AFRL-RH-WP-TR-2016-0092

Performance Assessment of the 3M Combat Arms Generation 4.0 Tactical Military Shooter's Ear Plug

Hilary L. Gallagher
Battlespace Acoustics Branch
Wright-Patterson AFB, OH

Nourhan K. Abouzahra
Oak Ridge Institute for Science and Education
Oak Ridge, TN

Billy J. Swayne
Ball Aerospace Technologies
Dayton, OH

June 2016

Interim Report

DISTRUBITON STATEMENT A: Approved for public release: distribution unlimited.

STINFO COPY

AIR FORCE RESEARCH LABORATORY
711 HUMAN PERFORMANCE WING,
HUMAN EFFECTIVENESS DIRECTORATE,
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

AFRL-RH-WP-TR-2016-0092 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//signed//
HILARY L. GALLAGHER
Work Unit Manager
Battlespace Acoustics Branch

//signed//
DAVID PANBOON, MAJ
Chief, Battlespace Acoustics Branch
Warfighter Interface Division

//signed//
WILLIAM E. RUSSELL
Chief, Warfighter Interface Division
Human Effectiveness Directorate
711 Human Performance Wing

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
24-06-2016

2. REPORT TYPE
Interim

3. DATES COVERED *(From - To)*
Sep 2015 – June 2016

4. TITLE AND SUBTITLE
Performance Assessment of 3M Combat Arms Generation 4.0 Tactical Military Shooter's Ear Plug

5a. CONTRACT NUMBER
FA8650-14-D-6501-0008

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Hilary L. Gallagher
Nourhan K. Abouzahra *
Billy J. Swayne**

5d. PROJECT NUMBER
5329

5e. TASK NUMBER
532916

5f. WORK UNIT NUMBER
H0K8 (532916EX)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
2610 Seventh St. Bldg 441
WPAFB, OH 45433

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Materiel Command
Air Force Research Laboratory
711 Human Performance Wing
Airman Systems Directorate
Warfighter Interface Division
Battlespace Acoustics Branch
Wright-Patterson AFB OH 45433

*Oak Ridge Institute for Science and Education
Oak Ridge, TN 37831
**Ball Aerospace Technologies
Dayton, OH

10. SPONSOR/MONITOR'S ACRONYM(S)
711 HPW/RHCB

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RH-WP-TR-2016-0092

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES
88ABW Cleared 01/17/2017; 88ABW-2017-0156.

14. ABSTRACT
Passive hearing protectors, capable of attenuating both continuous and impulsive noise, were designed to protect the hearing of individuals exposed to a variety of impulsive and continuous noise like gunfire, explosions, vehicles, and machinery. Preservation of ambient listening capabilities and situational awareness is necessary for many military operations. The 3M Combat Arms Generation 4.0 Tactical Military Shooter's Ear Plugs were assessed for: continuous noise attenuation, impulsive peak insertion loss, and sound localization. The Combat Arms Generation 4.0 Ear Plugs reduced the noise level in the ear when the user was exposed to continuous and/or impulsive noise. Conversely, the Combat Arms Generation 4.0 Ear Plugs reduced the spatial aural cues required to accurately localize sounds essential to maintaining situational awareness which resulted in a degradation of localization capabilities in comparison to the open ear performance.

15. SUBJECT TERMS passive hearing protection, noise attenuation, localization, blast, impulsive noise attenuation, REAT, IPIL

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	SAR	34	Hilary Gallagher
					19b. TELEPHONE NUMBER *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

THIS PAGE IS INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Understanding the noise attenuation performance of a hearing protection device is important in order to protect the user from excessive noise exposure and from over protection. It is also important to measure the performance of hearing protection devices to gain objective and accurate assessments of the performance of the device and the effect/s on the user's auditory system. The objective of this study was to measure the auditory performance of the 3M Combat Arms Generation 4.0 Tactical Military Shooter's Ear Plugs, which will be referred to as CAE Gen 4 in this report. The assessment included measurements for continuous noise attenuation, impulsive peak insertion loss, sound localization, and visual target acquisition time using an aurally-guided visual search task. CAE Gen 4 reduced the noise level in the ear when the user was exposed to continuous and/or impulsive noise. However, the CAE Gen 4 also reduced the spatial cues required to accurately localize sounds, an ability that is essential to maintaining situational awareness, which resulted in a degradation of localization capabilities in comparison to the open ear performance.

1.0 INTRODUCTION

Some military personnel work in unpredictable noise environments that require a more flexible type of hearing protection system in order to be mission effective while reducing the risk of permanent hearing loss and support mission effectiveness. The Combat Arms earplugs (CAE) produced by 3M are level-dependent hearing protection devices designed to provide the user protection from both continuous and impulsive noise while allowing the user to hear low-level sounds when necessary in order to maintain situational awareness. Two of the first products by 3M to serve this purpose were the CAE 370-1022 and Dual Ended (DE) CAE. These earplugs were developed to fill an operational need for a more flexible type of hearing protection (Figure 1). CAE 370-1022 were designed to provide the user with an open and closed setting. The user had to manually remove the ear plug from the ear to select the desired setting (open or closed). The DE CAE featured two ear tips. Each tip was a different color (yellow or olive green), and each color had a different mode/mechanical design. The yellow tip of the earplug, when inserted into the ear canal, allowed sound to pass through mostly unaffected, but reduced high level peak impulse noise. The olive green tip of the earplug, when inserted into the ear canal, acted as a conventional passive hearing protector for both continuous and impulsive noise exposures. Two major concerns with these designs were that the user could be completely exposed to noise when the earplug was transitioned between the open and closed setting as well as the fact that this transition would happen in the field when dust and dirt may have built up on the un-inserted ear tip before it was then inserted directly into the ear canal.

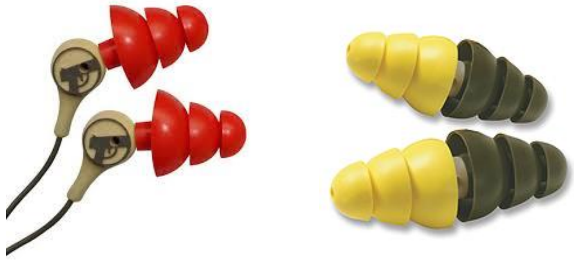

Figure 1. CAE 370-1022 and DE CAE

A new CAE was designed so that the user could more easily transition between modes without having to refit the earplug. The new design was called Combat Arms Generation 4.0 Tactical Military Shooter's Ear Plugs (CAE Gen 4), Figure 2.

Figure 2. CAE Gen 4

It was important to measure the performance of hearing protection devices to gain objective and accurate assessments of the performance of the device and the effect/s on the auditory performance of the user. A multifactorial assessment approach was used to determine if the newly designed CAE Gen 4 met the military's operational needs: continuous noise attenuation, impulsive peak insertion loss, and maintenance of auditory localization and visual target acquisition time.

2.0 **BACKGROUND**

Military ground operations frequently occur in complex environments that necessitate maintaining a balance between operational effectiveness and personnel safety. The goal of effectively protecting the hearing of personnel has been complicated by the need for warfighters to maintain access to acoustic information in the ambient environment (Figure 3). Firing even a small number of rounds from a weapon can cause temporary hearing loss, which can impair the ability of the operator to effectively monitor his/her auditory environment. Repeated unprotected exposures to small arms fire could eventually result in permanent hearing loss. Noise exposures from larger weapons and blasts could instantly cause permanent hearing loss if no protection is worn.

Figure 3. Marine Forces in Operational Environments

3.0 METHODS AND RESULTS

Level-dependent earplugs were developed to improve situational awareness by allowing the user to hear low-level sounds while mitigating hearing loss and tinnitus caused by exposure to loud, steady-state and impulse noise. The general approach for this assessment was to use American National Standards Institute (ANSI) measurement procedures for continuous noise attenuation and impulsive peak insertion loss and to use Air Force Research Laboratory (AFRL) defined procedures for localization.[1-3]

The overall methods and results are described in the following sections. The first section describes the hearing protector that was used in the study. The subsequent sections describe each measurement method including a description of the subjects, the facilities, and the details of the specific measurement methods and results.

3.1 Hearing Protection Device

The CAE Gen 4 are single ended, combat-ready ear plugs. The CAE Gen 4 were designed so the user could select the required level of noise protection based on the noise environment. For continuous noise protection, the earplug is placed in the closed mode. The open mode was designed to allow the users to hear low level sounds and still protect the auditory system during impulse noise events (Figure 4). The CAE Gen 4 is equipped with a toggle valve that can be easily operated by the user while in the ear, which allowed the user to switch between protection modes safely.

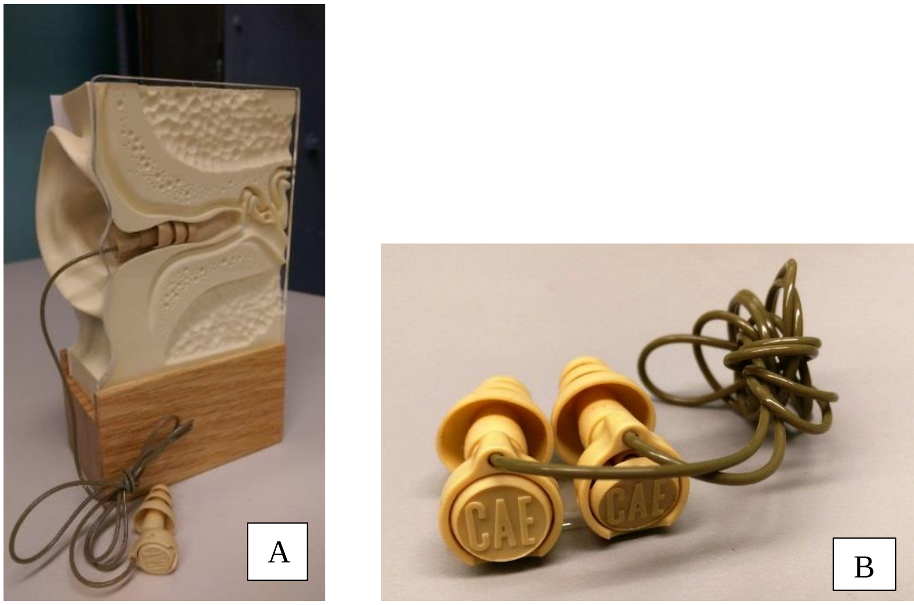

Figure 4. A. CAE Gen 4 in the ear and B. CAE Gen 4 with the toggle valve in the closed (left) and open (right) setting

3.2 Continuous Noise Attenuation

Continuous noise attenuation performance measurements were collected with the CAE Gen 4 in both the open and closed settings using human subjects. All human subjects were compensated volunteers. There were ten male and ten female subjects, ranging in age from 18 to 34 years. All subjects were required to have a technician administered screening audiogram via Hughson-Westlake method, with behavioral hearing thresholds inside the normal hearing range; 25 dB hearing level (HL) or better from 125 Hz to 8000 Hz.

