protection was used, audibility issues were critical and needed to be taken into consideration in the generalized model, in addition to distortion effects. Indeed, when the model was corrected for both audibility and distortion, the mean prediction error decreased to 1.7% compared to 22.4% when only the distortion component was considered. Similarly, the standard deviation of the prediction error decreased from 28.1 to 15.5%. Thus, superior performance was obtained for both unprotected and protected listening conditions when both audibility and distortion correction factors were used with the generalized model of speech intelligibility. No evidence of under or over prediction was observed with this approach.

2.2.4 Significance

A comprehensive set of modelling tools has been developed to provide quantitative analyses of the impact of hearing loss and use of conventional hearing protectors. The model can be used in the context of two important applications of direct relevance to the military environment: (1) the optimal selection of HPDs, and (2) the establishment of functionally-based hearing standards for the Canadian Forces personnel.

3.0 Rationale and objectives

Our previous research (Giguère et al., 2008a, 2010) provided new insight on the complex interaction between hearing loss and use of hearing protectors, and yielded significant advancements towards the development of predictive models of speech intelligibility with conventional passive HPDs. For modelling purposes, these devices can be easily characterized by a level-independent attenuation at various frequencies.

An important improvement is to extend the predictive model for use with communication headsets and other electronic hearing protection devices providing level-dependent transmission of surrounding sounds to the user. These devices typically include user-adjustable volume controls and automatic gain control functions to both enhance situational awareness in low-to-moderate noise levels and provide proper protection in high-level noises. Such advanced adaptive systems are increasingly used in the military but, from a modelling point-of-view, they require more complex characterization of electroacoustic performance than conventional passive HPDs. At the same time, relatively little data exists on the interaction between hearing loss and use of level-dependent attenuation/gain functions in advanced hearing protective devices (e.g. Abel et al., 1993; Dolan and O'Loughlin, 2005).

The speech intelligibility modelling procedures developed in Giguère et al. (2008a, 2010) also need to be adapted to facilitate knowledge transfer to the CF environment. One important step is the development of a software tool to automate the computational steps of the predictive model. The ultimate goal is to assist in the selection of hearing protection and communication equipment based on individual factors (e.g. hearing loss), task demands (e.g. communication distance, noise level, talker vocal effort) and other constraints in the field.

The key objectives of the current project are:

(1) To design and carry out a laboratory study that explores the effect of the interaction among the characteristics of the devices, level and spectrum of the noise background, and hearing status of the listeners on speech intelligibility in noise,
(2) To evaluate at least two different communication devices of interest to the CF, and
(3) To assess the impact of the advanced hearing protection devices on face-to-face communication in military noises based on the new data generated by this study and any other published relevant data and models.

The project was carried out over three stages:

Stage I: Design a study
Stage II: Test with human listeners, Conduct preliminary analysis, Begin modelling
Stage III: Analysis and Modelling

The research plan was as follows:

In Stage I, a detailed protocol for the experimental study was developed. It described the choice of the devices, the choice of the noise backgrounds used, the speech materials, the characteristics of the subjects (number, hearing profiles, screening criteria), the experimental conditions, the test facilities, and the acoustic and statistical analyses to be conducted.

In Stage II, the data collection with human subjects was carried out in the Noise and Communication Unit at the Audiology Research Laboratory of the University of Ottawa. The facilities include a dedicated noise simulation room that was used to generate military noises and carry out speech listening experiments with normal hearing subjects and individuals with hearing loss wearing advanced hearing protection communication devices. Objective data collection on the electroacoustical characteristics of the devices was also carried out.

In Stage III, the data collected in Phase II, as well as additional subjective data, were analyzed to assess the performance of the advanced communication devices tested in relation to the characteristics of the noise background and the degree of hearing loss of the listeners. A general discussion of the new findings is presented to assess the impact of advanced communication devices on speech communication and situational awareness in military environments.

4.0 Methods

4.1 General

The research project reported here builds on our previous study on the effects of passive hearing protectors on speech perception for individuals with hearing loss (Section 2.2). That study involved two testing phases with human subjects (Giguère et al., 2008a, 2010). The first phase involved normal hearing subjects in open-ear listening conditions and served to establish a generalized psychometric function relating SNR to percent intelligibility for a range of eight noises typical of the military environment. The second phase involved subjects with a wide range of hearing profiles and served to validate a predictive model of speech intelligibility while wearing passive hearing protectors.

The focus of this work was the effect of communication devices, instead of conventional passive hearing protectors. Only a selection of the eight noises from the previous study were considered. The generalized models from these noises have already been derived (Figures 16-18 and Tables 9-10 in Giguère and et al., 2008a), and thus no testing phase with normal hearing individuals was needed in the new study. Only testing with subjects presenting a wide range of hearing profiles was necessary, with and without a communication device fitted. Devices were operated in talk-through (or surround) mode at various volume settings.

The current study provided new data to test the validity of the speech prediction and modelling procedures for use with communication headset devices. In addition, the study was so designed that each subject was tested under the same speech and noise levels in various listening modes of the communication headset. This allows a direct comparative analysis of the effects of the different settings of the devices on speech intelligibility in noise for individuals with or without hearing loss.

4.2 Participants

A total of 45 English-speaking adults (24 males and 21 females), between the ages of 23 and 81 years old (mean = 48; SD = 16), with hearing profiles ranging from normal hearing (hearing thresholds ≤ 25 dB HL) to severe hearing losses (hearing thresholds up to 90 dB HL) participated. No restriction was placed on whether the hearing loss was of conductive, sensorineural or mixed origin.

Participant recruitment was carried out by means of posters displayed in various settings, including the University of Ottawa, audiology clinics, community centres and medical centres. Prior to their participation, subjects were required to read an information letter, sign a consent form and fill out a hearing history questionnaire. The ethics approval certificate is found in Appendix A. Testing with human subjects took place at the Research Unit on Noise and Communication at the University of Ottawa.

Participant hearing assessment was carried out in an IAC double-wall audiometric booth using a portable tympanometer (GSI 38; Grason-Stadler Inc., Milford NH, U.S.A.) and a clinical audiometer (AC40, Interacoustics A/S, Assens, Denmark) equipped with insert earphones (EARTONE 3A, Aearo Company, Auditory Systems Production, Indianapolis IN, U.S.A.) and bone conductor (B-71; Radioear Corporation, New Eagle PA, U.S.A.).

4.3 Devices

Two communication devices with hearing protection capabilities were selected for study, the NACRE QuietPro earplug (Nacre AS, Trondheim, Norway) and PELTOR Powercom Plus headset (3M, St. Paul, MN). Both were designed and commercialized for use in military and tactical operations, and include talk-through (or surround) modes and compatibility for use with a variety of radio communication systems. The choice of these communication devices was confirmed with the Scientific Authority at DRDC Toronto prior to testing to ensure that they are typical of models used in the Canadian Forces.

The NACRE QuietPro is a digital communication headset with in-the-ear transducers and disposable foam ear plugs (5 different sizes), which is increasingly used by NATO and various US agencies. The acronym NACRE stands for Natural Communication in Rough Environments. The NACRE QuietPro features automatic adaptive digital hearing protection with passive and active noise reduction (ANR) in addition to adaptive talk-through capabilities for stereo reproduction and amplification of surrounding sounds. The user can manually control the talk-through volume setting (11 volume settings in total), but with increasing sound level above 85 dBA the system gradually increases sound attenuation, first by automatically reducing and eventually shutting down the talk-through transmission, then by activating the ANR system. The passive attenuation of the NACRE QuietPro provides a noise reduction rating (NRR) of 29 dB, and the active attenuation provides an additional attenuation of 6-8 dB at the low frequencies. According to manufacturer’s data, the total mean attenuation ranges from 34 to 42 dB from 125 to 8000 Hz.

The PELTOR Powercom Plus headset is the third generation of Peltor’s tactical communication headsets. It is an analog earmuff-type device with boom microphone providing stereo talk-through capabilities (5 surround volume controls + OFF mode) to maintain situational awareness in low to moderate noise levels while still protecting hearing in high noise levels. The device hence provides level-dependent hearing protection (passive attenuation only), with a rated NRR of 25 dB. According to manufacturer’s data, the mean passive attenuation ranges from 19 to 39 dB from 125 to 8000 Hz.

Independent testing of the characteristics of the devices was carried out in two ways in this study. The passive attenuation was measured for each subject using the Real-Ear-At-Threshold (REAT) method (ANSI/ASA S12.6-2008), as described in Section 4.5.2. The gain provided by the devices at different volume settings of the talk-through (TT) or surround mode was also measured electroacoustically using an acoustic manikin (ANSI S3.36-1985 R2006), as described in Section 4.6. The frequency response and select compression parameters (type, threshold, ratio) were also documented.

4.4 Noises

Two of the eight noises from a previous study (Giguère et al., 2008a, 2010) were used in the current study (Noise 1 and 2). The acoustical characteristics of the two noise environments are summarized in Figure 4. The left column shows the distribution of global noise levels (dBA) in 1-dB steps over the entire set of 4-sec segments in each environment. The right column shows the spectral characteristics of the two environments. The equivalent continuous sound pressure level in each band is identified by the L_{eq} curve. The L_{10}, L_{50} and L_{90} curves represent the sound pressure levels that are exceeded 10%, 50% or 90% of the time in each frequency band, given the temporal fluctuations in the noise recordings. The insert in the upper right corner also shows: (1) the global L_{eq} (in dBA), (2) the fluctuation in the global level, as represented by L_{10}-L_{90} (in dBA), and (3) the average slope of the 1/3-octave spectrum (in dB/octave).

The two selected noise environments are acoustically different. Noise 1 (LAVIII) is moderately loud (L_{eq} = 95.3 dBA), highly fluctuating (L_{10}-L_{90} = 14.6 dB), and possesses the steepest spectral slope (-4.1 dB/Oct) among the eight noises from the previous study (Giguère et al., 2008a, 2010). Noise 2 (Bison) has a lower global level (L_{eq} = 89.5 dBA), is more steady (L_{10}-L_{90} = 4.2 dB), and possesses a shallower spectral slope (-2.6 dB/Oct).

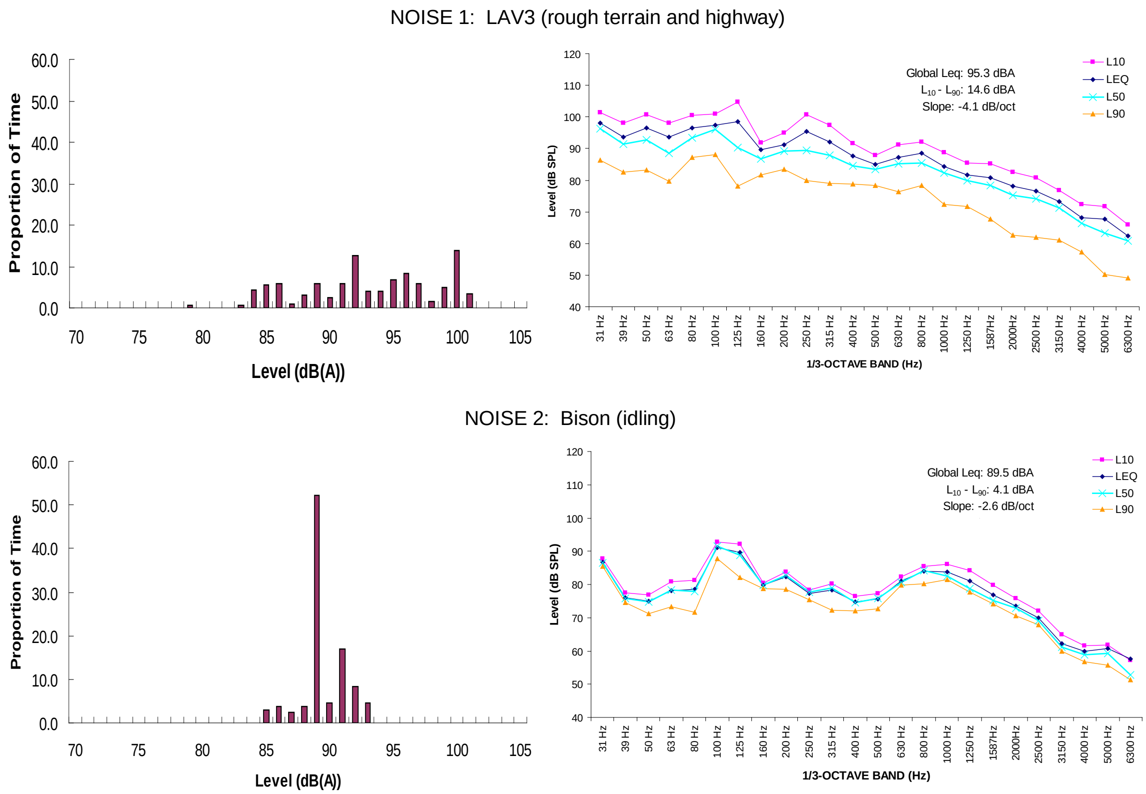

Figure 4: Acoustical characteristics of the two noise environments selected for the project.

4.5 Experimental conditions

Laboratory testing was conducted with 45 subjects and the two communication devices (NACRE QuietPro and PELTOR Powercom Plus). In order to achieve the greatest validity in the results, the subjects' age and hearing profiles were as wide as possible.

