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Literature Review:
Issues in Restorative Hearing

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Abstract

The auditory sense is a significant perceptual component of the dismounted infantry soldier's situation awareness. However, battlefield noise hazards necessitate the use of perceptually isolating hearing protection. This report seeks to review the progress made and key issues identified in developing a system to restore hearing capabilities to the protected listener. The auditory needs of the dismounted infantry soldier are described, followed by a description of the noise hazards encountered by the soldier. The implications of hearing protection and additional issues in restoring hearing are discussed. Scientific studies of restorative hearing systems are then detailed, starting from the simplest passive level-dependent systems and culminating in the most sophisticated transparent hearing systems, using a common protection, detection, localization, and speech intelligibility framework. Conclusions and recommendations for test criteria for future restorative hearing systems are given.

Résumé

L’ouïe est un élément sensoriel important de la perception globale d’une situation chez le soldat d’infanterie à pied. Mais à cause des dangers liés au bruit sur le champ de bataille, celui-ci doit porter une protection auditive qui l’isole sur le plan sensoriel. Le présent rapport tente d’examiner les progrès réalisés ainsi que les principales questions cernées lors de la mise au point d’un système visant à rétablir les capacités auditives de l’auditeur muni d’une protection antibruit. Nous décrivons les besoins auditifs du soldat d’infanterie à pied, ainsi que les dangers liés au bruit auxquels il fait face. Les répercussions de la protection auditive et d’autres questions touchant le rétablissement de l’audition sont abordées. Nous passons ensuite en revue les études scientifiques sur les systèmes de rétablissement de l’audition, allant des systèmes passifs les plus simples dépendant du niveau sonore jusqu’aux systèmes auditifs transparents les plus sophistiqués, en utilisant un cadre commun pour la protection, la détection, la localisation et l’intelligibilité vocale. Des conclusions et des recommandations concernant les critères d’essai des futurs systèmes de rétablissement de l’audition sont présentées.

Executive Summary

The auditory sense is a significant perceptual component of the dismounted infantry soldier's situation awareness. The noise hazards of a military environment typically demand the use of hearing protection. This protection can isolate the soldier from the environment, diminishing perceptual sensitivity, thereby degrading situation awareness and adversely impacting performance effectiveness, much in the same way as temporary or permanent hearing loss. Therefore, there is a need to both protect and restore the soldier's perceptual abilities. This report seeks to review the progress made and key issues identified in developing a system to restore hearing capabilities to the protected listener.

The dismounted infantry soldier requires auditory capabilities for detection, recognition, localization, and speech understanding on the battlefield. Sound is often used as an early warning system, alerting the soldier of potential threats. Extracting the nature of a sound source by the auditory signature and thereby inferring further information, provides the soldier with valuable strategic information. Accurate localization of nearby sources can be the difference in survival and therefore must be of paramount concern in restorative hearing systems. Speech signals must be understandable for verbal communication to be effective. Hearing is a vital component of the soldiers' sensory system and as such, degradation to any aspect of the soldiers' auditory capabilities will adversely affect their performance effectiveness.

Due to the overwhelming threat to hearing posed by both continuous and impulse noise in military environments, it is imperative to protect the soldier's hearing. Therefore any restorative hearing system must provide sufficient protection against both continuous and impulse noise hazards, be comfortable to wear for extended periods, be compatible with other equipment, and not create communication difficulties in noise, while restoring auditory awareness of ambient sounds and non-radio communications.

In protecting the soldier from the noise hazards present in the military environment, the utility of the auditory sense in maintaining situation awareness is degraded. Any restorative hearing system must first ensure that detection capabilities in all environments are restored to the soldier. Studies of the impact of Hearing Protection Devices (HPD) on the auditory sense collectively point to sound source localization as the primary area of degraded sensory awareness. Therefore restoring localization ability to the hearing protected soldier will be a key goal in any restorative hearing system.