The AFRL facility used for this portion of the study was specifically built for the measurement of the sound attenuation properties of passive hearing protection devices. The chamber, shown in Figure 5, its instrumentation, and measurement procedures were in accordance with ANSI S12.6-2008 American National Standard Methods for Measuring the Real Ear Attenuation of Hearing Protectors.[4] This standard requires measuring the closed (with device in place) and open hearing threshold of human subjects using a von Békésy tracking procedure. The thresholds were measured two times for the open ear condition and two times for the closed ear condition. The real-ear attenuation at threshold for each subject was computed at each octave frequency, 125 to 8000 Hz, by averaging the two trials (the difference between open and close ear hearing thresholds).

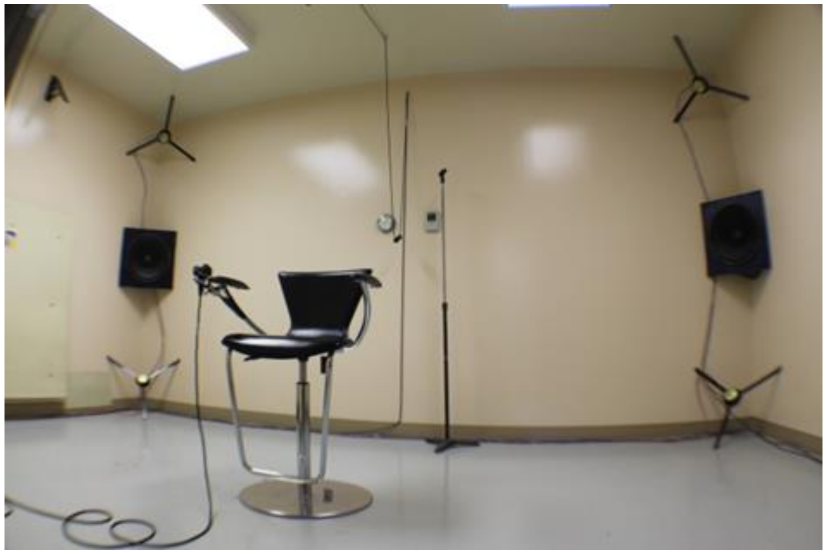

Figure 5. Facility used for measurement of continuous noise attenuation

Passive noise attenuation data were analyzed using the methods described in ANSI S12.68-2007 American National Standard Methods of Estimating Effective A-Weighted Sound Pressure Levels When Hearing Protectors are worn.[5] This ANSI standard detailed the methods for estimating the effective A-weighted SPL when hearing protectors are worn. The octave band method is the “gold standard” method for estimating a user’s noise exposure. This method requires both the noise spectra per octave band and the attenuation data per octave band. Mean and standard deviation (SD) noise attenuation data were calculated across subjects at each octave frequency band. A single Noise Reduction Rating (NRR) was also calculated for mean minus 1 and mean minus 2 standard deviations (Table 1). Figure 6 displays a graphical representation of the attenuation results at each measured frequency (mean minus 2 SD).

There was a large difference in noise attenuation at the low frequencies between the open and closed conditions. At the low frequencies, 125-250 Hz, the difference was as large as 10 dB or more; the difference decreased as the frequencies increased with only a 3 dB difference at 4000 Hz. The difference between the open and closed settings allow low-frequency sounds to pass through for improved situational awareness and face-to-face communications.

Table 1. Passive noise attenuation data for CAE Gen 4

Earplug		125	250	500	1000	2000	4000	8000	NRR Mean-1SD	NRR Mean-2SD
CAE Gen 4 Closed	Mean	20	21	24	25	29	30	34	20	15
	SD	7	6	5	4	4	6	3		
	Mean -1 SD	13	15	19	22	25	24	31		
	Mean -2 SD	6	9	13	18	21	19	28		
CAE Gen 4 Open	Mean	2	4	9	16	24	23	25	9	6
	SD	3	4	3	2	3	4	3		
	Mean -1 SD	0	0	5	14	21	19	22		
	Mean -2 SD	-3	-4	2	12	18	16	20		

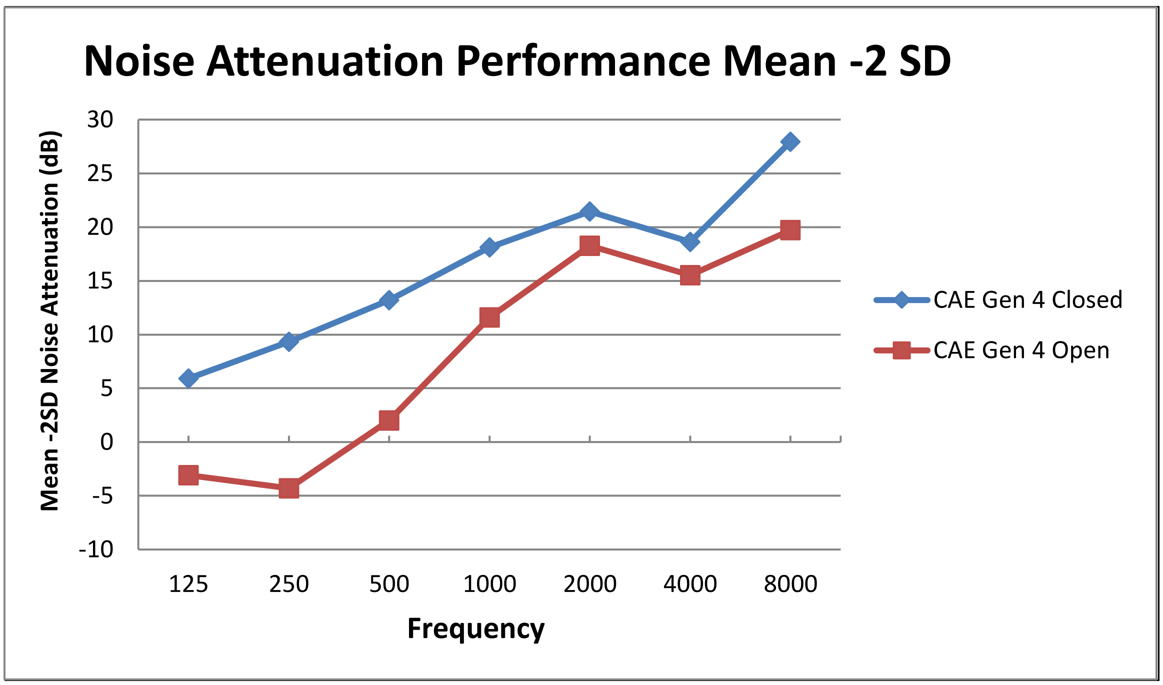

Figure 6. Passive mean -2SD noise attenuation data for CAE Gen 4

Two other methods were described in ANSI S12.68: Noise Level Reduction Statistics, Graphical (NRS_G) and Noise Level Reduction Statistics for use with A-Weighting (NRS_A). NRS_G and NRS_A were calculated for CAE Gen 4 and are displayed in Table 2 and Figures 7-10. The NRS_G rating is beneficial given that it requires knowledge of both the A- and C-weighted noise levels, and uses this additional information about the noise spectrum to more precisely estimate the range of protection provided. In a manner similar to the response of the ear, A-weighted noise measurements discriminate against low frequencies. C-weighted noise measurements do not discriminate against low frequencies, therefore, the difference between A- and C-weighted noise levels describe the low frequency content. For example, if the C-weighted noise was measured at 100 dB and the A-weighted noise was measured at 94 dB then the difference between the two weighting levels would be 6. Therefore, the range of protection provided by the hearing protector could be found in Figures 7 and 8 and/or Table 2 where B = 6. For example, if the noise environment was dominated by low frequency content (B = 13), the level of protection for the closed setting would range from 15.6 - 25.9 dB. However, if the setting was open, the level of protection would range from 1.6 - 6.3 dB. NRS_A is appropriate for unpredictable noise environments that may vary widely as is the case with many military operations. However, if one was considering a noise environment that was relatively constant (e.g., aircraft or other vehicles) then NRS_G should be used to calculate more accurate attenuation performance values.

