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An Evaluation of Selected Communications Assemblies and Hearing Protection Systems: A Field Study Conducted for the Future Force Warrior Integrated Headgear Integrated Process Team

by Angélique A. Scharine, Paula P. Henry, and Mary S. Binseel

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Human Research and Engineering Directorate, ARL

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14. ABSTRACT Radio communications and hearing protection are two critical components of the Future Force Warrior (FFW) ensemble. A field study was conducted to evaluate three different communication system concepts: bone conduction, communications earmuffs, and communications earplugs, all of which are being considered for the FFW ensemble. Eight Soldiers participated in a series of activities to evaluate each of the systems regarding communication effectiveness, comfort, environmental hearing, hearing protection, and ease of use. Objective and subjective data were collected in each of the following tasks: a road march, speech intelligibility in noise, speech intelligibility in noise in a moving vehicle, and speech intelligibility when chemical/ biological protective gear is worn. The results of the study suggest reducing selection to two concepts: the bone conduction system and the communications earplug. However, further testing and development are needed in order for either system to be in an acceptable form. Furthermore, a determination should be made regarding whether communication systems should be independent from the helmet. Both the Soldier's comfort and the Soldier's need for communications should be considered.					
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1. Introduction

Radio communications and hearing protection (C&HP) have been identified as two extremely important components of the Future Force Warrior (FFW) ensemble. Master requirements state that radio communications must be available at all times, including operations conducted in a chemical/biological (chem/bio) protective ensemble and during power or computer outages. Similarly, hearing protection is considered a critical element of the Soldier system because auditory information is vital in the battlefield, and human hearing must be protected against loud impulse and stationary noises. However, neither radio communication assemblies nor hearing protection devices should adversely affect Soldier protection from fragmentation and direct fire or auditory awareness of surrounding environments. Squad members need to hear each other and communicate by low-level speech signals. In addition, Soldiers should be able to detect subtle changes in environmental sounds, which indicate danger as well as opportunities. A sound made by an unseen helicopter flying above the tree line can provide a wealth of information about the situation on the battlefield. The presence or absence of bird sounds in the tree canopy, the sound of a snapped twig, or the sound of a gun safety being taken off must be heard by Soldiers to assure their safety and mission effectiveness. Therefore, radio communications interfaces must leave the ears open or restore environmental sounds. Equally important, hearing protection must have some form of hearing restoration or be level dependent and allow the Soldier to hear environmental sounds in quiet and in noise. It is also hoped that the provision of level-dependent hearing protection will be acceptable during all operational procedures and will increase the level of Soldier compliance with safety regulations. Currently, hearing damage has occurred not only during military conflicts but also during training exercises because Soldiers choose not to wear hearing protection.

The purpose of this field study was to compare four systems identified previously as candidates for the FFW headgear ensemble. Field study activities were designed to provide objective data about speech intelligibility for each of these systems as well as subjective data about user comfort and environmental hearing. This report outlines the primary findings from this study. It also outlines issues for ensuing testing.

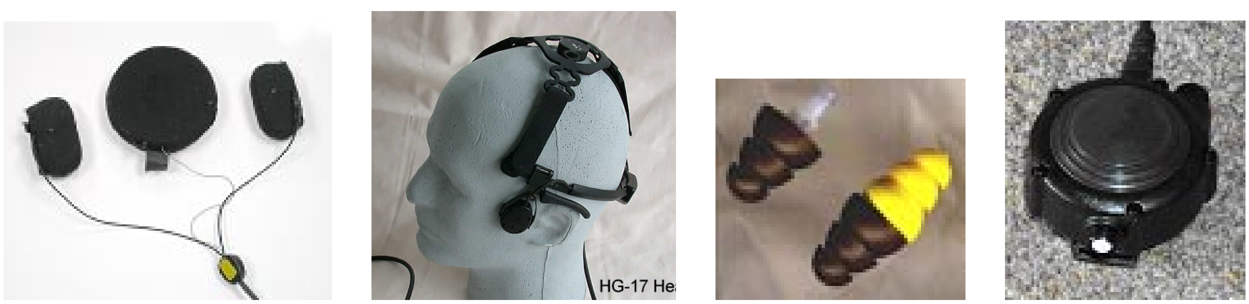
2. C&HP Systems

Three basic conceptual configurations of radio communication equipment and hearing protection are being considered by the Integrated Headgear Integrated Process Team for FFW applications. These three basic concepts evaluated in this study are head-worn bone conduction (BC), communication earmuffs (CEM), and communication earplugs (terminal attack communications

[TAC] and communications enhancement and protection system [CEPS]). With the exception of the CEPS[1], the devices tested in this study were prototypes, which require further development to reach planned capability.

2.1 Bone Conduction

The BC system uses a bone conduction contact microphone to transmit speech by picking up the vibrations of the bones of the skull, and two bone conduction vibrators that deliver the received transmissions to the listener. These components were incorporated into the padding of the helmet or placed in a webbed headset (Temco[2] HG-17) worn independently under an advanced combat helmet (ACH). The hearing protection component of this system is the combat arms earplug (CAE), a two-sided, triple flange earplug. The yellow side provides level-dependent hearing protection. At levels below approximately 110 dB sound pressure level (SPL), it provides little attenuation, allowing speech communications and environmental hearing via small orifices in the plug; however, high-level impulse noises are greatly attenuated because the turbulent sound pressure waves cannot pass through the orifices. The green side provides hearing protection against steady state noise and has a noise reduction rating (NRR) of 22 dB. A Temco BM-8 push-to-talk button, approximately 3 inches in diameter, was used to control transmission between the communication system and the test instrumentation. Figure 1 presents photos of the two implementations of the BC system, the CAE, and the push-to-talk button.



(a) (b) (c) (d)

Figure 1. Components of BC configuration: (a) Temco bone conduction contact microphone and vibrators contained in ACH helmet pads, (b) Temco HG-17 webbed headset, (c) CAE showing core with orifices that allow level-dependent hearing protection, and (d) Temco BM-8 push-to-talk button.

2.2 Earmuffs

The CEM implementation provided for this study was based on the Sordin[3] earmuffs with high-efficiency loudspeakers mounted in the cup of the earmuffs and a bone conduction contact microphone in the ear cup itself, directly over the ear canal. The instal-lation of this microphone was a prototypical component; these earmuffs are not currently on the market in this configuration. Hearing restoration was provided via binaural hear-through microphones on the

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[1]Communications & Ear Protection, Enterprise, AL 36331
[2]Temco Communications, Inc., South Barrington, IL 60010
[3]MSA Sordin, Mine Safety Appliances Company, Pittsburgh, PA 15238

front of each earmuff. A volume control and on/off switch on the outside of one of the earmuffs controlled the hear-through microphones. The hear-through microphones are turned off when the listener is in a noisy environment. Thus, the earmuffs provided communications and hearing protection (NRR = 24 dB). The Sordin push-to-talk button is approximately 4 by 1 by 1 inches. Figure 2 presents photos of the Sordin earmuffs and the accompanying push-to-talk button.

(a) (b)

Figure 2. Components of Sordin earmuff system: (a) earmuffs with hear-through microphones and a bone conduction microphone in the ear cup, and (b) push-to-talk button.

