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Better protection from blasts without sacrificing situational awareness

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Abstract

A large number of soldiers returning from war report hearing loss and/or tinnitus. Many deployed soldiers decline to wear their hearing protection devices (HPDs) because they feel that earplugs interfere with their ability to detect and localize the enemy and their friends. The detection problem is easily handled in electronic devices with low-noise microphones. The localization problem is not as easy. In this paper, the factors that reduce situational awareness – hearing loss and restricted bandwidth in HPD devices – are discussed in light of available data, followed by a review of the cues to localization. Two electronic blast plug earplugs with 16-kHz bandwidth are described. Both provide subjectively transparent sound with regard to sound quality and localization, i.e., they sound almost as if nothing is in the ears, while protecting the ears from blasts. Finally, two formal experiments are described which investigated localization performance compared to popular existing military HPDs and the open ear. The tested earplugs performed well regarding maintaining situational awareness. Detection-distance and acceptance studies are underway.

Sumario

Un gran número de soldados que regresan de la guerra reportan pérdidas auditivas y/o acúfenos. Muchos soldados en servicio se niegan a usar sus dispositivos de protección auditiva (HPD) porque sienten que los tapones auditivos interfieren con su capacidad para detectar y localizar al enemigo y/o a sus amigos. El problema de detección puede manejarse fácilmente con dispositivos electrónicos con micrófonos de bajo ruido. El problema de localización no es tan fácil de resolver. En este trabajo, los factores que reducen la conciencia situacional – hipoacusia y un ancho de banda restringido en dispositivos HPD – se discuten a la luz de los datos disponibles, seguidos de una revisión de la claves para la localización. Se describen dos tapones auditivos electrónicos para explosión, con un ancho de banda de 16 kHz. Ambos aportan subjetivamente un sonido transparente en relación con la calidad y la localización del sonido, p.e., suenan como si no existiera nada en el oído, a la vez que lo protegen de la explosión. Finalmente, se describen dos experimentos formales que investigan el desempeño en la localización, comparados con los HPD militares existentes y con un oído sin protección. Los tapones auditivos evaluados se desempeñaron bien manteniendo conciencia de situación. Están en proceso estudios de distancia de detección y de aceptación.

Key Words: Head motion, Localization, Situational awareness, Transparent blast plug earplugs

Introduction

Editor's remarks: This paper is an expanded version of the presentation given by the first author at the 35th National Hearing Conservation Association meeting in Orlando when accepting the 2010 Safe-in-Sound Excellence in Hearing Loss Prevention Award™ on behalf of Etymotic Research, Inc., for innovations which have had a direct impact on the quality, delivery, and effectiveness of hearing loss and tinnitus prevention programs. Continuing in this spirit of innovation, Etymotic is taking on a new hearing loss prevention challenge; the need to develop a hearing protector which affords adequate protection from blast/impulse noise while preserving auditory perception critical to wearers in military situations.

The paper reviews the basic problem that soldiers decline to wear hearing protection because they feel it interferes with their situational awareness; reviews some of what is known about the cues to accurate localization; describes two blast plug hearing protection devices (HPDs) designed to both protect and allow good localization; and briefly summarizes experiments that indicate both goals can be met.

It is well documented that military personnel exposed to blasts from firearms, explosions and other high-level peak noises are at high risk for hearing loss. Peak sound pressure levels (SPLs) greater than 160 dB that occur over periods as short as a few milliseconds are sufficient to cause damage to the unprotected ear. Exposure to gunfire or other explosions adds hearing loss to the long list of risks and dangers encountered by soldiers on the battlefield.

The most common HPD used in the military today is the Combat Arms™ earplug designed by the E-A-R division of 3M. It

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Abbreviations

AGC	Automatic gain control
AHAAH	Auditory hazard assessment algorithm for the human
HPD	Hearing protection device
HRTF	Head-related transfer-function
JND	Just noticeable difference
SPL	Sound pressure level
TTS	Temporary threshold shift

is an excellent passive earplug that provides more attenuation for high-intensity sounds than for low-intensity sounds. Its improved audibility has been a boon for the soldier. Its limitation is that it still provides up to 25 dB of attenuation for soft sounds at high frequencies, a limitation in cases where detecting distant activity is an important task (Casali et al, 2008). For example, a soldier wearing earplugs that attenuate 25 dB at high frequencies may fail to hear an enemy quietly approaching, or fail to understand critical communications from fellow soldiers.

Popular electronic earmuffs with automatic gain control circuitry (AGC) can provide improved soft-sound detection performance, but may fail to provide good localization performance (Casali & Keady, 2010).

To summarize the problem:

- Soldiers' survivability depends on their ability to fire before being fired upon, which in turn depends on good situational awareness.
- Soldiers on patrol may be subject to multiple blasts.
- Many soldiers decline to wear hearing protection in both ears, even when they are most likely to be exposed to a sudden blast (Brennan, 2009).

