Acoustical performance of the Communications Ear Plug (CEP) in combination with the Gentex SPH-5 flight helmet

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Technical Report
DRDC Toronto TR 2003-077
June 2003

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This study, approved by the Defence R&D Canada-Toronto Human Research Ethics Committee, was conducted in conformity with the Tri-Council Policy Statement: Ethical Conduct of Research Involving Human.

Abstract

An experiment was carried out to measure the real-ear attenuation at threshold provided by the Communications Ear Plugs (the CEP) and Gentex SPH-5 flight helmet with communications capability, worn alone or in combination. Word recognition in quiet and in Helicopter and Sea King noise was also assessed under the three ear conditions. Like the standard issue Aearo E-A-R® foam ear plugs, the CEP worn in combination with the helmet has the capability of increasing the sound attenuation achieved at low frequencies. The CEP has the added advantage of improving the speech-to-noise ratio of the communications channel. Ten subjects with normal hearing were tested. The results showed that the two devices worn in combination provided significantly greater attenuation than the helmet worn alone, by 6-16 dB over the frequency range tested. The best predictor of outcome at each frequency (0.25-8 kHz) was the addition of 5 dB to the higher of the attenuations realized for the devices worn alone. When the devices were worn in combination the level of speech required to achieve a 60% correct word recognition score decreased by about 18 dB due to a 13-dB increase in the absolute level of the speech reaching the ear in combination with a 5-dB increase in the attenuation of the external noise.

Résumé

Une expérience a été menée pour mesurer le déplacement du seuil d'audition avec les bouchons d'oreilles pour communications (CEP) et le casque de vol Gentex SPH-5 avec capacité de communication, portés seuls ou en combinaison. La reconnaissance vocale dans un milieu calme ainsi qu'au milieu du bruit présent dans un aéronef de transport et dans un hélicoptère Sea King a été évaluée avec les trois combinaisons possibles de protecteurs (séparément et ensemble). Tout comme les bouchons d'oreilles en mousse de marque Aearo E-A-R® distribués habituellement, les CEP portés en même temps que le casque de vol permettaient une meilleure atténuation du bruit présent aux basses fréquences. Les CEP avaient aussi l'avantage d'améliorer le rapport signal vocal/bruit du canal de communications. Dix sujets ayant une ouïe normale ont participé à l'étude. Selon les résultats de l'étude, le port simultané des deux dispositifs permet une atténuation du bruit beaucoup plus marquée que le port du casque seul, soit une diminution de 6 à 16 dB dans l'intervalle de fréquence étudié. La meilleure façon de prévoir le résultat à chaque fréquence (0,25 à 8 kHz) était d'ajouter 5 dB aux plus hauts niveaux d'atténuation obtenus lorsque les dispositifs étaient utilisés seuls. Lorsque les dispositifs étaient utilisés simultanément, le niveau phonique nécessaire pour obtenir un score de reconnaissance vocale de 60 % diminuait de 18 dB en raison d'une augmentation de 13 dB du niveau absolu d'intensité phonique dans l'oreille, associée à une atténuation de 5 dB du bruit extérieur.

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Executive summary

This study addressed the need for effective voice communication in military operations in combination with the requirement for noise abatement to conserve hearing. Measurements were made of (1) the attenuation provided by the Communications Ear Plug (CEP) and Gentex SPH-5 flight helmet, alone and in combination, and 2) speech understanding in Sea King helicopter and Hercules transport aircraft noise with these devices fitted. The CEP has the potential to provide more effective communication than is possible with a standard issue (yellow foam) ear plug worn under a flight helmet with communications capability, while still providing two "layers" of noise protection. Attenuation was assessed by means of the real-ear attenuation at threshold method. Speech levels were determined using the Modified Rhyme Test (MRT). Levels required for 60% correct speech recognition were estimated using the interactive Maximum Likelihood Procedure (MLP). Ten subjects participated in the experiment. In each subject, hearing protector attenuation (the difference between the protected and unoccluded hearing threshold) was measured for a set of eight noise bands with center frequencies ranging from 0.25-8 kHz, for the three hearing protector conditions. Speech recognition was assessed with each device worn alone and in combination in quiet and in the Sea King and Hercules noise backgrounds. The results showed that the wearing of the CEP and SPH-5 provided approximately the same level of attenuation from 0.5-4 Hz. At 0.25 kHz the CEP attenuation exceed the SPH-5 attenuation by 7.5 dB. At 6.3 kHz and 8 kHz, the SPH-5 attenuation exceeded the CEP attenuation by 8.5 dB and 11.5 dB respectively. Worn in combination the two devices provided significantly greater attenuation than realized with either device alone. The gain was well predicted by the addition of 5 dB to the higher of the two attenuations at each frequency. The speech levels required to achieve 60% correct word recognition were no different for the CEP and SPH-5. The at eardrum signal-to-noise ratios were close to 0 dB. When the protectors were worn in combination, the level of the speech required to achieve a 60% correct word recognition score could be decreased by about 18 dB due to a 13-dB increase in the absolute level of the speech reaching the ear combined with 5-dB increase in the attenuation of the external noise.

Abel, S.M., Crabtree, R.B., Odell, P. and Dunn, G. 2003. Acoustical performance of the Communications Ear Plug (CEP) in combination with the Gentex SPH-5 flight helmet. TR 2003-077 DRDC Toronto.

Sommaire

L’étude avait pour objet de répondre au besoin de communications vocales efficaces durant les opérations militaires tout en assurant une atténuation du bruit qui permette de préserver l’ouïe. Nous avons mesuré 1) le degré d’atténuation obtenu avec les bouchons d’oreilles pour communications (CEP) et le casque de vol Gentex SPH-5, portés seuls ou en combinaison, et 2) la reconnaissance vocale dans un hélicoptère Sea King et dans un aéronef de transport Hercules avec ces protecteurs. Les CEP peuvent permettre une communication plus efficace que les bouchons distribués habituellement (mousse jaune) portés sous un casque de vol avec capacité de communication, tout en offrant deux « barrières » de protection contre le bruit. Nous avons évalué le degré d’atténuation au moyen de la méthode REAT (méthode normalisée de mesure du déplacement du seuil d’audition). De plus, nous avons mesuré les niveaux phoniques au moyen du test de rimes modifié. Nous avons estimé les niveaux phoniques nécessaires à une reconnaissance vocale de 60 % au moyen d’une méthode interactive de vraisemblance maximale. Dix sujets ont participé à l’étude. Nous avons mesuré chez chacun d’eux l’atténuation du bruit avec les protecteurs auditifs (la différence entre le seuil d’audition avec et sans protecteur) portés séparément et ensemble pour une série de huit bandes sonores dont les fréquences centrales variaient de 0,25 à 8 kHz. Nous avons mesuré le degré de reconnaissance vocale avec chacun des protecteurs, portés seuls et simultanément, dans un milieu calme et dans le bruit ambiant d’un hélicoptère Sea King et d’un aéronef Hercules. Il ressort de l’étude que les CEP et le casque SPH-5 atténuent d’une manière à peu près équivalente le niveau de bruit entre 0,5 et 4 Hz. À la fréquence 0,25 kHz, les CEP atténuaient le bruit de 7,5 dB de plus que le casque SPH-5. À 6,3 kHz et à 8 kHz, l’atténuation obtenue avec le casque SPH-5 excédait de 8,5 dB et de 11,5 dB, respectivement, celle observée avec les CEP. Le port simultané des deux protecteurs permettait une atténuation du bruit beaucoup plus marquée que le port d’un seul des deux protecteurs. L’ajout de 5 dB au plus élevé des deux niveaux d’atténuation à chaque fréquence était un bon prédicteur du gain obtenu. L’intensité phonique requise pour obtenir une reconnaissance vocale de 60 % était semblable pour les CEP et le casque SPH-5. Le rapport signal/bruit au tympan était proche de 0 dB. Lorsque les protecteurs étaient portés simultanément, l’intensité phonique nécessaire pour obtenir une reconnaissance vocale de 60 % diminuait de 18 dB en raison de l’augmentation de 13 dB du niveau absolu d’intensité phonique dans l’oreille, associée à une atténuation de 5 dB du bruit extérieur.

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Table of contents

List of tables

List of figures

Acknowledgements

This research was carried out in response to questions raised by members of the Life Support Equipment Group, Aerospace Life Support Section, DRDC Toronto. The researchers are particularly grateful to Major A. Olafson for his insightful discussion of the issues and to WO P. Poulin and MCpl S. St-Cyr for their help with subject recruitment and helmet fittings.

