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"Active Hearing Protectors and Audibility of Critical Communications"
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Table of Contents

	Page No.
<u>Section1</u>	
List of Terms and Abbreviations	3
Abstract	4
Significant (Key) Findings	5
Translation of Findings	5
Outcomes/Impacts	6
<u>Section2</u>	
2.1 Laboratory Facilities	7
(a) Anechoic Chamber	7
(b) Refurbished Audiometric Sound Booth	7
2.2 Measurement Methods	7
(a) Probe Microphone for Measuring Sound Pressure at the Eardrum	7
(b) Psychoacoustic Methods	8
(c) Evaluation of Ear Cups for Active Hearing Protection Device	11
(d) Evaluation of Earphones for Active Hearing Protector Device	11
2.3 Development of Active Hearing Protector Proof-of-Concept	11
(a) Selection of Components	11
(b) Simulation of Proof-of-Concept Device	12
(c) Proof-of-Concept Device and Evaluation	15
(d) Test of Hypothesis I	18
(e) Test of Hypothesis II	19
(f) Test of Hypothesis III	20
2.4 Conclusions	21
2.5 Publications	23

List of Terms and Abbreviations

ANR - active noise reduction

A-weighting - frequency weighting of noise commonly used to reflect the hazard to hearing

dB - relative magnitude of two quantities (formally, $20 \times \log_{10}[\text{value \#1} / \text{value \#2}]$)

dBA - A-weighted sound pressure level (often 'sound level')

COM - communication (channel)

Δf - filter bandwidth, applied to subband filters

DSP - digital signal processor

E - error microphone (mounted inside ear cup of HPD)

f - frequency

G_n - amplification of communication channel subband 'n'

HATS - Head and torso simulator

HPD - hearing protection device

ISO - International Organization for Standardization

LMS - least means square algorithm

M - number of subbands

m - meter

MRT - Modified Rhyme test for word detection in noise or distortion

PNR - passive noise reduction of hearing protector

R - reference microphone (mounted on exterior surface of ear cup of HPD)

REAT - real ear at threshold

S - secondary source, or earphone (mounted inside ear cup of HPD)

Σ - sum (Σ^+), or subtract (Σ^-), signals

S-E - error path model (filter modelling transduction and sound propagation from S to E)

SNR - signal to noise ratio

SPL - sound pressure level (in dB re 2×10^{-5} Pa)

SSN - speech-spectrum shaped noise (noise with frequency spectrum that mimics that of speech)

STI - Speech Transmission Index (model for predicting speech intelligibility, as revised, STI_r)

STI_{speech} - model based on STI_r using speech as the probe signal, including coherence with noise

$STI_{\rho\text{-speech}}$ - model based on STI_{speech} including the correlation between speech at different frequencies

SWR - standing wave ratio

TNR - total noise reduction

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Final Report Abstract

A proof-of-concept hearing protection device (HPD) has been developed to improve the speech intelligibility of a built-in electronic communication channel while maintaining the audibility of a tonal warning sound external to the HPD, and adequate attenuation of environmental noise. The proof-of-concept device has been constructed from the mechanical components of a commercial hearing protector, and electro-acoustic and electronic components selected or developed as a result of the research conducted in this project. The device employs digital signal processing to divide the audio frequency range into separate, contiguous frequency bands that can be programmed to function independently. There are two separate and independent digital controllers. One controller is programmed to provide active noise cancellation to reduce environmental noise. The second is employed to control signals in the communication channel, which can be derived from a (remote) electronic communication source or from the environment external to the HPD. It is programmed to enhance the audibility of desired sounds, by adjusting the magnitude of the desired signal compared to that of the undesired noise.

The performance of the proof-of-concept device has been established by measurements involving human subjects under conditions of environmental noise and communication that do not pose a risk to hearing, and in simulation for other conditions. A probe microphone with a miniature plastic tube that is inserted in the ear canal has been developed to record sounds at the eardrum. The microphones are used to measure the attenuation of HPDs. Psychoacoustic tests have been developed to determine thresholds for the perception of pure tones, thresholds for the perception of pure tones or warning sounds in noise, and speech understanding in noise. A surrogate objective measure of speech intelligibility has been implemented to permit the performance of the proof-of-concept device to be evaluated in simulation (Speech Transmission Index - STI). By these means, it has been shown that the sound level at the ear can be automatically reduced by frequency and level to the extent required to avoid noise-induced hearing loss, while simultaneously minimizing over-protection from noise and so maintaining situational awareness. It has also been shown, by improved word scores when subjects wear the proof-of-concept device and by increased or acceptable STI values in simulation, that the intelligibility of speech in the communication channel can be improved while maintaining adequate control of environmental noise. It has further been shown that the audibility of a tonal warning sound external to the proof-of-concept device is not degraded compared to wearing a traditional passive circumaural HPD. We thus conclude that the hypotheses, and aims, of the original proposal have been confirmed by the performance of the proof-of-concept device.

Section 1

Significant (Key) Findings

The specific aims of this study were to develop a hearing protection device (HPD) incorporating active noise reduction (ANR) and an adaptive communication (COM) channel providing sound reproduction at the ear designed specifically to: 1) improve the speech intelligibility of a built-in COM channel; 2) maintain the perception of tonal warning alarm sounds external to the HPD, and 3) maintain adequate attenuation of environmental noise.

A proof-of-concept HPD has been developed to address the specific aims of this study. It has been constructed from the mechanical components of a commercial hearing protector and electro-acoustic and electronic components selected or developed as a result of the research described in this report. The device employs digital signal processing to divide the audio frequency range into separate, contiguous frequency bands that can be programmed to function independently, commonly termed "subbands".

Two separate and independent digital controllers are required to implement the signal processing necessary to achieve the aims of this study. One controller is programmed to provide active noise cancellation to reduce environmental noise. The second is employed to control signals in the COM channel, which can be derived from a (remote) electronic COM source or from the environment external to the HPD (e.g., a warning sound). It is programmed to enhance the audibility of desired sounds, by adjusting the magnitude of the desired signal compared to that of the undesired noise.

The performance of the proof-of-concept device has been established by psychoacoustic measurements involving human subjects under conditions of environmental noise and communication that do not pose a risk to hearing, and in simulation for other conditions. A probe microphone with a miniature plastic tube that is inserted in the ear canal has been developed to measure the attenuation of the HPD. A surrogate measure has been implemented to permit the speech intelligibility obtained using the proof-of-concept device to be evaluated in simulation (speech transmission index - STI).

By these means it has been shown that the sound level at the ear can be automatically reduced by frequency and level to the extent required to avoid noise-induced hearing loss, while simultaneously minimizing over-protection from noise and so maintaining situational awareness.

It has also been shown, by improved word scores when subjects wear the proof-of-concept device and by increased or acceptable STI values in simulation, that the intelligibility of speech in the COM channel can be improved while maintaining adequate control of environmental noise.

It has further been shown that the audibility of a tonal warning sound external to the HPD is not degraded when subjects wear the proof-of-concept device compared to a traditional passive circumaural HPD.

We thus conclude that the specific aims of the research have been achieved by the proof-of-concept HPD developed and evaluated in this project.