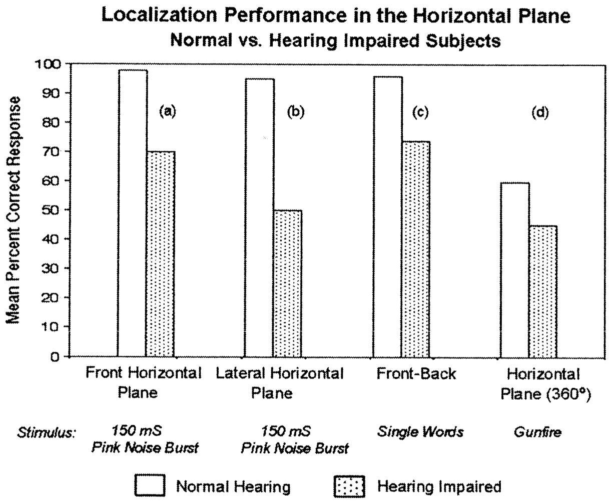

Figure 1. Localization performance vs. hearing loss from three studies: (a) and (b) Noble et al (1994), six normal-hearing subjects, 87 hearing-impaired subjects; (c) Edwards et al (2010), four normal-hearing subjects, 11 hearing-impaired subjects; (d) Casali & Keady (2010), nine normal-hearing subjects, four hearing-impaired subjects

- One out of four returning soldiers complains of hearing loss or tinnitus (Fallon, 2009).
- If returning soldiers have hearing loss, it follows that many soldiers still fighting have hearing loss—and thus reduced situational awareness; the soldiers have permanently lost some of their ability to detect soft sounds, and to accurately localize sounds, which puts them at increased risk of bodily harm.
- We have historically concentrated on the protection provided by earplugs, the 'more is better' belief, a belief that produces earplugs which many workers and soldiers decline to wear because it interferes with their hearing (Killion, 1993).

Two factors that reduce situational awareness

Hearing loss

Three studies provide data on localization performance vs. hearing loss. Nobel et al (1994) reported that subjects with sensorineural loss averaged 70% correct localization in the frontal-horizontal plane, and 49% correct in the lateral-horizontal plane, compared to 98% and 95% correct respectively, for normal-hearing subjects (see Figure 1). Edwards et al (2010) reported their hearing-impaired subjects showed a reduction in localization performance on front-back confusions. Casali and Keady (2010) reported an impaired ability to locate gunfire in subjects with hearing loss.

In addition to these studies, an early study of the effect of hearing loss on the interaural just-noticeable difference (JND) for time was reported by Hawkins & Wightman (1980). Their hearing-impaired subjects showed a dramatic increase in the interaural time difference needed for detection, to almost 0.4 ms(!) at 4000 Hz, compared to 60 μs for normal-hearing subjects. These data are shown in the right side of Figure 2. (0.4 ms is equivalent to nearly 45 degrees in horizontal space.) The likely mechanism for loss of localization, as suggested in the Hawkins data, is that many of the inner hair cells that normally send amplitude and timing information to the brain have been lost.

No direct information appears to have been published on the localization ability of deployed soldiers after months in the field. Nonetheless, it is reasonable to infer from the above studies that immediately after the first serious blast or close-proximity multiple rounds of gunfire, a large temporary threshold shift (TTS) will seriously impair both a soldier's ability to detect soft sounds and to localize all sounds. More importantly, recent experiments provide a possible explanation for the cases we have seen in which the threshold audiogram is normal but a substantial SNR loss occurs: Even after noise-induced TTS had recovered, the mice studied by Kugawa and Liberman (2009) showed an irreversible loss of synapses 24 hours post-exposure, and a delayed and progressive loss of cochlear neurons over many months, even though hair cells remain and recover normal function. Our own preliminary experiments show a strong correlation between SNR loss and loss of ability to localize gunshots. Thus soldiers may have impaired situational awareness, and thus be at increased risk, even with complete audiometric recovery from noise-induced TTS.

These are hardly new insights. Before the Combat Arms™ earplugs were available, an Army audiologist would often promote the use of HPDs by explaining that while wearing earplugs may reduce a soldier's ability to detect and localize sounds at first, over the course of a tour of duty, soldiers will almost certainly be safer (and more effective) if they wear earplugs to prevent the seemingly inevitable combat-related hearing loss (Cave & Curry, 2010).

Limited bandwidth

Two studies have shown an increase in localization errors when high-frequency sounds are filtered out (Musicant & Butler, 1984; Edwards et al, 2010). Figure 2 shows the effect on angle errors and front-back reversals. These findings are particularly relevant in light of the typical 5000–7000 Hz bandwidth of existing digital hearing aid and digital hearing-protection designs.