Introduction

Effective voice communication in military noise environments is a perpetual challenge in operational and training theatres. The traditional approach has been to protect the ears of noise-exposed individuals by providing a barrier against interfering noise and creating a better environment in which to listen. Such noise-excluding devices usually take the form of a headset or helmet featuring "circumaural" ear shells that surround the ears of the wearer, and cushions that conform to the sides of the head to make an airtight seal. Communications capability is provided by miniature speaker-like transducers built into the ear shells and wired to the external communication system.

Circumaural protective devices (including headsets and helmets) are less effective at attenuating noise at low frequencies than at high frequencies. In many transportation systems and particularly in rotary-wing aircraft, noise is found predominantly in the low frequency region. For effective communications in such an environment, crewmembers must operate the intercommunication system (ICS) at relatively high volume levels to ensure adequate speech understanding. The measurement of sound levels at the ears of crewmembers has shown repeatedly that communications traffic received through helmets and headsets adds appreciably (5 to 15 dB) to the noise exposure that would otherwise be sustained (Crabtree et al, 1998).

As a result of this situation, many helicopter flight crews resort to using foam ear plugs *in combination with* their flight helmets as a means of creating a comfortable listening environment. However, these devices, like their circumaural counterparts, are better protectors at high frequencies than at low frequencies. When worn in combination, significantly more low-frequency attenuation may be realized (Abel and Armstrong, 1992). From a communications standpoint, the practice of using ear plugs creates new problems: 1) communications, muffled because of diminished high frequency information, require higher operating levels for restoration, and 2) the ICS may not have sufficient undistorted gain reserve to compensate for the sound lost through the ear plug. A crewmember with a pre-existing hearing loss may already be a disadvantaged listener. In this situation, the use of ear plugs may seriously affect that person's ability to communicate (Abel et al., 1993).

In the past few years, the United States American Army Research Laboratories (USAARL) have developed a device known as the Communications Ear Plug (CEP) for use either alone or in combination with a circumaural protector (Mozo and Ribera, 1998). In essence, this new device (worn in both ears) is a hollow foam ear plug to which a miniature transducer is attached as shown in Figure 1. The foam ear tips screw-fasten to the transducers making changing tips an easy matter. The transducer is wired into the ICS such that communications are conducted directly into the ear canal. Thus, the CEP has the potential to provide the additional 'layer' of noise protection desired by aircrew already using a helmet and avoids the muffling effects of conventional ear plugs. The CEP in combination with the Hercules headset was subjected to a laboratory evaluation in Hercules aircraft noise (Bell, 2001), where it compared favourably with the best of a set of active noise reduction (ANR) headsets.

Purpose of the study

The intent of this investigation was to evaluate 1) attenuation and 2) speech recognition with the CEP and SPH-5 flight helmet, used alone and in combination, specifically to investigate the potential for use in Canadian Forces Sea King and Hercules aircraft. In Search and Rescue (SAR) Hercules operations, SPH-5 helmets are worn by the SAR Technicians and by the Loadmaster (Figure 2), and are used exclusively in the Sea King fleet. Both have an equivalent A-weighted sound level of about 98 dBA, but the sound spectra are very different. The specific interest was to determine whether the addition of the communication ear plugs would provide a significant increase in attenuation when compared with the single attenuation 'layer' provided by the helmet on its own, and if so, how that increase would impact speech understanding in noise. It was predicted that the greater the attenuation of the ambient noise, the lower the level of the speech required to achieve a predetermined performance level for word recognition.

Experimental design

Attenuation performance

The sound attenuation of the CEP and SPH-5 helmet (both separately and in combination) in human subjects was obtained using the Real-Ear Attenuation at Threshold (REAT) method specified in Canadian and American Standards for Hearing Protection (CSA-Z94.2-02, 2002; ANSI S12.6-1997, 1997). In this procedure, attenuation is derived by subtracting the free-field hearing threshold with the ears unoccluded from the threshold measured with the protectors in place, over a frequency range of 0.25-8 kHz. These measurements were carried out in a double-walled sound proof booth in the Hearing Research Laboratory at DRDC Toronto. The facility meets the requirements for hearing protector assessment outlined in ANSI Standard S12.6-1997.

Speech recognition performance

The Modified Rhyme Test (MRT) speech intelligibility test (House et al., 1965) has been standardized and used for many years, notably by the US military for assessing communications equipment in noise backgrounds. The MRT test material consists of 50 word sets containing six rhyming words each, for a total vocabulary of 300 words. Modern implementation of the traditional pencil-and-paper test involves presenting one of the 50 word sets or "screens" selected at random on a computer monitor as a 2 x 3 matrix, and presenting one of these words selected at random as an audio stimulus cued by a carrier phrase. Subjects respond on a button box having the same matrix layout as the words on the screen.

The Modified Rhyme Test was presented coupled with the adaptive Maximum Likelihood Procedure or MLP (Green, 1990) to establish the signal-to-noise ratio (SNR) at which a given percentage speech recognition proficiency (60% correct) is achieved in a given noise background. This hybrid process converges rapidly to the associated SNR.

The MRT/MLP protocol was run in quiet and in realistic noise fields for the CH-124 Sea King helicopter and CC-130 Hercules transport aircraft noise. These noise fields were faithfully reproduced in the Noise Simulation Facility at DRDC Toronto. Testing was conducted with the SPH-5 helmet and CEP used alone and in combination, using male and female voices. In all, there were 18 experimental conditions (3 backgrounds by 3 ear conditions by 2 voices).

Predictions

In this study, the performance of the CEP in combination with the SPH-5 compared with the performance of the flight helmet used alone was of particular interest. It was predicted that the resultant speech levels should show an advantage of using combined protection. This would imply a reduction in potentially hazardous exposures during flight. The CEP has inherent advantages over ANR technology in terms of much lower cost and no requirement for external power beyond that provided by the ear cups of the helmet. The data generated by the study will be used to model the exposure expected in the Sea King and Hercules, but could easily be extended to model exposure in other aircraft as well.

Methods and materials

Subjects

A group of ten male subjects of military working age (18-55 years) were recruited to participate in the study. Because the number of subjects to be tested was relatively small, it was decided to recruit only males. Gender has been shown to affect the attenuation achieved with both ear plugs and muffs (Abel et al., 1988; Abel et al., 2002).

Subjects were recruited by means of advertisements posted at DRDC Toronto (see Annex A). Volunteers were given a hearing screening test by a qualified technician to confirm that they met the requirements for Canadian Forces Hearing Category H1 hearing acuity, that is, no more than a 30 dB HL bilateral hearing loss at any frequency between 0.125 and 8 kHz. Previous research has shown that hearing loss in excess of 30 dB may affect speech recognition in noise.

All subjects were given the protocol to read and signed a Consent Form (see Annex B).

Procedure

Testing took place over four sessions on different days. The first session involved ear canal examination and screening audiometry (approximately 1 hour). The second session was devoted to helmet fitting (about 1.5 hours). In the third session (the test session) measurements were made of the attenuation of the helmet and ear plug under review (about 1.5 hours in the morning) and the assessment of speech recognition with these same devices (about 2 hours in the afternoon). During the fourth session, a follow-up screening hearing test was conducted (about 30 minutes).

Screening and helmet fitting

Candidates were screened for abnormal build-up of wax in the ears by trained medical personnel. In those who did not require irrigation of the external ear canals, screening audiometry was carried out to ensure that prospective participants meet the requirements of Canadian Forces Hearing Category H1. If the screening results met the stated criteria, candidates returned on a second day to be provided and individually fitted with an SPH-5 flight helmet at the Life Support Equipment Group within DRDC Toronto. It was recognized that proper fitting was pivotal to the outcome of the experiment. Participants used the same helmet for the duration of the experiment.

Because there was a remote risk that the sound exposure sustained during this experiment might cause temporary mild loss of hearing acuity, subjects were required to submit to a follow-up audiometric test following the experimental session to confirm that their hearing had not changed. If an increment of more than 10 dB (the margin of error) was noted, the plan was to re-evaluate hearing in a series of sessions spanning one month to ensure that hearing thresholds returned to pre-exposure values.