The experimental protocol included the following tests: (1) administration of the headphone version of the HINT screening protocol, (2) measurement of the passive attenuation of the communication devices using the standard REAT method (ANSI/ASA S12.6-2008), and (3) speech listening tests in the simulated noise environments using sentences from the HINT test. The latter comprised eight conditions per subject, i.e. 2 SNRs in each of four listening modes (see below). Each subject was tested using only one of the two communication devices (NACRE or PELTOR) and in only one of the two noise types (Noise 1 or 2). The limited number of available HINT sentence lists precluded testing more than one device and noise type per subject. All speech tests were carried out in English.

4.5.1 HINT screening

Speech reception thresholds (SRT) were measured, representing the level or SNR at which participants were able to correctly repeat 50% of the sentences presented. As described in Nilsson et al. (1994) and Soli and Wong (2008), the HINT protocol can be administered using loudspeakers under real sound field conditions or using headphones under simulated sound field conditions. The latter is the preferred method to eliminate the acoustic effects of the test environment. With this method, the spatial location of the speech and noise sources is simulated by processing the test material with digital filters representing head-related transfer functions (HRTFs) of the KEMAR manikin (Type 45BA; G.R.A.S. Sound & Vibration A/S, Holte, Denmark), independently for the left and right ear headphone signals. Virtual source locations can be simulated in this way. In this study, a SRT was measured in quiet and in three noise conditions: Noise Front (NF), Noise Right (NR) and Noise Left (NL), while the speech signal was always simulated from the front. Speech spectrum noise was used. The HINT scores from the three noise conditions were also combined to produce a composite score according to the following formula: $(2 \times NF + NR + NL)/4$. The composite score equally weights the contribution of directional hearing, as measured in Noise Right and Left, and non-directional hearing, as measured in Noise Front. This score represented the overall functional ability of the subject for speech perception in noise under binaural listening conditions. Table 2 shows the normative data for the English HINT (Vermiglio, 2008).

There is a total of 12 lists of 20 sentences in the HINT test. Each sentence contains four to six keywords representing simple daily utterances (examples: "*Big dogs can be dangerous*", "*They finished dinner on time*"). Four lists are required to administer the full HINT protocol for each subject, one for each speech/noise condition (Quiet, Noise Front, Noise Left and Noise Right). Lists were counterbalanced across subjects in this study as shown in Table 3.

Administration of the HINT screening protocol is software-controlled (HINT PRO 7.0; Bio-logic Systems Corp., Mundelein IL, U.S.A.). These tests were carried out in an IAC double-walled audiometric booth.

Table 2: Average headphone SRTs for young adults with normal hearing using the American English HINT (Vermiglio, 2008). The Speech signal is presented in Front in all conditions.

	Quiet (dBA)	Noise Front (dB SNR)	Noise Left or Right (dB SNR)	Composite (dB SNR)
Mean	15.6	-2.6	-10.1	-6.4
SD	3.1	1.0	1.3	0.9

Table 3: Experimental plan and distribution of HINT sentence lists (1-12).

Subject	Noise	Device	HINT screening	Speech tests in simulated military noises			
1 & 33	1	Nacre	1-2	No device	TT off	TT low	TT high
			3-4	5-6	11-12	7-8	9-10
2 & 34	2	Peltor	7-8	No device	TT off	TT high	TT low
			9-10	1-2	11-12	5-6	3-4
3 & 35	1	Peltor	11-12	No device	TT off	TT low	TT high
			1-2	9-10	3-4	5-6	7-8
4 & 36	2	Nacre	9-10	No device	TT off	TT high	TT low
			1-2	5-6	3-4	11-12	7-8
5 & 37	1	Nacre	11-12	No device	TT off	TT high	TT low
			7-8	1-2	3-4	9-10	5-6
6 & 38	2	Peltor	5-6	No device	TT off	TT low	TT high
			1-2	11-12	3-4	9-10	7-8
7 & 39	1	Peltor	1-2	No device	TT off	TT high	TT low
			5-6	7-8	11-12	3-4	9-10
8 & 40	2	Nacre	7-8	No device	TT off	TT low	TT high
			3-4	11-12	1-2	5-6	9-10
9 & 41	1	Nacre	9-10	No device	TT off	TT low	TT high
			5-6	7-8	1-2	3-4	11-12
10 & 42	2	Peltor	11-12	No device	TT off	TT high	TT low
			3-4	9-10	1-2	7-8	5-6
11 & 43	1	Peltor	9-10	No device	TT off	TT low	TT high
			3-4	11-12	5-6	7-8	1-2
12	2	Nacre	11-12	No device	TT off	TT high	TT low
			5-6	9-10	7-8	1-2	3-4
13 & 44	1	Nacre	3-4	No device	TT off	TT high	TT low
			9-10	11-12	7-8	5-6	1-2
14	2	Peltor	9-10	No device	TT off	TT low	TT high
			11-12	5-6	7-8	3-4	1-2
15	1	Peltor	3-4	No device	TT off	TT high	TT low
			7-8	5-6	9-10	1-2	11-12
16 & 45	2	Nacre	5-6	No device	TT off	TT low	TT high
			7-8	1-2	9-10	3-4	11-12
17	1	Nacre	7-8	No device	TT off	TT low	TT high
			1-2	9-10	5-6	11-12	3-4
18	2	Peltor	3-4	No device	TT off	TT high	TT low
			5-6	7-8	9-10	1-2	11-12
19	1	Peltor	5-6	No device	TT off	TT low	TT high
			9-10	1-2	7-8	11-12	3-4
20	2	Nacre	1-2	No device	TT off	TT high	TT low
			9-10	3-4	11-12	7-8	5-6
21	1	Nacre	5-6	No device	TT off	TT high	TT low
			11-12	3-4	9-10	1-2	7-8
22	2	Peltor	1-2	No device	TT off	TT low	TT high
			7-8	3-4	5-6	11-12	9-10
23	1	Peltor	7-8	No device	TT off	TT high	TT low
			11-12	3-4	1-2	9-10	5-6
24	2	Nacre	3-4	No device	TT off	TT low	TT high
			11-12	7-8	5-6	9-10	1-2
25	1	Nacre	1-2	No device	TT off	TT low	TT high
			11-12	7-8	3-4	9-10	5-6
26	2	Peltor	5-6	No device	TT off	TT high	TT low
			3-4	11-12	7-8	1-2	9-10
27	1	Peltor	9-10	No device	TT off	TT low	TT high
			7-8	5-6	11-12	3-4	1-2
28	2	Nacre	3-4	No device	TT off	TT high	TT low
			1-2	9-10	5-6	7-8	11-12
29	1	Nacre	11-12	No device	TT off	TT high	TT low
			9-10	3-4	1-2	5-6	7-8
30	2	Peltor	7-8	No device	TT off	TT low	TT high
			5-6	1-2	9-10	11-12	3-4
31	1	Peltor	9-10	No device	TT off	TT high	TT low
			3-4	5-6	11-12	1-2	7-8
32	2	Nacre	1-2	No device	TT off	TT low	TT high
			7-8	3-4	9-10	5-6	11-12

4.5.2 Measurement of device attenuation

The passive attenuation of the devices (device electronics off) was then measured for each subject with the Real-Ear-At-Threshold procedure, as defined in ANSI/ASA S12.6-2008. Attenuation was measured as the difference in binaural hearing thresholds without (open ear) and with (occluded ears) HPDs in place on the subject. This was performed independently over a set of 1/3-octave filtered pink noises from 125 to 8000 Hz in a diffuse field.

A software interface was developed to select and generate test stimuli, record subjects' responses and calculate hearing thresholds. An adaptive fixed-frequency Bekesy tracking threshold search was used. Subjects were instructed to depress a push-button when they heard the signal (the level then gradually decreased) and to release the button when they no longer heard the signal (the level then increased). Hearing threshold was calculated based on the last 6 reversals. The signal shaping parameters (pulse duration, rise/fall times, repetition rate, level step size, etc.) met the requirements specified in ANSI/ASA S12.6-2008. Results were stored in individual subject's files.

Attenuation measurements were carried out in a noise simulation room (Figure 5) of inner dimensions 4.29 m × 3.65 m × 2.42 m (length × width × height) using loudspeakers S1-S6 around the subject. A complete description of this facility and results of qualification tests for hearing protection measurements can be found in Giguère et al. (2008a)
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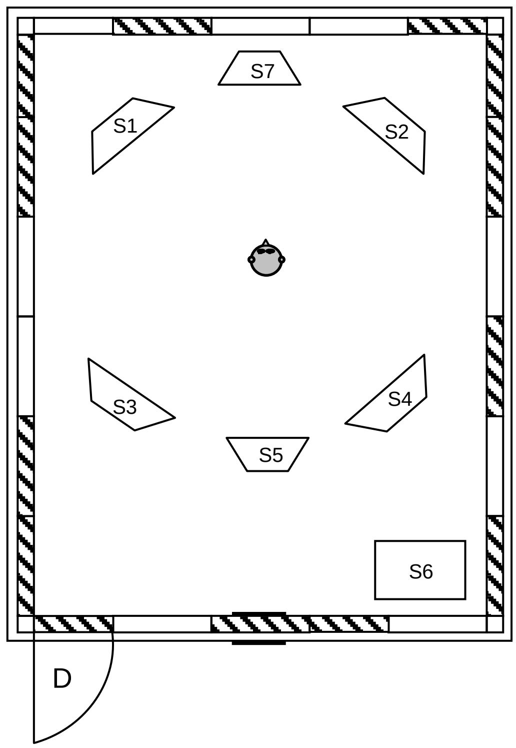

Figure 5: Layout of the simulation room and loudspeaker configuration. Sound absorptive and reflective panels are represented by shaded and unfilled rectangular shapes, respectively. S1-S6: Loudspeakers used to generate a diffuse noise field. S7: Loudspeaker used for speech material.

4.5.3 Speech testing in simulated military noise

Speech intelligibility measures in the two military noise environments consisted in presenting the remaining eight lists of HINT sentences (2 SNRs for each of four listening conditions) under frontal speech and diffuse field noise conditions in a noise simulation room (Figure 5), with and without a communication headset. Each subject could only be tested with one noise and one device, which were counterbalanced across subjects as shown in Table 3.

The four listening conditions investigated were: (1) unoccluded ear, (2) device with TT volume off (no talk-through, maximum attenuation), (3) device with TT volume at a low-gain position (-4 dB), and (4) device with TT volume at a high-gain position (+10 dB). These conditions were referred to as no device, TT off, TT low and TT high, respectively. All subjects were tested at the same settings. The first two listening modes were identical to those of the previous study with conventional hearing protectors (Giguère et al., 2008a, 2010) and allowed assessment of the effects of the communication devices when used as conventional hearing protectors with maximum possible attenuation and no electronic transmission of surrounding sounds. Performance with the talk-through settings at the low and high gain volumes was compared to the unoccluded ear (no device) to assess the quality and benefit of the talk-through transmission system in each device. These two experimental conditions were also compared to each other to investigate whether subjects with moderate or severe hearing losses could benefit from a higher volume setting to combat audibility effects. Note that the TT low and TT high positions were selected to correspond to approximately the same gain on the two devices, thereby allowing cross-comparison of the devices.

For the NACRE QuietPro device, TT low was set to volume 4 of the talk-through system which, according to the manufacturer's data, provides a gain for surrounding sounds of -4 dB (i.e. a slight attenuation of 4 dB). TT high was set to volume 10 of the NACRE QuietPro talk-through system, providing a gain of 10 dB. These gain estimates were verified electroacoustically using a manikin recording system with frontally-incident noise (Sections 4.6 and 5.1.1). For the PELTOR Powercom Plus device, TT low and TT high were set to volumes 1 and 4 of the surround mode, respectively. No manufacturer's data are available on the actual gain provided by the different surround mode volume settings. The gain provided by the two chosen volume settings were measured electroacoustically using a manikin with frontally-incident noise (Sections 4.6 and 5.1.2): -5.6 dB (TT low) and 9.0 dB (TT high). The gain difference between the two talk-through volume settings is about 14 dB for each device.

Half the subjects (23) were tested with the NACRE device, and the other half (22) were tested with the PELTOR device. Within each device, half the subjects (12 for the NACRE and 11 for the PELTOR) were tested in Noise 1 (LAVIII) and the other half (11) were tested in Noise 2 (Bison). The experimental plan is shown in Table 3. The unoccluded and TT volume OFF were tested first, followed by the TT conditions at two volume settings (low and high). The order of the latter two conditions was counterbalanced across subjects. Within subjects, the same two SNRs were targeted in the four listening modes to allow direct comparisons. Different SNRs were used for each subject to ensure word intelligibility performance in the 10-90% range for everyone, irrespective of hearing loss. These SNRs were determined during the unoccluded condition. Although scores below 10% and higher than 90% could be plotted on unoccluded vs occluded graphs, they are not as readily usable for model predictions as they indicate floor and ceiling effects. To change the SNR, only the speech level was varied; the noise level was not altered to ensure the simulated noise conditions were closely reflecting the noise level in the real military noise environments sampled. In cases of moderate to severe hearing losses, audibility effects can come into play under occluded conditions, drastically reducing intelligibility scores to 0%.

Listening tests were carried out in blocks of 20 sentences (one HINT list) in noise. The 20 sentences were individually presented each a different 4-second long noise segment. A sampling procedure was devised to extract a subset of 4-second noise segments from each environment that closely matched the underlying acoustical characteristics of the entire recordings from that environment (see Giguère et al., 2008a for additional information on noise recording and sampling process). This strategy ensured that the extracted subset of 4-second noise segments was a good representation of the environment so that the speech listening results would reflect the characteristics of the entire environment, not just one typical noise segment. The sampling procedure was repeated independently for each subject and noise environment to use as much of the available noise data as possible.