Engineering requirements for transparent blast plug earplugs

Cues to localization

If the goal is to design a 'transparent' blast plug, i.e. a sealed earplug that is perceived as if nothing is in the ear and does not interfere with detection or localization, it is important to understand the cues used in localization.

Interaural time and intensity difference cues are sometimes described as if they were the only cues that mattered for localization. These can not be the only important cues, however, because some persons with complete unilateral hearing loss can localize quite well. Etymotic Research Inc. has such an engineer, with no measureable hearing in one ear. In informal experiments outdoors, he located voices and finger snaps about as well as his engineering colleagues who used both ears.

What are the cues available to a single ear?

HEAD MOTION

Without head motion cues, it is often difficult to experience 'out-of-head' localization for frontal sounds. Most listeners have experienced an 'inside the head' perception when listening to earphones. When stereo was first introduced, there were several demonstration records available. One demonstration used a recording of a motorcycle coming from a distance to the right, passing 10 feet or so in front, and disappearing to the left. This demonstration worked quite well with loudspeakers. Under earphones, however, the motorcycle appeared to start out from the right at a distance, but as it approached the front, the sound appeared to move into the forehead, after which it receded into the distance on the left.

Koenig (1950), Kock (1950), and Hansen (experiments described in Pierce, 1960) performed a series of localization experiments at Bell Labs using a low frequency tone in an anechoic chamber. Their subjects could correctly localize the source of the tone within a few degrees. Suspecting the importance of head motion, the experimenters clamped their subjects' heads with a dental bite bar and rigid dental chair. Surprisingly, the subjects could localize just as well. Next, they had the subjects listen through earphones fed from amplified one-inch microphones in a dummy head called Oscar, (See Figure 3) which was clamped to each subject's head. Their subjects could also localize the source within a few degrees.

When Oscar's head was lifted slightly off the subject's head, so its microphones no longer moved with the subject's head motion, the subjects could no longer localize the tone with any precision. Apparently a bite bar was not adequate to prevent subtle motion of the head and ears of the subjects.

As a final experiment, Koenig arranged a mechanical link between the dummy head and the subject's head, with the subject listening through earphones in another room. The subjects could localize within a few degrees as long as the link was connected, but their localization became diffuse when it was removed and head rotation effects were eliminated.

HEAD-RELATED TRANSFER FUNCTIONS VS. HEAD MOTION

Although head-related transfer-function (HRTF) cues, sometimes called 'pinna cues', have often been credited as playing a major role in externalization and localization, it is relatively simple to demonstrate that head-motion cues are more important than pinna cues.

We demonstrated the over-riding importance of head motion using 'ear canal extension tubes' that eliminated pinna cues, as shown in Figure 4 (a). The tubes consist of a foam eartip with a 3-mm internal diameter tube through the center. The straight tubes

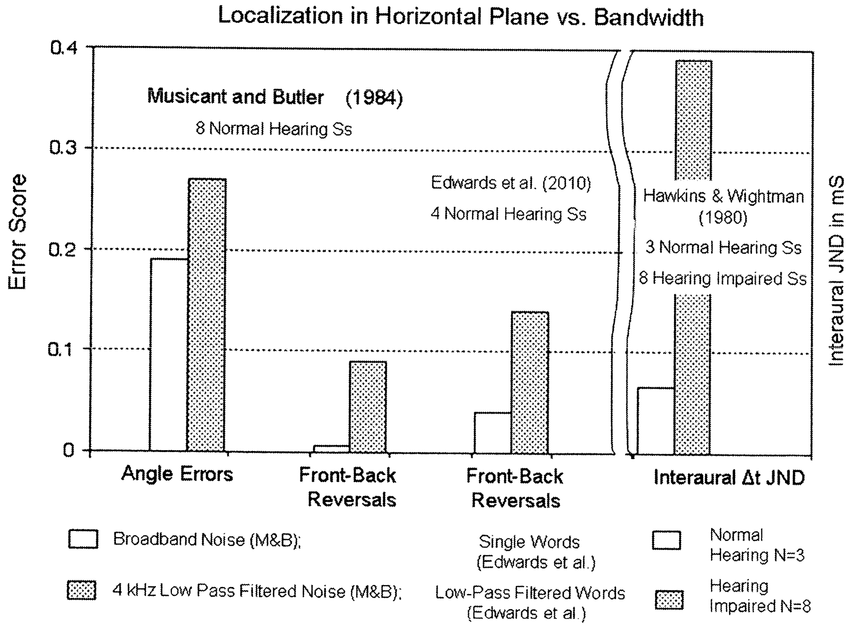

Figure 2. Localization in the horizontal plane as a function of audible bandwidth. To the right is shown the Interaural Δt (arrival time difference) just-noticeable difference (JND) obtained by Hawkins & Wightman (1980) for normal-hearing and hearing-impaired listeners.