Attenuation performance

Attenuation measurements were made during the morning of the third day in the Hearing Research Laboratory of DRDC Toronto. Subjects were seated in the centre of a double walled, semi-reverberant, soundproof room (IAC Series 1200) with inner dimensions of 3.5 m (L), by 2.7 m (W), by 2.3 m (H). They were tested first with their ears unoccluded (without a hearing protection device) and subsequently with the CEP, the CEP and helmet in combination and finally with the helmet alone. This order was chosen to minimize the need for repeated fitting of the CEP and donning and doffing of the helmet. For the occluded conditions, participants were instructed on how to properly insert the ear plugs and/or don the helmet prior to doing so themselves. They were also shown a model of the cross-section of the ear canal with an ear plug inserted, demonstrating that there was no danger of self-inflicted injury due to over-insertion of the ear plugs. Since subjects would be fitting their own CEPs, they were advised to wash their hands immediately before the test session in order to minimize any risk of infection to the outer ear canal.

Hearing thresholds were measured using a variation of Békésy tracking (Brunt, 1985). The stimulus was a train of short noise pulses. The duration of each pulse was 250 ms including rise and fall times of 50 ms. The time off between pulses was 150 ms. Threshold measurements were made once for each of eight one-third-octave noise bands centred at 0.25, 5, 1, 2, 3.15, 4, 6.3, 8 kHz. Participants were given a hand-held pushbutton and asked to press the button as soon as they detected the sound and to keep the button depressed until the sound was no longer audible. The sound level of consecutive pulses increased in steps of 1 dB until the button was depressed and then decreased at the same rate of change until the button was released. The tracking trial was terminated after a minimum of eight alternating intensity excursions with a range of 2 to 20 dB. Hearing threshold was defined as the average sound level of the eight final peaks and valleys. The maximum possible stimulus level (80 dB sound pressure level) was less than that specified in Treasury Board regulations for safe unoccluded listening (TB STD 3-12, 1990).

Speech recognition performance

Speech Recognition testing was performed on the afternoon of the third day in the Noise Simulation Facility of DRDC Toronto. The experimenter maintained contact with the subject via a video link. Subjects were tested with the CEPs fitted binaurally, the CEPs in combination with the helmet and helmet alone. As in the case of the attenuation measurements, this order of devices minimized the need for repeated fitting of the CEP and donning and doffing of the helmet. For each of these ear conditions, subjects were immersed in a sound field of either the Hercules aircraft or Sea King helicopter. As a control condition, testing was also done in quiet. For each of these nine combinations, speech recognition was tested using a male and female speaker. The order of background by speaker was counterbalanced across subjects to equalize learning effects.

The participants were required to don the test devices before the noise was turned "ON", to prevent the possibility of unoccluded exposure. Sound levels at the ear under the protectors due to this noise were expected to be less than 75 dBA for an exposure time not exceeding 2 hrs, thus are well within the 8-hour limit of 87 dBA permitted under Treasury Board requirements (TB STD 3-12, 1990). The stimulus level was internally set such that it did not exceed the level of background noise. The subject was provided with a "kill switch" with which to shut off the noise in case of difficulty.

For this test subjects were seated in front of a computer monitor. On each trial a display of six words was presented. The subject heard the phrase "next word…(one of the six alternatives)" and was required to choose the matching word on the display using a six-alternative key pad. The experiment was subject-paced and the display did not advance until a response had been made. Across successive trials within each protector by background condition, the carrier phrase was presented at a constant level, while the amplitude of the stimulus words varied. The SNR of the carrier phrase with respect to the background noise was chosen for clear intelligibility, since this was the cue that the stimulus word was about to be presented. During the first trial of a series, the stimulus word was presented at a clearly audible level. Based on whether the response was correct or incorrect, the next stimulus word was presented at a level having the maximum likelihood (greatest probability) of achieving a pre-selected performance level, in this case, 60% correct.

In effect, the MLP algorithm chooses a new position on the associated psychometric (intelligibility) function on the SNR axis. In subsequent trials, the maximum likelihood calculation is based on a progressively larger history of responses accumulated within the run, hence subsequent predictions quickly converge to the stimulus level producing the desired performance. Over 50 such trials, this implies about 30 correct responses and about 20 incorrect responses (for about 60% intelligibility).   After 50 trials the MLP is terminated and the level difference between the carrier phrase and the final stimulus word, along with the associated percentage score, are taken as the results of the run. These results are "normalized" via the psychometric function by solving for the level at exactly 60% correct. The lower the absolute level of the speech, the better the performance.

The relationships between the noise background and speech level must be precisely known in order to interpret the performance data. The sound levels at the ear drum were estimated by using an acoustical manikin (Kunov et al., 1986). A calibrated microphone represented the ear drum.

Results

In this study, the performance of the CEP in combination with the SPH-5 compared with the performance of the flight helmet used alone was of particular interest. It was predicted that the resultant speech levels should show an advantage of using combined protection. This would imply a reduction in potentially hazardous exposures during flight. The CEP has inherent advantages over ANR technology in terms of much lower cost and no requirement for external power. The data generated by the study will be used to model the exposure expected in the Sea King and Hercules, but could easily be extended to model exposure in other aircraft as well.

The results of the hearing screening are shown in Table 1 and Figure 3. These data confirm that the Canadian Forces H1 selection criteria were met. Average pure-tone hearing thresholds were less than 12 dB from 0.250-8 kHz. Across individuals, the maximum hearing threshold observed was less than 25 dB HL, except in the case of 8 kHz (left ear), where a value of 32 dB HL was observed.

Table 2 and Figure 4 show the mean hearing thresholds (dB SPL) and standard deviations obtained free field for the unoccluded and protected ear conditions. This data was used to calculate the real-ear attenuation at threshold within subject. A repeated measures analysis of variance (ANOVA) indicated that there were significant effects of ear condition and frequency and their interaction ($p<0.001$). The results indicate that with the plugs or helmet fitted separately, mid-frequency sounds (2-4 kHz) would have to be about 40 dB SPL to be heard. If the devices are worn in combination, mid-frequency sounds would have to be 45-55 dB SPL to be heard. This is similar to inducing a mild to moderate hearing loss.

The mean attenuation and standard deviations provided by the CEP, SPH-5 helmet and these devices in combination are shown in Table 3 and Figure 5. For conditions involving the helmet, attenuation increased with increases in frequency. The attenuation provided by the CEP increased with increases in frequency from 0.25-3.15 kHz and then remained fairly stable. The repeated measures ANOVA applied to these data indicated that there were significant effects of hearing protector condition, frequency and the interaction of these two factors ($p<0.0001$). Post hoc pair wise comparisons using Fisher's LSD method indicated that, except at 0.25 kHz, the two devices in combination provided significantly more sound attenuation that either the plugs or helmet worn alone. The latter were no different from 1-4 kHz, where they provided 30-40 dB of attenuation. In this range, the combination of devices provided an additional 7-17 dB of attenuation. At 0.25 kHz, the helmet provided the least attenuation (16 dB) and the combination the greatest attenuation (26 dB). Above 4 kHz, the plugs provided the least attenuation (39 dB at 8 kHz) and the combination the greatest attenuation (60 dB at 8 kHz).

The results of the speech recognition test are presented in Table 4 and Figure 6. A repeated measures ANOVA indicated that there were statistically significant effects of protector, background, protector by background, protector by gender of the speaker and background by gender of the speaker ($p<0.001$ or better). In the quiet condition, the mean speech levels required to achieve 60% correct word recognition scores ranged from 18.3 dB SPL to 32.5 dB

SPL across the six combinations of ear condition and gender of the speaker. When background noise was introduced, the level of the speech required to achieve the same performance level increased by 37.7 dB for the CEP condition, by 32.0 dB for the SPH-5 condition, and by 27.6 dB for the CEP/SPH-5 combination condition. Regardless of the background, quiet or noise, the speech level required for 60% correct word recognition decreased significantly when the combination of protectors was worn relative to each of the devices worn alone. The differences ranged from 12.9 dB for the quiet condition to 18.6 dB in the Sea King noise. As discussed below, these benefits will be diminished when differences in the voice level at the ear drum across the three hearing protector conditions are taken into account. In the two noise backgrounds, the choice of the single protector, plugs or helmet made no difference. With respect to the effect of gender of the speaker, there was a clear advantage for the female but only in quiet when the CEP was worn. The male/female difference in this condition was 5.8 dB.

In order to determine the relationship between sound attenuation and speech level, correlation coefficients were determined between these two measures within each noise by protector by gender of voice condition, for four of the frequencies at which attenuation was measured (0.5 kHz, 1 kHz, 2 kHz and 4 kHz). None of the observed correlation coefficients was statistically significant.