Table 2. NRS_G results for CAE Gen 4

Earplug		B = L_C - L_A			
		-1	**2**	**6**	**13**
CAE Gen 4-Closed	**80%**	25.1	21.7	19.1	15.6
	20%	30.9	28.2	27.2	25.9
CAE Gen 4 -Open	**80%**	17.4	10.3	5.8	1.6
	20%	20.9	14.3	10.8	6.3

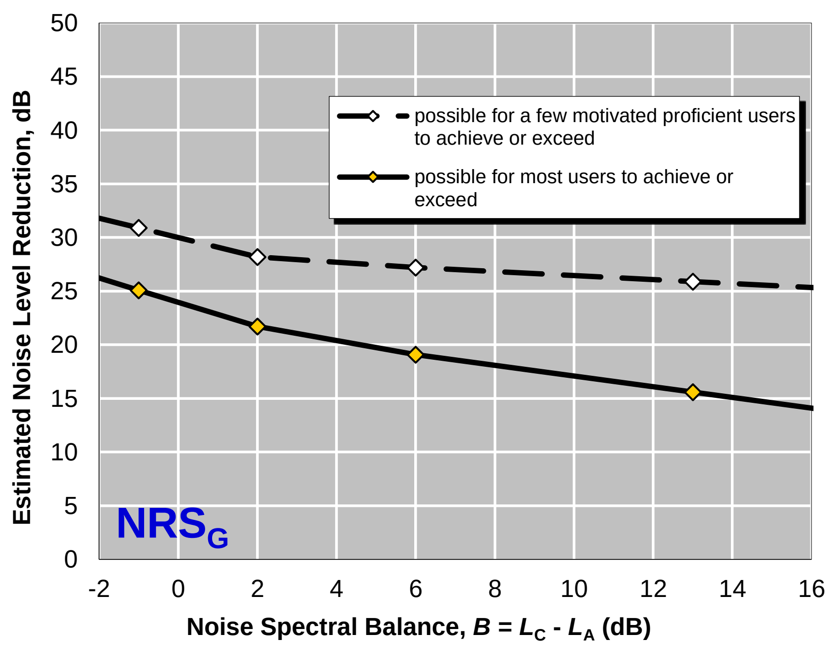

Figure 7. NRS_G results for CAE Gen 4, CLOSED

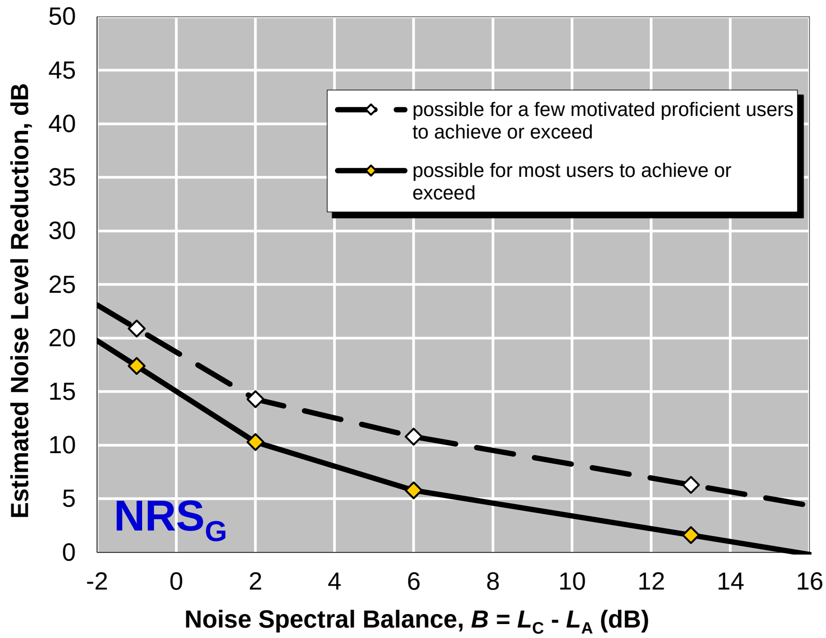

Figure 8. NRS_G results for CAE Gen 4, OPEN

NRS_A is the simplest method and can be used by subtracting the value directly from the measured A-weighted noise level to estimate the level of sound at the ear under the hearing protector. This method offers several advantages over the well-known NRR.[6] The NRR was developed to be subtracted from C-weighted noise levels, with a 7-dB adjustment that must be applied prior to subtracting it from A-weighted noise levels. C-weighted noise levels are often not measured, therefore, using NRS_A values eliminates the 7 dB correction factor required for NRR when A-weighted noise levels have been measured. Another advantage of the NRS_A is that it calculates two levels of protection to indicate the range of attenuation that could be achieved; this range reflects both the variation across the subjects in the test panel, providing insight into how hard/easy the device may be to fit, as well as variation in noise level reduction with the noise spectrum in which the device is used.[3] The lower value indicates the level of attenuation that the majority (80%) of users will be able to obtain; the higher value indicates the level of attenuation that only the most motivated proficient users (20%) will be able to attain. A narrow range indicates the hearing protection device provided a more stable and predictable level of protection. The attenuation values for the CAE Gen 4 in the open and closed setting was 10.1 and 22.1 dB on the lower end (80%), with and increase to 17.2 and 28.9 dB of attenuation on the higher end (20%), respectively (Figures 9-10). When the methods described in ANSI S12.68[5] (octave band method, NRS_G, and NRS_A) cannot be used, the use of the NRR (mean-2SD) is acceptable with the use of appropriate deratings.

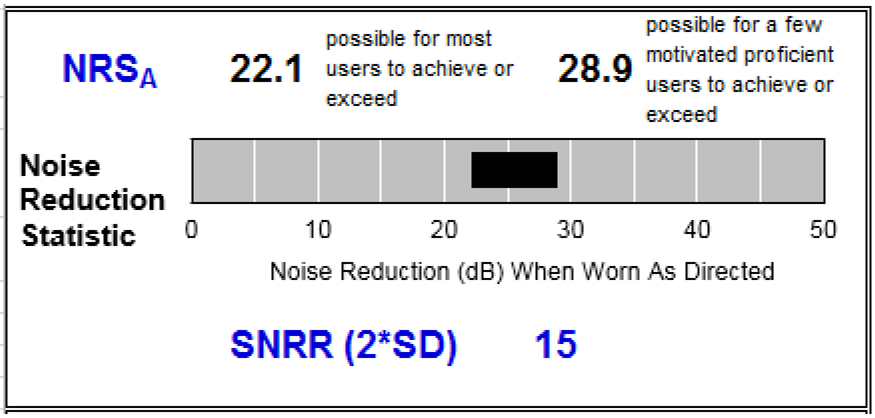

Figure 9. NRS$_A$ results for CAE Gen 4, CLOSED

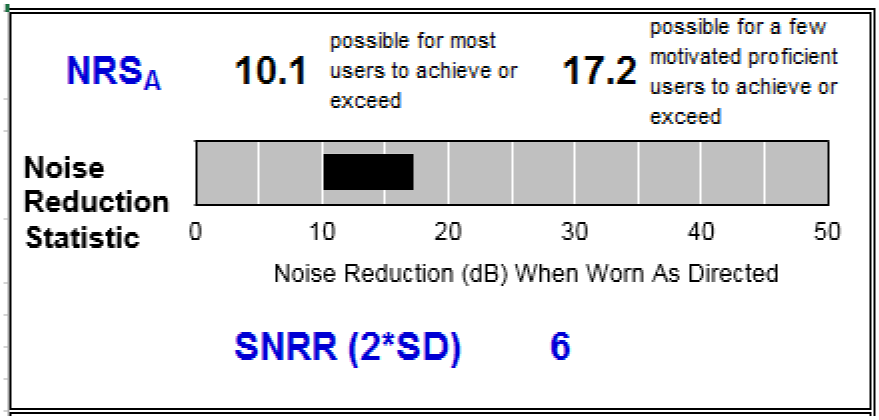

Figure 10. NRS$_A$ results for CAE Gen 4, OPEN

3.3 Impulsive Peak Insertion Loss

Impulsive Peak Insertion Loss (IPIL) (i.e., reduction in peak pressure of the impulsive noise) measurements for the CAE Gen 4 were conducted with the device in both the closed and open settings to determine the effect an acoustic blast may have on the auditory system of the user. Acoustic test fixtures (ATFs) were used in these measurements; the ATFs were ISL-1 type mannequin heads equipped with ¼" microphones in the ear canals. The ATF was fit with the CAE Gen 4 and was exposed to acoustic blasts at 170, 185, and 195 dB peak levels. The measurements were collected in accordance with ANSI S12.42-2010 American National Standard Methods for the Measurement of Insertion Loss of Hearing Protection Devices in Continuous or Impulsive Noise using Microphone-In-Real-Ear or Acoustic Test Fixture Procedures.[7] ANSI S12.42 requires measurements at 130, 150, and 168 dB SPL; however, measurements were conducted at 170, 185 and 195 dB SPL, which was more typical of a blast that a user may be exposed to in a military setting. The measurements were conducted on the test range of the French-German Research Institute of St. Louis (ISL) situated in Baldersheim, France. The test area was fortified with concrete structures and barriers capable of withstanding the detonation of C4™ explosive in excess of 300g. Using this mass of explosive it was possible to initiate a shockwave with a peak pressure level of up to 195 dB SPL and an

A-duration of about 1.5 ms. An A-duration of an impulsive signal is the time interval between impulse onset and the first crossing with the baseline of the waveform.

A ¼” microphone or slender probe (tapered pencil gauge) was used to measure the free-field pressure wave according to the International Test Operations Procedures (ITOP) 4-2-822, Electronic Measurement of Airblast Overpressure and Impulsive Noise.[8] Figure 11 shows the placement of the ATFs during the blast measurements. For each blast, the sound pressure level at the transducers was recorded. This included signals from the ATFs, each equipped with two microphones and pre-amplifiers (one for each “ear drum”) and 1 signal from the free-field pressure transducer (slender probe). Daily microphone calibrations were completed with a B&K 4226 calibrator.

Figure 11. Placement of ATFs and free-field pressure transducer

Pressure measurements were recorded using 16-bit digital recorders at a sampling rate of 100 kHz. In order to visualize the movements of the hearing protectors, high-speed video (minimum speed of 10,000 frames per second) was recorded of the ATFs right ear at 195 dB SPL.

Initially, an open ear measurement (no hearing protector) was conducted to calculate the free-field to ear canal transfer function using a 150 dB SPL nominal peak noise level with an A-duration of 2 ms. Figure 12 displays the pressure time histories of the 150 dB SPL impulses generated in the free sound field. This data was used to calculate the ATF Transfer Function of the Open Ear (TFOE) which was then used to compute the Impulse Peak Insertion Loss (IPIL) for the CAE Gen 4 earplug.

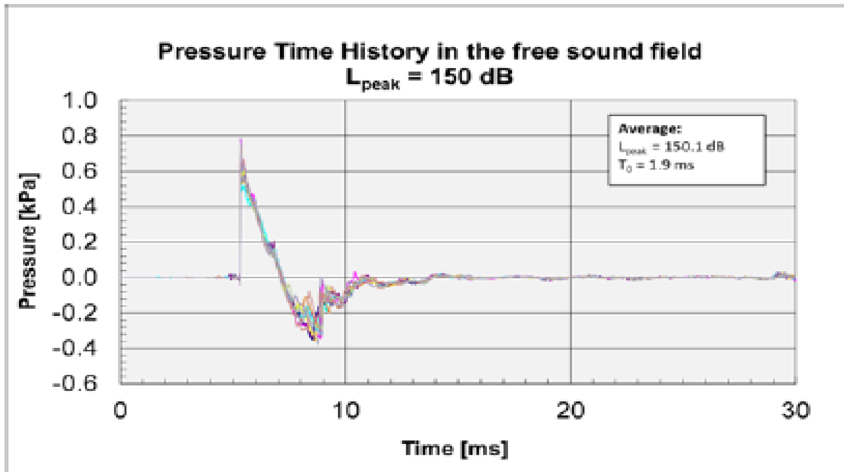

Figure 12. Pressure-time history of the impulses generated for the determination of the TFOE

For the calculation of the Insertion Loss (IL), the TFOE was calculated for all 1/3 octave-bands centered between 25Hz and 16 kHz. The TFOEs were used to calculate the IPIL; the complex transfer function with a resolution of 6.1 Hz has been calculated. Mean TFOE for left and right ears separately are graphed in Figure 13.