Figure 3. Left: 'Oscar' used in early Bell Labs experiments. Right: Kock's binaural arrangement to provide head-motion cues without pinna and head diffraction cues. Reprinted with permission from Journal of Acoustical Society of America. Copyright 1950, Acoustical Society of America.

in Figure 4 (a) are long enough so that when the eartip is sealed in the ear, the portion of the tube outside the foam protrudes straight out 25 mm, effectively doubling the acoustic length of the ear canal. This configuration effectively increases the distance between the two 'ear inlets' by more than 30%, and exaggerates the interaural time delay. These tubes also introduce unnatural peaks and valleys in the spectrum at the ear canal, radically altering the absolute spectral cues. Nonetheless, most listeners report essentially normal externalization and subjectively near-normal localization.

An alternate bent-tube configuration is shown in Figure 4 (b). The total tube length is the same as before, but the bend brings the sound inlet into the concha to pick up sound in front of the ear canal entrance. The subjective improvement in localization is relatively slight, suggesting that head motion itself is the most powerful cue to externalization.

Edwards et al (2010) compared completely-in-the-canal (CIC) hearing aids with behind-the-ear hearing (BTE) hearing aids. Since a CIC hearing aid leaves the concha open, and the microphone is located at the entrance to the ear canal, all of the head, pinna, and concha cues remain intact. Thus, the CIC configuration might be expected to provide better localization than an over- or behind-the-ear microphone location. It did not. With the limited audible bandwidth above 4000 Hz in their typical subject 'with standard gain prescription,' their 11 hearing-impaired subjects showed no average improvement in lateral plane localization, with either CIC or BTE hearing aids, even after six weeks accommodation time. The only significant improvement from the better pinna and concha cues afforded by the CIC aids was in front-back reversals.

SPECTRAL CUES

Even someone with unilateral hearing can localize the source of (1) a familiar broadband sound, or (2) one that is so short in

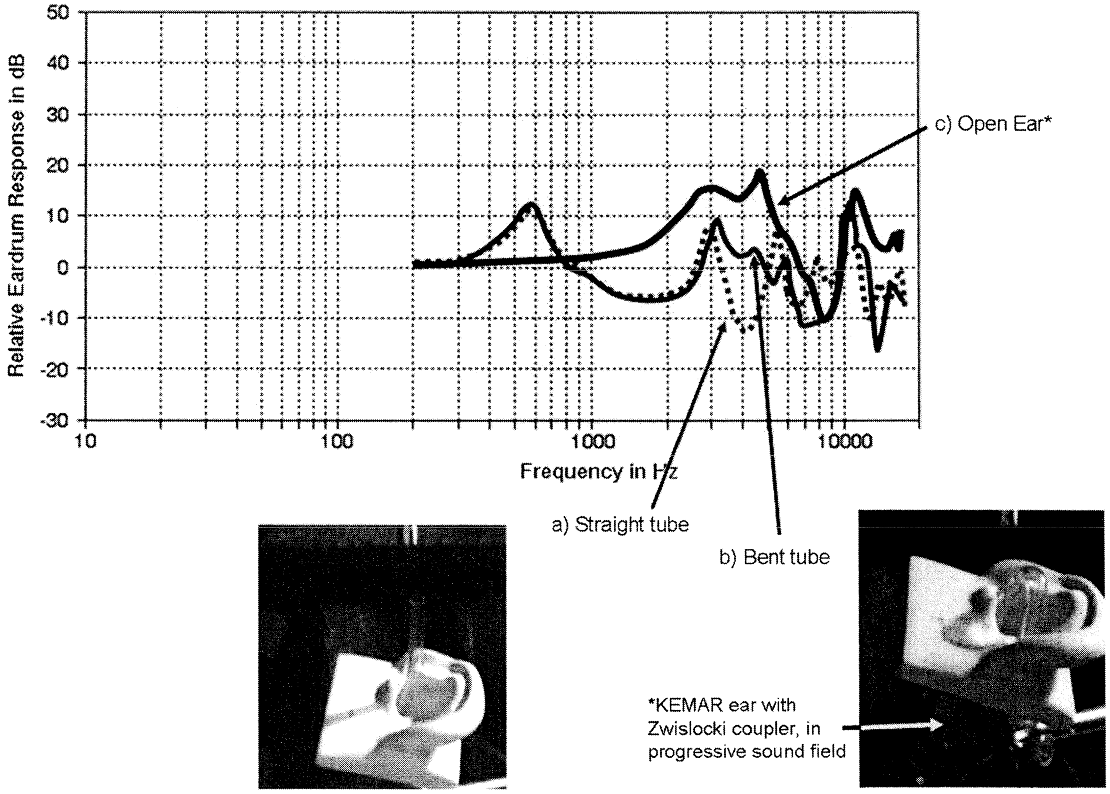

Figure 4. Ear canal extension tubes. (a) Straight tube increases the interaural time delay by near 30%, removes pinna cues, and radically changes the spectrum at the eardrum. (b) Bent tube picks up sound near the ear canal, but does not substantially improve subjective localization. (c) Open ear reference.