2.3 Integrated Communications Earplugs

The third concept considered was an integrated earplug that provides both hearing protection and communications. We were able to test two implementations of this concept: (1) the TAC earplug currently being developed by the U.S. Air Force Research Laboratory in conjunction with the Air Combat Command and the Air Force Special Operations Command, and (2) the CEPS[4] developed by Communications & Ear Protection, Inc., as part of a cooperative research and development agreement with the U.S. Army Aeromedical Research Laboratory at Fort Rucker, Alabama.

2.3.1 TAC

The TAC earplug uses two microphones, a bone conduction microphone inside the ear canal, which allows the user to communicate over a radio, and an external, "hearing aid" style microphone to provide hearing restoration. The current TAC prototype has foam insert earplugs that deliver received communications and provide 29 dB of attenuation (NRR). These are connected via wires to a box (approximately 5 by 3 by 1.5 inches) that allows the user to control the level of the communications input and to mute and control the levels of external sounds (gain ≈ 20 dB) provided by environmental microphones on the earplugs. A button allows the user to mute the environmental microphones when the listener is in noise. This interface box is designed to be attached to the uniform. Compression is triggered when sounds exceed 85 dB SPL to ensure that transmitted peak sound levels do not exceed 90 dB SPL. Currently, the TAC is being developed, and this is the first prototype. As such, it differs from its intended design in a number of ways.

[4]Currently, there is a patent pending at the United States Patent and Trademark Office.

All data reported here refer only to the prototype. Figure 3 presents a photograph of the TAC integrated communications earplug system.

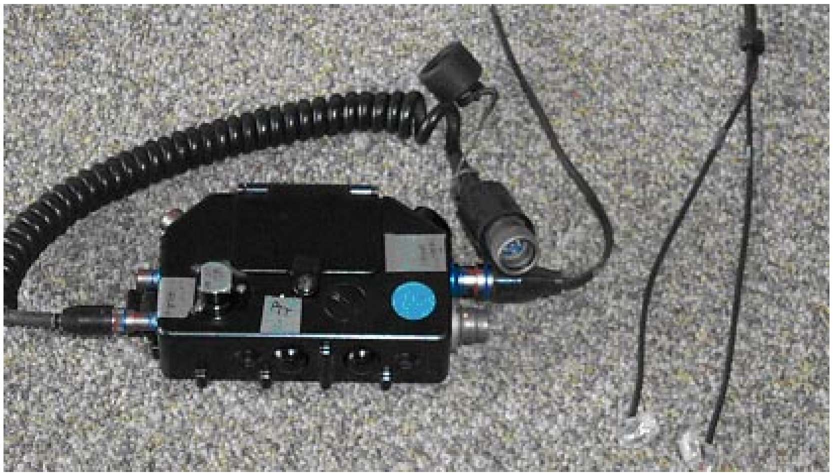

Figure 3. Components of TAC system: interface box with push-to-talk buttons, volume control, earplugs (disposable foam tips not shown).

2.3.2 CEPS

The CEPS, like the TAC, is an integrated communications earplug that provides hearing protection, hearing restoration, and communications. It differs from the TAC in that the microphone used to provide ambient sounds to the user also provides the input signal to the radio connector shown leaving the side of the CEPS module in figure 4. With this method, the user's voice and ambient sounds are output to the radio through the same microphone. The foam insert earplugs provide hearing protection (NRR = 29.5 dB). Wires connect the earplugs to a small box (approximately 1 by 2 by 1 inches) attached to a "hook and loop" yoke with a volume control that allows the user to control the level of sound from the external microphone (gain ≈ 12 dB). Figure 4 shows photographs of the CEPS system.

(a) (b)

Figure 4. CEPS system: (a) "hook and loop" yoke with interface box and earplugs, (b) close view of interface box and earplugs.

3. Field Study Activities

The investigators have adhered to the policies for protection of human subjects as prescribed in AR 70-25. Eight male Soldiers from Natick Soldier Center, Massachusetts, volunteered to participate in the study. Hearing tests were conducted on all Soldiers by one of the experimenters. Thresholds were recorded at octave frequencies from 500 to 8000 Hz plus 6000 Hz for each ear. Six of the eight Soldiers had normal hearing sensitivity bilaterally, defined as thresholds of better than or equal to 20 dB HL in both ears. Two Soldiers had mild hearing losses at 6000 Hz, one in only one ear and one in both ears. Figure 5 shows the average thresholds and standard deviations across frequencies for the Soldiers. These eight Soldiers were divided into two groups of four each. Each group participated in a different activity at any given time. This allowed different activities to run concurrently with a minimum of unoccupied time. The groups participated in a road march, played games of "Battleship[5]" (see section 3.2), and underwent speech intelligibility testing in three test environments (noise only, while riding in a vehicle, and while wearing chem/bio gear). Activities were designed to answer questions about comfort, environmental hearing in quiet and noise, and speech intelligibility when the communication systems were used in the presence of noise.

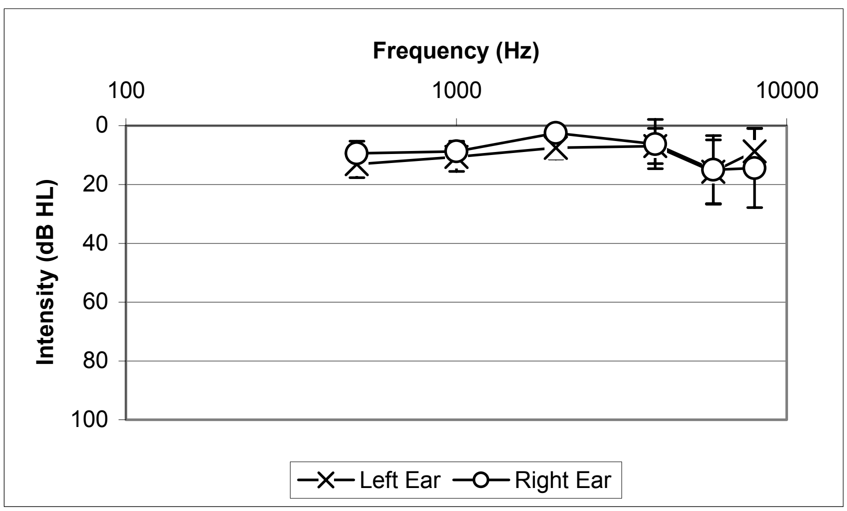

Figure 5. Average hearing thresholds for Soldiers participating in the present study. (Error bars indicate ±1 standard deviation. Thresholds of better than or equal to 20 dB HL[6] are considered normal hearing.)

[5]Battleship is a registered trademark of Hasbro, Inc.
[6]Hearing level: see appendix B.

3.1 Road March

The Soldiers completed a short road march (0.4 mile per leg for a total of 1.6 miles) while wearing each of the four systems. During this time, they wore their battle dress uniforms (BDUs) with the C&HP system and an ACH. Each Soldier was fitted with the proper sized helmet and was encouraged to adjust the padding to optimize fit. Padding was adjusted when needed to optimize fit with the earmuffs. Each system was equipped with a radio. Because some of these systems are prototypes, it was not possible to use them all with the same radio, nor did all the radios function equally well. Use of the radios was intended to demonstrate that all these systems would need to be connected to a radio to allow the Soldiers to gauge ease of movement while wearing each C&HP system and carrying a radio. The Soldiers were encouraged to talk to each other and to the experimenters while walking, thus testing their ability to hear their environment. Occasionally, an experimenter asked random questions over his radio to ensure that the radio systems were operational and properly interfaced.