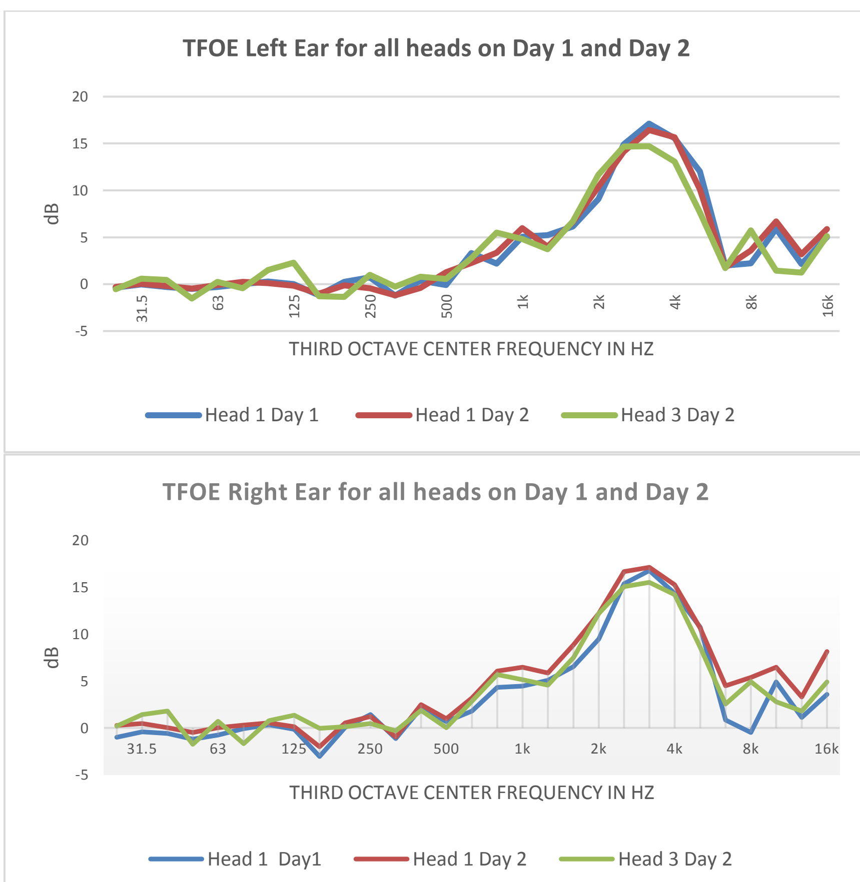

Figure 13. Mean TFOE for each head, each day, left and right ear

After the determination of the TFOE, the measurements were completed with the CAE Gen 4 in place. Each setting was measured five times at each peak noise level; each time, the earplugs were removed and refitted by an earplug of the same type.

The impulsive (blast) waves were generated by explosives. Figure 14 shows a schematic of the set-up. The type and the mass of explosive as well as the distance between the explosive and the ATF determined the peak noise level and the A-duration of the generated signal, as depicted in Table 3. Figure 15 shows an example of the pressure time history and sound spectrum for a 170 dB SPL noise level.

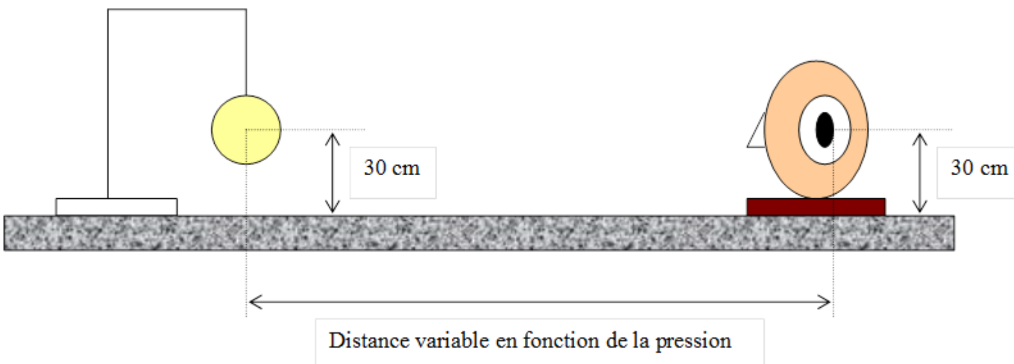

Figure 14. Schematic of the set-up of the explosive charge for the creation of a shock wave

Table 3. Type and mass of explosive and distance between ATF and explosive for different peak pressure levels and A-durations

Peak Noise Level (dB SPL)	Explosive Type	Mass (g)	Distance from ATF (m)	Measured Average A-Duration (ms)	Measured Average Peak Noise Level (dB SPL)
170	Primer (RDX 95/5)	35	6.5	2.3	170.8 (0.991 psi)
185	C4	130	3.4	2.2	184.6 (4.85 psi)
195	C4	300	2.2	1.7	195.9 (17.82 psi)

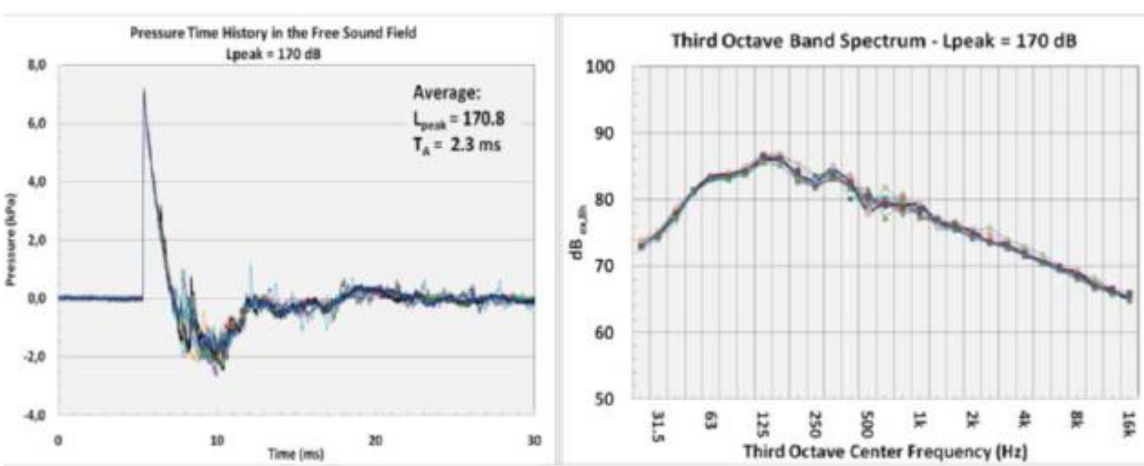

Figure 15. Pressure time history and 1/3 octave band spectrum for the 170 dB SPL noise level

The insertion loss for each ear and each peak pressure level were recorded. Table 4 lists the average IPIL for each setting at 170, 185, and 195 dB and is displayed in Figure 16. The level of protection for the CAE Gen 4 ranged from 32 dB during a 170 dB SPL impulse to 40 dB during a 195 dB SPL impulse. The IPIL response was not linear for either setting. The difference in IPIL data for the same device at the different peak pressure levels illustrated the need for measurements at various sound levels for an accurate understanding of the impulsive noise protection characteristics.

Table 4. Average IPIL data for each ear, at each measurement level

		170		185		195	
Earplug		**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
CAE Gen 4 -Closed	Mean	**42.7**	**37.7**	**36.3**	**36.9**	**40.5**	**35.9**
	SD	*1.9*	*0.5*	*0.8*	*1.0*	*1.7*	*2.1*
CAE Gen 4 -Open	Mean	**32.4**	**33.2**	**38.8**	**38.9**	**39.6**	**38.5**
	SD	*0.3*	*0.5*	*0.5*	*0.7*	*1.7*	*1.6*

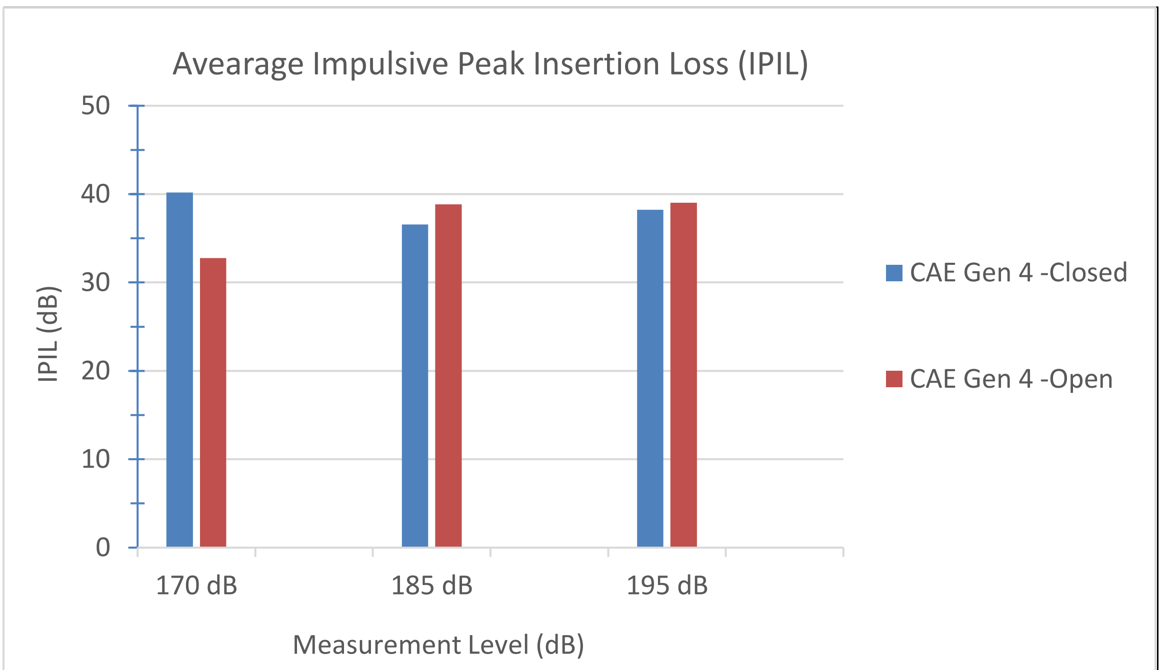

Figure 16. Average IPIL data for each measurement level, averaged across left and right ear

3.4 Auditory Localization

Localization performance was measured for 8 paid volunteer subjects; 4 male and 4 female subjects ranging from 18 to 32 years of age. All subjects had bilateral hearing threshold levels less than or equal to 15 dB from 125 to 8000 Hz. These 8 subjects were a subset of the 20 subjects used for continuous noise attenuation measurements.