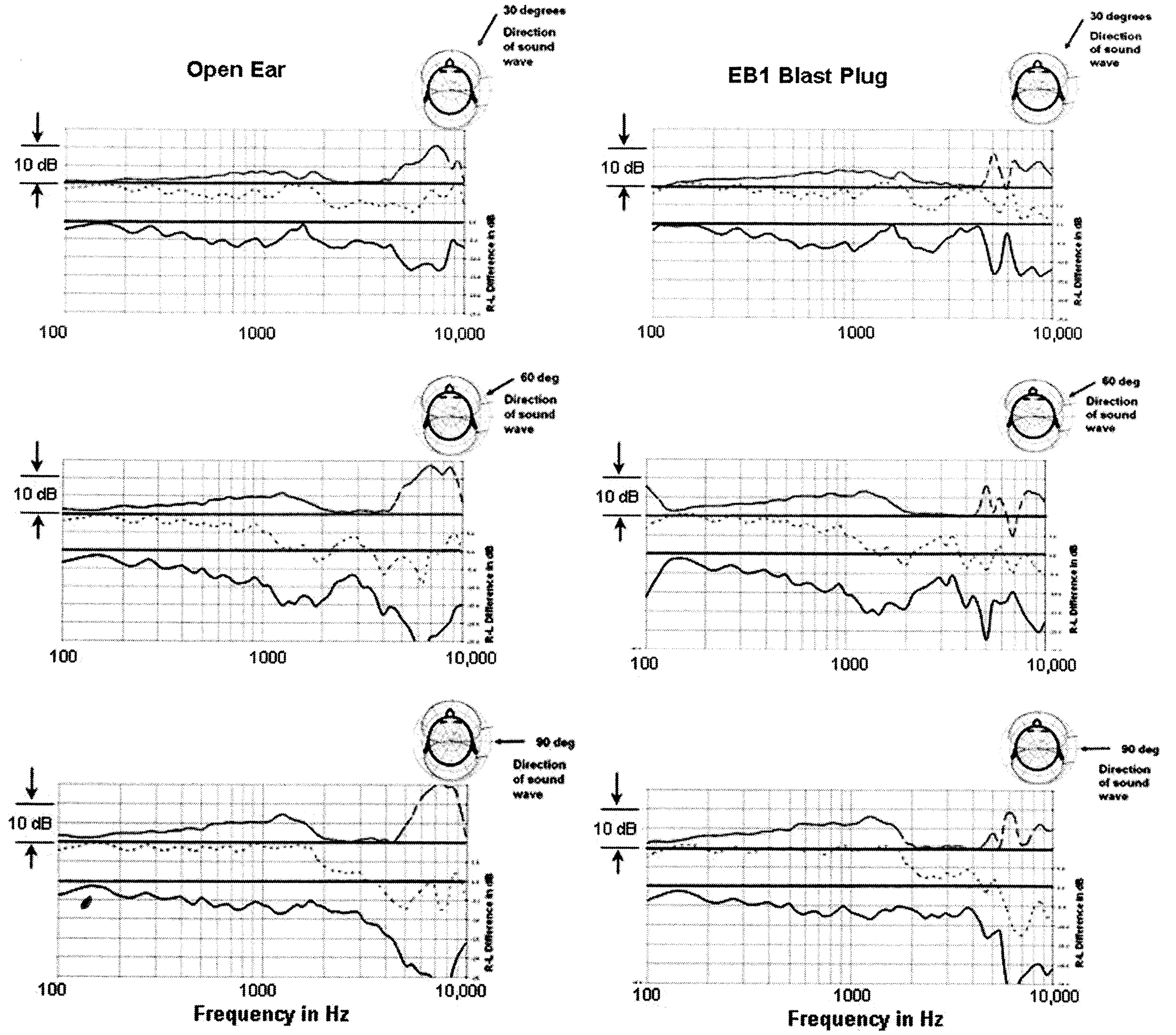

Figure 5. Spectrum at each eardrum-position microphone on the KEMAR manikin, and difference in spectra at the two ears. Responses at the near ear (top solid curve), far ear (dashed curve), and the difference (lower solid curve) are shown. Open ear curves are on the left; EB1 curves on the right, for three different angles of incidence.

duration that it is basically a click (so head motion cues are presumably not available). The classic plots showing the effect of horizontal-plane incidence of the spectrum at each ear, and the corresponding difference in spectra between ears, were given by Abbagnaro and Bauer (1975).