Translation of Findings

The unwillingness of workers to wear commercially available HPDs because of fear of not understanding speech or failure to hear warning sounds has been repeatedly documented in the occupational health literature, with commonly up to 50 % of noise-exposed workers avoiding using hearing protection in some industries. The growing costs of workers' compensation reflect the adverse consequences to their hearing. The belief that understanding speech is impeded by wearing HPDs, and so motivates against their use, has been documented in medical histories of noise-exposed workers since enactment of the Walsh-Healey Act. It continues to this day, with reports that soldiers suffering acute acoustic trauma in battle reply "better deaf than dead" when questioned why they did not wear the appropriate HPD. Similarly, in recent focus group sessions of miners, there was a common expression that underground survival is weighted well above the nuisance of hearing loss, and that warning noises from mining roofs and equipment, and communications with co-workers were major reasons for not wearing hearing protection.

An initial step in the translation of findings from this project, based on the successful implementation of the complex signal processing necessary to undertake a combination of tasks in a communication device, has been a patent application entitled "Method and device for improving the audibility, localization and intelligibility of sounds, and comfort of communication devices worn on or in the ear".

Commercialization of the concepts developed in this project, to produce HPDs that can improve speech intelligibility in noisy environments without degrading further the audibility of warning sounds compared to a traditional passive HPD, would be an important step towards overcoming the reluctance of many workers to wear hearing protection. Indeed, the audibility of warning sounds was significantly improved compared to a traditional passive HPD in one of the two noisy environments employed for the validation of device performance.

A further step would be to develop a device that could also enhance the audibility and localization of warning sounds to equal the performance obtained when hearing protectors are not worn. This subject should undoubtedly be a key focus for future research. The concepts employed in the present project would be a good starting point for further research when combined with a method for detecting and selectively amplifying a broad range of unknown warning sounds.

Outcomes /Impact

The goal of this research was to address the acoustical needs for HPDs identified by NIOSH and documented in the peer-reviewed literature. With refinement and commercialization of the concepts developed in this research project, the potential outcomes of this work should remove a primary cause of fear of using hearing protection, and so lead to greater acceptability, and consequently wider use, of HPDs in the workforce. The improved speech intelligibility should help increase the reliability of critical communications, and the modest improvement in the audibility of warning sounds already achieved in some noisy environments will help reduce the frequency of accidents. The wider use of HPDs by workers exposed to noise should reduce the risk of developing noise-induced hearing loss. With approximately 4.5 million workers in the U.S. unwilling to use HPDs at present, there is reason to expect substantial benefits in public and occupational health from devices embodying the concepts developed in this research.

Section 2: Scientific Report

2.1 Laboratory Facilities

(a) Anechoic Chamber

A suitable test facility with defined sound field properties first needed to be confirmed and equipped with an appropriate sound reproduction system. A noise survey was conducted of the two possible test facilities in the Acoustics Laboratory at the University of Connecticut Health Center (anechoic chamber and reverberation room), and in adjacent rooms to determine the sources of background noise. From the results it was concluded that the anechoic chamber could better serve the needs of the project, and renovations have been undertaken to further reduce the background noise, which was identified as originating from machinery located outside the chamber. This decision was a change to the initial research plan, and necessitated redesigning the acoustic source for experiments requiring environmental noise (e.g., factory or military noise), a work item not anticipated as the original research plan envisaged using the reverberation room. A pseudo-diffuse sound source (in a horizontal plane), consisting of four sound sources positioned at the corners of a distorted (i.e., "randomized") horizontal "square", was shown to satisfy the sound field requirements at the position of the subject's head when each unit is fed by signals with randomized time delays.

In consequence, four loudspeaker towers positioned at the corners of a distorted horizontal "square" have been assembled from tweeters, woofers, and sub-woofers forming vertical arrays. Each tower consists of a JBL SRX715F woofer and tweeter, and SRX718 sub-woofer. Transducers, audio signal processors, and amplifiers with sufficient power to produce the sound levels required for the study in our anechoic chamber (i.e., to simulate an industrial noise and a military noise environment) have been integrated with computer control of all signals. The production of a pseudo-diffuse sound field from a single channel recording (e.g., single electronic .wav file) requires delaying the output from each loudspeaker tower relative to the other towers, and introducing reverberation. The signal manipulations are performed within the psychoacoustic constraint that a subject experiences only one sound image. The extensive signal processing, together with the electrical power required (8 kW), has resulted in a sound source with "flat" frequency response from 40 Hz to 10 kHz (± 3 dB).

(b) Refurbished Audiometric Sound Booth

It became evident as work proceeded that the rate of ramp-up of activities would lead to a bottleneck in scheduling time in the anechoic chamber during the latter years of the project. Thus a situation was envisaged in which the anechoic chamber was required simultaneously for HPD device and algorithm development, and for unrelated psychoacoustic tests on subjects. To reduce scheduling conflicts, and the consequent undesired slowing of progress, we acquired a commercial hearing booth rendered surplus elsewhere on campus, primarily for HPD device and algorithm development. It consists of a 9' x 8' 6" test room with acoustically treated walls, ceiling and ventilation ducts, and a similarly treated 7' x 8' 6" control room. The booth has been equipped with a sound source to reproduce environmental noise. Loudspeakers and audio amplifiers not envisaged in the original proposal were purchased for this purpose.

2.2 Measurement Methods

(a) Probe Microphone for Measuring Sound Pressure at the Eardrum

A review of alternate methods in the literature confirmed that a miniature microphone connected to a soft, plastic, miniature tube that is inserted in the ear canal to within 5 mm of the eardrum will serve the needs of the project, namely to monitor sound pressures within the ear canal without impeding a subject's hearing or interfering with the wearing of a circumaural hearing protector. Our initial device consisted of a 30 mm long, 0.94 mm outside diameter, medical grade silicon tube attached to a miniature electret microphone with dimensions approximately 3.5 x 2.5 mm. The microphone and probe tube were held in place by an earplug. A probe microphone constructed in this way has an acoustic frequency response that is set by the dimensions of the probe tube (tube length and inner diameter) and microphone

volume, forming a low-pass acoustic filter above about 2 kHz. The need to monitor frequencies up to at least 6 kHz to predict speech (and warning signal) perception necessitated the development of frequency compensation to restore the microphone's sensitivity at high frequencies. An electronic circuit was initially custom designed for this purpose. Improved compensation was obtained by using an optimization routine in MATLAB to identify an inverse filter that produced an overall response after compensation that is flat from 30 Hz to 6 kHz (± 1 dB). Accordingly, the electronics were reconfigured to function as a microphone preamplifier.

A second generation of devices was subsequently developed, consisting of a probe microphone (described above) attached to a custom fitted earmold. The latter is fabricated for each subject from an ear impression and does not occlude the ear canal. The earmold is our own design, and consists of two slender arms that attach to the base of the concha and a sleeve that rests along the upper surface of the ear canal. The small diameter flexible tube, attached to the miniature electret microphone, is inserted in the sleeve. A photograph of the device is shown in Figure 1.