Discussion

The present experiment was conducted to determine the speech levels that would be required to achieve word recognition scores of 60% correct when wearing communications ear plugs and helmets, alone or in combination in background noise. The devices chosen were the Communications Ear Plug (CEP) with the Gentex SPH-5 flight helmet. The backgrounds chosen were quiet and Hercules and Sea King aircraft noise. The noise had an equivalent sound level of about 98 dBA. The prediction was that the greater the attenuation of the ambient noise by the protector(s), the less the level that would be required for the speech. REAT measurements were made in the same subjects to determine differences in attenuation provided by these same devices when worn alone or in combination.

The results demonstrated that the two devices in combination provided more attenuation than was achieved when each was worn alone. A number of different equations have been derived to predict combined attenuation (Behar, 1991; Berger, 1983; Damongeot et al., 1989). Three were explored: (1) the 5 dB rule-of-thumb, in which 5 dB is added to the higher attenuation of the pair of devices tested singly, (2) the algebraic sum of the attenuation achieved with each device and (3) an equation published by Berger (1983) that utilizes both the algebraic sum and the bone conduction limit into account. The observed attenuation for the combination of the CEP and SPH-5, along with the predictions generated by the three equations are shown in Figure 7. The 5 dB rule appears to provide the closest fit except at 3.15 kHz and 4 kHz. A surprising finding was that observed combined attenuation exceeded the bone conduction limit from 3.15-8 kHz. It may be that the bone conduction pathways to the inner ear are blocked to some degree by the wearing of the helmet. A previous study (Abel and Armstrong, 1992) provided evidence that both the 5 dB rule and combination of single attenuations provided poor fits to the data. The difference in result may be due to the fact that in the earlier study, the devices were fit by trained personnel. In the current study, each subject fitted his own hearing protectors with the guidance of trained personnel.

The wearing of the plugs and helmet in combination proved to be beneficial for speech recognition. In quiet, the speech level required to attain 60%correct with the helmet alone was about 32 dB SPL. This value corresponds to the level of whispered speech. When the devices were worn in combination in quiet there was a gain of 12.9 dB compared with the value observed for the helmet alone. This was due to the fact that with the helmet alone the speech level was 12.8 dB higher than with the two devices in combination. Levels with the CEP were comparable to those with the devices in combination.

With the helmet fitted, the 98 dBA noise background was reduced by 33 dBA to 65 dBA. This calculation was made using the average attenuation in the speech frequency region (i.e., 1, 2, 3.15 kHz). The observed speech level in noise was 63 dB SPL, giving a speech-to-noise ratio of about –2 dB. These results are in line with previous studies that have demonstrated that normal listeners achieve 60% correct with an unprotected speech-to-speech babble ratio of 0 dB (Abel et al., 1990). When the devices were worn in combination in noise, the speech level required to meet the 60% criterion decreased by 17.3 dB relative to the speech level required when the helmet was worn alone. Subtracting the 12.9 dB contributed by the amplification due to the devices in combination, measured in quiet, the gain would be 4.4 dB.

This outcome is close to the 5 dB increase over the higher of the two single sound attenuations found when the devices were worn in combination.

Conclusion

The results showed that the wearing of the CEPs binaurally in combination with the SPH-5 helmet resulted in a significant increase in attenuation over the attenuation provided by the helmet alone of 6-16 dB across the frequency range tested. The addition of 5 dB to the greater of the attenuations observed for the two devices worn singly provided a close approximation to the attenuation realized with their combination. When the CEP and SPH-5 helmet were worn in combination, the level of the speech could be lowered by almost 18 dB to achieve the same performance level as when the devices were worn alone. This was due to the 13-dB increase in the absolute level of the speech at the ear combined with the 5-dB increase in the attenuation of the external noise.

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Table 1

Pure-tone hearing thresholds obtained with screening audiometry

	Frequency in Hz							
	250	500	1000	2000	3150	4000	6300	8000
Right Ear	0.3 (4.8)*	0.1 (5.5)	0.9 (4.5)	-1.9 (4)	0.9 (5)	3.3 (7)	6.5 (10.6)	3.5 (5.3)
Left Ear	0.1 (4.3)	-3.3 (5.9)	-0.5 (4.6)	-1.6 (4.6)	2.2 (8.4)	7.1 (10.3)	9.8 (8.5)	11.8 (9.8)

*Mean(dB HL) (SD) N=10

Table 2

Unoccluded and protected free-field hearing thresholds in quiet

	Frequency in Hz							
HPD	**250**	**500**	**1000**	**2000**	**3150**	**4000**	**6300**	**8000**
Unoccluded	17.8 (3.5)*	8.8 (4.8)	1.7 (3.7)	2.4 (5.4)	1.6 (4.8)	1.7 (3.9)	11.4 (4.9)	11.4 (5.2)
CEP	40.9 (8.5)	33.0 (7.9)	31.6 (5.0)	36.2 (3.5)	39.0 (5.5)	39.2 (5.4)	48.9 (8.4)	50.6 (8.3)
SPH-5	33.4 (4.3)	29.1 (6.5)	31.8 (4.5)	33.2 (7.2)	39.9 (6.1)	41.1 (6.5)	57.4 (6.9)	62.1 (5.4)
CEP+SPH-5	43.5 (5.7)	41.2 (5.8)	37.9 (5.4)	44.2 (5.3)	53.2 (5.2)	56.6 (3.3)	66.7 (7.1)	70.8 (4.0)

*Mean(dB SPL) (SD) N=10

Table 3

Attenuation achieved with the CEP, SPH-5 and CEP and SPH-5 in combination

	Frequency in Hz							
HPD	**250**	**500**	**1000**	**2000**	**3150**	**4000**	**6300**	**8000**
CEP	23.1 (6.7)*	24.2 (4.9)	28.7 (3.9)	33.8 (3.5)	37.3 (2.5)	37.4 (2.9)	37.5 (5.6)	39.2 (5.3)
SPH-5	15.6 (2.8)	20.3 (4.2)	30.1 (4.1)	30.8 (5.2)	38.3 (4.1)	39.3 (4.2)	46.0 (4.2)	50.7 (3.8)
CEP+SHP-5	25.7 (3.8)	32.4 (5.6)	36.2 (5.4)	41.8 (4.9)	51.5 (4.3)	54.9 (3.7)	55.3 (5.3)	59.5 (3.3)

*Mean(dB) (SD)   N=12

Table 4

Speech levels required to obtain 60 per cent correct word recognition scores

		Ear Condition		
Background	**Gender**	**CEP**	**SPH-5**	**CEP+SPH-5**
Quiet	**M**	22.9 (4.8)*	31.0 (4.1)	18.3 (4.3)
	F	27.1 (5.4)	32.5 (4.4)	19.4 (5.4)
Hercules	**M**	59.7 (4.7)	62.1 (3.8)	44.8 (2.9)
	F	60.8 (3.2)	60.5 (3.7)	45.9 (4.2)
Sea King	**M**	65.1 (4.6)	66.2 (4.9)	47.8 (4.4)
	F	65.0 (5.2)	66.1 (4.2)	47.3 (3.4)