In our laboratory, we obtained data on the KEMAR manikin with open ears and with the Etymotic Research EB1 electronic Blast-PLG™ earplugs described below. Data were obtained in an anechoic chamber at 1-m distance from the sound source. The curves in Figure 5 are normalized to sound at 0 degrees incidence.

Our open-ear data look similar to that of Abbagnaro and Bauer. The similarity in directional cues from both absolute spectra and from spectral differences between ears provided by the EB1 unit is consistent with anecdotal reports that the EB1 units are subjectively transparent for sound quality and localization.

The important spectral cues for vertical localization were identified by Butler and Belendiuk (1977). There is a spectral 'notch' of 10–20 dB at 7000 Hz for sounds directly in front, which moves to 9000 Hz for sounds arriving in front from a 60-degree elevation. Roffler and Butler (1968) reported that a bandwidth extending beyond 7000 Hz was required for localization of sounds in the vertical plane.

ACCOMMODATION TIME

The central auditory system is incredibly plastic, so that even behind-the-ear hearing aids with a poor real-ear frequency response can provide reasonably good situational awareness after four to six weeks accommodation time.

The visual system provides easily described examples of brain plasticity. Kohler (1962) reported on experiments with goggles. In one case, goggles tinted blue on the left half of each glass and yellow on the right half, were strapped to subjects' heads. When first worn, a white wall seen through the goggles appeared as a blue wall in the left visual field and a yellow wall in the right. After a period of a few weeks of wearing the goggles, however, a white wall seen through the goggles appeared uniformly white, and stayed white even if the subjects shook their heads vigorously back and forth. This extraordinary mental feat requires real-time processing of more than 100 Megapixels on the retina (80 Gb/s processing for a video with 32 bit color).

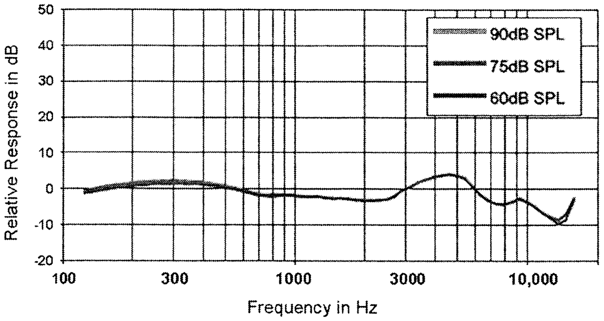

Figure 6. Estimated insertion (real-ear) frequency response of the EB1 unit. The superimposed curves are for 90, 75, and 65 dB SPL and below. The response does not change with input level, as would be expected of an open ear.

'Monocular vision' provides another, more common, example. Someone with good distance vision but who needs glasses for close-up work can use a single 'close up' contact lens. One eye is focused for close up work, the other for distance vision. In the first author's experience, at first the user sees a fuzzy image in one eye, but that may be mostly clear in a week. The first author's experience with 'monocular vision' was that there was no fuzziness left after six weeks, when looking either close or far.

Two electronic blast plugs with 16-kHz bandwidth

EB1 device: Transparency

The EB1 electronic BlastPLG™ earplug was designed to be acoustically transparent from the softest sounds up to about 115 dB SPL (The 115 dB peak was chosen so common transient sounds—and the Chicago Symphony Orchestra—would not create annoying overload distortion). The goal was to provide devices that soldiers would be willing to wear, because they sounded nearly the same as the open-ear condition. An early report from three Marines in heavy artillery training at Twenty-nine Pines, California, indicated the answer can sometimes be 'yes'. They wore them day and night to avoid headaches and the need to wear icepacks on their ears each night (Monser, 2009, personal communication).

In the EB1, the real-ear acoustic gain is set to produce the same eardrum pressure with the unit sealed in the ear as with the unit removed, i.e. essentially equal to the open ear. In standard terms used in the hearing aid industry, the insertion gain at each frequency is as close to 0 dB as possible. The 84% 25-band accuracy score (Killion, 1979) of the response shown in Figure 6—based on Zwislocki-coupler measurements—exceeds that of virtually every stereo earphone and hearing aid on the market, and approaches that of Etymotic's ER-4 series in-ear earphones.

For the soldier with mild high-frequency hearing loss, the 'HI' switch position on the EB1 introduces 15 dB of high-frequency gain for soft sounds. That extra gain progressively returns to transparent operation above 90 dB.

EB1 blast protection

For input SPLs from 115–180 dB, the sound output of the EB1 units in either switch position is limited by the maximum possible motion of the tiny receiver diaphragm. Thus, a maximum of approximately 115 dB SPL can be produced in the ear canal by the EB1 unit itself.