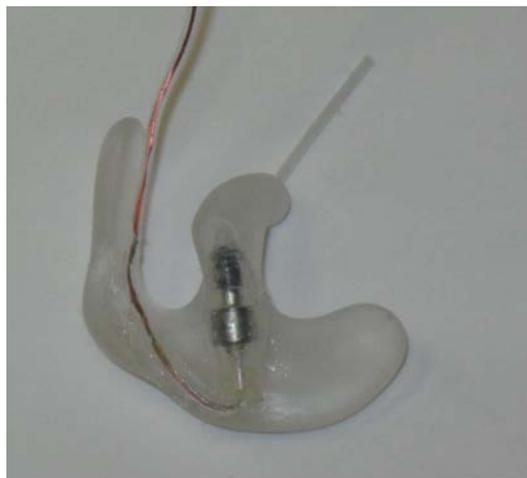


Figure 1: Photograph of probe microphone and custom ear mold to fit within the ear canal

Prior to final assembly, during which the probe microphone is glued to the ear mold, the probe tube is adjusted within the ear mold by determining the frequency responses and standing wave ratio (SWR) patterns at frequencies up to 12 kHz, for different probe tip positions in the ear canal. By studying the frequency responses for selected SWR minima, we have been able to demonstrate that the tip of the probe tube can be repeatedly positioned to record sound pressures with a precision of, typically, ± 2 dB up to 6 kHz. In this way, the sound pressure levels (SPLs) sensed may be compensated for the known SWR pattern, to produce levels that are within ± 2 dB of those at the eardrum for frequencies up to 6 kHz. The ability to reconstruct sound pressures at the eardrum from sounds sensed deep in the ear canal, where wave propagation is one dimensional (i.e., plane wave), removes potential differences between physical and psychoacoustic metrics of HPD attenuation, and so reduces the need for psychoacoustic testing. Thus although this work took longer than projected in the original timetable, its success greatly accelerated the testing of HPDs. The device has been described at two conferences and in Proceedings papers.

(b) Psychoacoustic Methods

Psychoacoustic procedures have been implemented to conduct all the tests summarized in the proposal. Specifically, these are the measurement of: hearing threshold in a quiet environment (Real Ear at Threshold - REAT); hearing threshold in environmental noise (Masked Threshold); speech

intelligibility in noise (Modified Rhyme Test - MRT), and; threshold for perceiving a warning sound in environmental noise. The procedures have been coded in MATLAB, and control the specialized equipment purchased for performing psychoacoustic tests (Tucker-Davis Technology System 3 instruments). Speech and warning sounds are reproduced in the anechoic chamber by a small, high-fidelity, low distortion loudspeaker positioned 2.4 m in front of the subject with tweeter at ear height (Paradigm Signature S1 v2). The same signal from the Tucker-Davis instruments can also drive earphones directly, such as those within our active HPD.

To perform measurements, subjects sit with a computer-controlled touch screen at a convenient height in front of them and initiate each test by pressing the play "button". Stimuli, and the subject's response, depend on the task undertaken. For REAT and masked threshold measurements, stimuli are pure tones 500 ms in duration and include 20 ms cosine rise and fall ramps. A three-down, one-up psychophysical response procedure is employed with the initial stimulus level above that corresponding to the (previously determined) audiometric threshold at the same frequency. The amplitude of the step size is adaptive and is reduced, with the minimum size ultimately 2 dB. Thresholds are calculated from six reversals under this condition. Masked threshold measurements also include environmental noise at a preset SPL. An equivalent procedure is employed for the detection of a warning sound in noise, in which the pure tone stimulus is replaced by a synthesized alarm sound constructed according to the provisions of an International Standard (ISO 7731:2003). For MRT measurements, one of six words displayed on the touch screen is randomly presented within a carrier phrase, e.g., "Circle the ... (insert test word) ... now". Subjects are instructed to choose one word by touching the screen, and initiate the next trial when ready. The procedure is fully automated. There are 50 trials in each test from which a word score is derived for the preset speech signal-to-noise ratio (SNR), or speech signal distortion. The experimental set-up showing the subject, touch screen, miniature loudspeaker "talker" or alarm sound source, and the four loudspeaker towers producing the environmental noise are shown in Figure 2.



Figure 2: Photograph showing the subject, touch screen, miniature loudspeaker "talker" or alarm sound source, and the four loudspeaker towers producing the environmental noise

A key consideration in our approach to determining the attenuation of the HPD and its influence on speech intelligibility is to substitute an objective metric of attenuation or speech intelligibility for the psychoacoustic testing of subjects whenever practicable. The purpose of the surrogate metric is to speed the development of the active hearing protector by replacing psychoacoustic measurements on multiple

subjects that require many days of testing with a physical measurement that can be conducted in about an hour. In consequence, verifying the relationship between the proposed objective test and the corresponding psychoacoustic test is of paramount importance. In this context, it should be noted that the probe microphone technique we have developed for recording sound pressures at the eardrum (described above) eliminates any difference between the active (and passive) attenuation of a HPD measured physically or subjectively by subjects, so that the validation of objective metrics consequently focused on the determination of speech intelligibility.

Models describing the relationship between our chosen objective metric of speech intelligibility, the Speech Transmission Index (STI), and our corresponding psychoacoustic metric, the MRT, have been developed for distorted speech sounds such as occur in digital communication systems. A common distortion is center clipping. The models have also been validated for speech sounds in environmental noise. To obtain agreement when speech is corrupted by environmental noise or distortion, we have developed two models: the first takes into account the coherence between the probe sound, which is running speech, and environmental noise ("STI speech"), and the second, in addition, accounts for the correlation between speech sounds at nearby frequencies ("STI ρ -speech"). The performance of these models is summarized in Figure 3. In this diagram, the performance of the traditional STI model in speech-spectrum shaped noise (SSN) is shown by the line (for STI_r) and the performance of our two models by the open and filled diamonds, respectively. The performance of the two models when the communication signal is subjected to center clipping is shown by the circles. It can be seen that only the model "STI ρ -speech" (filled circles) replicates the relationship between MRT scores and STI obtained in noise.

The models have been described at two conferences and have been summarized in two Conference Proceedings. Manuscripts describing the models are currently being prepared for journal publication.

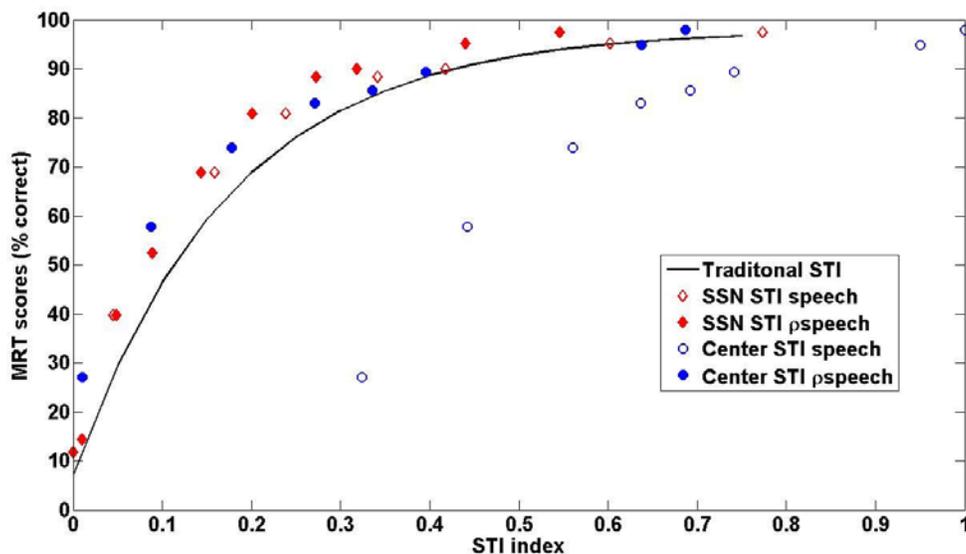


Figure 3: Mean MRT scores and predictions using three models for STI: open symbols - STI_{speech} , filled symbols - $STI_{\rho-speech}$, and line - STI_r . Results are shown for speech-spectrum shaped noise (SSN), and center clipping (Center)

We are not aware of, and do not have, an objective metric for the perception of a warning sound in environmental noise, and consequently employ a psychoacoustic test that uses a synthesized alarm

sound as described above, or the backup alarm on a forklift truck. The environmental noise is factory or military noise.