All measurements were collected in the AFRL's Auditory Localization Facility (ALF) at Wright Patterson Air Force Base (WPAFB), Figure 17. The aluminum-frame geodesic sphere is 14 feet in diameter with 4.5 inch full-range loudspeakers, each of which is equipped with a cluster of four light-emitting diodes (LED) located at each of the 277 vertices on its inside surface. The ALF apparatus is housed within an anechoic chamber. The subject stood on a platform in the center of the sphere. The location of the platform had the potential to distort the signals from the speakers located directly below the subject, therefore only 237 loudspeakers, evenly distributed, above -45° elevation, were used in this study. The distance between speakers ranges roughly between 12° and 15°.

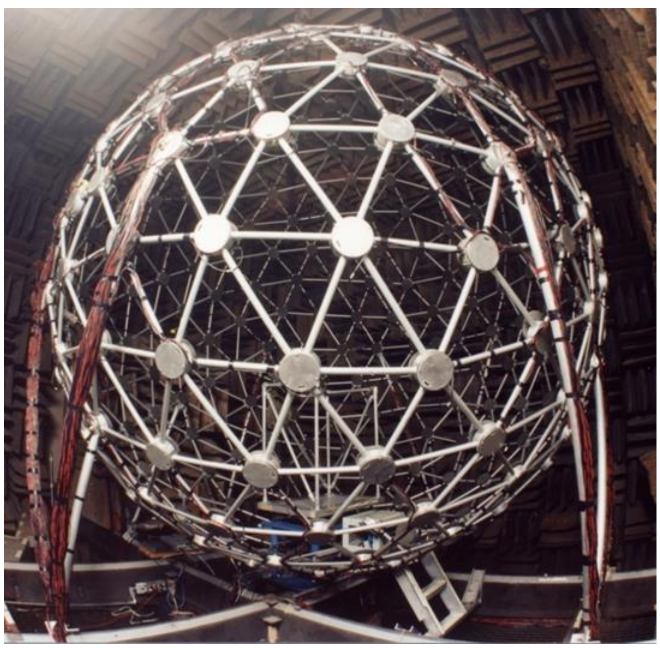

Figure 17. Auditory Localization Facility (ALF) at WPAFB

An Intersense IS-900 ultrasonic tracking system was used to continuously measure the position and orientation of the subject's head as well as the orientation of a hand-held wand, which the subjects used to make their localization responses (Figure 18). The tracking system included a head tracker coupled with a response wand. The head tracker was mounted on the subjects' head to provide tracking data on the X, Y, and Z coordinate location of the head, as well as the yaw, pitch and roll during the duration of each trial. The head tracker also assisted the subject in aligning his/her head to the 0° azimuth, 0° elevation speaker location at the beginning of each trial. The response wand was equipped with a joystick and five buttons which could be programmed for various purposes depending on the task. For this study, the subjects made their localization responses by pressing a single button while pointing the wand at their desired response location.

Figure 18. Intersense IS-900 tracking system

The stimuli were presented to the subjects in two different conditions. In one condition, the stimulus was a 250-ms burst of broadband (200 Hz - 16 kHz) pink noise. This duration was chosen in order to reduce the possibility that a subject would initiate a head movement during the stimulus presentation. Such a movement would provide dynamic localization cues. In addition many real world sounds encountered by the user are likely to be short duration (e.g. weapons fire, explosions). In another condition, a broadband (200 Hz - 16 kHz) pink noise was presented continuously until a localization response was made. This allowed subjects to make use of dynamic localization cues and move their heads during stimulus presentation to orient to the sound.

The test configurations were the CAE Gen 4 in both the closed and open setting and a control configuration labeled as "Open" (open ear). The experiment was coded and executed using the MATLAB programming language by Mathworks™. For each configuration the subject fit him/herself with the appropriate device according to the directions provided by the manufacturer. The fit was verified by the experimenter. The experimenter then directed the subject from the control room, where the fitting took place, into ALF. Once inside the sphere, the standing subject was raised or lowered by adjusting the height of the platform to ensure the subject's head was in the center of the sphere.

To start each trial the subject aligned his/her head to a loudspeaker located directly in front of them (0° azimuth, 0° elevation) and pressed a button on the response wand. A stimulus was presented randomly from one of the 237 loudspeakers in the sphere. The stimuli were presented at a 5:1 ratio as either a 250-ms burst of pink noise or a presentation of continuous pink noise, respectively. The subject would then locate and select the target speaker by pointing at it with the wand and clicking the response button to enter his/her selection. The LED cluster at a particular location would activate when the wand was pointed at that location so the subject could verify the location of his/her response. After a response was recorded, the LED cluster of the actual target speaker was activated to give the subject feedback on his/her performance.

Each of the 8 subjects completed 320 trials in the burst noise condition and 64 trials under the continuous noise condition for each device configuration and one control condition in which no device was worn. Both burst and continuous stimuli could be presented in a single block of trials. All stimuli were presented at 65 dB SPL.

Two metrics of particular interest were percentage of angular errors > 45˚, and percentage of front-back reversals.[1,3] Both of these metrics were obtained from the same data set. Angular error is the difference between the actual target location and the subject's response location as measured by the distance between the two points along the surface of the sphere. The rationale behind our use of angular errors > 45˚ was its operational relevance. Specifically, we assume that if an operator's attention can be directed to within 45°, he/she will then be able to use visual information from the scene to acquire the target. Table 5 and Figure 19 show the percentage of mean angular errors that were >45º with each hearing protector for the burst and continuous noise conditions. Subject data were collected with an "open" ear configuration (open ear) in order to serve as a reference point for determining how wearing a CAE Gen 4 affected localization performance. Subjects had errors >45° 3.1% of the time in the burst noise condition and 0.6% in the continuous noise condition when no device was worn. The data demonstrated that localization performance was degraded substantially when the CAE Gen 4 were worn in the burst noise condition, with errors >45° roughly 23% of the time in both closed and open settings. Very small differences were found when comparing the results between the open and closed settings. Also, the percentage of angular errors > 45˚ remained under 5% for all configurations for the continuous noise conditions. This level of accuracy is most likely attributed the length of the stimuli. With the longer audio cue, subjects had adequate time to locate the general area of the target.

Table 5. Percentage of mean angular errors > 45˚ for burst and continuous noise conditions

Earplug		Burst (%)	Continuous (%)
Open Ear	Mean	3.1	0.6
	SD	0.7	0.6
CAE Gen 4 -Closed	Mean	23.1	4.1
	SD	1.6	1.7
CAE Gen 4 -Open	Mean	23.9	4.7
	SD	1.6	1.8

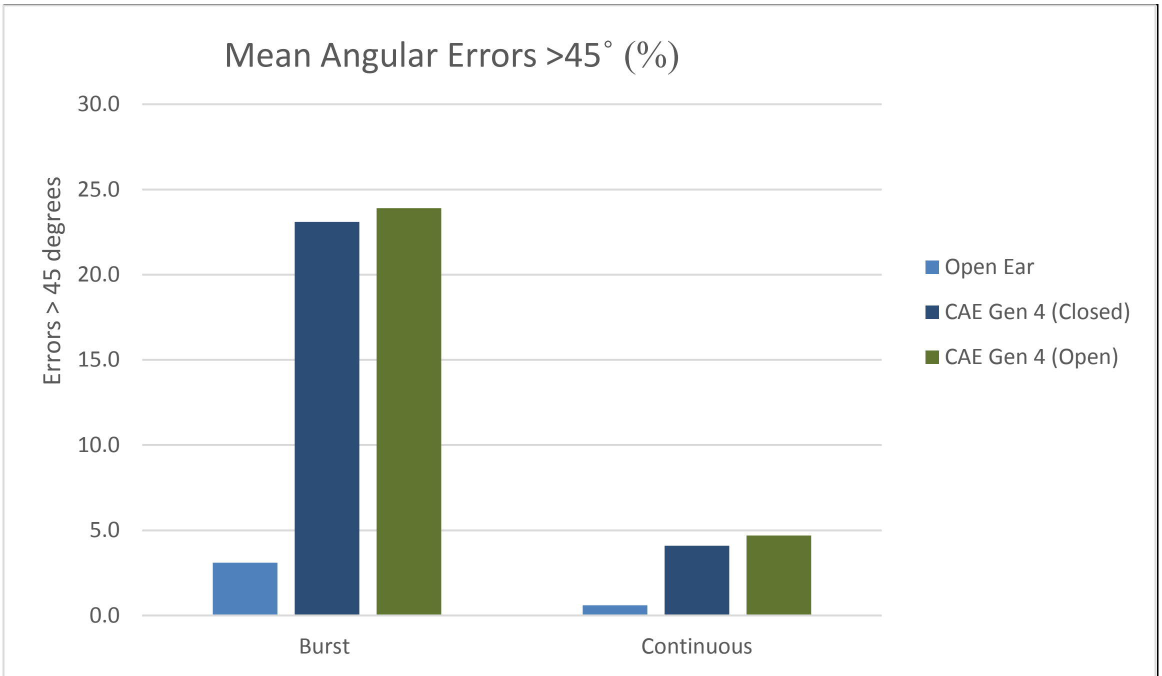

Figure 19. Percentage of mean angular errors > 45˚ for burst and continuous noise conditions

Front-back reversals occur when a subject is unable to determine whether a sound is in front of them or behind them. The percentage of front-back reversals is displayed in Table 6 and Figure 20. In the "Open" ear configuration, the subjects had front-back confusions 6.7% of the time in the burst noise condition and 0.2% in the continuous noise condition. The data for front-back reversals demonstrated that localization performance for burst noise was degraded when the CAE Gen 4 earplugs (closed or open) were worn. The number of front-back confusions increased to 20.5% and 18.3% for the closed and open settings, respectively. For the continuous conditions, the percentage of front-back reversals stayed under 1% across all configurations. As with percentage of angular errors > 45˚, this level of accuracy is most likely attributed the length of the stimuli. With the longer audio cue, subjects had adequate time to locate the general area of the target.