In attempting to restore hearing capabilities to the protected soldier there are many issues to consider. Any system that does not appropriately consider all of the issues will lead to user dissatisfaction and likely will not be used. A number of issues are discussed in relation to restoring hearing to the protected listener. Scientific studies of restorative hearing systems are detailed, starting from the simplest passive level-dependent systems and culminating in the most sophisticated transparent hearing systems, using a common protection, detection, localization, and speech intelligibility framework.

The ideal solution will protect the soldier from hazardous auditory signals while providing the soldier the full benefit of his/her auditory system. In other words, protection from dangerous impulse and continuous noise will not interfere with the soldier's normal auditory situation awareness. This can be measured in the protection, detection, localization, and speech intelligibility framework used throughout the report. Furthermore, the ideal solution will allow for

extensions of the auditory system in areas such as supernormal auditory detection, aural focusing, supernormal auditory localization, and enhanced speech intelligibility. Finally, the ideal solution will create synergies in the implementation of advanced display concepts such as 3D audio displays and spatialized radio communications. Additional considerations critical in the implementation of any solution include comfort, ballistic protection, chemical and biological threat protection, energy requirements, compatibility with other equipment, maintenance, and cost.

From this review, key elements in the evaluation of future transparent hearing systems have emerged. Conclusions and recommendations for test criteria for future restorative hearing systems are given.

Sommaire

L’ouïe est un élément sensoriel important de la perception globale d’une situation chez le soldat d’infanterie à pied. Les dangers liés au bruit d’un environnement militaire obligent habituellement ce dernier à porter une protection auditive. Cette protection peut isoler le soldat de son environnement, réduisant son acuité sensorielle, altérant par voie de conséquence sa perception de la situation et sa performance, à peu près de la même manière qu’une déficience auditive temporaire ou permanente. Il est donc nécessaire tant de protéger que de rétablir les capacités perceptuelles du soldat. Le présent rapport tente d’examiner les progrès réalisés ainsi que les principales questions soulevées lors de la mise au point d’un système visant à rétablir les capacités auditives d’un auditeur muni d’une protection antibruit.

Le soldat d’infanterie à pied a besoin de ses capacités auditives pour détecter, reconnaître, situer ce qui se passe et comprendre la parole sur le champ de bataille. Le son est souvent utilisé comme système de pré-alerte, avertissant le soldat de dangers potentiels. Le fait de pouvoir déchiffrer la nature de la source d’un son par sa signature auditive et d’ainsi déduire d’autres renseignements, permet au soldat d’obtenir des informations stratégiques précieuses. La localisation exacte de sources voisines peut faire la différence entre la vie et la mort; c’est un aspect primordial qui doit donc être pris en compte dans les systèmes de rétablissement de l’audition. Les signaux vocaux doivent être compréhensibles pour que la communication verbale soit efficace. L’ouïe est un élément vital du système sensoriel du soldat et, partant, la dégradation de tout aspect des capacités auditives de ce dernier aura un effet négatif sur sa performance.

À cause des immenses dangers pour l’audition associés aux bruits continus et impulsionnels dans les environnements militaires, il est impératif de protéger l’ouïe du soldat. Ainsi, tout système de rétablissement de l’audition doit assurer une protection suffisante contre les dangers liés aux bruits continus et impulsionnels, doit pouvoir être porté confortablement pendant de longues périodes, être compatible avec d’autre matériel et ne pas créer de problèmes de communication dans un milieu bruyant, tout en rétablissant la perception auditive des bruits ambiants et des communications non radiophoniques.

En protégeant le soldat contre les dangers liés au bruit qui sont présents dans l’environnement militaire, on se trouve à réduire le rôle de l’ouïe dans la perception globale d’une situation. Tout système de rétablissement de l’audition doit d’abord permettre au soldat de recouvrer ses capacités de détection dans tous les environnements. Des études de l’impact sur l’ouïe des dispositifs de protection antibruit montrent dans l’ensemble que la localisation de la source d’un bruit est le principal aspect touché lorsque la perception de la situation est réduite. Le rétablissement de la capacité de localisation du soldat portant une protection auditive sera donc l’un des principaux objectifs visés par tout système de restauration de l’audition.