(c) Evaluation of Ear Cups for Active Hearing Protection Device

Two characteristics of ear cups are of critical importance when evaluating a passive circumaural HPD for potential modification into a feedforward ANR HPD: passive noise reduction (PNR) and the predicted ANR. The former was measured directly, and the latter was predicted from the coherence between the sound pressure at a miniature microphone positioned on the outer surface of the ear cup and a second microphone at the entrance to the ear canal. Several commercially available passive circumaural HPDs were evaluated using these metrics in order to select an ear cup that would offer the best performance for a HPD with feedforward ANR. The attenuation and coherence were evaluated in a reverberation room at frequencies from 100 Hz to 8 kHz. Tests were conducted using both a Head and Torso Simulator (HATS) (Brüel & Kjør Type 4128C) and human subjects.

The passive attenuation was calculated from the difference between the power spectrums of white noise with and without each ear muff mounted on HATS, as recorded by the microphone located at the artificial "eardrum". Coherence was measured from a microphone (Knowles FG 23629-P16) placed on the outer surface of the ear cup along the axis of the ear canal. The same measurements were conducted on human subjects but with the microphone at the artificial eardrum replaced by the custom-fitted probe microphone device described in section 2.2(a). Power spectrum and coherence were calculated and averaged over 100 measurement periods using a dynamic signal analyzer (Agilent 35670A). A signal bandwidth from 0 to 1600 Hz was used, as coherence values were negligible above these frequencies and the level of passive attenuation remained approximately constant.

(d) Evaluation of Earphones for Active Hearing Protection Device

An artificial ear was purchased to facilitate the evaluation of miniature loudspeakers (G.R.A.S. model 43AA). The ear cup of a commercial circumaural (passive) HPD was modified to permit miniature loudspeakers to be mounted on a baffle plate that divided the volume enclosed by an ear muff approximately in half. Loudspeakers were assessed for sensitivity and frequency response when the ear muff was mounted on the artificial ear, as determined by the microphone located at the artificial eardrum. Consideration was also given to the size of the transducers, as the performance requirements differ for ANR, or speech and warning sound reproduction. The former requires the generation of high SPLs at frequencies below 1 kHz, to cancel the large sound pressures associated with environmental noise, and the latter broad bandwidth to reproduce speech or other desired sounds (e.g., from 500 Hz to 6 kHz).

2.3 Development of Active Hearing Protector Proof-of-Concept

(a) Selection of Components

The predicted attenuation was used to select an optimal ear cup for conversion into an active HPD. The total noise reduction (TNR) was calculated by combining the measured PNR and the ANR estimated using the coherence function. The performance of the ear cup selected is shown in Figure 4. It can be seen from the diagram that the active attenuation (red) complements the passive attenuation (blue), to provide a broad range of frequencies at which the total attenuation available is predicted to exceed 30 dB. A photograph of the ear cup is shown in Figure 5.

With the commercial availability of miniature microphones of adequate sensitivity and flat frequency response to above 10 kHz (e.g., Panasonic WM-61A), the selection of the remaining hardware components for the device focused on the earphone or, if required, separate earphones for ANR and for speech reproduction. While both options were considered, a single earphone was chosen and can be seen mounted within the ear cup in Figure 5.

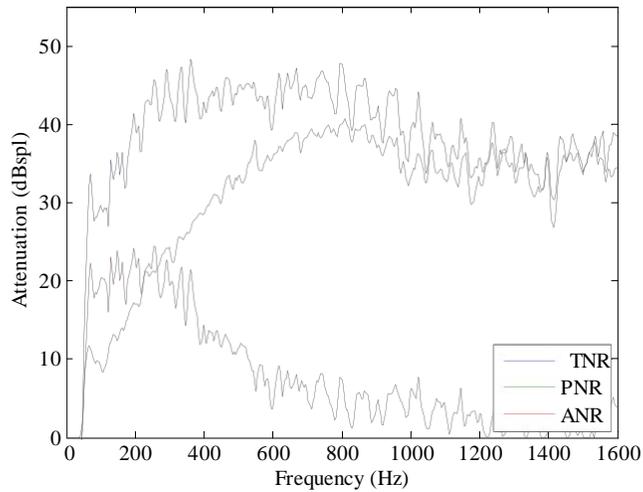


Figure 4: Total noise reduction (TNR), passive noise reduction (PNR) and active noise reduction (ANR) for selected commercial ear cup

The method for selecting ear cups and the performance of several candidate commercially manufactured ear cups has been reported at a conference and published in the Conference Proceedings.



Figure 5: Selected earphone mounted within selected ear cup. Miniature microphones were subsequently attached to the outer surface of the ear cup and the center of the earphone to form an "active ear cup".

The final components consist of a commercial floating point digital signal processor (DSP) (a Texas Instruments TMS320C6713), and in-house custom designed and constructed analog circuits to interface between the electronic and electro-acoustic components. The operation of the DSP is controlled by a personal computer. Identical, independent active electro-acoustic systems have been constructed for the left and right ears.

(b) Simulation of Proof-of-Concept Device

An algorithm for a simple "broadband" (i.e., all frequencies) feedforward ANR HPD was first developed. Acceptable ANR could be obtained from an "active ear cup" consisting of the selected ear

prescribed for hearing conservation (operations not shown in the block diagram). The COM signal is also removed from the signal from microphone E (indicated by subtraction, Σ). A so-called error path model, which is a filter that mimics the conversion of electrical signals to sound by the earphone, the transmission of sound to microphone E, and the conversion of sound to an electrical signal by the microphone, is required for this purpose (model S-E). The same model is used to pre-filter the environmental noise from microphone R before subband processing as a means for improving performance, to obtain the so-called "filtered X" algorithm. By removing the COM signal from the combined noise and COM signal detected by microphone E, the residual environmental noise SPL at the ear can be measured in each subband to permit appropriate speech SNRs to be established to improve intelligibility (operations also not shown in the block diagram).

The residual environmental noise at the ear is also used to control the feed-through of sound from the external environment, as sensed by microphone R, to the COM channel signal input (not shown in Figure 6). This is done for two purposes. In circumstances in which the overall residual SPL at the ear is below hearing conservation guidelines, environmental noise may be fed through the COM signal processor, after subband processing, at a level that provides hearing protection but minimizes the sense of isolation from the external environment commonly experienced by users of HPDs. Thus, this frequency and level sensitive processing reduces the loss of situational awareness. A second purpose of feeding environmental noise into the COM signal processor is to search for the presence of a warning sound in the external environment. The algorithm currently employed for this purpose uses a narrow-band filter first to identify the presence of a pre-determined warning sound and then to amplify this signal prior to reproduction by the earphone, S.