Participants were instructed that the purpose of the task was to evaluate comfort and ability to hear their environment while wearing hearing protection. They were explicitly told not to evaluate their systems by how well their radios worked. They were asked to take notes on the systems immediately following the march, but final feedback was not obtained until later in the week when they answered the questionnaire.

3.2 Battleship Game

Playing the game of Battleship requires players to attempt to hit the opponent's ships by giving the coordinates of a "guess". The opponent is required to verify these coordinates and provide the other player with feedback about whether this guess was a "hit" or a "miss". This allowed the participants to test their ability to communicate with each other in a noisy environment where hearing protection is needed.

Two small sound-treated booths of similar size (3.7 by 3.4 by 2.4 m and 3.7 by 4.5 by 2.4 m) and acoustic characteristics (ambient noise < 20 dB A-weighted and reverberation time[7] ≈ .6 s) were used during testing (Scharine, Tran, & Binseel, 2004). Pairs of participants sat in the booth while impulse battleground noise with peak levels of 75 to 78 dB A-wtd was presented over loud-speakers. They were instructed to play one game of Battleship while wearing each of the different C&HP systems. They did not use the communications component of the systems—only the environmental hearing component. Following the games, they were asked to rank the systems in terms of their comfort, attenuation of environmental noise, and speech intelligibility.

[7]Reverberation time is the amount of time that it takes the sound pressure level to drop 60 dB after the offset of an impulse sound.

3.3 Speech Intelligibility Tests

The speech intelligibility portion of the experiment objectively measured the ability of the listeners to correctly identify speech stimuli using all four test systems in all possible speaker-listener system combinations (with one exception as explained next). The three conditions used in the speech intelligibility evaluation were (1) a test chamber with noise and the Soldiers wearing BDUs (noise-only condition); (2) the same test chamber with noise and Soldiers wearing BDUs with chemical protective equipment (chem/bio[8] condition); and (3) Soldiers riding in an M113 armored personnel carrier (APC) moving at about 10 mph (APC condition).

3.3.1 The Call Sign Acquisition Test (CAT)

The speech intelligibility evaluation was conducted in three different conditions with the CAT (Rao, Letowski, & Blue, 2002; Rao & Letowski, 2003). The CAT is a military-relevant speech intelligibility test developed by the U.S. Army Research Laboratory (ARL). It consists of all 126 possible combinations of the 18 two-syllable Army phonetic alphabet items and the seven one-syllable numbers from one through eight (nine is not used because it is pronounced "niner" in radio communications). Table 1 shows the 18 alpha and seven numeric components of the CAT "words".

Table 1. CAT alpha and numeric components.

Letters			Numbers
Alpha	Hotel	Tango	One
Bravo	Kilo	Victor	Two
Charlie	Lima	Whiskey	Three
Delta	Oscar	X-ray	Four
Echo	Papa	Yankee	Five
Foxtrot	Quebec	Zulu	Six
			Eight

3.3.2 Speech Intelligibility in Noise Only

The tests described in this section and the next were conducted in ARL's hostile environment simulator (HES). The HES is a large sound-treated chamber (17.3 by 3.4 by 6.7 m) with ambient noise levels less than 30 dB A-wtd and with reverberation times less than 0.3 s (Scharine et al., 2004). The HES is instrumented with multiple speaker arrays. Large speakers provide the capability of creating noise levels as great as 140 dB to simulate military vehicle noise, weaponry, or other custom battle-noise environments. In the noise-only condition, recorded noise from the M113 was reproduced at a 92-dB A-wtd sound level[9]. The participants read or listened to others reading CAT words while wearing the various test systems.

[8]Also known as MOPP (mission-oriented protective posture) gear.

[9]Originally, it was intended that all noises played at the same level as experienced in the M113. However, because of equipment problems during testing, it was not possible to play noise at that level. At 92 dB A-wtd, the listeners were still making a significant number of errors, thus allowing for useful comparisons.

3.3.3 Speech Intelligibility When Chemical/Biological Gear is Worn

The chem/bio condition was conducted in the same chamber as the noise-only condition with the same noise recording. However, the background noise level and personal equipment were different from the noise-only trials. In the chem/bio condition, the background noise was played at 105 dB A-wtd. All participants wore the JSGPM (joint services gas protective mask, or XM50 mask). Two participants wore the prototype protective suits provided by the FFW integrated headgear IPT, and the other two wore a detachable chemical-protective hood with their BDUs. The different personal protective equipment was driven by the fact that only two FFW suits were available for the experiment. The chemical-protective hood was considered the closest surrogate for the FFW suit hood because its material and design were closer to the FFW design than the other available surrogate, the JSLIST (joint services lightweight integrated suit – toxic) parka with attached hood. In the chem/bio condition, all the test systems were worn under the suit/hood, with the exception of the Sordin earmuff system when used with the FFW suit. The Sordin earmuff-style system would not fit under the hood of the FFW suit, so it was worn over the hood.

3.3.4 Speech Intelligibility When Soldiers are Riding in a Tracked Vehicle (APC condition)

The final condition tested speech intelligibility while Soldiers rode in the M113 APC. In this condition, Soldiers wore the test systems and standard BDUs. There was no artificially generated background noise in the APC; however, the APC was generating sound levels of about 105 dB A-wtd when moving at about 10 mph. The sound levels of the noise when the APC was moving 10 mph were equivalent to the levels used for the chem/bio portion of the study. Performing the same test in an APC added the dimensions of vibration and motion to the speaking and listening tasks.

3.3.5 Speech Intelligibility: Experimental Design

For all three conditions, each participant served as both "talker" using three systems (not the CEPS[10]) and "listener" using all four candidate systems. Each participant from the four-person group wore a different test item (the CEPS, TAC, bone conduction with CAE, or Sordin ear-muffs). The person assigned the talker role then read a randomized set of all 126 CAT words. The other three participants listened and wrote what they perceived was said (or left a blank space if they did not hear or could not identify the word) on a pre-printed form. The talker role was rotated among the participants according to a predetermined Latin square scheme until the

[10]The basic configuration of the CEPS is designed to work in noise levels below 90 dB SPL. By design, the external microphone used to transmit communications also transmits ambient noises, and this is a problem in high noise environments. Therefore, in the conditions of this test, the CEPS did not work well for speech communication. However, the CEPS can be used in high noise environments if a noise-canceling microphone is added to the configuration. Unfortunately, this configuration was not available for our evaluation, and our intent was to test performance in a high noise environment. Therefore, rather than test the CEPS in a context for which it was not designed, this function was not evaluated.

persons wearing the bone conduction, the Sordin earmuffs, and the TAC system had all served as the "talker"; the person wearing the CEPS did not act as talker. During any one round of three CAT lists, each Soldier wore a single system and acted as a talker once and as a listener twice, except for the Soldier wearing the CEPS, who listened for all three lists. After a complete round, the Soldiers changed C&HP systems, and the talking/listening tasks were repeated until all Soldiers had used all four systems. Thus, each Soldier listened nine times and talked three times, for a total of 12 lists of 126 CAT words. Table 2 illustrates a sample counterbalance design for one round. Note that although the same set of 126 CAT words was used, a different random order was used for all 12 lists. Participants also wore the equipment in different orders following a predetermined Latin square design.