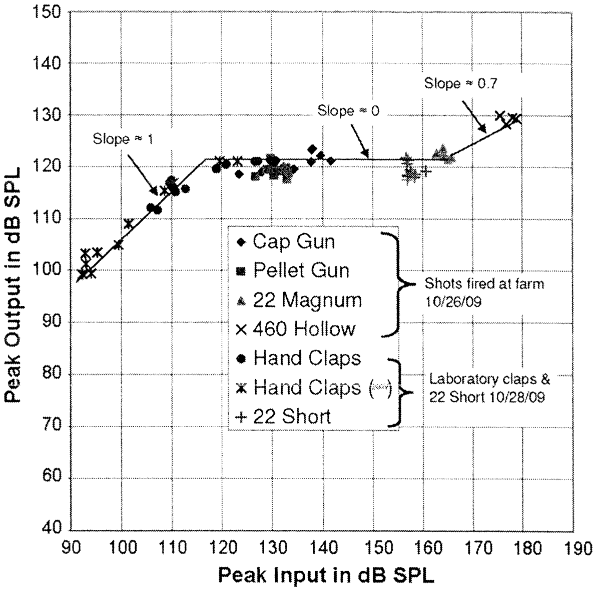

Figure 7. Blast data measured on the EB1. The 50-dB attenuation for 180-dB SPL input is a result of the steel 'ear canal' in the GRAS artificial ear simulator. In real ears, the attenuation is limited to that of the eartip, typically 40 dB for a deeply sealed foam eartip.

In practice, for large blasts the SPL in the ear canal is limited by the passive attenuation of the triple-flange or foam eartip. Deeply sealed in the ear, the triple-flange eartip gives 35 dB attenuation and the foam eartip gives 40 dB or greater attenuation (Berger, 2003). Thus a 170 dB SPL peak blast will produce approximately130 dB peak in the ear canal with a foam eartip.

In testing Etymotic ER-4 earphones, Berger (2003) found equal or greater high-frequency attenuation from the earphone-plus-foam-eartip than from a foam earplug alone, presumably because of the additional mass introduced by the earphone. The EB-series units use the same sound tube and eartips used in those Etymotic earphones, and have approximately the same mass (2.2 gm vs. 3.9 gm), (See also Berger et al, 2003.)

Figure 7 shows the measured EB1 output data obtained with a variety of firearms. In each case, the EB1 earplug was located to the side and 18 inches from the muzzle. The SPL in front of the earplug was measured with a 0.25-inch B&K reference microphone biased at 28 V, which was linear to 185 dB SPL. The eardum-equivalent output behind the eartip was measured in a GRAS artificial ear simulator used for blast tests. A special high-SPL GRAS 0.25-inch mic was used in the GRAS simulator. Both were mounted eight feet off the ground to avoid ground-echo interference with the direct blast waveform.

All data were subjected to an auditory hazard assessment algorithm for the human (AHAAH) model analysis (Price, 2007), which indicated that a single 165 dB SPL shot, unprotected and unwarned would probably be unsafe, while more than 100 such shots would be potentially safe with the attenuation of the EB1 device in place. More importantly, the AHAAH analysis indicated that one round of unwarned exposure to the 178 dB peak SPL impulse might produce an estimated 8 dB permanent hearing loss, and 10 rounds of unwarned exposure might produce an estimated 50 dB permanent hearing loss.

EB15 device: Response and blast protection

The EB15 design is intended for soldiers on a Humvee or near diesel generators, or who might be subjected to the noise of