A software interface controlled the SNR that was selected for each HINT list and the stimulus presentation sequence. The interface read a script file listing the exact sequence of sentence and noise files to deliver for a given subject. Sentence files from the English HINT test (Nilsson et al., 1994) were used. For each subject and noise environment, the noise files came from the subset of noise samples extracted with the sampling strategy. Noise began 0.5 second before each sentence and typically lasted 1.0 second or more after the sentence ended.

Speech testing in simulated military noises was carried out in the same noise simulation room as used for hearing protector attenuation (Figure 5). Military noises were generated through loudspeakers S1-S6 around the subjects, while the speech material was frontally incident through loudspeaker S7. A complete description of this facility can be found in Giguère et al. (2008a). Extensive sound field qualification procedures based on ANSI/ASA S12.6-2008 for a diffuse sound field and ANSI/ASA S3.6-2010 for a quasi-free sound field were carried out. A brief summary is given below.

Uniformity of the diffuse sound field generated by the noise loudspeakers (S1–S6) in the final configuration was tested by measuring the range in octave-band levels over the reference listening point (subject and chair absent) and six positions off-centered by 15 cm in the left-right, up-down, and front-back axes, using pink noise stimuli and an omnidirectional microphone (Type 4189; Brüel & Kjaer Sound & Vibration Measurement A/S, Naerum, Denmark). Left-right differences were 1.9 dB or less in each octave band, and the range over the seven positions was 3.7 dB or less. Directionality of the diffuse sound field was also tested using a cardioid microphone (Sennheiser ME64; Sennheiser Electronic GmbH & Co. KG, Wedemark, Germany), with front-to-back rejection greater than 25 dB, rotated in three orthogonal planes at the reference point. The range in octave-band levels was 6.2 dB or less in each plane and octave band, except at 2000 Hz in two planes where the range reached 8.2 dB due to a lower sound level coming directly above. Finally, uniformity of the quasi-free sound field from the speech loudspeaker (S7) was tested. Left-right differences were 0.5 dB or less in each octave band, and the range over the seven positions was 4 dB or less. The speech transmission index measured between the speech loudspeaker and the reference point was 0.97 (no noise present), indicating that speech perception would be unaffected by the stimulus delivery system and room characteristics.

Additional information on calibration procedures of the room configuration, including equalization of room/equipment frequency response, reverberation time, and sound field uniformity and directivity can be found in Giguère et al. (2008a).

4.6 Electroacoustic measurements

An objective method using a standardized manikin (ANSI S3.36-1985 R2006) was used to obtain accurate estimates of gain of the communication devices at different volume settings of the talk-through (NACRE QuietPro) and surround (PELTOR Powercom Plus) modes. A similar approach was taken by Dolan and O'Loughlin (2005) to characterize amplified earmuffs.

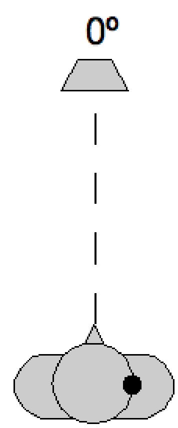

Figure 6: Setup for the objective measurement of device gain and output level.

Electroacoustic gain was measured objectively using a Head And Torso Simulator (HATS) (Type 4128; Brüel & Kjaer Sound & Vibration Measurement A/S, Naerum, Denmark) connected to a microphone power supply (Type 2804; Brüel & Kjaer Sound & Vibration Measurement A/S, Naerum, Denmark) and sound level meter (Type 2235; Brüel & Kjaer Sound & Vibration Measurement A/S, Naerum, Denmark) equipped with a third-octave/one-octave filter bank (Type 1625; Brüel & Kjaer Sound & Vibration Measurement A/S, Naerum, Denmark). Speech spectrum noise was used for testing, at levels ranging from 40 dBA to 90 dBA. These stimuli were presented directly in front of the manikin at a 1-m distance, as shown in Figure 6. Sound measurements were made in the ear-simulator microphone in the right ear of the manikin without (open ear) and with each communication device in place (occluded ear).

4.7 Data analysis procedures

The audiometric data (Section 4.2) and the HINT screening scores (Section 4.5.1) allowed documentation of the audibility (at threshold) and distortion (supra threshold) components of the hearing loss for each subject, as described in Giguère et al. (2008a, 2010).

The subjective REAT attenuation data (Section 4.5.2) together with the electroacoustic measurements on the acoustic manikin (Section 4.6) allowed documenting the transmission characteristics of the devices (attenuation or gain) at various talk-through volume conditions.

The speech intelligibility scores in the simulated military noise environments (Section 4.5.3) were pooled across subjects in a manner similar to Figure 2 to compare performance in the different headset listening modes in relation to unoccluded listening. Comparisons of special interest included TT off versus no device, TT low and TT high versus no device, and TT low versus TT high. These comparisons were also used to highlight device, noise type and hearing loss profile effects.

5.0 Results

5.1 Electroacoustic measurements with manikin

5.1.1 NACRE QuietPro

Figure 7 shows the at-ear manikin sound levels as a function of the direct field stimulus levels for eight of the eleven volume settings of the talk-through system (TT2, TT3, TT4, TT5, TT6, TT8, TT10, TT11) for the NACRE QuietPro, as well as the open ear case. As shown, manikin sound levels (output) increase with increasing stimulus levels (input) in all volume setting conditions, up to a manikin level of about 90 dBA. The shape of these curves for gain settings TT6 and above shows that the talk-through system in the NACRE

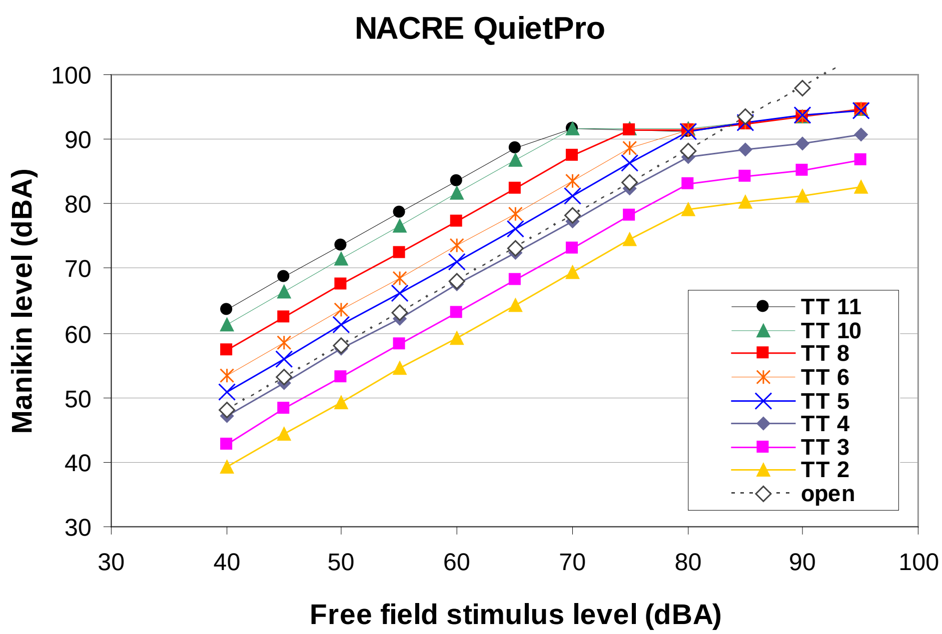

Figure 7: Input-output curves for the NACRE QuietPro in speech spectrum noise.

QuietPro acts like an "output-sensitive" automatic gain control (AGCo) circuit for hearing aids (Dillon, 2001; Volanthen and Arndt, 2007). As expected, the manikin levels are higher with increasing TT volume setting (TT11 > TT10 > TT8 > TT5 > TT2) for low to moderate stimulus levels (< 70 dBA). The manikin open ear levels are in-between the TT4 and TT5 conditions, indicating that this range of settings corresponds to a neutral position (i.e. gain ≈ 0 dB at low-moderate levels). Other features include "input-sensitive" compression characteristics at a free field threshold of 80-dBA with a compression ratio of about 4:1. Overall, the output limit of the device is set to an at-ear level of about 93 dBA. Note from Figure 7 that the difference between open-ear manikin levels and free field stimuli is about 8 dB. The output limit of the device thus corresponds to an equivalent free level of approximately 85 dBA, near the regulatory limit for Federal employees (Department of Justice. Canada Occupational Health and Safety Regulations (SOR/86-304), Part VII, Levels of Sound. Ottawa, ON; 18 November 2009.)

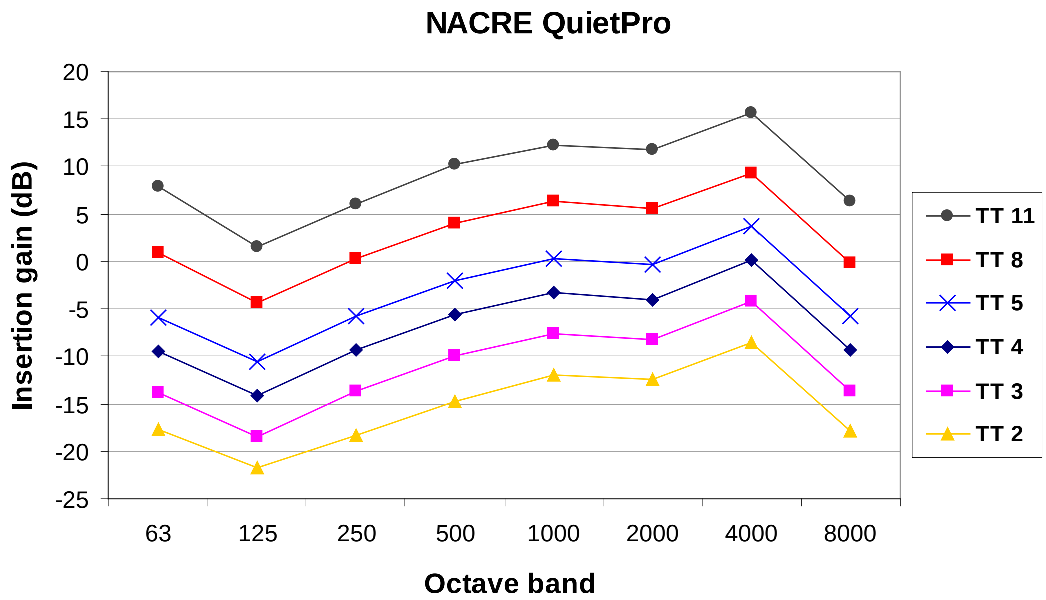

Figure 8: Insertion gain of the NACRE QuietPro as a function of frequency in pink noise at 60 dBA.

Figure 8 shows the insertion gain of the NACRE for octave bands ranging from 63 to 8000 Hz for a pink noise stimulus input at 60 dBA, a level at which the device acts as a linear system. At a given setting, the gain is maximal around 4000 Hz. The gain curves are essentially parallel across the various TT volume settings, indicating that the gain increase from setting to setting is uniform in the range 63-8000 Hz. From these curves, the insertion gain averaged over four frequency bands (500-4000 Hz) was calculated. The results are reported in Table 4. A positive gain value indicates that the device amplifies surrounding sounds when the talk-though system is operating. A negative gain value indicates that the device transmits surrounding sounds at a level lower than without the device in position (open ear). These calculated gain values are very close to the data supplied by the manufacturer (unspecified stimuli and procedure).

Table 4: Insertion gain of the NACRE QuietPro averaged over 500-4000 Hz in pink noise (60 dBA) for six TT volume settings.

	NACRE QuietPro					
	TT 2	TT3	TT4	TT 5	TT 8	TT 11
Gain (dB) Measured	-11.9	-7.5	-3.2	0.4	6.3	12.5
Gain (dB) Manufacturer	-12	-8	-4	0	6	12

Table 5: Electronic hissing noise generated by NACRE QuietPro for six TT volume settings.

	NACRE QuietPro					
	TT 2	TT3	TT4	TT 5	TT 8	TT 11
At-ear level (dBA) Measured	39.3	40.1	41.6	44.0	48.9	54.7
Equiv. free field level (dBA)	31.3	32.1	33.6	36.0	40.9	46.7

Finally, electronic devices such as the NACRE QuietPro generally emit a low level of hissing noise when powered. Table 5 lists the noise level measured at the manikin's ear for different TT settings when no external stimulus is present. As seen, the amount of hissing noise generated increases with TT setting, from about 39 dBA at TT2 to 55 dBA at TT11. When these values are reported in terms of an equivalent free field level, the hissing noise varies from about 31 to 47 dBA over the range of TT settings.

5.1.2 PELTOR Powercom Plus

Figure 9 shows the at-ear manikin sound levels as a function of the direct field stimulus levels for the five volume settings of the surround mode (1 to 5) for the PELTOR Powercom Plus, as well as the open ear case. Manikin sound levels (output) increase in a linear fashion (rate of 1.0 dB/dB) with increasing stimulus levels (input) in all volume setting conditions, up to an input of about 60 dBA (compression threshold). Thereafter, the device shows gain compression, i.e. the increase in output level is less than the increase in input level. The compression ratio is about 4:1, that is the output level increases by 1 dB for each 4 dB increase in input level. As expected, the manikin levels are higher with increasing surround volume for a given stimulus level, and all gain curves are parallel to each other. These characteristics clearly indicate that the surround system in the PELTOR Powercom Plus acts like an "input-sensitive" automatic gain control (AGCi) circuit for hearing aids (Dillon, 2001; Volanthen and Arndt, 2007). The manikin open ear levels are very close to the surround 2 condition for input levels up to 60 dBA, indicating that this setting is approximately the neutral position (i.e. gain ≈ 0 dB at low-moderate levels).