In order to eliminate differences in speech intelligibility that might be attributable to poor radio transmission and differences in radios, four Radio Shack[11] 277-1008C mini-amplifier-speakers were used to form an intercom system. Each amplifier was labeled for use with a corresponding communications system. The output from the talker was split three ways and plugged into the input of each of the three amplifiers that corresponded with the listening systems. Each listener was plugged into the output jack of his corresponding system (see figure 6). Because the output levels of the different talker systems varied, the listener was required to adjust the volume to a comfortable level free of distortion before each list. Power adaptors (rather than batteries) were used to avoid changes in output strength during testing.

Figure 6. Intercom system formed by four mini-amplifiers.

[11]Radio Shack is a registered trademark of the Tandy Corporation.

Table 2. Sample order of talker/listener assignments for one round.

CAT List	Volunteer 1	Volunteer 2	Volunteer 3	Volunteer 4
List 1	BC/Talker	CEPS	TAC	CEM
List 2	BC	CEPS	TAC/Talker	CEM
List 3	BC	CEPS	TAC	CEM /Talker

3.4 Questionnaire

At the end of the fourth day, a short questionnaire (see appendix A) was given to all the participants, and they were provided with the notes they had taken earlier. The intent was to obtain listeners' feedback about their preferences after they had worn the C&HP systems in a variety of contexts. The questionnaire and the rankings obtained after the Battleship game were the main sources of information about perceived comfort and environmental hearing. We have also obtained information about which system seemed the most viable in its current form. Final questions concerned selection of the best concept (rather than the specific systems) if it were functioning optimally.

4. Results

4.1 Comments From the March

Table 3 lists some of the most common statements made by the participants after the road march. These were collected from the Soldiers' notes and are intended to give a qualitative picture of the Soldiers' perceptions. Each column gives the comments for a particular system. The numbers following each statement indicate the number of times a particular statement was made (if more than once). Since many of the points made by the Soldiers are similar to comments made in the questionnaires, further discussion of their comments is provided in appendix A.

Table 3. Comments from the March. (Numbers in parentheses indicate the number of participants making an equivalent comment.)

Bone Conduction (BC)	Earmuffs (CEM)
Very comfortable (4) Combat Arms earplugs itch/ uncomfortable Push-to-talk button is too big Sound was muted/faint (2)	Headband uncomfortable (5+) Listening clear/best enhanced hearing (4) Did not work (4) Outside sound not over-amplified Liked push to talk button
TAC	**CEPS**
Uncomfortable Difficult to put on and kept falling off (3) Heavy (2) Can hear environmental noise well (4) Wind noise is too loud/seemed over-amplified[12] (4)	Lightweight and comfortable (5) Do not like plugs / worry about wires pulling plugs out of ears (3) No wind noise (2) Can hear well (3)

4.2 Battleship Game

The Battleship game gave the Soldiers experience with the natural hearing/hearing restoration component of their communications system while completing a task that required accurate speech communication in noise. Table 4 gives a summary of the rankings given by the Soldiers after completion of this activity.

Table 4. Ranking data for Battleship (1 = best, 4 = worst).

Ranking	Comfort	Noise Attenuation	Speech Intelligibility	Overall Rank
1	BC / CEM	CEM	CEPS	BC
2	CEPS	CEPS	BC	CEPS
3	TAC	BC	TAC	CEM
4		TAC	CEM	TAC

Bone conduction and earmuffs were ranked highest in terms of comfort. This contrasts with complaints of discomfort while the earmuffs were worn during the road march. The Soldiers were wearing their helmets during the road march task and it is likely that most of the discomfort issues were attributable to poor fit and warmth when worn with the helmet.

The earmuffs were designated as providing the most noise attenuation. It is unlikely that actual attenuation differed much between the four systems. In general, earmuffs are less effective for lower frequencies and on average, both earmuffs and earplugs are equally effective for frequencies of 1000 Hz or higher (Berger, 2000). The attenuation provided by earplugs can be vulnerable to the quality of fit. The earplugs used in the study were primarily fit by the Soldiers themselves with occasional assistance from one of the experimenters.

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[12]One Soldier made the perceptive comment that distant sounds seemed louder than near ones. Undoubtedly, this was an artifact of the compression circuitry provided for hearing protection, but this comment is important for further development of a system of this type.

The CEPS and BC systems were both ranked higher for speech intelligibility and were the top two systems favored overall. This ultimate ranking suggests that situational awareness and comfort were more important to the Soldiers than absolute protection.

4.3 Speech Intelligibility

The CAT was scored as the number of items where both parts (alpha and numeric) were identified correctly. Each data point is the percent correct of a possible 126 items for a single CAT list. Speech intelligibility is determined by the microphone and the loudspeaker. Therefore, with the exception of the CEPS, each system was used for both listening and talking. The resulting CAT scores were then analyzed two ways by the system used for talking (BC, EM, and TAC) and by the system used for listening (BC, EM, TAC, and CEPS). Figure 7 presents the mean percent correct scores for each of the CH&P systems for each of the study conditions. The error bars indicate the standard error for each condition.

Thus, for each of the testing conditions, the CAT scores could be grouped as having three levels of C&HP talker system and four levels of C&HP listener system. A repeated measures ANOVA (analysis of variance[13]) was conducted on both of these groupings to test the statistical significance of the differences between CAT score, which was attributable to testing condition and C&HP system. Equipment failures caused several problems during testing and resulted in some missing data. During significance testing, the following problems were encountered and resolved as noted.

The bone conduction microphone in the communications earmuffs did not function well in the chem/bio condition because the earmuffs would not fit under the hoods. It became apparent after the first group of Soldiers was tested that scores were nearly always zero. Thus, this particular system was not used for talking with the second group.

The TAC system failed numerous times during the chem/bio condition. These data points were not included in the averages as grouped by either talker or listener system. However, this meant that only one data point was available to evaluate bone conduction as a listening system. In order to test bone conduction as a listening system, the missing data points were replaced with the score in the single successful trial.

[13]A statistical method for making simultaneous comparisons between two or more means; a statistical method that yields values that can be tested to determine whether a significant relation exists between variables.