*Mean dB SPL (SD) N=10

Figure 1 The Communications Ear Plug

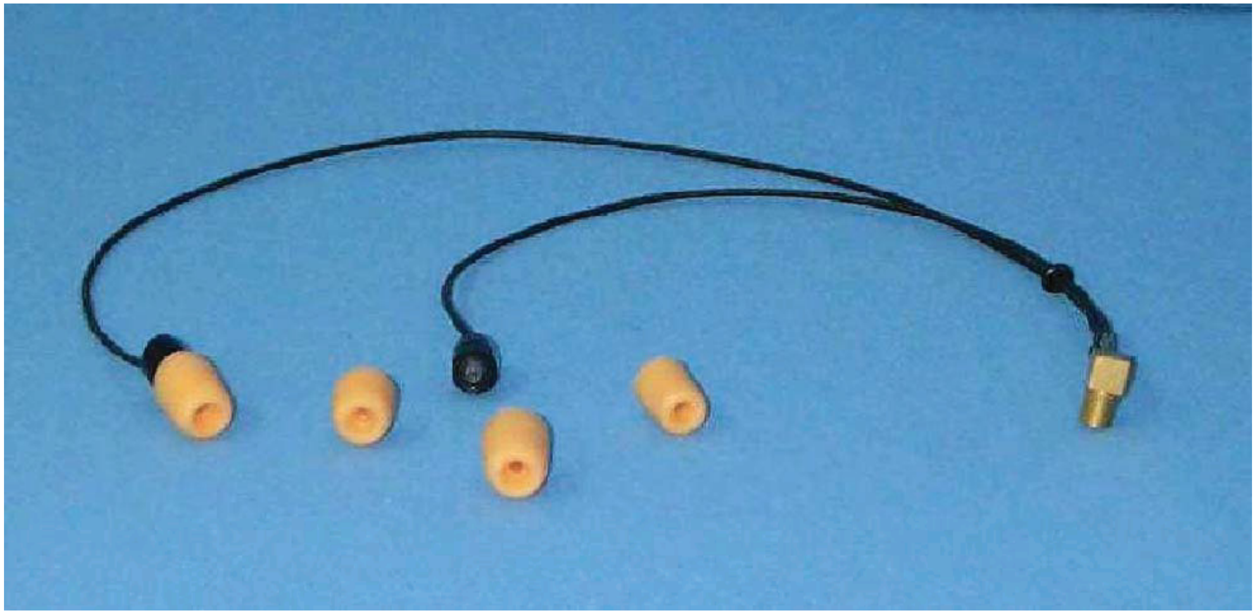


Figure 2 The SPH-5 Helmet in Combination with the Communications Ear Plugs

Figure 3 The results of screening audiometry

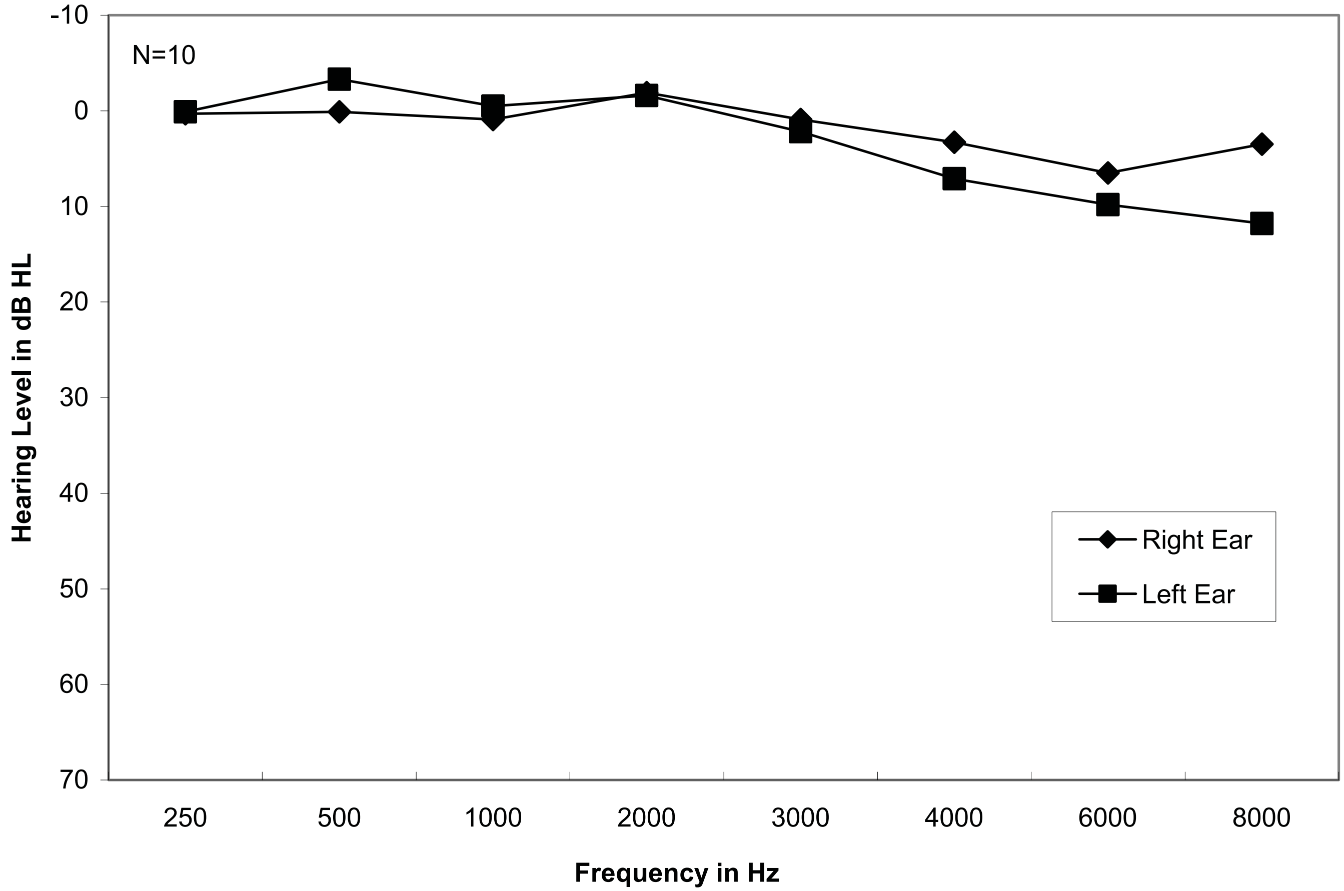


Figure 4 Unoccluded and protected free-field hearing thresholds in quiet