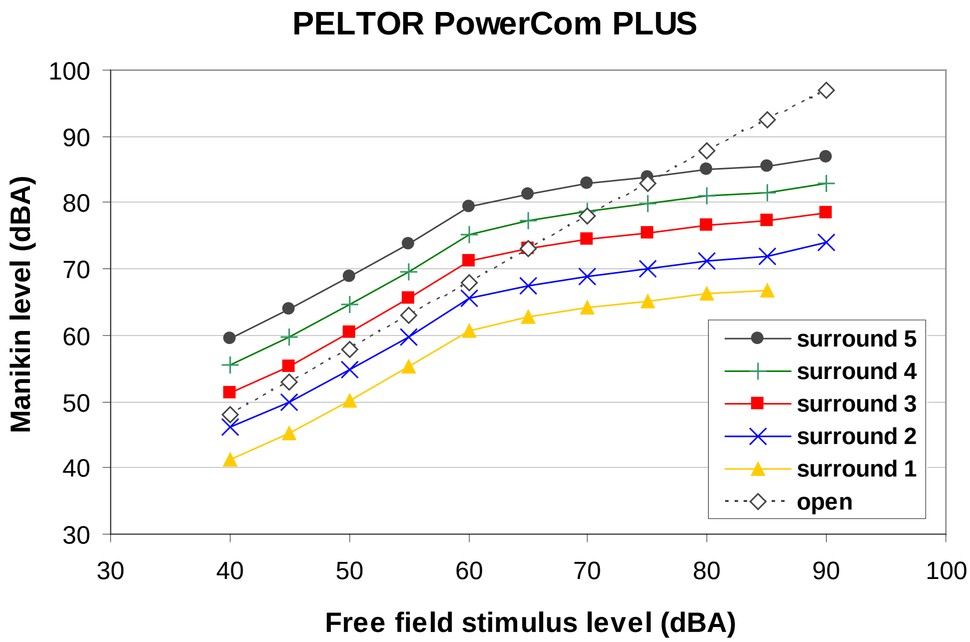

Figure 9: Input-output curves for the PELTOR Powercom Plus in speech spectrum noise.

Figure 10 shows the insertion gain for octave bands ranging from 125 to 8000 Hz at each surround setting for speech spectrum noise at 60 dBA. As for the NACRE device, the gain increase over successive surround settings is essentially uniform over frequencies. The gain is maximum at 4000 Hz and there is a dip of about 5 dB at 1000 Hz. The insertion gain of the device averaged over the four frequency bands 500-4000 Hz is reported in Table 6. Comparative values from the device manufacturer are not available, although the specification sheet indicates that the device amplifies up to 18 dB. This corresponds closely to the difference in measured gain between surround 1 and surround 5 (18.5 dB).

The level of electronic hissing noise from the PELTOR Powercom Plus is listed in Table 7. The amount of hissing noise is about 10 dB lower in the PELTOR than the NACRE (Table 5) at an equivalent insertion gain. For example, the equivalent free field hissing noise is about 26 dBA for the PELTOR at the neutral gain position (surround 2), while it is 36 dBA for the NACRE at the neutral position (TT 5).

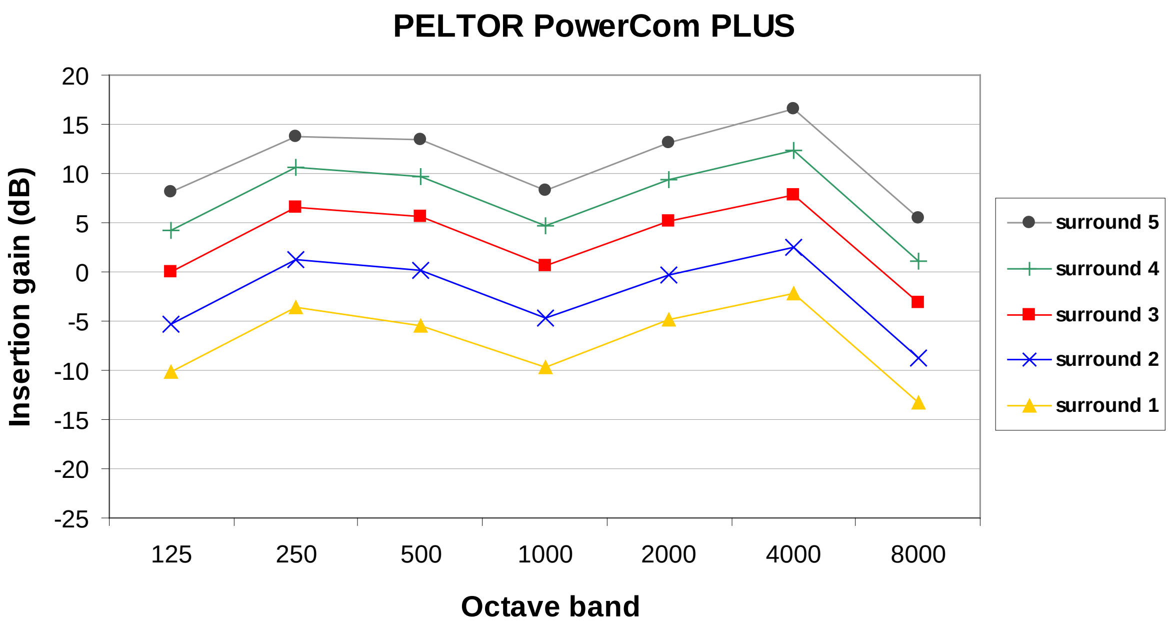

Figure 10: Insertion gain of the PELTOR Powercom Plus as a function of frequency in speech spectrum noise at 60 dBA.

Table 6: Insertion gain of the PELTOR Powercom Plus averaged over 500-4000 Hz in speech spectrum noise (60 dBA) for the five volume settings of the surround mode.

	PELTOR Powercom Plus				
	Surround 1	Surround 2	Surround 3	Surround 4	Surround 5
Gain (dB) Measured	-5.6	-0.6	4.8	9.0	12.9

Table 7: Electronic hissing noise by PELTOR Powercom Plus for five settings of the surround mode.

	PELTOR Powercom Plus				
	Surround 1	Surround 2	Surround 3	Surround 4	Surround 5
At-ear level (dBA) Measured	33.0	34.3	37.3	40.6	43.8
Equiv. free field level (dBA)	25.0	26.3	29.3	32.6	35.8

5.2 Data collection with human subjects

Forty-five English-speaking subjects were tested using the protocol described in Section 4.5. Subjects covered a wide range of hearing profiles, which are described as follows based on the five-frequency (500-4000 Hz) pure-tone average (PTA): (1) Within normal limits (hearing thresholds ≤ 25 dB HL at all frequencies, (2) Slight-to-Mild (PTA≤ 25 dB HL with hearing thresholds greater than 25 dB HL at one or more frequencies, (3) Mild-to-Moderate (PTA between 26 and 40 dB HL), and (4) Moderate-to-Severe (PTA between 41 and 55 dB HL).

The goal was to recruit 48 individuals, with a total of twelve individuals meeting the criteria for each of the four hearing loss profiles. This has been achieved for all profile categories, except for the Moderate-to-Severe group, where only 9 subjects could be recruited. Care was also taken to ensure a certain uniformity in hearing profiles across the two devices and two noises. Based on their hearing profile, individuals were assigned randomly to one of four possible noise-device combinations, such that there were at least two subjects from each hearing loss category for each noise-device combination (PELTOR-Noise 1, PELTOR-Noise 2, NACRE-Noise 1 and NACRE-Noise 2). This ensured that the two devices and two noises were tested with approximately equivalent samples of subjects.

5.2.1 Summary of hearing thresholds and hearing profiles

Each participant's hearing thresholds are plotted as a function of frequency in Figure 11 (upper panel = right ear; lower panel = left ear). Table 8 provides summary statistics of hearing thresholds for both ears. Among the 45 individuals recruited, twelve had normal hearing sensitivity defined as air conduction detection thresholds for pure tones no greater than 25 dB HL (ANSI/ASA S3.6-2010) between 250 and 8000 Hz in both ears, and the remaining 33 had sensorineural hearing losses. For those with hearing impairment, there was generally greater hearing loss for the higher frequencies than for the lower frequencies.

In order to study the interaction of communication devices with hearing loss in subsequent analyses, the audiograms were classified based on severity and interaural asymmetry. For this purpose, hearing thresholds between 500 and 4000 Hz were retained, given their importance for speech understanding. The following rules were used to determine asymmetry: (1) interaural threshold difference ≥ 10-dB at three frequencies, or (2) difference ≥ 15-dB at two frequencies, or (3) difference >15-dB at one frequency. Based on these rules, 22 participants had symmetrical hearing, 16 had a right-ear advantage and the remaining 7 had a left-ear advantage.

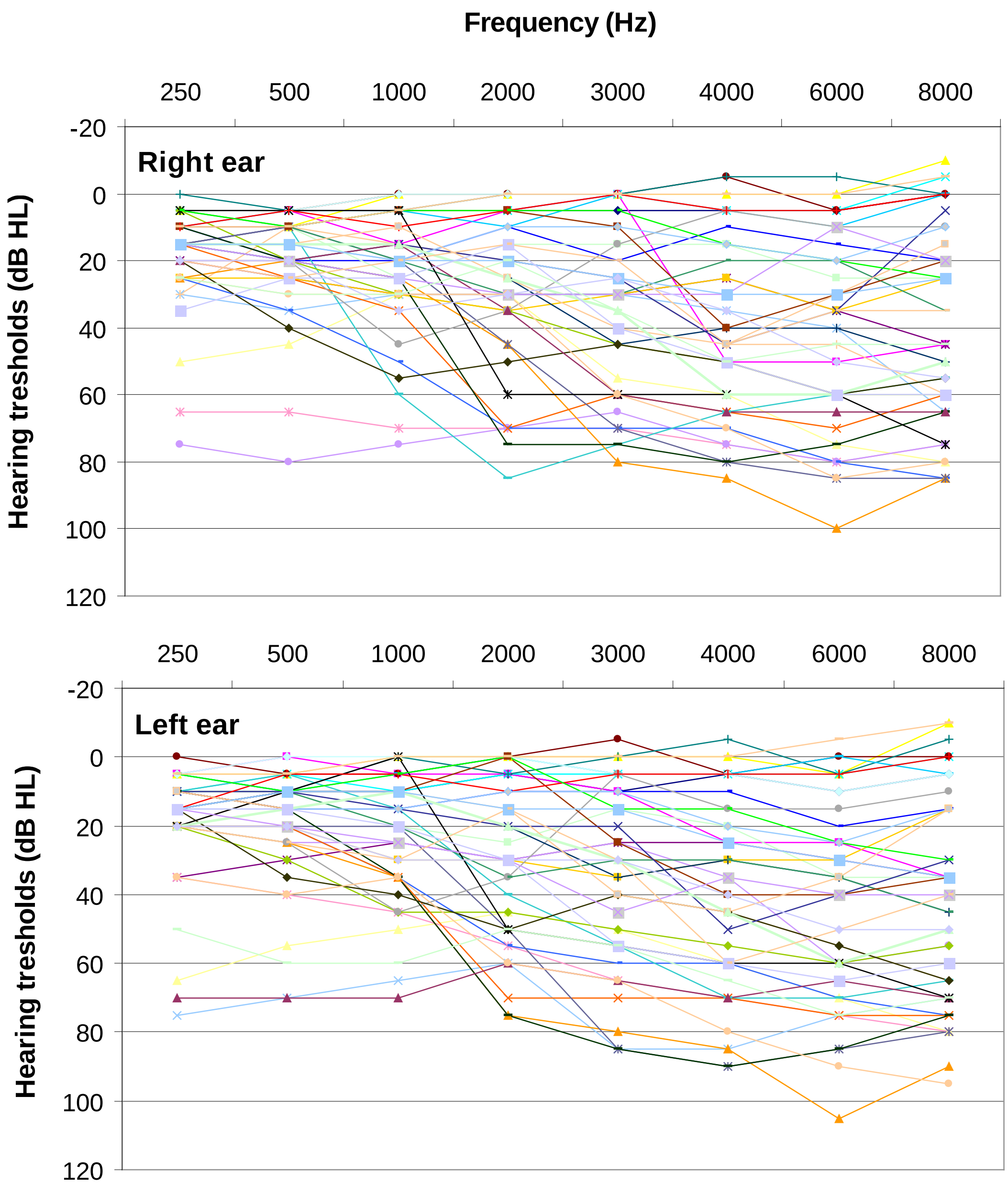

Figure 11: Individual hearing thresholds for the 45 subjects as a function of audiometric frequencies from 250 to 8000 Hz [upper panel = right ear; lower panel = left ear].

Table 8: Summary statistics of hearing thresholds (dB HL) over the 45 subjects.