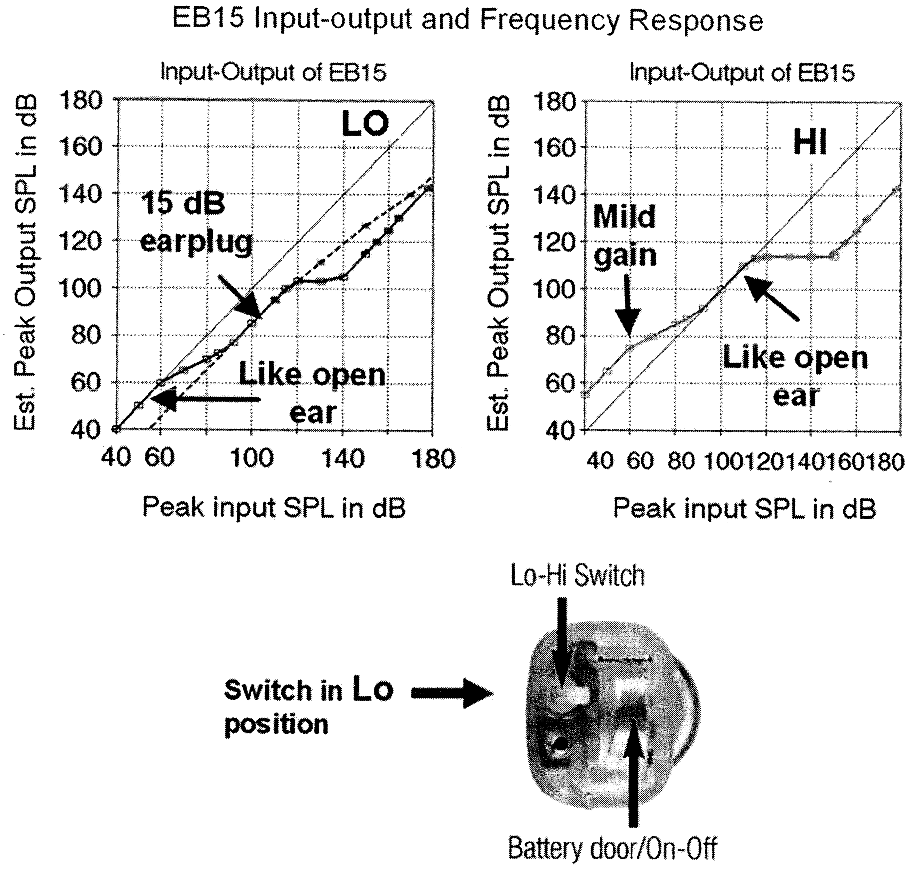

Figure 8. Input-output characteristic of EB15 BlastPLG earplug, measured in the Zwislocki coupler ear simulator.

near-continuous rapid-fire weapons in a firefight. The EB15 provides transparent operation only up to about 60 dB SPL, with gain reducing above that so that at 90 dB and above it becomes a 15 dB high-fidelity earplug.

As with the EB1, the EB15 'HI' switch position introduces 15 dB of wideband gain for soft sounds, which reduces to 0 dB (transparent operation) above 90 dB SPL. Also as with the EB1 unit, in the HI switch position the EB15 sound output is limited to approximately 115 dB SPL until, at very high levels, the sound in the ear canal is limited by the attenuation of the eartip used.

Unlike the EB1, however, maximum output of the EB15 in the LO switch position is limited to approximately 105 dB SPL, extending the region of hearing protection (see Figure 8).

Formal localization experiments with EB1 and EB15 units

In addition to informal preliminary experiments, and favorable reports from hunters (equal or improved ability to localize game), two formal studies have been completed to date.

Localization of backup alarm

Casali and Alali (2010) conducted an experiment to determine a subject's ability to localize a backup alarm. Their summary (page 31) was that the very small localization difference between the EB15 and the open ear, 'supports a conclusion that the EB15 LO [switch position] BlastPLG™ is suitable for providing protection against many noise hazards that surround the presence of backup alarm warning signals which must be localized, and the localization performance for those alarms will be no worse than that of the open ear, at least for normal hearers.'

At a later point the report states: 'The conclusions for that comparison [between the EB1 and the open ear] are quite straightforward, due to the high consistency across all four dependent measures and across all combinations of noise level (60 and 90 dBA) and backup alarm type (standard and spectrally-modified).' These conclusions were based on the fact that the range of reported advantage or disadvantage for the various localization measures was less than ±3% compared to the open ear, differences labeled as very small.

Localization of gunshots

A second experiment (Casali & Keady, 2010) was conducted outdoors in a clearing surrounded by a deep forest in the Blue Ridge Mountains near Roanoke, Virginia. Each subject stood facing a US flag as reference. After a blank was fired from one of eight randomly-sequenced locations 150 feet into the woods, the subject was asked to speak the number of the sign nearest the location from which the shot was judged to have been fired.

The authors found that in this experiment, performance of the EB1 and the EB15 BlastPLG™ earplugs and the Combat Arms earplugs were not significantly different. The Peltor Com-Tac II earmuffs gave significantly poorer localization performance, and the open ear gave significantly better localization performance than the others.

From the report (pp. 40–41): 'Next, with all these cautions as a preface, the following general conclusions are offered. (1) On most measures and across the two noise conditions, both of the Etymotic BlastPLG™ devices (EB1-LO, EB15-LO) exhibited localization performance that was close in line with the level-dependent end of the Combat Arms earplug, which is the most common enhanced hearing protector currently used by the US military.' In these experiments, the open-ear condition ranked best. In nearly all graphs and on all measures of localization performance, the Peltor Com-Tac II earmuff-based device ranked lowest in localization performance.

Both reports are available: www.etymotic.com/download/Casali&Alali2010.pdf and www.etymotic.com/download/Casali&Keady2010.pdf .

Summary

The EB1 and EB2 electronic BlastPLG™ earplugs passed both formal and informal tests of situational awareness. The ability of these to block high-intensity sounds is limited only by the choice of eartips. The remaining and crucial question is whether or not these will be accepted and worn by the soldiers. Detection-distance and acceptance studies are underway.

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Declaration of interest: The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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