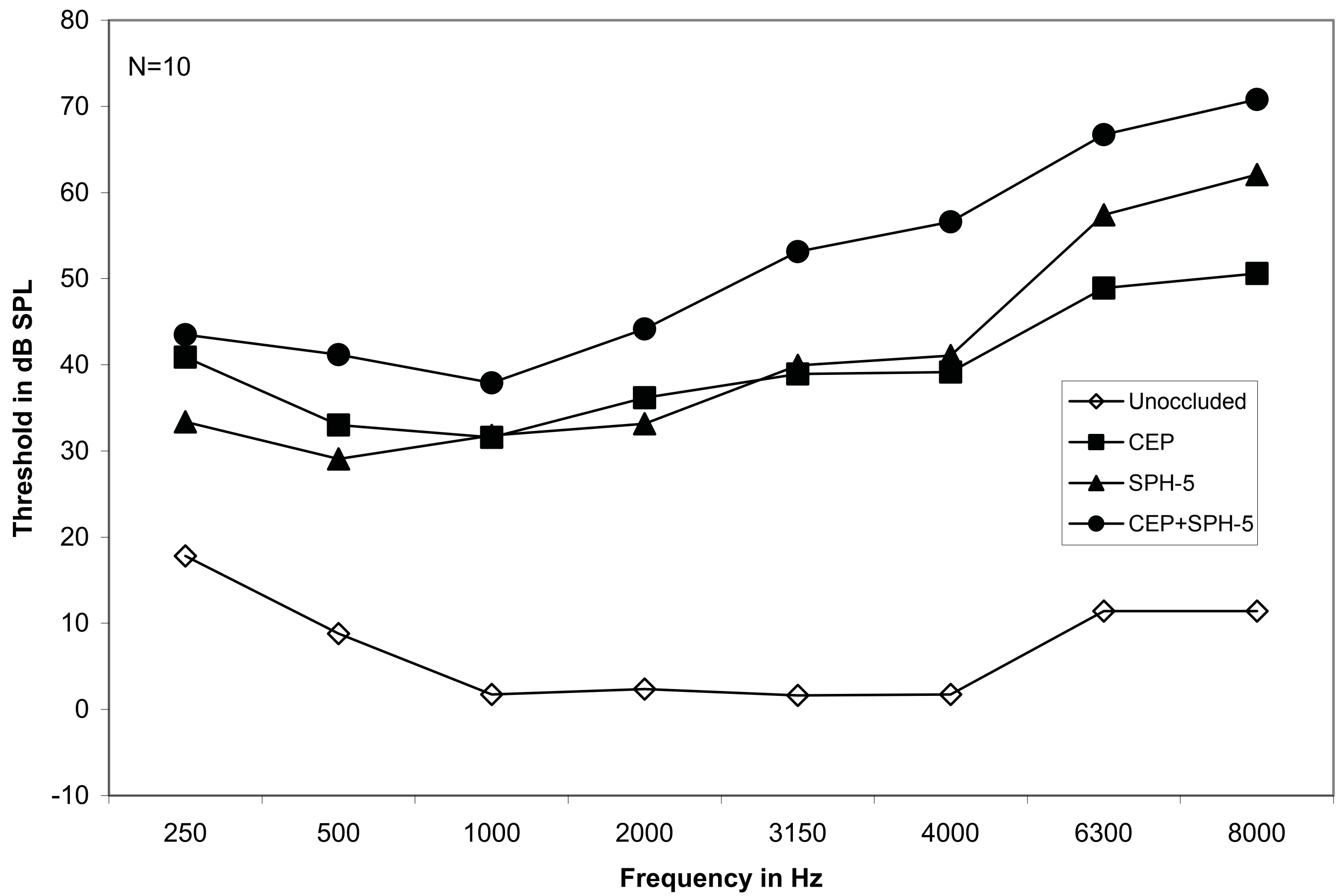


Figure 5   Hearing protector attenuation

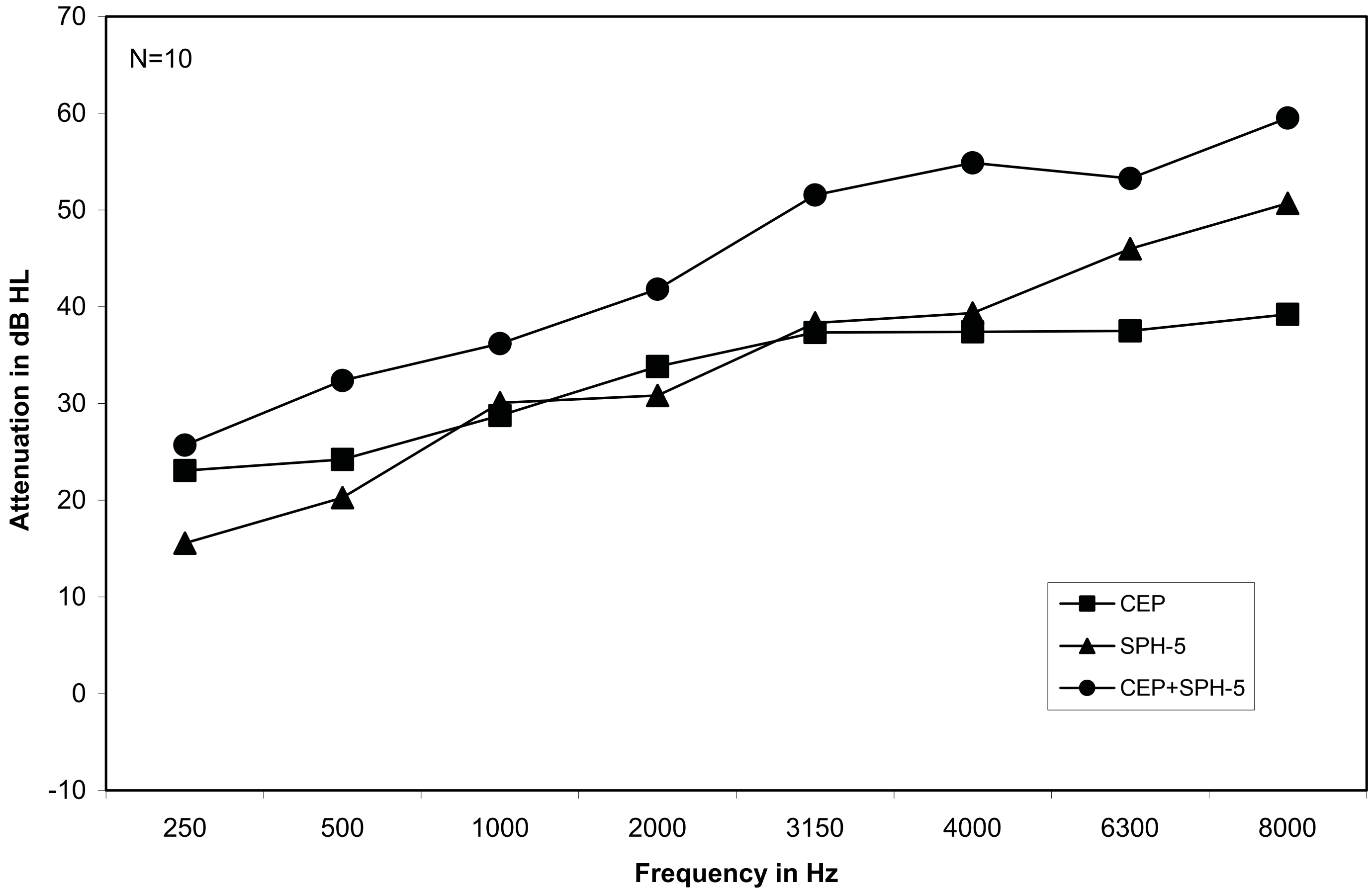


Figure 6 Speech level required to obtain 60 per cent correct word recognition

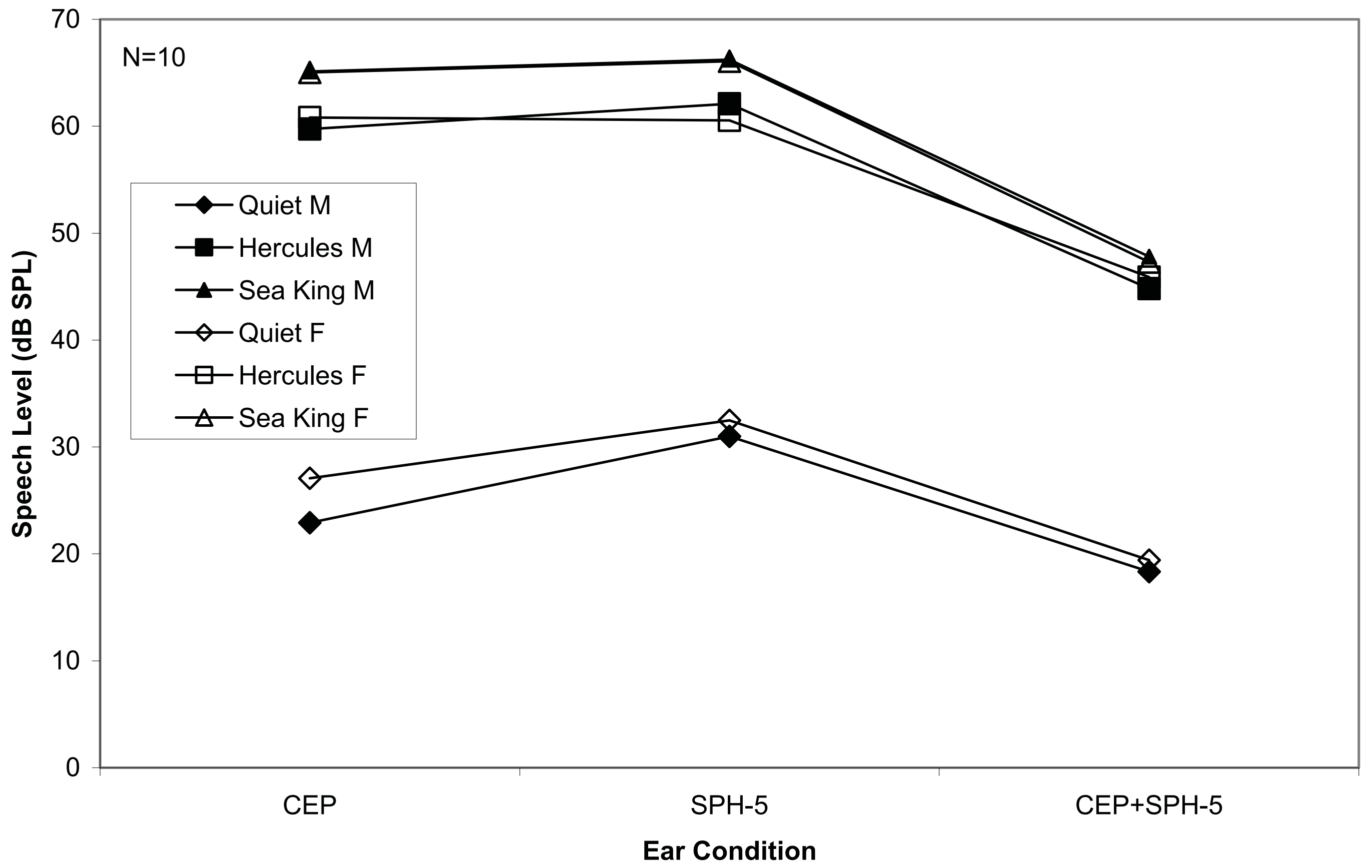
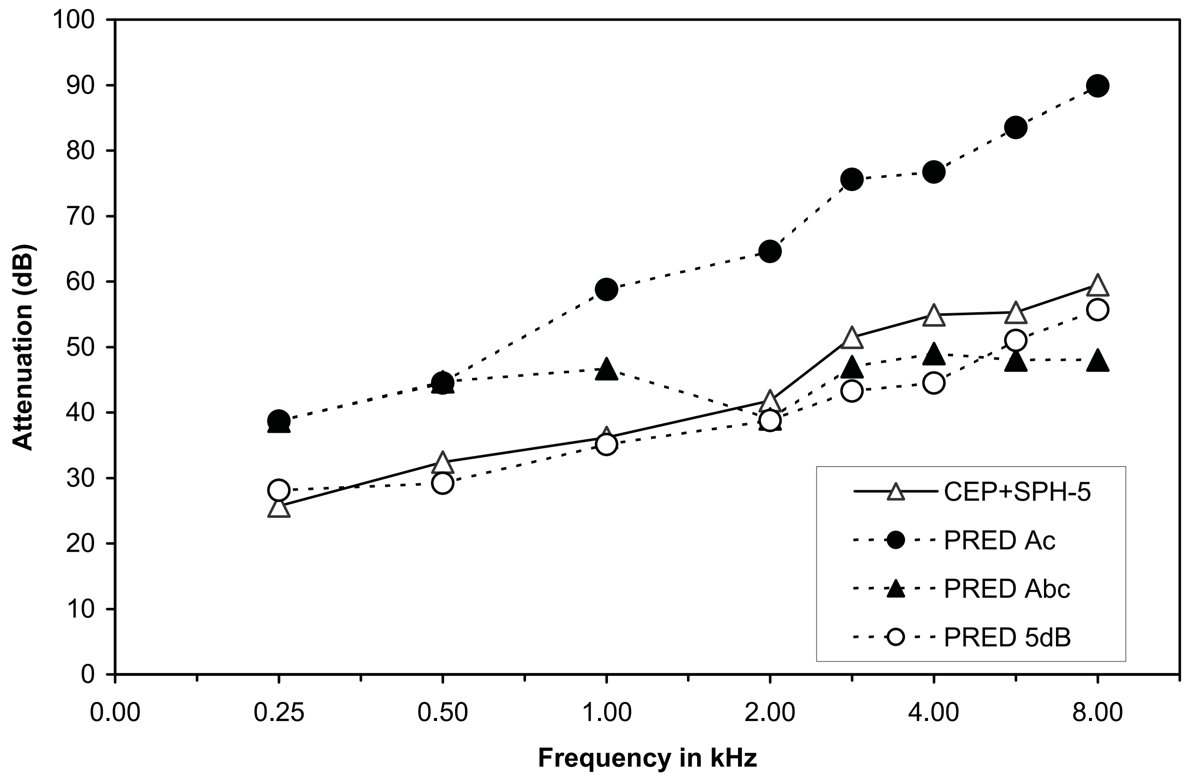