The simulation of the proof-of-concept device involved all electronic elements (e.g., filters, amplifiers, analog to digital converters, etc.), acoustic elements (e.g., time for sound to propagate between transducers, acoustic filters, acoustic resistances), and electro-acoustic elements (microphones and loudspeakers). The acoustic and electro-acoustic elements were measured directly on our active ear cup (see Figure 5). In this way, the simulation provided a realistic representation of a physical system, yet allowed the effects of changes in coding and performance requirements to be rapidly evaluated (e.g., ANR limited to avoid overprotection from noise). At any time an algorithm could, in principle, be ported to the DSP of the physical proof-of-concept device. Hence we have demonstrated in simulation that the signal processors can control noise effectively, provide feed-through of environmental noise to reduce the loss of situational awareness, and enhance speech intelligibility. The improvement in speech intelligibility is much greater than that obtained by a conventional fullband ANR HPD. The improvement results from the frequency bands of the COM channel subband controller extending to the highest speech frequencies, and by optimizing separately the speech SNR in each subband.

Table 1 shows the results of two experiments evaluating the performance of simulations of three types of circumaural HPDs: 1) a conventional passive HPD; 2) a broadband ANR HPD with a fixed COM channel gain, and; 3) a subband ANR and COM signal processing HPD as described here and with the basic elements shown in Figure 6. To demonstrate the ability of the proof-of-concept device simulation to meet a desired speech SNR target, the initial COM channel gain was set to yield a STI value of 0.2 when the combined environmental noise and speech produced a SPL of 80 dB at the ear before signal processing. Under these circumstances, the environmental noise external to the HPD would be > 90 dB, and the unprocessed speech in the COM channel would not be fully understood. Reference to Table 1 (columns labeled '12 dB target SNR') shows that the proof-of-concept device simulation properly identifies the reduced noise at the ear provided by ANR and increases the COM channel gain to meet a target speech SNR of 12 dB. This target has been shown to be preferred by users of critical communication systems (e.g., air traffic control). In contrast, the conventional broadband ANR system, which lacks the capability to adjust separately speech and noise levels, maintains maximum noise reduction irrespective of whether the COM signal is present or absent. The improvement in STI from 0.2 to 0.7 obtained in the proof-of-concept device simulation by subband processing together with speech SNR adjustment corresponds to a substantial improvement in word recognition, from 60% to 95% words correct.

Table 1: Comparison of the Noise (N) and Noise + Speech (N+S), in dB SPL, and STI values from Passive, Broadband, and Subband HPD Simulations

	12 dB target SNR			80 dB SPL max.		
	N	N+S	STI	N	N+S	STI
Passive	79.4	80.0	0.2	-	-	-
Broadband	59.7	60.3	0.2	73.3	85.1	0.9
Subband	60.8	72.3	0.7	74.4	80.8	0.6

To test the capability of the proof-of-concept device simulation to maintain adequate attenuation of environmental noise, the SPL of the environmental noise was set to 73-74 dB for systems 2 and 3 when the ANR was operating (i.e., when the environmental noise external to the HPD would be > 105 dB). The COM channel gain was set to provide an SNR of 12 dB, so that the combined noise plus speech (N+S) exceeded the maximum SPL at the ear selected for hearing conservation, which was chosen to be 80 dB SPL. Reference to the Table (columns labeled '80 dB SPL max.') shows that the proof-of-concept device simulation identified the SPL at the ear exceeded 80 dB SPL, and in consequence reduced the COM channel gain to minimize the potential damage to hearing. The reduction in the STI to 0.6 results in an acceptable decrease in word recognition to 90%. The conventional broadband ANR system maintained an excess SPL at the ear, being unable to separately adjust speech and noise levels.

The results of these simulations were considered to provide sufficient information to permit construction of a proof-of-concept HPD that could be worn by, and tested on, human subjects. The simulation of the proof-of-concept device, and of passive and active circumaural HPDs, has been described at conferences and a manuscript on this work has been accepted for Journal publication.

(c) Proof-of-Concept Device and Evaluation

As already noted, the aims of this study were to develop a HPD proof-of-concept incorporating ANR and an adaptive COM channel providing sound reproduction at the ear designed specifically to: 1) improve the speech intelligibility of a built-in COM channel; 2) maintain the perception of a tonal warning alarm sound external to the HPD, and 3) maintain adequate attenuation of environmental noise. Based on the foregoing work, a proof-of-concept device has been constructed from the mechanical components of a commercial hearing protector and the electro-acoustic and electronic components selected or developed by the research described in previous sections of this report. The device concept is shown in Figure 7.

As can be seen from the photograph, the device concept employs the ear cups, cushions, and headband from a commercial passive circumaural HPD, into and onto which the earphones and microphones have been mounted. The nomenclature of the electro-acoustic components is the same as that used in the block diagram of Figure 6 and the algorithm description of section 2.3(b). The electronic components are currently not packaged nor optimized for portable use, as befits a proof-of-concept, and are located remotely from the hearing protector. A photograph of the electronic system for controlling sounds at one ear is shown in Figure 8.

The performance of the proof-of-concept subband ANR and COM signal processing device has been assessed by measurements conducted with human subjects as well as by simulation. The criteria for including and excluding subjects are listed in Table 2. Each subject was first examined by the study physician, and audiometric hearing threshold levels were determined by trained personnel. After the initial clinical examinations, successful candidates attended our laboratory for in-depth assessment of their hearing, their ability to perform psychophysical tests and their understanding of individual words spoken out of context in American English.



Figure 7: Proof-of-concept ANR and COM signal processing device showing commercial passive circumaural HPD, reference microphone (R), error microphone (E), and secondary source loudspeaker (earphone) (S)



Figure 8: Photograph showing proof-of-concept electronics for controlling sounds at one ear

Table 2: Inclusion and Exclusion Criteria for Subjects

	Inclusion Criteria	Exclusion Criteria
a.	Anatomical features. Subjects will be selected without regard to head size or shape, provided the cushion of the hearing protector can form an airtight seal against the head.	Anatomical features. Persons with anatomical features (e.g., bony protrusions) that could prevent the cushion of the hearing protector from forming an airtight seal against the head.
b.	Otosopic examination. Persons with no evidence of external or middle ear infections, or impacted cerumen, will be included.	Otosopic examination. Persons with evidence of external or middle ear infections, or impacted cerumen, will be excluded. Persons will have an opportunity for re-evaluation if treated.
c.	Psychophysical testing. Persons capable of the decisions necessary to perform tests involving the perception of sounds.	Psychophysical testing. Persons incapable of decisions necessary to perform tests involving the perception of sounds.
d.	Hearing sensitivity. Persons with pure-tone, air conduction hearing threshold levels of less than 20 dB hearing level, as determined by audiometry at frequencies from 125 to 8000 Hz, and whose thresholds differ between ears by no more than 5 dB	Hearing sensitivity. Persons with pure-tone, air conduction hearing threshold levels determined by audiometry at frequencies from 125 to 8000 Hz of 20 dB hearing level, or more, and/or whose thresholds differ between ears by more than 5 dB.
e.	Reproducibility of hearing thresholds. Persons whose hearing thresholds vary by less than 6 dB when determined repeatedly by audiometry.	Reproducibility of hearing thresholds. Persons whose hearing levels vary by 6 dB, or more, when determined repeatedly by audiometry.
f.	Language proficiency. Subjects must be capable of identifying similar-sounding individual words spoken out of context in American English.	Language proficiency. Persons incapable of identifying similar-sounding individual words spoken out of context in American English.
g.	Plastics in contact with the skin. Subjects should not react to plastics in contact with the skin of the ear canal.	Allergic reaction to Teflon/other plastics. A plastic tube is inserted into the ear canal: persons with a known allergic reaction to Teflon and other plastics will be excluded.