Table 6. Percentage of front-back reversals for the burst and continuous noise condition

Earplug		Burst (%)	Continuous (%)
Open Ear	Mean	6.7	0.2
	SD	1.0	0.4
CAE Gen 4 -Closed	Mean	20.5	0.8
	SD	1.5	0.7
CAE Gen 4 -Open	Mean	18.3	1.0
	SD	1.5	0.8

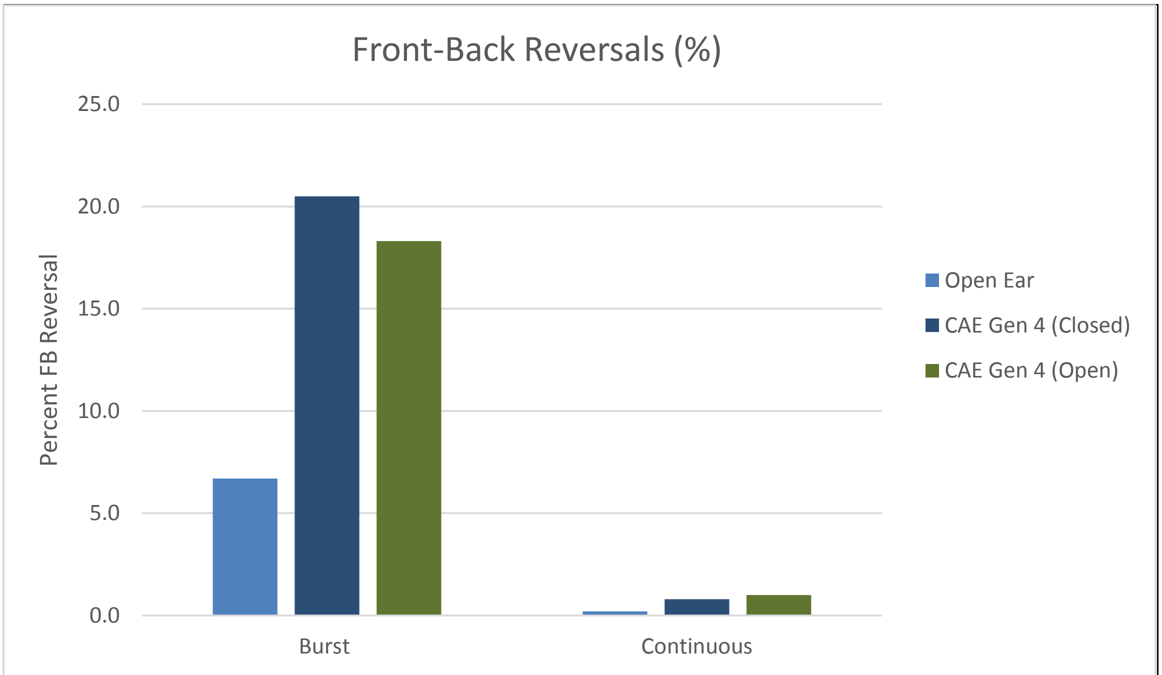

Figure 20. Percentage of front-back reversals for the burst and continuous noise condition

3.5 Aurally Guided Visual Search

Data were collected in an aurally-guided visual search task using the same 8 subjects that participated in the localization measurements. All measurements were collected in ALF at WPAFB. The facility design and setup, as well as the subject fitting procedure and setup procedure once inside facility, are described in detail in Section 3.4.

As previously indicated, a cluster of four LEDs was mounted at the center of each speaker in ALF. Subjects were required to identify a visual target in the presence of 50 visual distracters at randomly selected positions around the sphere. For this task, the target stimulus was a cluster of LEDs in which either two or four LEDs were illuminated. The distracter stimuli were clusters of LEDs with either one or three illuminated LEDs. In most conditions, a 250-ms burst of broadband (200 Hz - 16 kHz) pink noise was played from the loudspeaker at the target location at a predetermined sound level. In addition, each subject completed 60 trails in an open (open) visual only condition where the subject was given no auditory clue and forced to visually search for the target. The time required for the subject to find and accurately identify the target was measured as a function of the noise-burst SPL with the communication device, with the "Open" configuration (open ear) as a reference.

To start each trial the subject aligned his/her head with a designated loudspeaker located directly in front of them (defined as 0° azimuth, 0° elevation) and pressed the trigger button on the underside of the response wand. At this point, 50 distracter stimuli were illuminated along with the one target stimulus. The subjects' task was to quickly locate the target stimulus and identify whether two or four LEDs were illuminated at the target location by pressing a response button on the top of the ALF response wand. After the subject recorded his/her response, he/she would realign to the front speaker to begin the next trial. The reaction time was an indirect measure of the quality of the localization cue.[9-14]

The configurations were the CAE Gen 4 closed, the CAE Gen 4 open, and a control condition labeled as "Open" (open ear). Each of the 8 subjects completed 180 trials per configuration, with 60 trials at 15, 40, and 70 dB. Levels were selected that spanned a range from quiet to easily audible (not to exceed 85 dB SPL at the eardrum).

Previous results from our lab have shown a large reduction in the time it takes to acquire a visual target when a sound that is easily detectable and localizable was played from the target location, relative to the condition in which no audio cue is presented and a visual search is required. The mean search time for subjects in this visual only condition was 12.2 seconds. This "worst-case scenario" acts as a ceiling for the search times. A reference point at 12.2 seconds for the visual only search was added to Figure 21. The averaged response times decreased with increasing presentation level as the auditory stimuli become more audible and localizable (Table 7 & Figure 21). However, even at the maximum presentation level, the search times were still at least twice as long when wearing CAE Gen 4 versus open ear.

Table 7. Response time (in seconds) for each condition at each noise level

Earplug		15 dB	40 dB	70 dB
Open Ear	Mean	4.7	1.5	1.4
	SD	0.7	0.1	0.1
CAE Gen 4 -Closed	Mean	12.1	7.1	4.1
	SD	1.0	0.7	0.7
CAE Gen 4 -Open	Mean	11.5	6.0	2.8
	SD	0.9	0.6	0.3

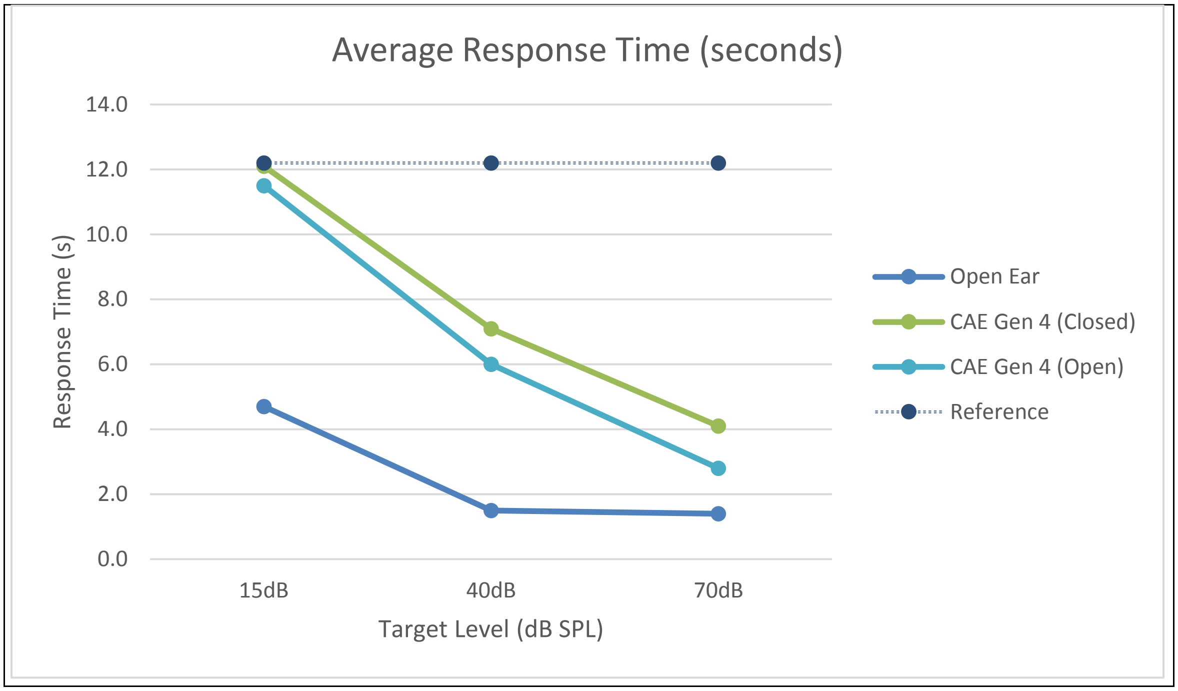

Figure 21. Average response time for an aurally guided visual search task

4.0 DISCUSSION

All hearing protection devices can and should be assessed in multiple ways to describe the performance of the device and the effects on an operator's ability to perform the mission. Subjective and objective measurements can be conducted to characterize a device's noise attenuation performance as well as any effect on situational awareness that may result. Passive continuous noise attenuation, impulsive peak insertion loss, sound localization, and response time using an aurally guided visual search task, were all assessed for the CAE Gen 4.