Figure 7 Modelling the attenuation of the CEP and SPH-5 in combination



Annex A

CALL-FOR-SUBJECTS POSTER

Title of Experiment:
Acoustical performance of the Communications Ear Plug (CEP) in combination with the Gentex SPH-5 Flight Helmet

Purpose of Experiment:
The intent of the proposed study is to evaluate 1) attenuation and 2) speech reception properties of the Communications Ear Plug (CEP) and the SPH-5 flight helmet used alone and in combination, specifically to investigate the potential for effective use in Canadian Forces Sea King Helicopter and Hercules Transport aircraft.

Subjects Required:
Twelve males of working age (18-55 yrs) are required. Both military personnel and civilians are invited to participate.

Procedures:
The experiment will be conducted over four sessions on four separate days. The total time commitment is 6.5 hrs. On Day 1, participants will be screened for freedom from wax build-up in the ears by trained medical personnel and will be asked to undergo a screening hearing test to ensure that they meet the requirements of Canadian Forces Hearing Category H1. On day 2**,** successful candidates will be custom-fitted with the flight helmet. Since they will be fitting ear plugs, participants will be advised to wash their hands immediately before the test session in order to minimize any risk of infection to the outer ear canal.

During the morning segment of the test session (day 3), participants' hearing thresholds will be assessed with the ears uncovered, with the helmet in place and with the CEP and helmet in combination. One-third-octave noise bands centred on eight different frequencies will be presented to participants via three loudspeakers. The participant's task will be to indicate when they are able to hear the stimulus by depressing a hand-held pushbutton.

In the afternoon segment of the test session, participants will wear the helmet and CEP alone and in combination in two types of aircraft noise and in quiet. Participants will be asked to complete a self-paced speech discrimination test (Modified Rhyme Test, MRT). On the workday immediately following the test session (day 4), participants will receive a further hearing test to ensure that hearing thresholds have not changed.

Location of Experiments:
Auditory screening will be conducted in Room B102 and ear examinations will be carried out in the Central Medical Board facilities. Helmet fitting will be done in Room 54220. Testing will take place in the Hearing Research Laboratory (Room 1520) and in the Noise Simulation Facility (Room B105) at DRDC Toronto.

Duration of Subject Participation:
Testing will take place over four sessions The first (ear examination and hearing test) will take about 1 hr to complete. The second session (helmet fitting) will take 1.5 hrs to complete. The third (test) session will be no longer than 3.5 hrs and will be divided about equally into morning and afternoon segments. The final session (follow-up hearing test) will take no more than 0.5 hr. The total commitment over three separate days is 6.5 hrs. The first two sessions may be conducted on the same day if convenient, without loss of remuneration.

Risks to Subject:
Only remote risks are associated with participating in this experiment.

Benefits:
Benefits include a more thorough understanding of layered ear protection and it's application to Canadian Forces aircraft environments.

Compensation:
Remuneration for participation in this study will be provided according to guidelines for stress allowance provided by DRDC Toronto.

Points of Contact:
Patricia Odell, phone (416) 635-2000 ext. 3024, e-mail: patti.odell@drdc-rddc.gc.ca
Dr. Sharon Abel, phone (416) 635-2037, e-mail sharon.abel@drdc-rddc.gc.ca

Annex B

VOLUNTARY CONSENT FORM FOR HUMAN SUBJECT PARTICIPATION

Research Project Title:
Acoustical Performance of the Communications Ear Plug (CEP) in combination with the Gentex SPH-5 Flight Helmet

Principal Investigator and Run Director: Dr. Sharon Abel
Co-investigator: Mr. Brian Crabtree
Research Assistant: Ms. Patricia Odell

1 I, ____ (name, address, phone no.) hereby volunteer to participate as a test subject in the DRDC Toronto experiment to study the effectiveness of attenuation and speech reception of the Communications Ear Plug (CEP) and Flight Helmet model SPH-5, worn singly and in combination. I have read the associated Protocol (L-398) and have had a chance to ask the investigators any questions that I may have had. However, should I have any further questions concerning this study, I am welcome to contact Dr. Sharon Abel at (416) 635-2037 for additional information.

2. I am aware that I am expected to participate in four sessions on four separate days. In the first, my ear canals will be examined by trained medical personnel to ensure they are clear of ear wax build-up or other condition that may prevent me from participating. .If I pass this examination, I will have my hearing measured by a trained technician to make sure that my hearing is sufficiently acute for me to participate in this study, On the second day, the flight helmet will then be custom-fitted to my head by members of the trials team. (If possible, the first and second sessions may be combined. This will not result in a decrease in the remuneration I will receive.) On the third day, in the morning segment of the test session, my hearing thresholds will be measured in a quiet room without the protective devices, with the helmet and CEP alone and in combination. I will be instructed to listen carefully for a test signal and to press a hand switch when I hear it. I understand that my hearing thresholds will be measured using a one-third-octave noise band centred at 8 different frequencies (250, 500, 1000, 2000, 3150, 4000, 6300 and 8000 Hz).

3. In the afternoon segment of the test session, I will be asked to complete a speech intelligibility test in two types of aircraft noise and in quiet, while I wear the helmet and CEP alone or in combination. Sets of six words will be presented on a computer monitor as one of them is presented through the helmet or CEP. I will be asked to select the word that I heard, then a fresh screen will be presented and I will respond again. The speech level of the words will be adjusted by the system, and I will not be able to correctly identify all of the words that are presented.