Right ear	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**3000 Hz**	**4000 Hz**	**6000 Hz**	**8000 Hz**
Mean	17.7	19.6	22.9	27.8	31.9	37.7	40.2	38.6
SD	15.0	15.3	17.9	23.2	25.4	26.7	28.3	29.6
Minimum	0.0	5.0	0.0	0.0	0.0	-5.0	-5.0	-10.0
Maximum	75.0	80.0	75.0	85.0	80.0	85.0	100.0	85.0
Left ear	**250 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**3000 Hz**	**4000 Hz**	**6000 Hz**	**8000 Hz**
Mean	19.3	19.9	22.3	28.7	33.9	39.6	43.3	41.3
SD	16.6	16.9	18.2	22.8	26.3	27.7	28.4	30.0
Minimum	0.0	0.0	0.0	0.0	-5.0	-5.0	-5.0	-10.0
Maximum	75.0	70.0	70.0	75.0	85.0	90.0	105.0	95.0

The five-frequency PTA was used to classify participants into four hearing profiles, as defined earlier. Although these categories do not strictly follow the usual clinical boundaries for hearing loss, they served to group individuals of the current sample for analytical and comparative purposes. The mean PTA across both ears was used for symmetrical hearing losses, whereas the best ear PTA was used in cases of asymmetrical hearing losses. The subjects were distributed as follows across the four hearing loss profile categories: 12 subjects each for Normal, Slight-to-Mild and Mild-to-Moderate profile groups, and 9 subjects for the Moderate-to-Severe category. Table 9 provides summary statistics of the PTA by hearing profile category for both ears.

Table 9: Summary statistics of the five-frequency (500-4000 Hz) PTA (dB HL) by hearing profile.

Hearing profile	Parameter	Right-ear PTA	Left-ear PTA	Average PTA
Normal (n=12)	Mean	5.5	5.6	5.5
	SD	5.0	4.6	4.8
	Minimum	0.0	1.0	0.5
	Maximum	16.0	14.0	15.0
Slight-to-Mild (n=12)	Mean	22.6	21.0	21.8
	SD	5.2	6.3	5.5
	Minimum	14.0	9.0	12.0
	Maximum	30.0	31.0	28.5
Mild-to-Moderate (n=12)	Mean	37.8	32.1	35.0
	SD	14.0	4.1	7.7
	Minimum	27.0	27.0	27.0
	Maximum	73.0	39.0	50.5
Moderate-to-Severe (n=9)	Mean	51.9	48.6	50.2
	SD	8.5	4.7	6.1
	Minimum	44.0	44.0	44.0
	Maximum	70.0	55.0	62.5
Overall (n=45)	Mean	28.0	25.4	26.7
	SD	19.1	16.1	17.2
	Minimum	0.0	1.0	0.5
	Maximum	73.0	55.0	62.5

5.2.2 HINT screening test results for individuals presenting various profiles of hearing impairment

The distribution of HINT screening performance in noise was tallied over the 45 subjects in the three experimental noise conditions (Front, Left, Right) and the computed score (Composite). The distributions are shown in Figure 12. For comparative purposes, the norms for the American English HINT (Table 2) are displayed as vertical dashed lines in Figure 12. All distributions were skewed to the right of the norms towards elevated HINT thresholds, indicating supra threshold deficits for this subject sample. This was expected since only 12 of the 45 subjects had normal hearing thresholds. As shown in Figure 12, several subjects had HINT scores in noise that were 5 to 10 dB over the norm, indicating significant difficulties in noise.

The summary statistics of each HINT condition are shown in Table 10 by hearing profile category and over the entire group of 45 subjects. The mean HINT speech reception threshold in Quiet increased from 17.7 dBA (Normal) to 43.5 dBA (Moderate-to-Severe) over the four different hearing categories, a 25.8 dB difference. In Noise Front, the mean HINT threshold increased from -2.1 dB SNR (Normal) to +1.7 dB SNR (Moderate-to-Severe), a 3.8 dB difference. Averaged over Noise Left and Noise Right, the mean HINT threshold for side conditions increased from -9.9 dB SNR (Normal) to -2.1 dB SNR (Moderate-to-Severe), a 7.8 dB difference. Finally, the mean HINT Composite score (Section 4.5.1) increased from -6.0 dB SNR to -0.2 dB SNR, a 5.8 dB difference.

Table 11 presents the deviation between the mean HINT thresholds in Table 10 and the normative values from American English (Table 2). For the Normal hearing category, the deviation from the norm was only 2.1 dB in Quiet, and 0.5 dB or less in the three Noise conditions and the Composite score. This indicates that the group of normal hearing subjects performed as expected in all conditions on the HINT. In contrast, the results for the other subject categories showed progressively larger deviations from the norms as hearing loss increased from Slight-to-Mild to the Moderate-to-Severe profiles. For the latter group, the mean HINT threshold in Quiet was about 28 dB above the norm, further highlighting deficits in absolute audibility (Table 9) for this group. As seen in Table 11, the mean deviation from the norm in the noise conditions was 4.3 dB for Noise Front, 8.4 and 7.7 dB for Noise Left and Right respectively, and 6.2 dB for Noise Composite for this group of subjects. Supra threshold deficits were thus clearly evident in the subject sample.

Altogether, Figures 11 and 12 highlight the heterogeneous nature of the subject sample with individuals presenting a wide range of absolute hearing thresholds and supra threshold abilities. Such a sample distribution was desired in this study to test level-dependent communication headsets over a wide range of auditory abilities (Section 5.2.4).

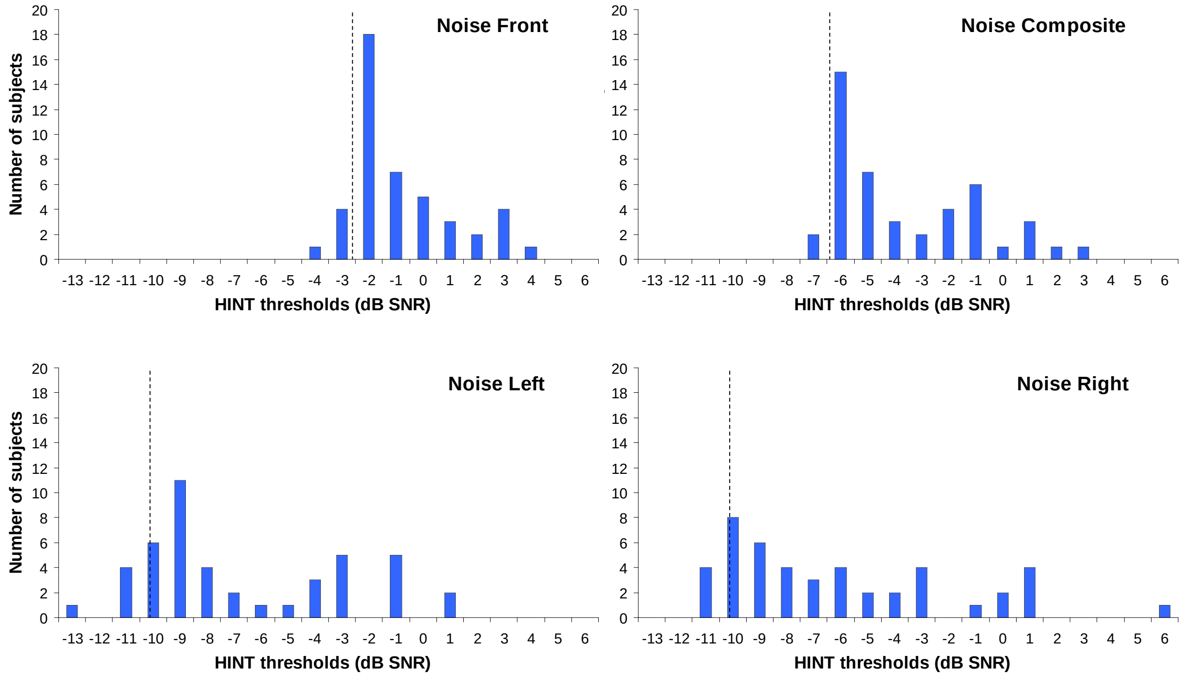

Figure 12. HINT performance in a sample of 45 individuals presenting various profiles of hearing impairment.

Table 10: Summary statistics of HINT performance by hearing profile and for the 45 subjects.

Hearing profile	Parameter	Quiet (dBA)	Noise Front (dB SNR)	Noise Left (dB SNR)	Noise Right (dB SNR)	Composite (dB SNR)
Normal (n=12)	Mean	17.7	-2.1	-9.8	-9.9	-6.0
	SD	2.8	0.7	0.9	1.1	0.5
	Minimum	13.7	-3.7	-11.4	-12.6	-6.8
	Maximum	21.9	-1.1	-8.4	-8.7	-5.0
Slight-to-Mild (n=12)	Mean	26.7	-1.5	-7.8	-8.5	-4.8
	SD	4.8	1.0	1.5	1.4	1.0
	Minimum	20.1	-3.0	-10.0	-9.8	-5.9
	Maximum	33.6	0.1	-5.6	-4.7	-2.9
Mild-to-Moderate (n=12)	Mean	35.4	-0.6	-4.2	-4.7	-2.5
	SD	4.3	1.7	4.8	3.7	2.6
	Minimum	29.4	-2.4	-10.5	-10.5	-6.1
	Maximum	44.3	2.5	5.6	1.3	2.5
Moderate/Severe (n=9)	Mean	43.5	1.7	-1.7	-2.4	-0.2
	SD	8.3	1.5	2.1	1.5	1.1
	Minimum	27.9	0.0	-4.3	-3.8	-1.5
	Maximum	51.2	3.5	1.0	0.9	1.7
Overall (n=45)	Mean	30.0	-0.8	-6.1	-6.6	-3.6
	SD	10.7	1.8	4.1	3.7	2.6
	Minimum	13.7	-3.7	-11.4	-12.6	-6.8
	Maximum	51.2	3.5	5.6	1.3	2.5

Table 11: Mean deviation of HINT performance from norms (Table 10 versus Table 2).

Hearing profile	Quiet (dBA)	Noise Front (dB SNR)	Noise Left (dB SNR)	Noise Right (dB SNR)	Composite (dB SNR)
Normal (n=12)	2.1	0.5	0.3	0.2	0.4
Slight-to-Mild (n=12)	11.1	1.1	2.3	1.6	1.6
Mild-to-Moderate (n=12)	19.8	2.0	5.9	5.4	3.9
Moderate/Severe (n=9)	27.9	4.3	8.4	7.7	6.2
Overall (n=45)	14.3	1.8	4.0	3.5	2.8

5.2.3 Device attenuation using the REAT method

For each participant, passive attenuation was measured at five one-third octave frequencies (250-4000 Hz) in a diffuse field, with either the NACRE QuietPro device or the PELTOR Powercom Plus earmuffs. For these tests, the devices were set to off, so that they behaved as conventional non-electronic HPDs. The attenuation data are summarized in Figure 13. Manufacturer's data are also included for comparative purposes.

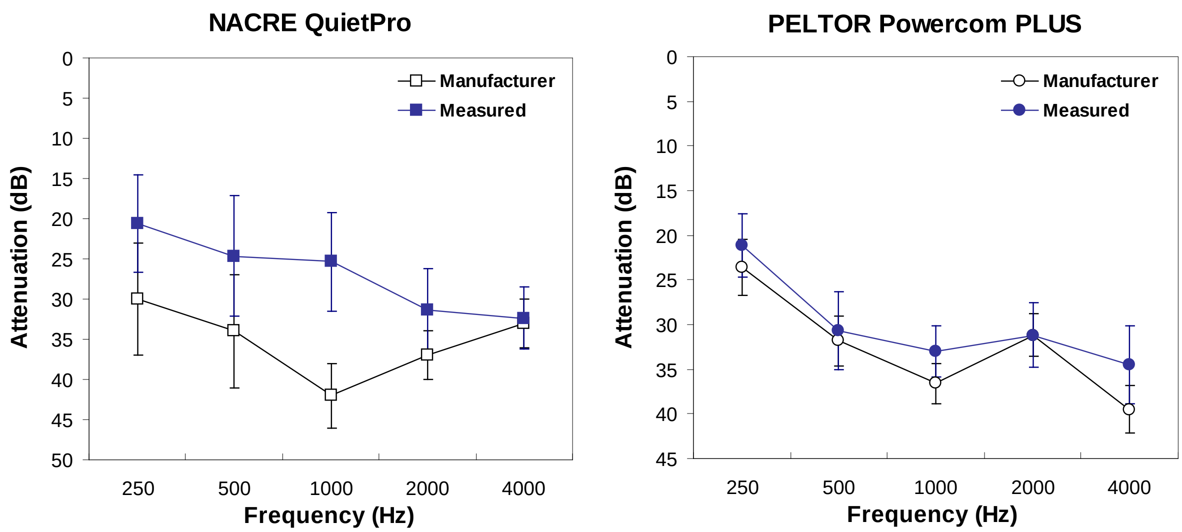

Figure 13: Mean attenuation values [left panel = NACRE QuitPro (n = 23); right panel = PELTOR Powercom Plus (n = 22)]. Error bars represent ± 1 standard deviation.

For the PELTOR earmuff-type device, measured attenuation closely mirrored the manufacturer's data, whereas larger discrepancies were noted for the NACRE insert-type device, particularly at 1000 Hz (17 dB difference). More complex fitting procedures for the NACRE device, and individual differences in ear canal shapes and sizes may in part account for these differences. For both devices, the standard deviation of measured attenuation was similar to values reported by the manufacturer (within 2.5 dB); however, standard deviation was consistently greater for the NACRE than for the PELTOR device.

5.2.4 Effects of communication devices on speech intelligibility in noise

Unprotected and protected intelligibility scores are contrasted in Figure 14 for each of the two noise environments (N1 and N2) and device talk-through settings (off, low gain, high gain). In this figure, unprotected and protected scores for each subject data point were obtained at the same SNR; however, the SNR was different over subjects to minimize floor and ceiling effects (see Section 4.5.3). Over all subjects, noises and talk-through settings, a total of 135 and 104 unprotected-versus-protected data points were obtained at the same subject-dependent SNR for the NACRE and PELTOR device, respectively.