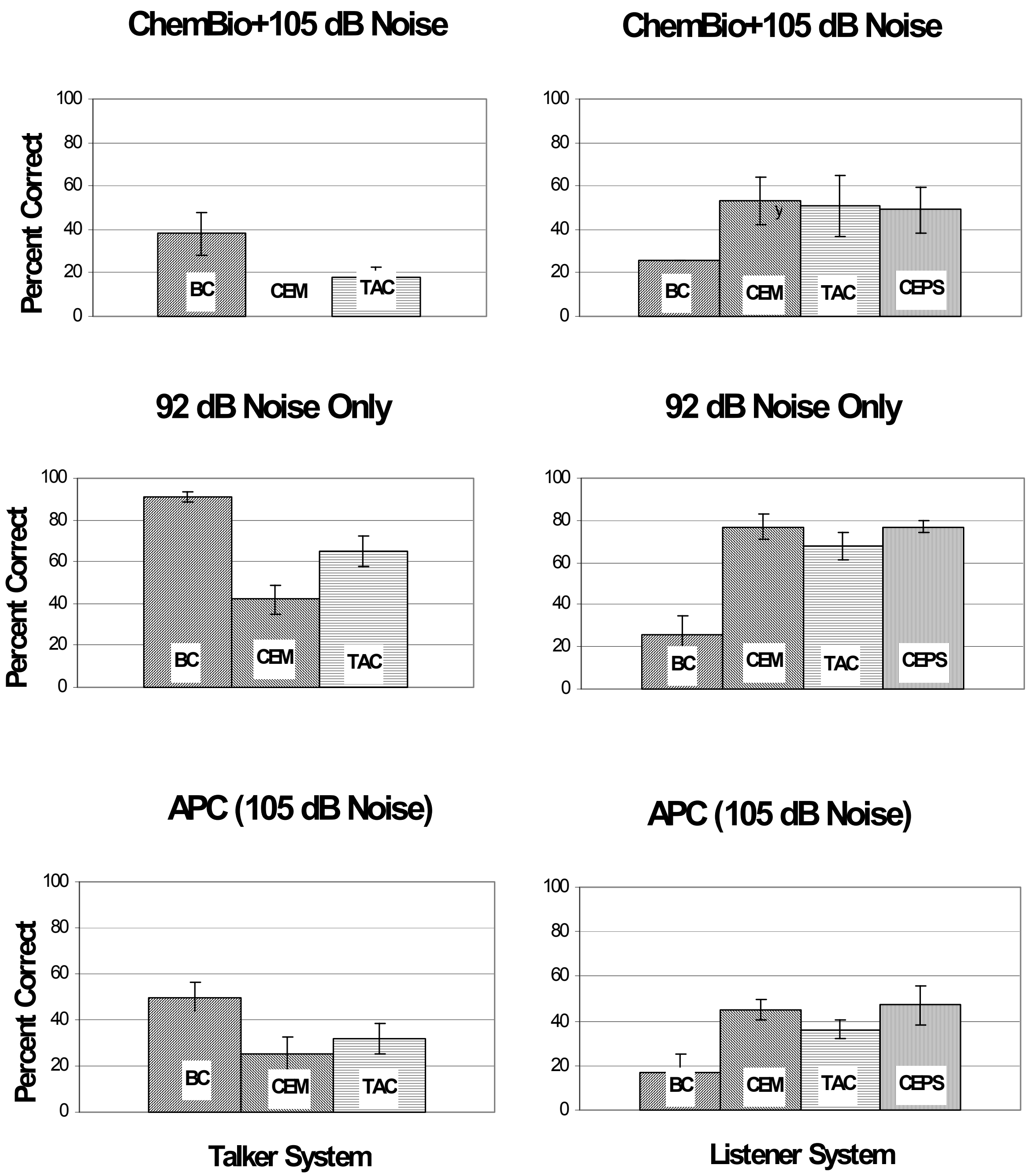

Figure 7. Average speech intelligibility results by environment. (Note. Scores only include tests for which systems were operational; see text.)

4.3.1 Scores Grouped by Talking System

Scores on the CAT tests differed significantly, depending on the test condition, $F(2,6) = 161.31$, $p < .001$. The main effect of talker system was significant, $F(2,6) = 47.54$, $p < .001$. Planned comparisons of talker scores for the BC system versus the other systems showed that performance with the BC system was significantly better, $F(1,3) = 123.16$, $p = .002$. Scores obtained when the talker was wearing the TAC system were also significantly better than those obtained with the earmuffs, $F(1,3) = 12.884$, $p = .037$. The relative performance of the three talking systems did not differ significantly with test condition.

4.3.2 Scores Grouped by Listening System

Once again, scores differed because of test condition, $F(2,12) = 10.215$[14], $p = .003$. Speech intelligibility scores also differed significantly, depending on the system used to listen, $F(3,18) = 15.58$, $p < .001$. Planned comparisons showed that scores obtained when the listener was wearing the BC system were significantly lower than those obtained with the earplug systems, $F(1,6) = 28.01$, $p = .002$. The difference between the two earplug systems was not significant. The relative performance of the four listening systems did not differ significantly between test conditions.

4.3.3 Main Speech Intelligibility Findings

When we look at the scores grouped by talker system, it is clear that the microphone in the bone conduction configuration performed best in all three conditions. Speech intelligibility scores were lowest when the earmuffs were used as a talker system. The placement of the bone microphone in the ear cup did not provide enough of a rigid contact surface between the microphone and the bony portion of the ear to transmit vibration. When the earmuff system was worn in the chem/bio testing, it did not function at all.

In general, the communications earplugs provided transmissions to the listener that were equivalent or slightly better than those of the earmuffs and significantly better than those of the BC system. The difference between the two earplug systems when used for listening was not significant. As a listener system, the Sordin earmuffs scored equivalently to the earplug systems.

4.4 Questionnaire Results

Figure 8 shows the questionnaire results. The full questionnaire is included as appendix A. The y-axis represents the number of respondents who chose a particular system. The first question asked was "which of the current systems, as is [15], would a Soldier take with him if faced with a difficult listening situation?" As can be seen in figure 8a, the BC and TAC systems tied with three votes each. The second question asked was "which of the systems provided the best speech intelligibility?" The BC system beat the TAC by half a vote (because one person indicated that he would use bone conduction for talking but the CEPS for listening). The third question concerned the ability to hear environmental sounds (through natural hearing or hearing restoration). The Soldiers seemed to like all systems equally well for this purpose.

[14]Missing data were handled differently for talking and listening systems, so the F scores are slightly different.

[15]Since the CEPS is not intended to be used (in this configuration) for speech transmission in high noise levels (>90 dB SPL), participants were only able to use the system for speaking during the road march portion of the study. Questionnaire ratings about a system "as is" reflect that fact.

The fourth and fifth questions were which system was the most comfortable and which was the least comfortable (figure 8d). Earmuffs were chosen by three Soldiers as the most comfortable and by two Soldiers as the least comfortable. The BC and CEPS systems were deemed equally comfortable; the TAC system was judged least comfortable. Comments suggest that the contradictory results for the earmuffs are attributable to the Soldiers' dislike of having wires hanging from their ears countered by the discomfort of having a headband underneath the helmet. Those who found the BC system uncomfortable were displeased by the CAE, which they found itchy, and by the large push-to-talk button. Those who were unhappy with the CEPS disliked having wires hanging from their ears. The TAC was also disliked for its wires. Although both the TAC and the CEPS systems had wires connecting to the earplugs, the mechanism for supporting the wires on the CEPS appears to have been better tolerated[16]. Further, many complained about the size of the interface box on the TAC.

Question 6 asked about the quality of hearing protection of each system. Hearing protection usually is marketed with an NRR in decibels, an objective measure indicating the number of decibels by which a particular noise is attenuated when tested during controlled conditions. However, the actual attenuation experienced by users will vary because of individual differences in ear canal shape and user fit, especially for earplugs. The perceived subjective quality of that attenuation is further affected by the frequency ranges attenuated and other nonspecific factors. Therefore, although earmuffs were favored slightly more overall, it is more likely that listeners were not consistently inserting the foam tips appropriately or felt that the circumaural muffs provided more isolation from noise. Recall that the Soldiers primarily inserted the earplugs themselves with some assistance by experimenters. User fit typically results in a lower NRR than fit conducted by another person. The NRR of the earmuffs is lower than that of the foam earplugs.