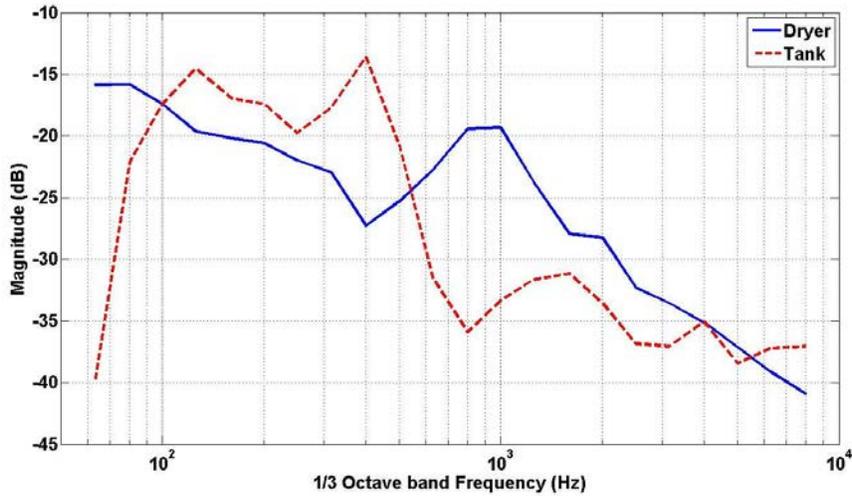


Figure 9: One-third octave-band spectra of an industrial dryer and a military tank. The relative SPLs of the noise sources have been adjusted and are shown as used to evaluate hypothesis I.

Seven subjects, five male and two female, participated in the psychoacoustic tests to evaluate the performance of the proof-of-concept device. All complied with the inclusion criteria in Table 2. The methodologies employed in the psychoacoustic tests, and the test environment, have been described in section 2.2(b). Custom probe microphones were made for six of the subjects in these experiments (see section 2.2(a)), which resulted in only six subjects being available to test hypothesis I. The tests of hypotheses were conducted using two noise sources: the noise of an industrial dryer in a paper making factory, and the noise at the commander's position of a Leopard military tank. One-third octave-band spectra for these noise sources are shown in Figure 9, with arbitrary overall SPLs.

(d) Test of Hypothesis I, that "... the A-weighted sound level at the ear can be adequately reduced by tailoring the reduction of the HPD automatically by frequency and level to the extent required by the environmental noise"

The performance of the subband proof-of-concept ANR and COM signal processing device when worn by human subjects has been compared with the performance of a passive circumaural HPD and a subband ANR proof-of-concept device without adaptive COM channel processing so that environmental noise feed-through was disabled. The performance has also been evaluated in simulation (see section 2.3(b)), but is described here solely for measurements performed at subjects' eardrums. As noted above, the data are derived from the six subjects for whom custom molded earplugs containing probe microphones were available. The results are summarized for the mean attenuation at the subjects' eardrums in Figure 10 for the industrial and military noise sources of Figure 9. Data were obtained when the A-weighted sound level of the industrial dryer was set to 90 dBA at the location of the ear (in the absence of the subject), and that of the military tank was set to 92 dBA. The relative magnitudes of the SPLs produced by the two noise sources are shown in Figure 9, where it can be seen that the sources possessed different spectral shapes, the tank possessing more intense low frequencies, and the dryer more intense mid frequencies (especially at frequencies around 1 kHz).

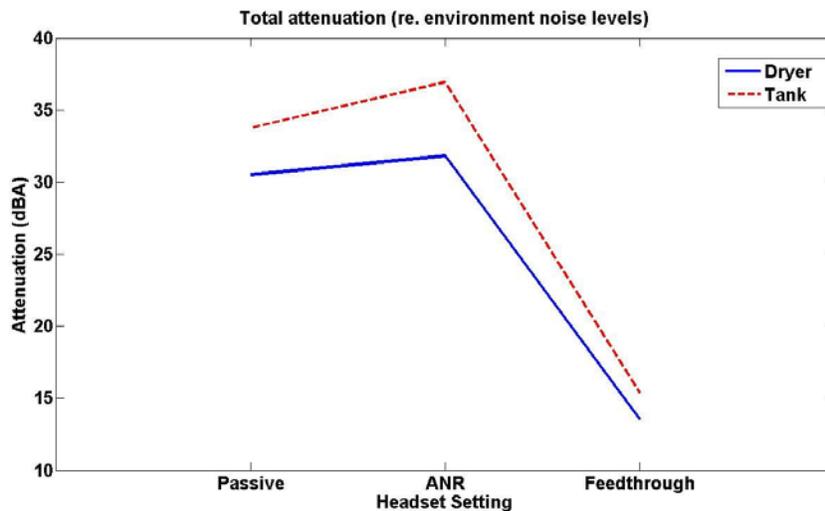


Figure 10: Attenuation of industrial dryer (90 dBA) and tank noise (92 dBA) for a passive HPD and a subband ANR device concept with, and without, adaptive communication channel processing

Inspection of Figure 10 reveals that the attenuation at the subjects' ear of the two noise sources depends on the device covering the ears. The passive HPD and the proof-of-concept subband ANR device without adaptive COM channel feed-through processing provide more than 30 dBA overall attenuation of noise, with the higher mid-frequencies of the dryer leading to less overall noise reduction.

Reference to the ANR predicted in Figure 4 confirms that little active noise control can be expected at frequencies above 800 Hz, that is, at frequencies at which the SPL of the dryer noise exceeds that of the tank. Consequently, the total A-weighted attenuation of dryer noise is also expected to be less, as can be seen from Figure 10.

With each noise source only 90 or 92 dBA at the location of the subjects' ears, reducing the sound levels at the eardrum by 30 dBA, or more, as done by the passive HPD and proof-of-concept subband ANR device without adaptive COM channel feed-through processing will lead to SPLs at the eardrum of, typically, 60 dBA and will result in substantial over-protection from noise. In these circumstances there is a need for environmental noise feed-through to the user to combat the loss of situational awareness. Reference to Figure 10 reveals that this is achieved by the proof-of-concept subband ANR and adaptive COM signal processing device with feed-through, by reducing substantially the attenuation of the hearing protector compared with the passive device ($p < 0.001$ for dryer and tank noise; t-test). In this example, in which the environmental noise was set to 90-92 dBA to avoid risks to the hearing of subjects and the target noise at the eardrum was set to 75 dBA, it can be seen that the noise at the eardrum becomes close to 75 dBA for both dryer and tank noises, indicating that the processing is sensitive to the level and frequency of the noise. The proof-of-concept subband ANR and COM signal processing device which includes feed-through will reduce environmental noise at the ear when it exceeds a preset sound level for hearing conservation, though this has been demonstrated primarily in simulation (see experiment 1 of section 2.3(b)) and not with human subjects, as it would involve sound levels at the ear in excess of 100 dBA if hearing protection is not worn or the cushion sealing the ear cup to the head fails. The maximum attenuation would be that shown in Figure 10 for the ANR device without adaptive COM signal processing (i.e., ~30 dBA). This result can be, and has been, confirmed in simulation (see section 2.3(b)). Thus we conclude from experiments on human subjects, and by simulations, that hypothesis I has been confirmed.