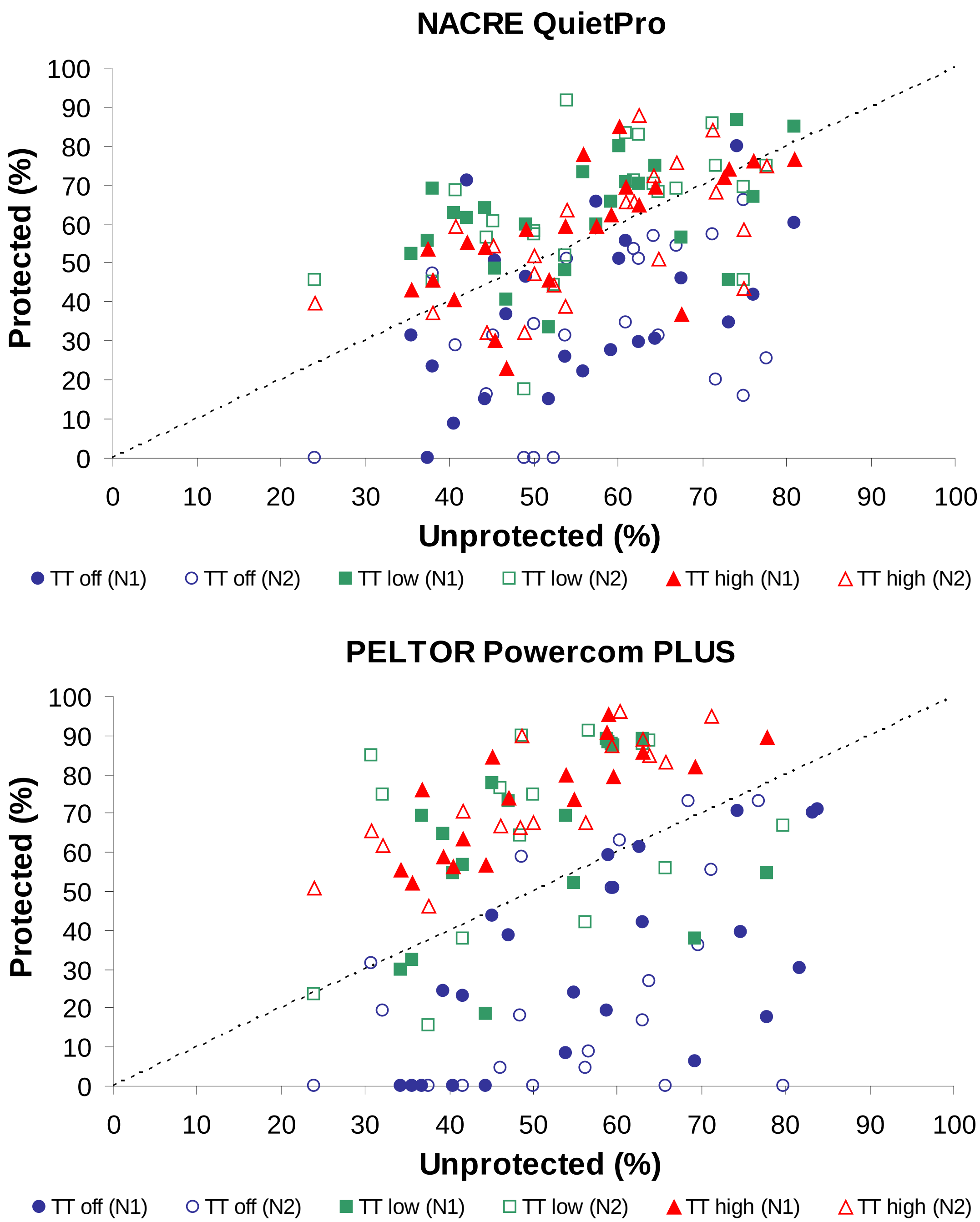

Figure 14: Unprotected versus protected speech intelligibility scores for each subject in two noises (N1 and N2), for three device talk-through settings (off, low gain, high gain) [upper panel = NACRE QuietPro; lower panel = PELTOR Powercom Plus].

Should the communication devices have no or little effect on speech intelligibility, data points would fall along the diagonal line across the two panels in Figure 14. Wearing of both devices can sometimes improve (data points above diagonal lines) or hinder (data points below diagonal lines) speech intelligibility. Cursory inspection of Figure 14 reveals a concentration of data points below the diagonal for the passive attenuation condition (TT off) in both devices and noises. In contrast, data points for amplified talk-through conditions (TT low and high) are concentrated near or above the diagonal.

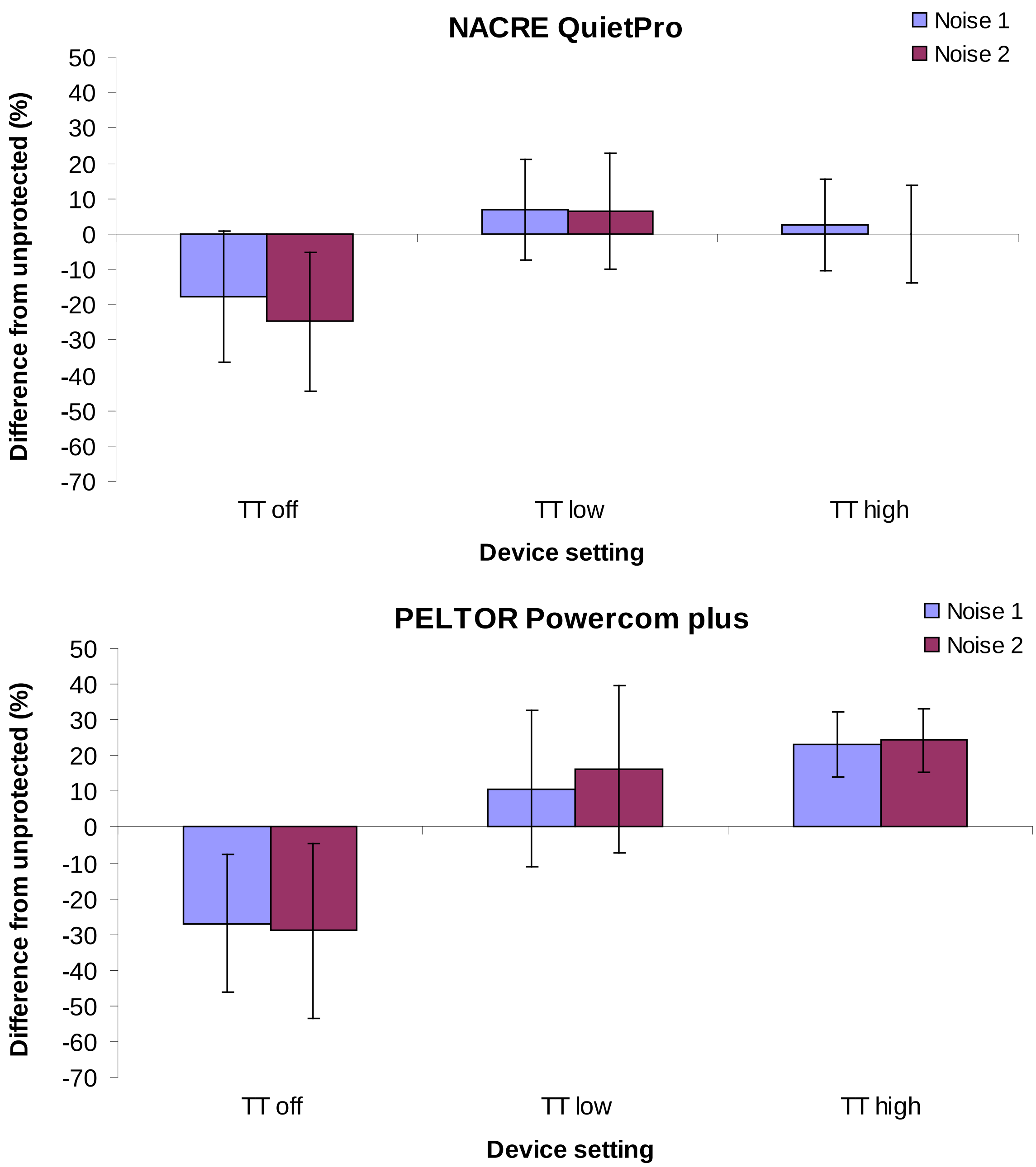

Figure 15: Overall effect of communication devices on speech intelligibility in the two noise environments and three conditions of use (TT off, TT low and TT high) compared to unprotected condition (no device). Data averaged over all subjects. A positive difference indicates better protected than unprotected performance.

In Figure 15, the difference in speech intelligibility between the protected and unprotected conditions is computed over all subjects to highlight the effects of noise environment and talk-through conditions for each device. For the PELTOR device, the condition with electronics powered off (passive attenuation) lead to a decrease in performance by 27-29% compared to unprotected listening over the subject sample in this study covering a wide range of hearing profiles. The conditions with amplified talk-through, on the other hand, yielded a benefit compared to unprotected listening by 11-15% and 23-24% in the low and high gain settings respectively. The results were similar for the NACRE device in the condition with electronics powered off, a 17-25% decrement in performance compared to unprotected listening. In the conditions with amplified talk-through, however, use of the NACRE had only a small effect on performance, a 6-7% intelligibility benefit in the low gain setting and a 0-2% benefit in the high gain setting. As shown in Figure 15, for both devices there is very little difference in performance in the two noise environments tested in any of the listening conditions. The data points are pooled across noises in subsequent analyses.

The influence of hearing profile was also examined, with results displayed for each device in Figures 16 and 17. Protected-versus-unprotected data points are presented for each hearing profile category in separate panels. Again, if the communication devices were not influencing speech intelligibility, data points would fall near the diagonal line across all panels. As clearly seen in both figures, the difference between protected and unprotected condition not only depended on the talk-through setting in this study, but it interacted with hearing profile. For subjects with hearing thresholds within normal limits, the passive attenuation condition (TT off) did not seem to hinder speech intelligibility in the majority of cases for both devices. Indeed, except for two data points, filled circles lie near the diagonal in Figures 16 (NACRE) and 17 (PELTOR). Conditions with amplified talk-through gain settings either did not affect intelligibility (TT high for NACRE) or improved speech intelligibility in noise (TT low for NACRE, and TT low and high for PELTOR) for subjects with normal hearing.

For all remaining profiles in which hearing loss was present (Slight-Mild, Mild-to-Moderate, Moderate-Severe), passive attenuation (TT off) generally reduced speech intelligibility, as indicated by all but two filled circles falling below the diagonal in Figures 16 and 17, and this effect was more evident with increasing degrees of hearing loss. As hearing loss increases, signal audibility thus becomes a crucial contributing factor of the reduction in speech intelligibility when passive hearing protection is used. Differences in the effects of both hearing protectors also became evident. The PELTOR earmuff-type device appeared to yield greater decreases in speech intelligibility compared to the NACRE insert-type communication system when used in passive mode. For the most impaired hearing profile (Moderate-to-Severe), intelligibility virtually dropped to zero or near-zero values for all cases using the PELTOR device (filled circles in bottom-right panel of Figure 17) while some speech intelligibility remained in most cases with the NACRE (filled circles in bottom-right panel of Figure 16). This is likely related to differences in the attenuation achieved by the two devices (Figure 13), the PELTOR yielded more attenuation than the NACRE, on average, and showed less variability across subjects.

For all hearing loss categories, the higher gain setting (TT high) almost fully restored intelligibility to unprotected values for users of the NACRE device, and provided significant gains in speech recognition in noise for PELTOR users over unprotected listening. Without exception, all filled triangles in Figure 17 lie above the diagonal. Similarly, apart from the most impaired hearing profile, the low gain setting (TT low) restored intelligibility to unprotected values using both devices, and in some cases offered additional benefits for speech recognition in noise (especially when using the PELTOR device).