Question 8 was an open-ended invitation for comments; table 5 gives the most common responses.

Given that several of the systems were prototypes and incomplete, we included a question about which concept, rather than actual system, the Soldier would prefer if all the negative aspects were corrected. In this question, three concepts were described: bone conduction, earmuffs, and earplugs. Recall that both the TAC and the CEPS are a form of earplug solution. Also recall that the BC system requires some form of hearing protection, most likely earplugs. Four Soldiers chose the bone conduction concept as their favorite, indicating that it would be improved if the signal received were louder and if the earplugs and the push-to-talk button were replaced. Three chose the earplug concept but wished for a wireless solution or a better design of the support for the wires. Note that despite the fact that many Soldiers disliked having things in their ears, they chose systems other than earmuffs.

[16]Note that earplugs and their wires can be supported by a headband (such as the one shown in the questionnaire) or by the helmet itself. The CEPS is already available in these two forms, but these were not available for this evaluation.

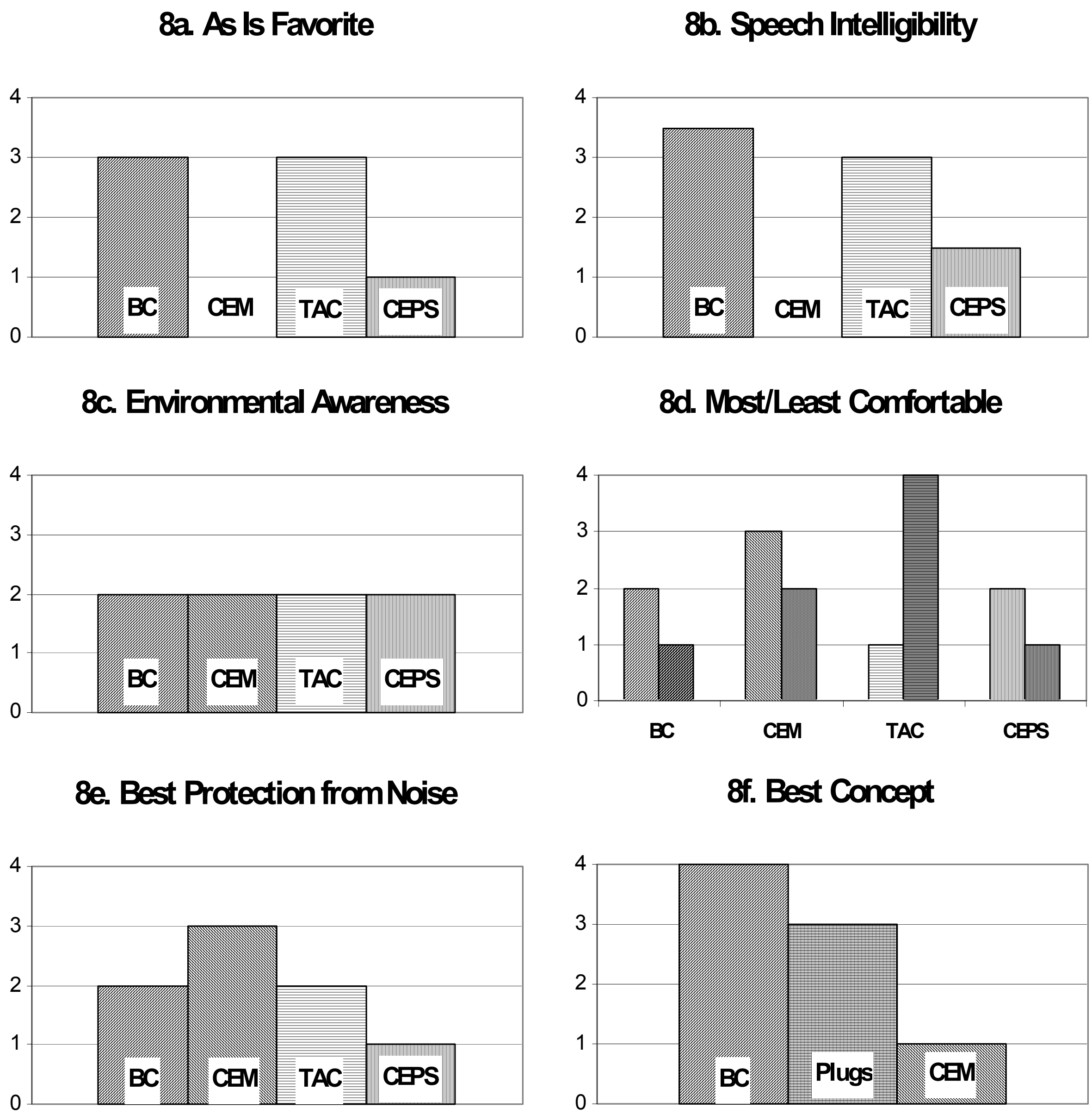

Figure 8. Questionnaire results.

Table 5. Common responses to question 8 of the questionnaire.

Bone Conduction	CEM	TAC	CEPS
Need to redesign the earplugs. Need to work on the fit of the receivers (vibrators). Push-to-talk button is too big. A good system, comfortable. Best system to talk with.	Not easy to hear with I loved not having to stick things in my ears Difficult to fit under helmet Microphone did not work in high noise environments Best protection	Needs work. Wires were difficult to work with. Wires become a problem with the chem/bio ensemble. Too heavy. Custom fit earplugs would be inconvenient.	Lightweight. Clear speech. Wires sometimes pull out of ears.

5. Discussion

It is not possible to choose a single winner from the systems in their current implementation. No system showed superior speech intelligibility for both listening and talking. It appears that the bone conduction configuration and the integrated earplug configuration did equally well as concepts and both should be included in future tests. In regard to the specific technical details, all systems evaluated in this study had various serious flaws that may be eliminated in the future. However, in this report we can only make statements about the equipment used in the current tests. Under these constraints, we discuss the merits and flaws of each system and describe the limitations upon which these assessments are based. In so doing, we also identify questions that remain to be answered and improvements that need to be made.

5.1 Bone Conduction Configuration

5.1.1 Comfort

The BC configuration included both the headset and the hearing protection. Therefore, ratings of comfort included the BC configuration and the CAE. Although this system has the potential to be the most comfortable system, the study indicates that the triple flange design of the CAE is not easily tolerated. Given that the primary advantage of these earplugs is that they provide a low-cost form of level-dependent hearing protection, it is hoped that a similar but more comfortable option will be developed that uses the same core component. For example, the core that contains the orifice allowing level-dependent hearing could be placed in a foam insert or a custom-molded plug.

The unwieldy size of the push-to-talk button is a minor concern that is easily fixed, but it must not be overlooked as it was mentioned several times as a poor feature of the BC system.