(e) Test of Hypothesis II, "A signal processing strategy for an active noise controller can be developed and implemented to improve speech intelligibility in the communication channel of a circumaural HPD equipped with ANR while maintaining the overall noise reduction consistent with occupational exposure regulations"

This hypothesis has been tested and confirmed by simulation, as described above in section 2.3(b). It has been further tested using the proof-of-concept subband ANR and COM signal processing device when worn by human subjects. The performance of the proof-of-concept device has been compared with that of a passive circumaural HPD and a subband ANR proof-of-concept device without adaptive COM channel gain processing. The results are summarized by the mean MRT scores (\pm standard deviation (SD)) from seven subjects in Figure 11, for the industrial and military noise sources of Figure 9. They were obtained when the sound level of speech was set to 60 dBA at the ear, as recorded by the error microphone (see Figure 7), and the environmental noise outside the HPD was adjusted to ~90 dBA, so that the speech SNR at the ear was -10 dB prior to signal processing. Additionally, the sound levels outside the HPDs were chosen to avoid risks to the hearing of subjects.

Inspection of Figure 11 reveals that the MRT scores in the environmental noise produced by the industrial dryer and military tank depend on the device covering the ears. Subjects wearing the passive HPD and the proof-of-concept subband ANR device without adaptive COM gain processing (labeled "Fixed Gain COMs Active ANR HPD in Figure 11) produced similar mean MRT scores. The differences between the mean MRT scores are not statistically significant. Significantly greater MRT scores (i.e., improved speech understanding) resulted when the subjects wore the proof-of-concept subband ANR and COM signal processing device compared to the device without subband COM signal processing ($p < 0.001$ for dryer noise, and $p < 0.002$ for tank noise; t-test).

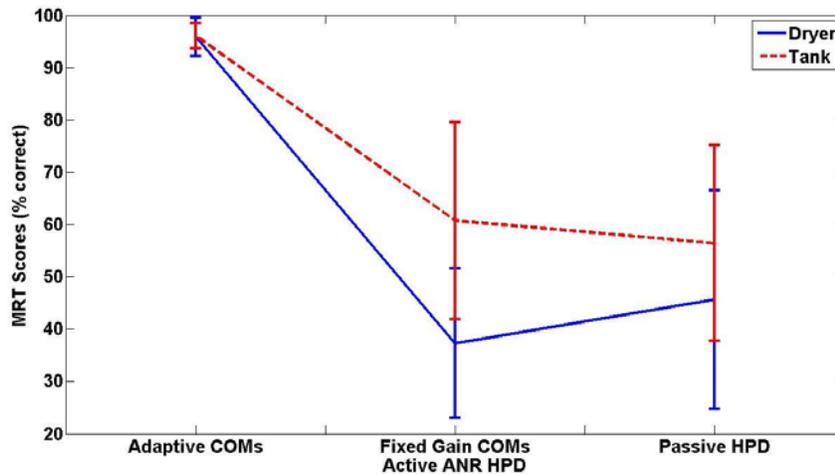


Figure 11: Mean MRT scores (\pm SD) in industrial and military noise for speech SNR of -10 dB (without processing) for a passive HPD and a subband ANR device concept with, and without, COM signal processing

The proof-of-concept subband ANR and COM signal processing device will reduce both environmental noise and COM signals at the ear when they exceed a preset maximum sound level, though this has only been demonstrated in simulation (see experiment 2 in section 2.3(b)) and not with human subjects, as it would involve sound levels at the ear in excess of 100 dBA if hearing protection is not worn or the cushion sealing the ear cup to the head fails. Thus, these results demonstrate the improvement in word recognition, and hence speech intelligibility, obtained by adaptive ANR and COM signal processing to optimize the speech SNR in each subband while maintaining the overall noise reduction to a preset maximum sound level. Hence we conclude from experiments with human subjects, and by simulations, that hypothesis II has been confirmed.

(f) Test of Hypothesis III, "... a combination of signal processing strategies can be developed to improve speech intelligibility in the communication channel and not degrade the perception of a tonal warning sound external to the circumaural HPD while maintaining adequate noise reduction"

The performance of the subband proof-of-concept ANR and COM signal processing device has been compared with the performance of a passive circumaural HPD and when no HPD is worn by the subject. A typical warning sound as specified by ISO 7731:2003 was employed. The results are summarized by the mean detection threshold for the warning sound (\pm SD) for seven subjects in Figure 12, for the industrial and military noise sources of Figure 9, and also when there was no environmental noise. The A-weighted sound level of the environmental noise outside the HPD was adjusted to ~90 dBA, so that the environmental noise at the ear was ~70 dBA prior to signal processing. As in previous experiments, the sound levels outside the HPDs were chosen to avoid risks to the hearing of subjects. The condition without environmental noise was introduced to establish the magnitude of the improvement in warning sound detection that could be achieved in a future device. It should be noted that the aim of this project was to develop a concept device that did not degrade the detection of warning sounds while adaptively processing both environmental noise and speech in order to fulfill the requirements of hypotheses I and II.

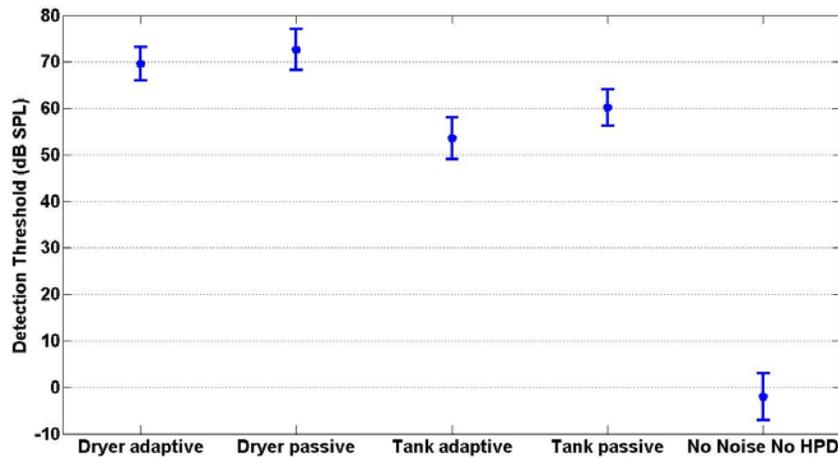


Figure 12: Mean detection threshold (\pm SD) in dB SPL in \sim 90 dBA industrial dryer or military tank noise, for a passive HPD, an active subband ANR and COM signal processing device concept, and when no HPD is worn in quiet

Inspection of Figure 12 reveals that the mean detection threshold (in dB SPL) in the environmental noise produced by the industrial dryer and military tank depends on the device covering the ears. Subjects wearing the passive HPD and the proof-of-concept subband ANR and COM signal processing device required similar mean SPLs at the threshold for detecting the alarm sounds. Thresholds were somewhat lower for alarm detection in the tank noise compared to the dryer noise, probably reflecting the different spectral content of the noises (see Figure 9). There was a tendency for the threshold to decrease (i.e., improve) when the proof-of-concept subband ANR and COM signal processing device was worn. This trend reached statistical significance for the tank noise ($p < 0.05$, t-test). Detection thresholds were close to the threshold of hearing when no HPD was worn and there was no environmental noise, as expected, demonstrating that there is potential for improving alarm signal detection when hearing protectors are worn and environmental noise can be preferentially suppressed. Overall, however, the detection of the alarm was not impeded by the proof-of-concept subband ANR and COM signal processing device when compared to a traditional passive circumaural HPD. Hence we conclude that hypothesis III has been confirmed.