4.1 Localization and Aurally Guided Visual Search versus Attenuation

Military personnel are exposed to various noise environments depending on their mission: continuous and/or impulsive noise, predictable and unpredictable noise environments. Also, depending on their mission, the metrics measuring the performance of the hearing protection device may carry different weighting. For some missions, auditory localization may be more important than noise attenuation, while for other missions attenuation may be more important than localization. These different weightings should be considered by those who are selecting hearing protection for a particular mission or group of users. The multiple CAE designs were developed to provide the user an option between a high level of continuous noise protection and the ability to hear "wanted" sounds while still being protected from often unpredictable impulse noise events. Typically, the hearing protector that has high levels of continuous noise attenuation also has a large negative effect on sound localization performance. [15] That is true of the CAE Gen 4 in the closed setting. The NRS_A was 22-29 dB with localization errors > 45˚ at 23% and front-back reversals at 20% for the burst noise conditions. The CAE Gen 4 in the open setting provided a reduced level of attenuation (NRS_A was 10-17 dB) with similar sound localization performance (errors > 45˚ at 24% and front-back reversals at 18%) to the closed setting. The inverse relationship between continuous noise attenuation and sound localization demonstrated by similar level-dependent hearing protectors is not exhibited here. One possible explanation could be related to the design of this particular earplug. Fitting instructions for the CAE Gen 4 did not designate a proper orientation for plug in the user's ear. If the plug is twisted so that open/closed vent is facing inwards, towards the ear and head, the user could experience a shadow effect that would allow sound in ear, but potentially distort the aural cues from the stimuli.

4.2 Comparison of Various CAE Versions

A comparison between the continuous noise attenuation performance of the CAE Gen 4 and the older versions of the CAE was completed to determine if any differences were found across devices. Continuous noise attenuation measurements on the CAE 370-1022 and the DE CAE were conducted in accordance with ANSI S12.6-2008 at AFRL prior to this study. Table 8 and Figure 22 display the results. Overall, the continuous noise attenuation performance among the various CAE has remained fairly consistent throughout the design changes. The NRR Mean-2SD for each CAE was within 2 dB across versions for the closed and open settings, respectively. Octave band attenuation was within 4 dB across all frequencies for the open setting and within 5 dB across all frequencies for the closed setting, with the exception of 8000 Hz in the closed setting.

Table 8. Passive noise attenuation data for CAE

		Frequency (Hz)							NRR	
Earplug		125	250	500	1000	2000	4000	8000	Mean -1SD	Mean -2SD
CAE Gen 4 - Closed	Mean	20	21	24	25	29	30	34	20	15
	SD	7	6	5	4	4	6	3		
CAE Gen 4 - Open	Mean	2	4	9	16	24	23	25	9	6
	SD	3	4	3	2	3	4	3		
DE CAE –Green (Closed)	Mean	24	24	25	28	30	32	43	21	16
	SD	4	5	6	6	5	6	5		
DE CAE –Yellow (Open)	Mean	0	1	5	17	23	21	21	7	4
	SD	3	2	3	3	4	3	6		
CAE 370-1022 - Closed	Mean	25	25	26	30	30	32	33	21	15
	SD	8	8	7	7	4	6	5		
CAE 370-1022 - Open	Mean	-2	0	6	18	23	24	25	8	5
	SD	2	2	2	2	3	3	4		

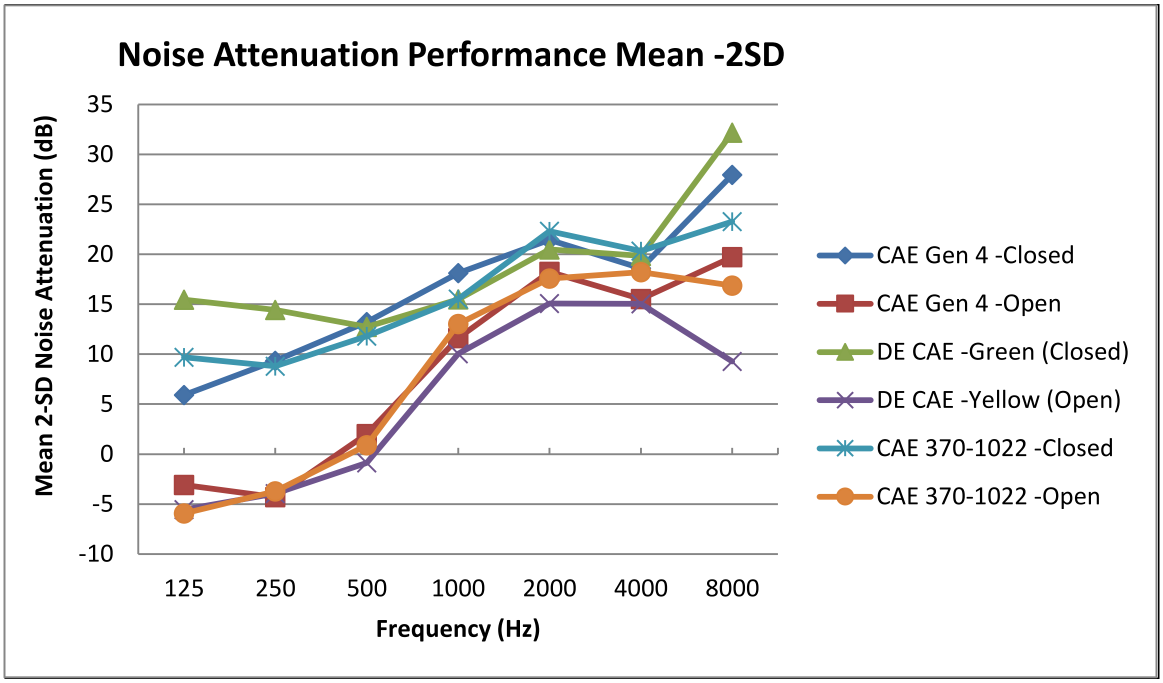

Figure 22. Passive mean noise attenuation data for multiple versions of CAE

3M recently released a new version of CAE, CAE Gen 4.1 (Figure 23). The newly updated earplug had a different design where the thumb switch on the CAE Gen 4 was replaced with a more ergonomic rocker switch. This switch allows the user to switch more easily between the open and closed settings while the plug is inserted in the ear. 3M also added a rubber earpiece that was designed to rest in the concha bowl and stabilize the earplug in the ear. Impulsive peak insertion loss (IPIL) data were collected for the CAE Gen 4.1 during the same measurement session as the CAE Gen 4. The results are below in Figure 24. In general, the CAE Gen 4, in both closed and open settings, outperformed the CAE Gen 4.1 in the respective settings, most notably at the 170 and 185 dB SPL measurement levels. At 195 dB SPL, IPIL performance across both earplugs, in both settings was within 2 dB.

Figure 23. CAE Gen 4.1

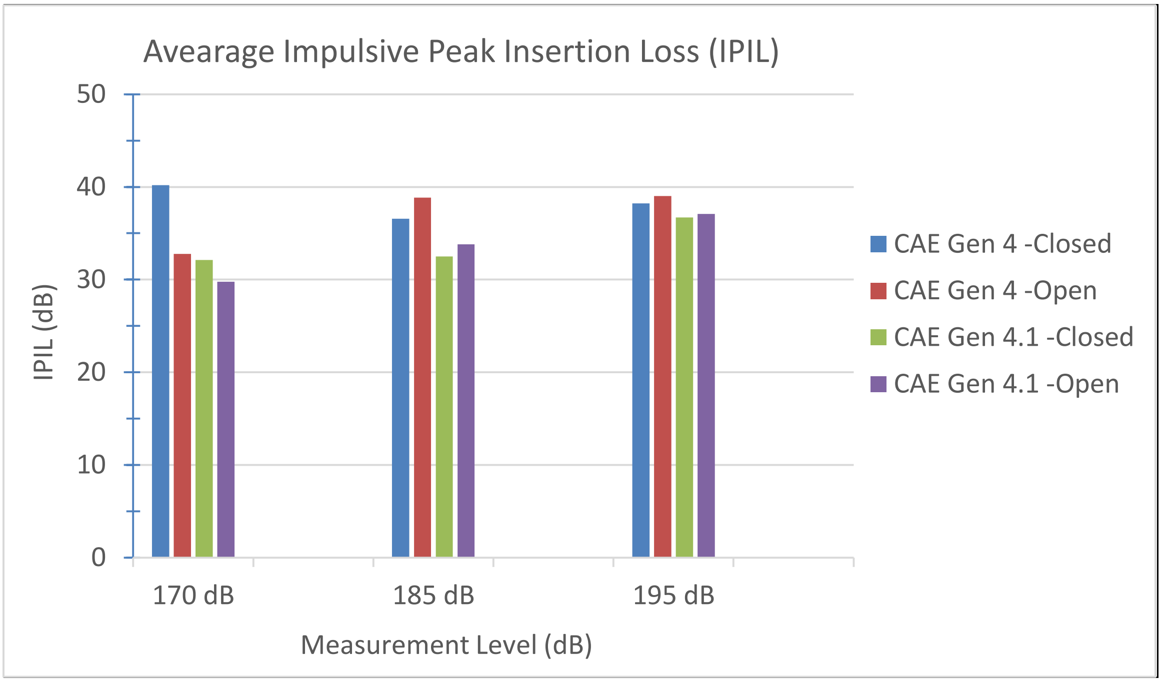

Figure 24. Average IPIL data for each measurement level, averaged across left and right ear

A comparison of localization data for the DE CAE and CAE Gen 4 is presented in Figures 25 and 26. For angular errors greater than 45˚ and front-back reversals, the DE CAE Yellow (Open) outperformed the DE CAE Green (Closed). However, the CAE Gen 4 had similar performance when comparing the open and closed settings. The design changes made in the development of the CAE Gen 4 (to eliminate the need to remove the earplug from the ear canal) reduced the percentage of errors greater than 45˚ in the closed setting from the DE CAE to the CAE Gen 4, but increased the percentage of errors when in the open setting.