5.1.2 Speech Intelligibility

Placement and power of the vibrators, the “listener” component of this configuration, still needs some work. Some Soldiers were able to hear quite well, but others reported difficulty. This difference is probably attributable partly to less-than-optimal vibrator placement for some listeners. The vibrators in this configuration were part of a webbed cap, and depending on the Soldier’s head shape, they might be located on the temporal area, the zygomatic arch, or the cheek area. The auditory research team at ARL has compared thresholds for different placements of bone vibrators. The zygomatic arch is an appropriate site for transducer placement, but sufficient pressure must be applied and placement must be directly over the bone (not on the softer cheek area). This may explain the differences in performance among the Soldiers. More important, the power deficiency of BC vibrators needs to be addressed in the future designs to improve their performance in high noise environments.

5.1.3 Environmental Hearing

In general, there was little comment, positive or negative, about the effectiveness of the CAE for allowing environmental hearing. We believe that this is because they were, as designed, essentially acoustically transparent and fulfilled their mission. We consider it to be a positive finding.

5.2 Earmuffs

5.2.1 Comfort

Analysis of the questionnaire results and comments heard during the study clearly demonstrated that Soldiers found the earmuffs uncomfortable to wear with a helmet. When a helmet was not required, such as during the Battleship game, earmuffs were deemed most comfortable, and the Soldiers preferred not to have earplugs in their ears. These paradoxical results are clarified by the finding that only one participant chose earmuffs as the appropriate ideal concept.

5.2.2 Speech Intelligibility

Analysis of the speech intelligibility measures showed that although Soldiers were able to understand speech well through the earmuffs, these scores were not significantly different than other systems. The bone conduction microphone in the ear cup did not pick up and transmit speech well because of the lack of contact with a bony surface to pick up vibrations from the skull[17].

5.2.3 Environmental Hearing

The earmuffs provide restoration without amplification with a maximum input/output ratio of 1:1. They also had the lowest maximum output, 82 dB SPL. Therefore, the Soldiers found the restoration less offensive but less impressive.

Because the earmuffs are difficult to implement with the helmet and because other systems provide adequate communications and hearing protection, we do not recommend the use of earmuffs.

[17]In fairness, the placement of the bone microphone inside the ear cup of the earmuff was a prototypical configuration, and a different placement would probably work well. The recommendation against earmuffs was based entirely on the fact that they were not a preferred concept.

5.3 Integrated Earplugs

The CEPS is more mature than the TAC and is currently fielded. Therefore, although we can anticipate what is planned for the final version of the TAC, we can only compare it to the CEPS in the TAC's current state. To the extent that the current version of the TAC differs from the proposed final version, this will be noted.

5.3.1 Comfort

Although the TAC promises a custom-molded earplug that should be comfortable and provide good hearing protection, it currently has a foam insert tip that is quite similar to that of the CEPS. Several Soldiers commented that the wires seemed to pull on the plugs in the ears. Even though both systems connect via wires to a radio through some form of interface box, the smaller controls on the CEPS and attachment to a yoke (reducing the length of unsupported wire) were preferred to the larger interface box of the TAC. This difference in size of the two interface boxes may become less important in the future because the proposed design of the TAC has a control mechanism similar to the CEPS. There are a number of possible solutions to the issue of the wires pulling on the plugs. The CEPS has two alternate configurations that were not tested here. One of them (shown in the questionnaire) suspends the wires from a headband. Another version has the earplugs connected to an aviation helmet. It is likely that either of these options would make the earplugs feel more secure. Another factor in the choice of suspension method is whether communications without the helmet is to be provided.

Although the developers of the TAC plan to implement custom ear molds and the CEPS offers these as an option, neither of the systems in the form tested had custom fit ear molds. Those advocating the use of custom earplugs maintain that they are more comfortable and provide better hearing protection than generic plugs. However, attenuation measurements of properly fitted foam earplugs and custom fitted earplugs show that foam earplugs provide equal or superior attenuation for all frequencies (Berger, 2000). Many users fail to insert the foam plugs properly, thus negating the measured benefits. Proponents of custom fit earplugs argue that such plugs are easier to insert properly. It is also not clear whether custom fit earplugs are more comfortable than foam earplugs. Some of this depends on the depth to which the earplug extends into the ear canal and on the seal that the plug makes with the ear. Deeper plugs that seal the ear are often reported to be less comfortable, even though they provide better protection.

The implementation of custom fit plugs can present a logistical problem. Obtaining a good fit requires trained personnel to make ear impressions. Audiologists who dispense hearing aids sometimes require several patient visits to successfully fit a hearing aid. If hearing restoration is provided electronically, the tiny electronic components (similar to those in hearing aids) can easily break. If a custom plug is used, systems cannot be exchanged if the electronics break. It is suggested that if a custom plug is used, any electronic components should be modular and removable from the plug itself. Further, if a custom plug is used, on-site customization is recommended rather than an ear impression which is then sent elsewhere for the creation of earplugs.

5.3.2 Speech Intelligibility

It is not possible to compare the communications microphone of the two earplug systems because the CEPS was not designed for the noise levels used in the current study. Further, although the BC system outperformed the TAC as a talker system, it is possible that the in-the-ear bone conduction microphone of the TAC would work better when used with a custom molded earplug. It is not possible to make a recommendation based on the current performance of these systems; however, as noted before, it is suggested that a decision be made about the desirability of custom molded earplugs.

5.3.3 Environmental Hearing

Both systems provide hearing restoration through the use of an external microphone. One can mute input from this microphone by pushing a button (TAC) or turning down the volume control (CEPS). Currently, the TAC's external microphone lacks a wind screen; this drawback was noted by several listeners who commented on the system's sensitivity to wind. These systems limit loud impulse sounds, preventing them from passing through the external microphone; however, there are perceptual differences in the results of this processing and the CEPS was preferred for environmental hearing.

5.3.4 Other Factors

The two earplug systems differ in both battery type and life. The TAC uses a 9-volt battery and the CEPS uses two AAA batteries. Currently, the TAC requires much more power than the CEPS and when the batteries are depleted, the system shuts off immediately. The systems used in the current study required new batteries on a daily basis, and loss of power resulted in loss of data during testing. In the future, the system is supposed to use an AA battery, and additional power will be provided by the radio. It is unknown whether the processing capability is the reason for the current higher power requirements or if there is some other reason.

5.4 Communications Without a Helmet: Unknown Costs and Benefits

System developers are still unclear whether the communications system should be an integrated part of the helmet or should be independent of the helmet. This decision depends on whether the advantage of independent communications outweighs any disadvantages of having separate pieces of equipment. In the present study, all evaluated systems were independent of the helmet. There is one exception: during the road march, one of the four systems (the BC system) was integrated into the pads of the helmet, while the other three systems were used with the helmet but not integrated into it. This made the BC system easier to manage because the hanging wires did not impact donning of the helmet. A detachable cable would probably solve this problem.

With respect to the communications earplug concept, as demonstrated with the CEPS and TAC systems, it is likely that the weight of the wires connecting to the earplugs needs to be supported someplace on the head or near it. The two alternate forms of the CEPS (headband or helmet) show how a communications earplug can be independent of the helmet or attached to the helmet and still support the wires. As with the BC system, a detachable cable might be preferable to a permanently attached one, thereby preventing entanglement. However, independent communications may be preferable and further study in this area is needed.

6. Conclusions

The primary recommendation resulting from this study is to select two of the three conceptual configurations for future tests: the BC system and the communications earplug. However, neither of these two configurations is adequate in its current implementation. In order for either system to be considered, the following issues and questions must be resolved.