4. In a screening session held on the workday following the test session (the fourth day), my hearing will be re-measured to confirm that my hearing thresholds have not changed. If

an increment of greater that 10 dB (the margin of error) is noted, my hearing will be tested repeatedly to ensure that any change due to the study is temporary.
It has been explained to me that the initial ear examination and hearing screening session should take no longer than 1 hr to complete, that the helmet fitting will take approximately 1.5 hrs, that the test session will not exceed 3 1/2 hrs in total duration, and that the follow-up hearing test will take about 30 minutes.

5. It has been explained to me that the initial ear examination and hearing screening session should take no longer than 1 hr to complete, that the helmet fitting will take approximately 1.5 hrs, that the test session will not exceed 3 1/2 hrs in total duration, and that the follow-up hearing test will take about 30 minutes.

6. I have been informed that there are minimal risks associated with this experiment. The only discomfort that may arise during my participation is being confined in a small room for a period of time and being exposed to noise that is considered to be non-hazardous to my hearing. There may also be some mild discomfort associated with wearing the test samples. Also, I acknowledge that my participation in this study, or indeed any research, may involve risks that are currently unforeseen by DRDC Toronto. I understand and accept these minor risks.

7. If, for any reason and at any time, I feel uncomfortable with continuing, I may terminate my participation in this study without prejudice.

For military personnel on permanent strength at CFEME: Approval in principle by Commanding Officer is given in Memorandum 3700-1 (CO CFCME), 18 Aug 94; however, members must still obtain their section Head's signature designating approval to participate in this particular experiment. CF personnel are considered to be on duty for disciplinary, administrative and Pension Act purposes during their participation in the experiment.

For other military personnel:
All other military personnel must obtain their Commanding Officer's signature designating approval to participate in this experiment.

8. Benefits associated with this project include a more thorough understanding of noise/communications devices that might be suitable for use in CF aircraft.

9. I am aware that participation in this study entitles me to a total remuneration in the form of a stress allowance in the amount of $ 56.46 for completion of the entire experiment. If I do not complete the experiment, I am entitled only to payment for the number of hours completed.

I understand that by signing this consent form I have not waived any legal rights I may have as a result of any harm to me occasioned by my participation in this research project beyond all risks I have assumed.

Volunteer's Name: ____
Signature: ______________________________ Date_____________________
Name of Witness to Signature: ______________________________________
Signature: ______________________________ Date_____________________

Family member or contact person (name, address, daytime phone number & relationship)

____

Notes:
For Military personnel on permanent strength of CFEME: Approval in principal by Commanding Officer is given in Memorandum 3700-1 (CO CFEME), 18 Aug 94: however, members must still obtain their Section Head's signature designating approval to participate in this particular research project.

For other military personnel: All other military personnel must obtain their commanding Officer's signature designating approval to participate in this research project.

For civilian personnel at DRDC Toronto: Signature of Section Head is required designating that the volunteer subject is considered to be at work and that approval has been given to participate in this research project.

Section Head/Commanding Officer's Signature
CO's Unit______________________________ Date___________________

Principal Investigator: ____
Signature: ______________________________ Date_____________________

In the event that I may have any further questions regarding this study before, during or after my participation, I may contact the Defence Research and Development Canada (DRDC), P.O. Box 2000, 1133 Sheppard Avenue West, Toronto, Ontario M3M 3B9. This communication can be made by surface mail, in person, by phone or e-mail to any of the DRDC Toronto numbers and addresses listed below:

Principal Investigator: Dr. Sharon M. Abel,
Phone: (416) 635-2037, e-mail: sharon.abel@drdc-rddc.gc.ca
Chair, DRDC Toronto, Human Research Ethics Committee (HREC): Jack P. Landolt, PhD,
Phone: (416)635-2120, e-mail: jack.landolt@drdc-rddc.gc.ca

I am aware that I will be provided with a copy of this consent form so that I may contact any of the above-mentioned individuals some time in the future should that be required.

List of symbols/abbreviations/acronyms/initialisms

ANOVA – Analysis of Variance

ANR – Active Noise Reduction

CEP – Communications Ear Plug

CFEME – Canadian Forces Environmental Medicine Establishment

CSA – Canadian Standards Association

dB – Decibel

dBA – Decibel A-Weighted

dB SPL – Decibel Sound Pressure Level

Hz - Hertz

IAC – Industrial Acoustics Company

ICS – Intercommunication System

IL – Insertion Loss

MLP – Maximum Likelihood Procedure

MRT – Modified Rhyme Test

REAT – Real Ear Attenuation at Threshold

SAR – Search and Rescue

SNR – Signal-to-Noise Ratio

DOCUMENT CONTROL DATA SHEET

1a. PERFORMING AGENCY DRDC Toronto	2. SECURITY CLASSIFICATION UNCLASSIFIED Unlimited distribution - (NON-CONTROLLED GOODS) DMC A REVIEW: GCEC December 2012
1b. PUBLISHING AGENCY DRDC Toronto	

3. TITLE

(U) Acoustical performance of the Communications Ear Plug in combination with the Gentex SPH-5 flight helmet

4. AUTHORS

Sharon M. Abel, R.Brian Crabtree, Patricia Odell and Garry Dunn

5. DATE OF PUBLICATION June 31 , 2003	6. NO. OF PAGES 30

7. DESCRIPTIVE NOTES

8. SPONSORING/MONITORING/CONTRACTING/TASKING AGENCY

Sponsoring Agency: DRDC Toronto Aerospace Life Support Section
Monitoring Agency:
Contracting Agency :
Tasking Agency: DRDC Toronto Aerospace Life Support Section

9. ORIGINATORS DOCUMENT NO. Technical Report TR 2003-077	10. CONTRACT GRANT AND/OR PROJECT NO. 16cb19	11. OTHER DOCUMENT NOS.

12. DOCUMENT RELEASABILITY

Unlimited distribution

13. DOCUMENT ANNOUNCEMENT

Unlimited announcement

14. ABSTRACT

(U) An experiment was carried out to measure the real-ear attenuation at threshold provided by the Communications Ear Plugs (the CEP) and Gentex SPH-5 flight helmet with communications capability, worn alone or in combination. Word recognition in quiet and in Helicopter and Sea King noise was also assessed under the three ear conditions. Like the standard issue Aearo E-A-R® foam ear plugs, the CEP worn in combination with the helmet has the capability of increasing the sound attenuation achieved at low frequencies. The CEP has the added advantage of improving the speech-to-noise ratio of the communications channel. Ten subjects with normal hearing were tested. The results showed that the two devices worn in combination provided significantly greater attenuation than the helmet worn alone, by 6-16 dB over the frequency range tested. The best predictor of outcome at each frequency (0.25-8 kHz) was the addition of 5 dB to the higher of the attenuations realized for the devices worn alone. When the devices were worn in combination the level of speech required to achieve a 60% correct word recognition score decreased by about 18 dB due to a 13-dB increase in the absolute level of the speech reaching the ear in combination with a 5-dB increase in the attenuation of the external noise.

(U) Une expérience a été menée pour mesurer le déplacement du seuil d’audition avec les bouchons d’oreilles pour communications (CEP) et le casque de vol Gentex SPH?5 avec capacité de communication, portés seuls ou en combinaison. La reconnaissance vocale dans un milieu calme ainsi qu’au milieu du bruit présent dans un aéronef de transport et dans un hélicoptère Sea King a été évaluée avec les trois combinaisons possibles de protecteurs (séparément et ensemble). Tout comme les bouchons d’oreilles en mousse de marque Aearo E?A?R® distribués habituellement, les CEP portés en même temps que le casque de vol permettaient une meilleure atténuation du bruit présent aux basses fréquences. Les CEP avaient aussi l’avantage d’améliorer le rapport signal vocal/bruit du canal de communications. Dix sujets ayant une ouïe normale ont participé à l’étude. Selon les résultats de l’étude, le port simultané des deux dispositifs permet une atténuation du bruit beaucoup plus marquée que le port du casque seul, soit une diminution de 6 à 16 dB dans l’intervalle de fréquence étudié. La meilleure façon de prévoir le résultat à chaque fréquence (0,25 à 8 kHz) était d’ajouter 5 dB aux plus hauts niveaux d’atténuation obtenus lorsque les dispositifs étaient utilisés seuls. Lorsque les dispositifs étaient utilisés simultanément, le niveau phonique nécessaire pour obtenir un score de reconnaissance vocale de 60 % diminuait de 18 dB en raison d’une augmentation de 13 dB du niveau absolu d’intensité phonique dans l’oreille, associée à une atténuation de 5 dB du bruit extérieur.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) noise attenuation; hearing protection