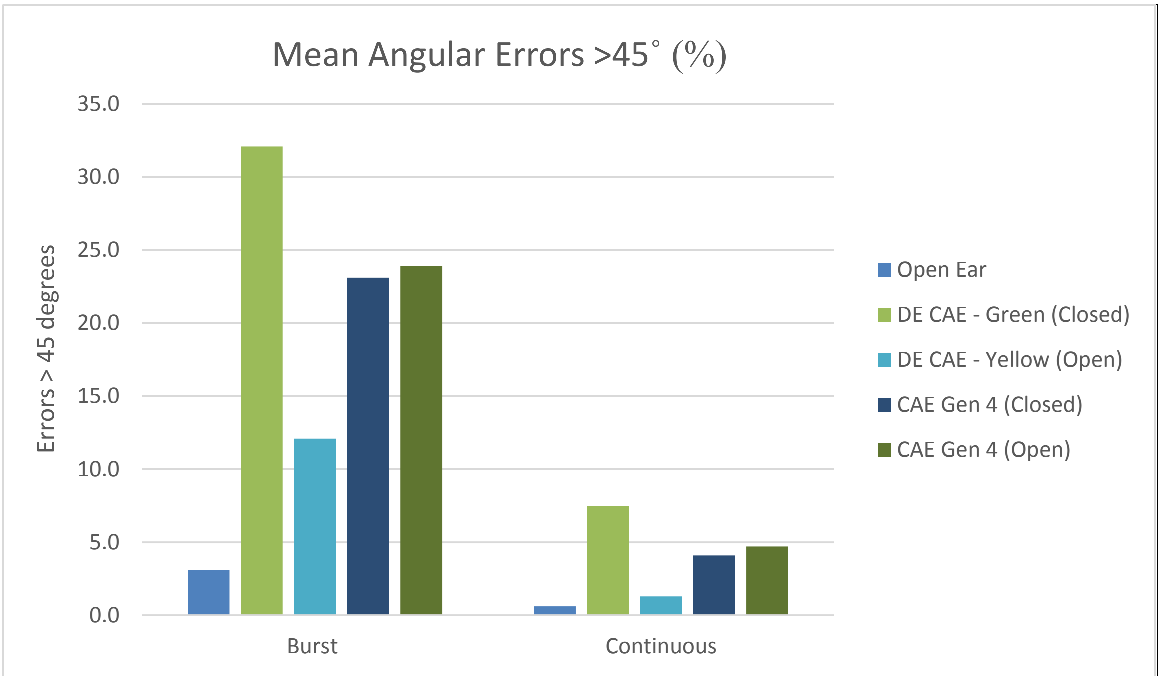

Figure 25. Percentage of mean angular errors > 45˚ for burst and continuous noise conditions

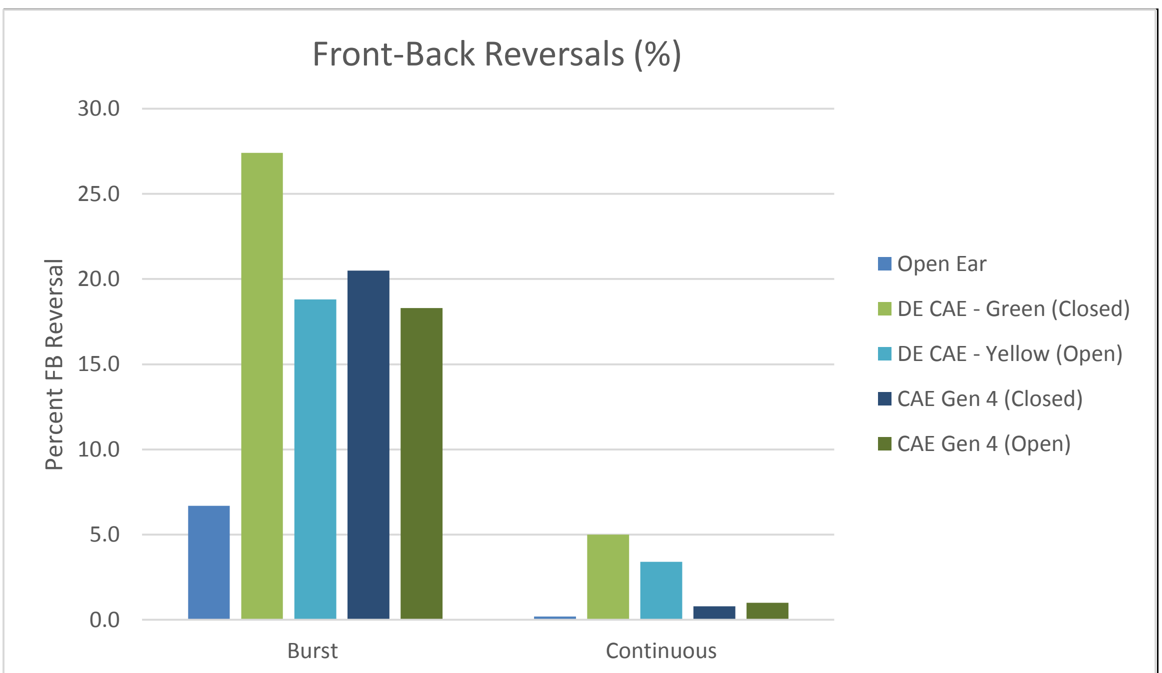

Figure 26. Percentage of front-back reversals for the burst and continuous noise condition

5.0 CONCLUSION

Level-dependent passive hearing protection devices can potentially provide high levels of attenuation in both continuous and impulsive noise environments. However, due to the level of noise attenuation, communication effectiveness and situational awareness could be negatively affected. The 3M Combat Arms Generation 4.0 Tactical Military Shooter's Ear Plugs (CAE Gen 4) were evaluated for: continuous noise attenuation, impulsive peak insertion loss, sound localization, and response time using an aurally guided visual search task. The CAE Gen 4 (open and closed) reduced the noise level in the ear when the user was exposed to continuous and/or impulsive noise. Consequently, the CAE Gen 4 (open and closed) reduced important aural cues required to localize sounds essential to maintaining situational awareness. These reduced aural cues also increased the amount of time required to acquire a visual target. Although donning level-dependent passive earplugs provides the ability to adapt to multiple noise environments, improvements are still necessary to align the user's occluded (with earplug in place) localization performance and reaction time to his/her unoccluded performance.

When considering a hearing protector, it is necessary to prioritize the needs for the operational environment of the end user and the performance metrics of the device. The results of the hearing protector and communication device performance assessment may provide insight into the development of design criteria for the next generation of devices, and assist in choosing the best device or combination of devices for a given operational mission.

6.0 REFERENCES

1. Brungart, D. S., Kordik, A. J., Simpson, B. D., & McKinley, R. L., Auditory localization in the horizontal plane with single and double hearing protection. *Aviation, Space, and Environmental Medicine, 74,* 937-946, 2003.
2. Bolia, R. S. & McKinley, R. L., The effects of hearing protectors on auditory localization: evidence from audio-visual target acquisition, *International Journal of Occupational Safety and Ergonomics,* Vol 6, No. 3, 309-319, 2000.
3. Abel, S., Baudou, J., Bjorn, V., Buck, K., De Boodt, F., Drullman, R., Henry, P., James, S., McKinley, R.L., Sarafian, D., Van Der Veken, P., Hearing Protection - Needs, Technologies, and Performance, NATO RTO TG-147 Final Technical Report, April, 2010.
4. ANSI/ASA S12.6-2008, "American National Standard Methods for Measuring the Real Ear Attenuation of Hearing Protectors".
5. ANSI S12.68-2007, "American National Standard Methods of Estimating Effective A-Weighted Sound Pressure Levels When Hearing Protectors are Worn".
6. Council for Accreditation in Occupational Hearing Conservation, "Redefining the NRR", *The Newsletter of the Council for Accreditation in Occupational Hearing Conservation,* Volume 19: 2, 2007.

7. ANSI S12.42-2010, “American National Standard Methods for the Measurement of Insertion Loss of Hearing Protection Devices in Continuous or Impulsive Noise using Microphone-In-Real-Ear or Acoustic Test Fixture Procedures”.
8. International Test Operations Procedures (ITOP) 4-2-822, Electronic Measurement of Airblast Overpressure and Impulse Noise.
9. Bolia, R. S., D’Angelo, W. R, & McKinley, R. L., Aurally Aided Visual Search in Three-Dimensional Space, *Human Factors*, Vol 41, No. 4, 664-669, Dec 1999.
10. McKinley, R. L., & Bolia, R. S., The effects of hearing protectors on reaction times in audiovisual target acquisition. Proceedings of the 7th International Congress on Noise as a Public Health Problem, Sydney, Australia, pages 205-208, 1998.
11. McKinley, R. L., D’Angelo, W. R., Nelson, W. T., Perrott, D. R., & Bolia, R. S., Three experiments in aurally aided visual search. *Journal of the Acoustical Society of America* 102:3139, 1997.
12. McKinley, R.L., D'Angelo, William R., Haas, Michael W., Perrot, David R., Nelson, W. Todd, Hettinger, Lawrence J., Brickman, Bart J., "An Initial Study of the Effects of 3-Dimensional Auditory Cueing on Visual Target Detection," *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting*, 119-123, October 1995.
13. Perrot, David R., Cisneros, McKinley, R. L., & D'Angelo, William R.," Aurally Aided Detection and Identification of Visual Targets," *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting*, 104-108, October 1995.
14. Simpson, B. D., Bolia, R. S., McKinley, R. L., and Brungart, D. S. Sound localization with hearing protectors: Performance and head motion analysis in a visual search task. *Proceedings of the 46th Annual Meeting of the Human Factors and Ergonomics Society 105:*1024, 2002.
15. Gallagher, Hilary L., McKinley, Richard L., Theis, Melissa A., Swayne, Billy J., & Thompson E.J. (2014) Performance Assessment of Passive Hearing Protection Devices. AFRL-RH-WP-TR-2014-0148.

7.0 LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AFRL	Air Force Research Laboratory
ALF	Auditory Localization Facility
ANSI	American National Standards Institute
ATF	Acoustic Test Fixtures
CAE	Combat Arms Earplug
dB	Decibel
DE	Dual Ended
HL	Hearing Level
Hz	Hertz
IPIL	Impulse Peak Insertion Loss
ISL	Institute of Saint Louis
ITOP	International Test Operations Procedures
LED	Light Emitting Diodes
NRR	Noise Reduction Rating
NRS_A	Noise Level Reduction Statistics for use with A-Weighting
NRS_G	Noise Level Reduction Statistics Graphical
REAT	Real Ear Attenuation at Threshold
SD	Standard Deviation
SPL	Sound Pressure Level
TFOE	Transfer Function of the Open Ear
WPAFB	Wright Patterson Air Force Base