6.1 Bone Conduction Configuration

1. Improve or replace the CAE for hearing protection.
2. Improve power output of the vibrators for high noise environments.
3. Miniaturize components and consider multiple small transducers in place of the two bone vibrators.

6.2 Integrated Earplug Configuration

1. Make a decision about feasibility of custom made earplugs.
2. Ensure that the communications microphone provides speech communications in high noise environments.
3. Evaluate the human factors issues related to the suspension of the wire.

6.3 Independent Communications

Finally, it is suggested that one of the imminent evaluations be used to identify whether communication systems should be independent from the helmet or integrated with the helmet. Both the Soldier’s comfort and the Soldier’s need for communications should be considered.

7. References

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Appendix A. Questionnaire

Subject Number ___________   MOS _________________

During this week, we have given you the opportunity to try four systems (see page 2) in a variety of contexts. They each provided communications and hearing protection that allowed for natural or restored hearing. Now we want YOUR opinion about which system gave you the best communications and hearing with hearing protection. We also want to know which system was the most comfortable and the easiest to wear. The radios are NOT a part of the evaluation. In the end, the communications system will be used with the radio that is to be fielded.

Scenario:

You are a member of a team assigned to recon an area in a small village in order to clear and occupy it. There are a number of enemy observers located there who are directing artillery fire. There is also some heavy machine gun fire coming from various directions. It is very noisy and chaotic here. You need to have radio communications because you are being radioed information about possible enemy locations obtained from aerial photographs being taken by UAVs (unmanned aerial vehicles) and you need to radio your observations. You also need to communicate by direct voice with the team members around you as you all try to determine whether buildings are occupied and clear the region of non-combatants.

1. Given a choice, which of these communications and hearing protection configurations would you take with you? (circle one)

(A) Bone conduction pads with combat arms earplugs
(B) Earmuffs with bone conduction microphone
(C) TAC earplugs
(D) CEPS earplugs

2. You got a chance to hear how speech sounds through each of these systems during noisy conditions, while wearing chem/bio gear and while riding in an M113. Which of these four configurations would you choose for radio communications? (circle one)

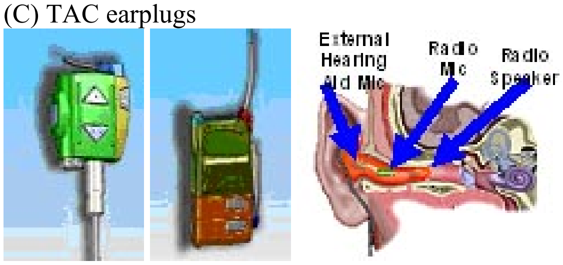
(A) Bone conduction pads with combat arms earplugs
(B) Earmuffs with bone conduction microphone
(C) TAC earplugs
(D) CEPS earplugs

OPTIONS

(A) Bone conduction pads with combat arms earplugs

(B) Earmuffs with bone conduction microphone

(C) TAC earplugs



(D) CEPS earplugs[18]

3. Soldiers often complain of not being able to hear their surroundings while wearing hearing protection and communications systems. You got a chance to try out the hearing restoration / natural hearing of these four systems during the march and during the Battleship game. Which of these four configurations allowed you to best hear your team members (non-radio communication) and the surrounding environment? (circle one)

(A) Bone conduction pads with combat arms earplugs
(B) Earmuffs with bone conduction microphone
(C) TAC earplugs
(D) CEPS earplugs

4. Which of the four configurations was the MOST comfortable to use? (circle one)

(A) Bone conduction pads with combat arms earplugs
(B) Earmuffs with bone conduction microphone
(C) TAC earplugs
(D) CEPS earplugs

5. Which of the four configurations was the LEAST comfortable to use? (circle one)

(A) Bone conduction pads with combat arms earplugs
(B) Earmuffs with bone conduction microphone
(C) TAC earplugs
(D) CEPS earplugs

6. Which of the four configurations above provided you with the best hearing protection? (circle one)

---

[18]At the time of test preparation, we did not have a photograph of the CEPS in the configuration that was used in the test. This was verbally explained to the participants when they answered the questionnaire.

(A) Bone conduction pads with combat arms earplugs
(B) Earmuffs with bone conduction microphone
(C) TAC earplugs
(D) CEPS earplugs

7. Share with us any other comments or suggestions that you have (e.g., ease of donning/doffing, use in vehicles, or use in field, etc.). Are there any changes that you would suggest for any of these systems? Are there any other issues that you would like us to consider?

8. During these tests you tried three different concepts:

(1) Bone conduction microphone with bone conduction speakers combined with "natural hearing" earplugs.
(2) Earmuffs with a bone conduction microphone.
(3) Communications earplugs

Given that these systems are prototypes and that some improvements may be needed, which concept did you like the best and would you prefer if the problems were fixed? (Select one of the above). Why did you prefer it? What would you want fixed?

Appendix B. Glossary of Acronyms

ACH	advanced combat helmet: similar to the personal armor system for ground troops (PASGT) Kevlar[19] helmet but with less ear and cervical coverage for improved hearing and increased field of view in both standing and prone positions. The ACH is also lighter and offers improved ballistic protection. It is currently being introduced as the standard helmet (sometimes referred to as the MICH [modular integrated communications helmet] or the TC 2000).
APC	armored personnel carrier; in this case, the M113.
ARL	U.S. Army Research Laboratory
BC	bone conduction: a communications system based on bone conduction of sound energy, rather than air conduction, implemented by microphones and vibration placed on the head.
BDU	battle dress uniform
CAE	combat arms earplug: an Army earplug with two sides, giving continuous noise protection with one side and level-dependent impulse noise protection with the other.
C&HP	communications and hearing protection
CAT	call sign acquisition test: a speech intelligibility test consisting of all 126 possible combinations of the 18 two-syllable Army phonetic alphabet items and the seven one-syllable numbers from one through eight.
CEM	communications earmuffs: an earmuff-based C&HP system
CEPS	communications enhancement and protection system: an earplug-based C&HP system.
Chem/Bio	chemical-biological: as in chem/bio protective gear, such as protective masks, gloves, boots, and overgarments (see MOPP).
dB	decibel: a unit for measuring the relative strength of a signal. It is the logarithmic ratio of the strength of the signal of interest to the strength of a reference or comparison signal.
dB A-wtd	decibels, A weighted: a measure of the energy present in a sound, weighted for the sensitivity of the human ear at various frequencies. Energy at frequencies at which the ear is sensitive is weighted greater than energy at ear-insensitive frequencies.
FFW	Future Force Warrior: previously known as Objective Force Warrior
HES	hostile environment simulator
HL	hearing level: the number of decibels above audiometric zero at which a measured ear barely hears a sound.

[19]Kevlar is a registered trademark of E.I. duPont de Nemours & Co., Inc.

Hz	Hertz: cycles per second (a measure of frequency)
IPT	integrated product team
JSGPM	joint services gas protective mask
JSLIST	joint services lightweight integrated suit – toxic: a chemical-biological protective suit.
NRR	noise reduction rating: an industry rating of the attenuation of hearing protection devices
SPL	sound pressure level: a measure, in decibels, of the ratio of the pressure of a sound wave relative to a reference sound pressure, typically referenced to 20 μPa (micropascals).
TAC	terminal attack communications: an earplug-based C&HP system

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