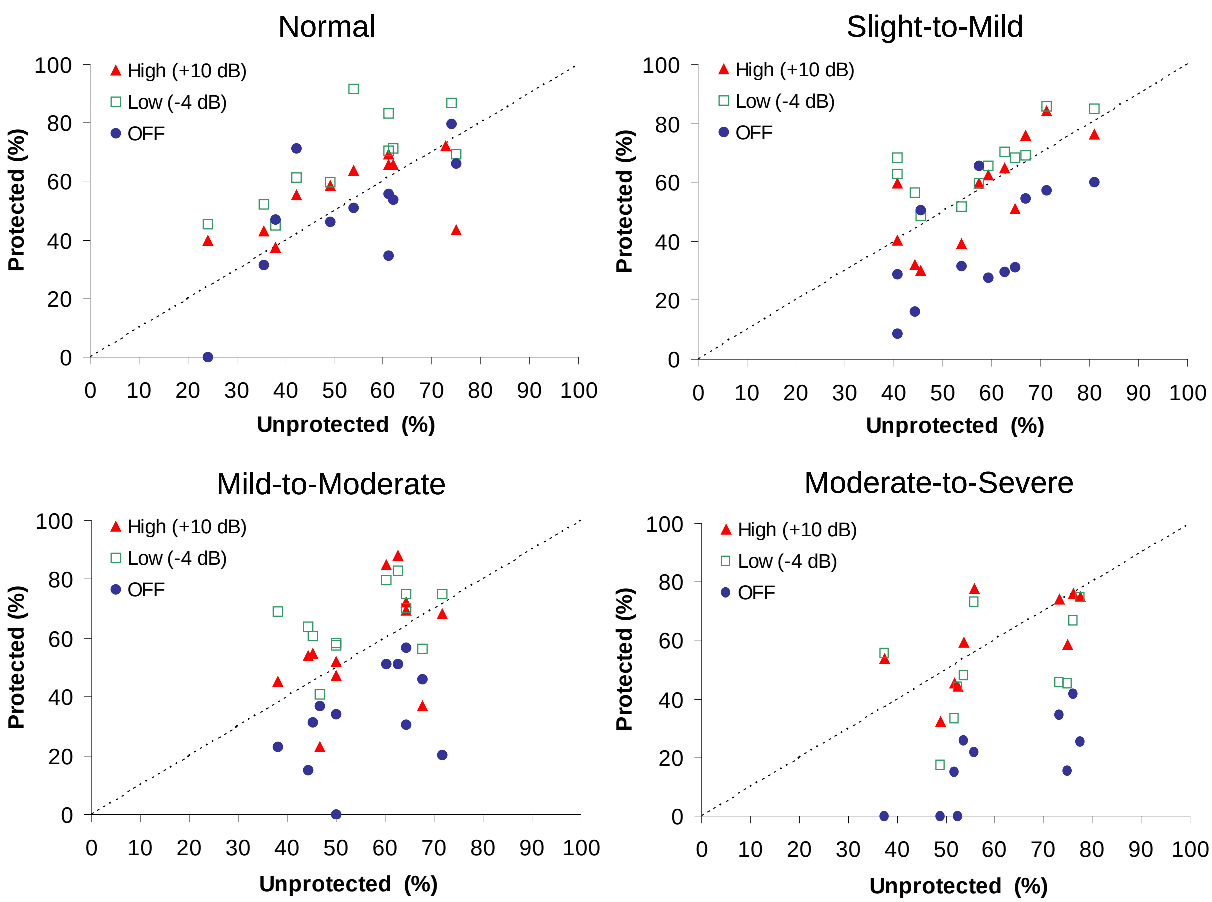

Figure 16: Unprotected and protected speech intelligibility scores across all noise environments and talk-through gain settings for individuals with various hearing profiles using the NACRE device.

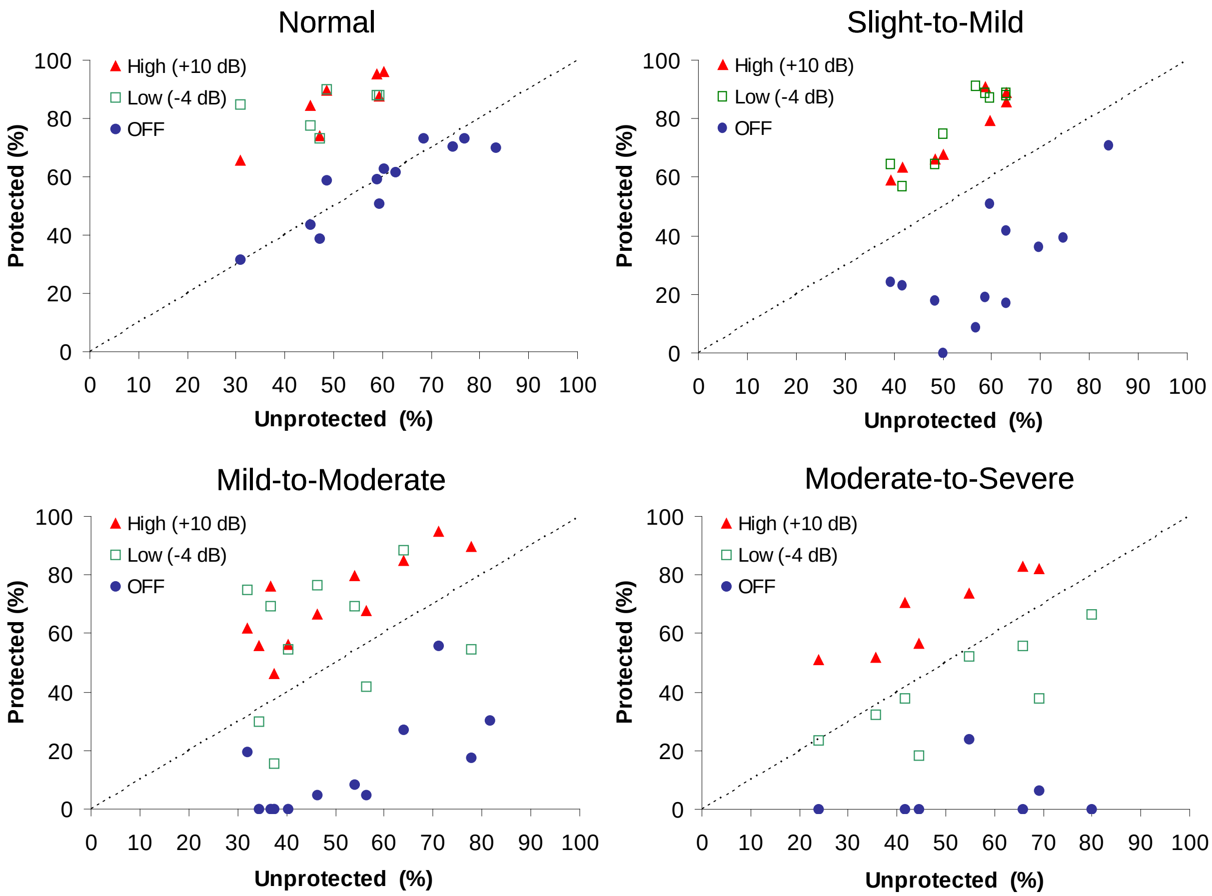

Figure 17: Unprotected and protected speech intelligibility scores across all noise environments and talk-through gain settings for individuals with various hearing profiles using the PELTOR device.

Finally, Figure 18 provides a summary of the speech intelligibility benefits of wearing the two devices compared to unprotected listening. Data is averaged over subjects and noises. The most interesting feature is the very similar results across all hearing categories when a high talk-through gain setting is used. For the NACRE, there is virtually no effect of wearing the device in TT high compared to unprotected listening, a difference -1 to +4% is found over the four hearing profile categories. For the PELTOR, wearing the device in TT high yielded a 19-34% benefit compared to unprotected listening over the four profiles.

The results in TT high in Figure 18 are in sharp contrast with the condition when the talk-through mode is in the OFF position. In this case, normal hearing subjects show little effect compared to the unprotected condition, but all categories of subjects with hearing loss are affected and there are wide performance differences across categories. For individuals with Moderate-to-Severe hearing loss, the average decrement in performance is 42 and 50% for the NACRE and PELTOR devices respectively. In Figure 18, setting the devices in TT low yielded a large improvement over the TT off position and even offered a benefit compared to unprotected listening in all but the most impaired hearing profile.

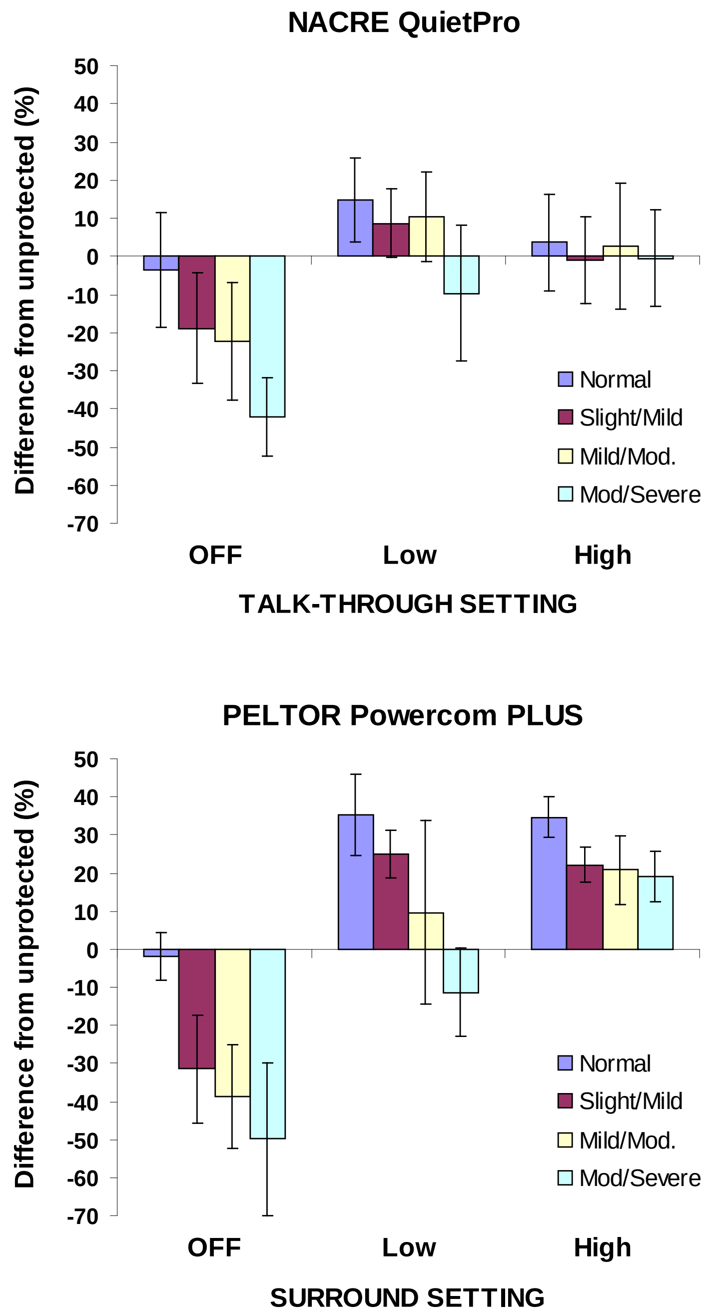

Figure 18: Overall effect of communication devices on speech intelligibility as a function of hearing profile. Data averaged across subjects and noise environments. Error bars represent ± 1 standard deviation [upper panel = NACRE device; lower panel = PELTOR device].

6.0 General discussion

6.1 Effects of communication devices on speech intelligibility in military noises

In this study, two advanced tactical communication devices with level-dependent attenuation characteristics were investigated: the NACRE QuietPro, a digital insert device with active noise reduction capabilities, and the PELTOR Powercom Plus, an analog earmuff-type device. These devices are equipped with in-the-ear (NACRE) or boom (PELTOR) microphones for radio communications with remote locations; however, in the present study, only speech perception in face-to-face communications through the devices was investigated. This was carried out in a noise simulation room reproducing the acoustical characteristics of two military noise environments, LAVIII (rough terrain and highway) and Bison (idling) vehicles at 80-95 dBA, in a diffuse sound field. The speech material was presented from one loudspeaker directly in front of the subject at a one meter distance. The methods followed closely a previous study (Giguère et al., 2008a, 2010) conducted to investigate the effects of passive hearing protectors on speech intelligibility in military noises, in interaction with hearing loss.

The main results of the present study are illustrated in Figure 18. This figure shows the difference in percent correct word intelligibility between three listening conditions with communication hearing protection devices fitted and unprotected listening. The first protected listening condition was achieved by setting the device electronics in the OFF position, thereby achieving passive linear attenuation. The results for the NACRE QuietPro and PELTOR Powercom Plus showed virtually no effect on speech perception in noise for normal hearing subjects compared to unprotected listening. With increasing degrees of hearing loss, wearing the devices in passive mode led to progressively larger decreases in speech perception. In the most impaired hearing profile (Moderate-to-Severe loss), the mean decrease in word intelligibility was 42% for the NACRE QuietPro and 50% for the PELTOR Powercom Plus.

The results with two communication devices in passive mode closely paralleled those obtained in the previous study on two passive hearing protectors (Giguère et al., 2008a, 2010), reproduced as Figure 3 in the present report. As shown in this figure, the AOSafety Indoor earplug and PELTOR H10A earmuffs either provided a small benefit or had no effect on speech perception for the group of subjects with normal hearing, while larger and larger adverse effects were noted with increasing hearing loss. In the most impaired hearing profile (Moderate-to-Severe loss), the mean decrease in word intelligibility was 22% for the AOSafety earplug and 57% for the PELTOR H10A compared to unprotected listening. Interestingly, the decrement in score for this subject group was monotonically related to the attenuation achieved by the four devices used in both studies. Averaged over the speech frequency range (500-4000 Hz), the mean REAT attenuation achieved for the two communication devices in passive mode (Figure 13) and the two passive hearing protectors (Figure 22 in Giguère et al., 2008a) is as follows: AOSafety earplug = 18.5 dB; NACRE QuietPro = 28.4 dB; PELTOR Powercom Plus = 32.3 dB; PELTOR H10A = 35.9 dB). Clearly and unsurprisingly, more attenuation resulted in greater losses of audible speech cues for subjects with hearing loss, and this effect worsened with increasing degrees of hearing loss.

Two other protected listening conditions were investigated in the present study, whereby the talk-through or surround mode of the level-dependent communication devices was turned on to achieve a low (-4 dB) and high (+10 dB) level of amplification. It is important to note that these levels of amplification are maintained only at relatively low to moderate external noise conditions. Above 70-80 dBA for the NACRE QuietPro (Figure 9) and 60 dBA for the PELTOR Powercom Plus (Figure 7), the devices automatically reduce the amount of sound transmitted to achieve an effective protection for the user. At an external level of 90 dBA, for example, the sound transmitted by the PELTOR Powercom Plus is equivalent to a free field level of about 75 dBA in surround 4 mode (83 dBA manikin level – 8 dB free field correction), in effect a 15 dB attenuation. The sound transmitted by the NACRE QuietPro in TT10 mode under the same conditions is equivalent to a free field level of about 85 dBA (93 dBA – 8 dB), an effective attenuation of external sounds by 5 dB.