2.4 Conclusions

A proof-of-concept HPD has been developed to improve the speech intelligibility of a built-in communication channel, while maintaining the perception of a tonal warning alarm sound external to the HPD, and adequate attenuation of environmental noise. The proof-of-concept device has been constructed from the mechanical components of a commercial hearing protector, and electro-acoustic and electronic components selected or developed as a result of the research described in this report. The device employs subband signal processing in which the total frequency range is divided into separate, contiguous frequency bands that can function independently. In order to satisfy the timing requirements to achieve noise cancellation, a delayless feedforward subband structure is employed to actively control environmental noise. A second, separate subband structure is employed to control independently signals in the COM channel, which can be derived from a (remote) electronic communication source or from the environment external to the HPD. The first controller provides ANR, and the second enhances the audibility of desired sounds.

The performance of the proof-of-concept device has been established by measurements involving human subjects under conditions of environmental noise and COM signals that do not pose a risk to hearing, and in simulation for other conditions. In this way, it has been shown that the A-weighted sound level at the ear can be automatically reduced by frequency and level to the extent required to avoid hearing loss, while avoiding over-protection from noise and so maintaining situational awareness. It has also been shown that the intelligibility of speech in the COM channel can be improved while maintaining adequate control of environmental noise, by improved word scores when subjects wear the proof-of-concept device and by increased or acceptable STI values in simulation. It has further been shown that the perception of a tonal warning sound external to the proof-of-concept device is not degraded compared to wearing a traditional passive circumaural HPD. We thus conclude that all three hypotheses have been confirmed by the performance of the proof-of-concept device.

The successful implementation of the complex signal processing necessary to undertake the described combination of tasks in a communication device has led to a patent application entitled "Method and device for improving the audibility, localization and intelligibility of sounds, and comfort of communication devices worn on or in the ear".

2.5 Publications

Journal Articles

Brammer AJ, Laroche C: [2012] Noise and Communication - A Three-Year Update. *Noise & Health*, in press. Review of current status of issues surrounding speech communication and perception of warning sounds in noisy environments that confirms the relevance of the aims of the project to current occupational health needs.

Bernstein ER, Brammer AJ, Yu G: [2012] Improving speech understanding in communication headsets: Simulation of adaptive subband processing for speech in noise. *Int. J. Industr. Ergonom.*, in press. Manuscript describing the simulation of the proof-of-concept hearing protector to achieve aims #1 and #3, namely to improve the speech intelligibility of a built-in communication channel (aim #1), and maintain adequate attenuation of environmental noise (aim #3) (see section 2.3(c)).

Brammer AJ, Yu G, Bernstein ER, Cherniack MG, Tufts JB, Peterson DR: [2010] Predicting the intelligibility of speech corrupted by nonlinear distortion. *Canadian Acoustics* 38(3):80-81. Short paper summarizing the model developed for predicting speech intelligibility when communication signals are corrupted by distortion. It is used during development of the proof-of-concept device (for aim #1 described above).

Bernstein ER, Brammer AJ, Yu G, Cherniack MG, Peterson DR: [2010] Ear cup selection for feedforward active noise reduction hearing protectors. *Canadian Acoustics* 38(3):82-83. Short paper describing the methods used to identify suitable ear cups, and results for several candidate cups. The most suitable ear cup was chosen for the proof-of-concept device (for all aims).

Brammer AJ, Yu G, Bernstein ER, Peterson DR, Cherniack MG, Tufts JB: [2009] Monitoring sound pressure at the eardrum for hearing conservation. *Canadian Acoustics* 37(3):108-109. Short paper describing the development of a probe microphone mounted in a custom earplug to record sound pressure at the eardrum (used for aim #3 described above).

Proceedings

Brammer AJ, Yu G, Bernstein ER, Cherniack MG, Tufts JB, Peterson DR: [2011] Intelligibility of speech corrupted by nonlinear distortion. *Proc of 10th International Congress on Noise as a Public Health Problem*, London UK, 287-292, July 24 – 28. Paper summarizing the model developed for predicting speech intelligibility when communication signals are corrupted by distortion. It is used in the development of the proof-of-concept device (for aim #1 described above).

Giguère C, Laroche C, Brammer AJ, Vaillancourt V, Yu G: [2011] Advanced hearing protection and communication: Progress and challenges. *Proc of 10th International Congress on Noise as a Public Health Problem*, London UK, 225-233, July 24 – 28. Review of current status of issues surrounding speech communication and audibility of warning sounds when wearing hearing protectors in noisy environments that confirms the importance of the aims of the project to current occupational health needs.

Brammer AJ, Yu G, Bernstein ER, Peterson DR, Cherniack MG, Tufts JB: [2009] Field measurement of sound pressure at the eardrum. *Proc of Inter-Noise2009*, Ottawa, Ontario Canada IA, 1-7, August 23 - 26. Paper describing the development of a probe microphone mounted in a custom earplug to record sound pressure at the eardrum (used for aim #3 described above).

Brammer AJ, Yu G, Peterson DR, Bernstein ER, Cherniack MG [2008] Hearing protection and communication in an age of digital signal processing: Progress and prospects. Proc of 9th International Congress on Noise as a Public Health Problem, Foxwoods CT, 1-8, July 21 - 25. Review of status of issues surrounding speech communication when wearing active hearing protectors in noisy environments that confirms the relevance of the aims of the project to current occupational health needs.

Abstracts

Bernstein ER, Brammer AJ, Yu G, Cherniack MG, Peterson DR [2011] Integrating speech enhancement with subband active noise control to improve communication in hearing protectors. J. Acoust. Soc. Am. 130:2469. Abstract describing the simulation of the proof-of-concept hearing protector to achieve aims #1 and #3 described above.

Yu G, Brammer AJ, Swan K, Tufts JB, Cherniack MG, Peterson DR [2010] Relationships between the modified rhyme test and objective metrics of speech intelligibility. J. Acoust. Soc. Am. 127:1903. Abstract describing the relationships between objective metrics of speech intelligibility and word scores obtained with human subjects using the MRT. They are used in the development of the proof-of-concept device (for aim #1 described above).

Patents

Brammer AJ, Bernstein ER [2012] Method and device for improving the audibility, localization and intelligibility of sounds, and comfort of communication devices worn on or in the ear. U.S. Patent Application (September). Full patent application using material of the provisional patent application to detail methods and devices for achieving the aims of the project.

Brammer AJ, Bernstein ER [2011] Method and device for improving the audibility, localization and intelligibility of sounds, and comfort of communication devices worn on or in the ear. U.S. Provisional Patent (October). Provisional patent application detailing methods and devices for achieving the aims of the project.