The speech intelligibility results with the two communication devices in low and high gain settings are shown in Figure 18. Clearly, there was a marked improvement in speech perception compared to the passive mode (OFF) for all hearing profile categories, including normal hearing. Furthermore, intelligibility results for both devices at both gain settings were at or above unprotected listening results for all subject groups from Normal to Mild-to-Moderate hearing profiles. Results for the Moderate-to-Severe hearing profile category were also markedly improved by setting the devices to a low gain position compared to OFF, yet remained below unprotected listening; however, in the high gain position, results were at or above unprotected listening as for other subject groups.

Inspection of Figure 18 shows that the benefit of level-dependent amplification was larger for the PELTOR Powercom Plus than the NACRE QuietPro, especially at the high gain setting. At this setting, the PELTOR provided a benefit of 19-34% across subject groups compared to unprotected listening, while the NACRE had a neutral effect. This is likely due to the different position of the external sensing microphones on these two devices. For the NACRE, the external microphones are located on the outside end of the transducer housing that sits in the concha cavity, close to the ear canal entrance. There is little directional sound shadowing effects in this case. For the PELTOR, the external microphones are mounted on the earcups directly up front, several centimetres from the ear canal entrance. Moreover, the size of the earcups is such that it may contribute direction-dependent sound reflections and shadowing effects around the human head. One can expect directional effects from this arrangement, with frontal sound being favoured over other directions. Given the choice of frontal speech in diffuse noise in this study, wearing the PELTOR device likely resulted in a small increase in SNR over the unprotected condition, but no change in SNR for the NACRE. Conversely, had speech intelligibility been investigated for rearward speech incidence, wearing the PELTOR likely would have resulted in a small decrease in SNR, given the frontally located and shadowed external microphones in this case. Such directional speech perception effects for level-dependent earmuffs, including the PELTOR device, have been independently observed in very recent work compiled in Giguère et al. (2011). Compared to a passive attenuation mode, powering the amplified earmuffs and external microphones led to an increase of 10-15% word intelligibility for frontal speech in diffuse pink noise, but a decrease of 15% for rearward speech in the same noise. Typically, a 1-dB increase in SNR leads to 8% increase in word intelligibility (Giguère et al., 2008b). The directional effects observed thus correspond to a 2 dB increase in SNR for frontal speech and a 2 dB decrease in SNR for speech from the rear.

Finally, the effect of noise environment is illustrated in Figure 15. As shown, speech intelligibility results for both devices were very similar in the two noises tested in all listening conditions. Since these noises were selected to be acoustically different in terms of spectral and temporal characteristics from among a set of eight military noises from a previous study (Giguère et al., 2008a, 2010), this supports the view that noise type is not a major factor impacting the main findings reported in this study. While noise spectrum and temporal characteristics have a large absolute effect on speech intelligibility (Rhebergen et al., 2008) in any particular listening condition, the relative effect of noise type in unprotected versus protected listening conditions appears minimal.

6.2 Impact on situational awareness

Adequate functional hearing abilities requiring good signal detection, speech perception and sound localization are of utmost importance in military field operations to ensure mission success and survival. The nature of missions can be very varied and none of the aural tasks above can be singled out as more or less important. For example, complex and overlapping speech messages need to be attended to and understood in very noisy vehicular command post operations (Abel et al., 2010). On the other hand, fine detection and distance evaluation of enemy camp or threat sounds in otherwise quiet environments are needed in reconnaissance or raid missions (Casali et al., 2009). Military tasks often require use of hearing protection or communication devices and must be carried out despite the presence of noise-induced hearing loss among some members.

Conventional hearing protectors are often judged to compromise aural communication tasks or to be uncomfortable, difficult to fit or incompatible with other protective gear. As a result, there is considerable resistance to use them over one or both ears in operations that have life-threatening or safety implications (Suter, 1989; Abel, 2008). Advanced active hearing protection and communication devices with level-dependent attenuation are rapidly being introduced into the marketplace with the dual purpose of providing effective protection against noise and enhancing communications (Giguère et al., 2011). These devices, however, are very complex and can be used in a wide range of different control settings. Unfortunately, and in sharp contrast to the hearing aid industry, there is sparse and widely disparate disclosure of electroacoustic technical data by manufacturers of advanced active hearing protection devices. 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. Furthermore, there is very little empirical data on laboratory or field performance available through independent studies with human listeners, especially for those individuals with hearing loss.

The present study addressed one of a number of issues of direct relevance to situational awareness in the field; namely, speech perception in noise in interaction with hearing loss and protection device in a face-to-face communication situation. The laboratory data collected in simulated military noise fields indicated that the devices tested showed promising results for individuals with hearing loss up to moderately-severe hearing loss profiles, by restoring speech intelligibility to near unprotected performance or even above unprotected performance in many cases. The two devices tested, while only a small sample of an emerging class of advanced hearing protection systems, differed markedly in design: one device is an earmuff-type analog device while the other is a digital insert device.

In the current study, military noise recordings in light-armoured vehicles were reproduced in the simulation room to reflect the natural fluctuations of the noises in the real environments and operational conditions of the vehicles, from typically 80 dBA to an upper laboratory limit of 95 dBA short-term for ethical considerations. For normal hearing subjects, 50% word intelligibility score can be achieved at a SNR of about -12 dB for frontal speech in the two noises tested, and the psychometric function relating intelligibility z-scores to SNR has a slope of about 0.23 z-unit/dB (Table 10 in Giguère et al., 2008a). The latter translates into a slope of 9%/dB. Assuming a satisfactory communication performance of 90% percent word correct, which translates into 95+% sentence intelligibility, normal hearing subjects could reach this level of performance at a SNR of about -7.5 dB (-12 dB + 40% / 9%/dB). Averaged over males and females, shouted speech at a one-meter distance is about 85 dBA (Kryter, 1985). This means that normal hearing subjects could theoretically achieve satisfactory performance at one-meter distance up to a noise level 92.5 dBA in face-to-face communications. Assuming a 6 dB decrease in sound level with each doubling of distance due to geometric spreading, normal hearing subjects could also achieve satisfaction performance up to a noise level of 83 dBA at a 3-meter distance and 72.5 dBA at a 10-meter distance in shouted conditions.

As shown in Table 11, subjects with hearing loss require a greater SNR to achieve the same speech intelligibility performance in noise than normal subjects. For example, the mean deviation of HINT Noise Composite thresholds from the normative values is 1.6 dB for Slight-to-Mild hearing profiles and 6.2 dB for Moderate-to-Severe profiles. This means that, under shouted speech conditions, the maximum noise levels for which satisfactory communication can be achieved at 1-, 3- and 10-meter face-to-face distances will be less than for a normal hearing population by the amounts indicated above for each hearing profile group. Viewed in a different way, the Slight-to-Mild hearing profile group could achieve satisfactory communication performance in shouted speech at the same noise level as for a normal hearing population, but at a distance 17% shorter. For the Moderate-to-Severe hearing profile, a 50% shorter distance (half of normal hearing individuals) would be needed. These hearing profiles covers the range of hearing grades (H1-H4) in use in Canadian Forces (A-MD-154-000/FP-100, Annex C). Of course, individuals can deviate considerably from the group mean, by up to 6.1 dB in this study for HINT Noise Composite thresholds (Table 10), and this needs to be taken into consideration for the assessment of any particular individual.

The above analysis was based on unprotected listening results. When the two advanced hearing protection devices evaluated in this study are used in active mode, speech perception performance in noise will typically be at par or slightly better than unprotected performance for all hearing profiles (Figure 18). When used in a high-attenuation passive mode, performance for normal hearing individuals will be maintained; however, individuals with hearing loss will incur important operational limitations in terms of the maximum communication distance possible under shouted conditions.

Other auditory abilities than speech perception in noise are required in the field to maintain adequate situational awareness, e.g. detection of distant sounds and evaluation of the distance of threats (Casali et al., 2009), and the spatial localization of sounds (Abel et al., 2007, 2009). The impact of advanced communication devices on these auditory tasks is equally important. Ergonomics issues, such as the compatibility of the devices with other protective gear such as helmet (Abel et al., 2009) and the ease of manipulation of volume and other control settings (Casali et al., 2009) also need to be taken into consideration in the selection of the proper device for each user or application.

Finally, the performance of advanced communication devices on aural communication tasks cannot be dissociated from their protective performance. The output limiting characteristics of the two devices tested in this study appear set to ensure that sound exposure remain below 85 dBA in equivalent free field level (= 93 dBA at-ear levels) in all talk-through (or surround) control settings in continuous noise environments up to at least 100 dBA (Figures 7 and 9). However, independent data on the protection against impulse noise is sparse, due to technical challenges in equipment requirements and availability. This may change since the recent promulgation of ANSI/ASA S12.42 (2010) and first commercial Acoustic Test Fixture meeting the requirements of this standard (Type 45CB; G.R.A.S. Sound & Vibration A/S, Holte, Denmark).

7.0 Conclusions

This research project studied the effects of two active level-dependent communication devices, one insert-type and one earmuff-type, on speech intelligibility in military noises in relation to the hearing status of listeners.

The main finding of the study is that while the active devices performed similarly to conventional passive hearing protection when used in passive mode (electronics powered off), they showed large benefits over conventional devices when powered to provide a high talk-through gain. When used in 80-95 dBA military noises, both devices showed promising results for individuals with hearing loss, by restoring speech intelligibility to near unprotected performance or even above unprotected performance in many cases. At the same time, the output limiting characteristics of the devices are set to ensure that the sound exposure remain below 85 dBA in equivalent free field level (about 93 dBA at-ear levels) in all talk-through (or surround) settings. These findings indicate that the current technology of high-end tactical communication devices may provide substantial benefits for enhanced situational awareness for all military hearing grades in noisy face-to-face communications.

Recommendations for follow-up research work include:

- a comprehensive evaluation of the impulse noise protection capabilities of level-dependent tactical devices according to the new standard ANSI/ASA S12.42-2010;
- further investigations of the directional dependence of earmuff-type tactical devices on speech intelligibility in noisy face-to-face communications;
- research on the intelligibility and sound quality of received radio signals, in interaction with face-to-face communications in divided attention tasks; and
- an investigation of the Lombard effect and speech production changes associated with amplified listening and enhanced voice feedback resulting from the use of tactical communication devices.

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Annex A – Ethics certificate and renewal

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Véronique	Vaillancourt	Health Sciences / Others	Co-investigator

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File Number: H12-05-03B

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Recherche sur la modelisation des effects de la protection auditive individuelle et des appareils de communication sur la reconnaissance de la parole dans le bruit. (U)

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(U) The effects of two advanced level−dependent communication devices on face−to−face speech intelligibility in military noises were investigated. Devices were the NACRE QuietPro and the PELTOR Powercom Plus. Noises from the LAVIII and Bison light−artillery vehicles were reproduced in a noise simulation room at 80−95 dBA. Over 45 subjects covering a wide range of hearing profiles from normal hearing to severe hearing loss were tested using sentences from the Hearing−In−Noise Test (HINT). When used as passive devices with the electronics powered off, the two devices performed as expected from conventional hearing protectors having the same amount of attenuation. In this mode, there were large performance differences among subject groups in terms of the effects of wearing the devices compared to unprotected listening. However, when used in active talk−through (or surround) mode, both devices showed large speech intelligibility benefits over the passive mode and demonstrated a level of performance often exceeding that in unprotected listening. The subject group with the most impaired hearing benefitted the most from the active mode. The findings indicate that the current technology of high−end tactical communication devices could provide substantial benefits in situational awareness during noisy military operations for all hearing grades.

(U) Deux appareils de communication haute gamme avec isolation acoustique dépendante du niveau sonore ont été évalués lors d'essai de reconnaissance de la parole en situation bruyante face à face. Il s'agit des appareils NACRE QuietPro et PELTOR Powercom Plus. Des bruits militaires en provenance de véhicules blindés légers de type LAVIII et Bison ont été reproduits dans une salle d'écoute à des niveaux sonores de 80−95 dBA. Un total de 45 sujets couvrant un large éventail de profils auditifs de normal à perte sévère ont été testés à l'aide des phrases du test de parole « Hearing−In−Noise Test (HINT)». Lors de tests d'écoute en mode passif avec circuits électroniques non alimentés, les deux appareils ont procuré des résultats similaires à ceux attendus par des protecteurs contre le bruit conventionnels possédant un même niveau d'isolation acoustique. De grandes différences de performance ont été observées entre les différents groupes de sujets en ce qui a trait à l'effet du mode d'utilisation passif comparativement à l'écoute sans protection. Par contre, lors de tests d'écoute en mode actif avec amplification des sons extérieurs, les deux appareils ont procuré un bénéfice important en reconnaissance de la parole par rapport au mode passif et démontré un niveau de performance souvent au−delà des résultats sans protection auditive. Le groupe de sujets présentant la perte auditive la plus sévère a bénéficié le plus du mode actif. Ces résultats semblent indiquer que la présente technologie d'appareils de communication tactique haute gamme puisse offrir une présence situationnelle rehaussée lors d'opérations militaires bruyantes pour toutes les catégories d'audition.

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(U) hearing protection; communication in noise

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