Il y a de nombreux aspects à considérer lorsqu’on essaie de rétablir les capacités auditives du soldat muni de protecteurs antibruit. Tout système qui ne tient pas compte comme il convient de tous ces aspects ne satisfera pas l’utilisateur et ne sera probablement pas utilisé. Nous abordons un certain

nombre de questions liées au rétablissement de l'audition chez l'auditeur muni de protecteurs antibruit. Nous passons ensuite en revue des études scientifiques portant sur les systèmes de rétablissement de l'audition, allant des systèmes passifs les plus simples qui dépendent du niveau sonore jusqu'aux systèmes auditifs transparents les plus sophistiqués, en utilisant un cadre commun pour la protection, la détection, la localisation et l'intelligibilité vocale.

La solution idéale protégera le soldat des signaux sonores dangereux tout en le faisant bénéficier de tous les avantages de son système auditif. Autrement dit, la protection contre le bruit impulsionnel et continu dangereux ne nuira pas à la perception auditive normale d'une situation. Cet aspect peut être mesuré dans le cadre que nous avons utilisé tout au long du rapport pour la protection, la détection, la localisation et l'intelligibilité vocale. En outre, la solution idéale permettra d'étendre les possibilités du système auditif dans des domaines comme la détection auditive supranormale, la focalisation auditive, la localisation auditive supranormale et l'intelligibilité vocale améliorée. Enfin, la solution idéale créera des synergies dans l'application de concepts de représentation avancés tels que la représentation des contenus audio 3D et les communications radio spatialisées. Au nombre des autres aspects critiques à considérer dans l'application de toute solution figurent le confort, la protection balistique, la protection contre les dangers chimiques et biologiques, les besoins énergétiques, la compatibilité avec d'autre matériel, l'entretien et le coût.

Un certain nombre d'éléments clés de l'évaluation des systèmes auditifs transparents de l'avenir sont ressortis de cet examen. Nous présentons des conclusions et des recommandations relatives aux critères d'essai pour les systèmes futurs de rétablissement de l'audition.

Table of Contents

List of Figures

1. Introduction

The auditory sense is a significant perceptual component of the dismounted infantry soldier's situation awareness (SA). Situation awareness has been defined simply as "knowing what is going on around you" (Endsley, 2000, pp. 5). A more detail definition includes "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" (Endsley, 1988, pp. 97). Clearly perceptual systems play a central role in developing and maintaining situation awareness. Next to vision, hearing is perhaps the most important sensory system to the soldier. The auditory system is used extensively for communication and can provide information in situations where the visual system is limited (e.g. poor lighting, visual barriers, etc.). Auditory cues on the battlefield are essential for detecting, recognizing, and identifying the state of friendly and enemy forces. As well, auditory cues are essential for establishing the distance and direction of their sources.

Hazards present in military environments dictate the use of protective equipment. The noise hazards of a military environment typically demand the use of hearing protection. This protection can isolate the soldier from the environment, diminishing perceptual sensitivity, thereby degrading situation awareness and adversely impacting performance effectiveness, much in the same way as temporary or permanent hearing loss. Therefore, there is a need to both protect and restore the soldier's perceptual abilities. Similar problems of auditory isolation have been acknowledged and solutions proposed in other domains, such as law enforcement (Tocidlowski, 2000) and recreational hunting (Lindley, Palmer, Goldsteirn, & Pratt, 1997).

This report seeks to lay the groundwork for the development and evaluation of a system to restore hearing capabilities to the dismounted infantry soldier while maintaining the necessary level of hearing protection. The soldier's auditory needs and noise hazards to the soldier will be briefly reviewed. The impact of hearing protection on the dismounted soldier will be examined and issues in restoring hearing will then be discussed. Finally, research on contributing technologies to restoring hearing will be surveyed and the initial efforts in developing a system for restoring hearing capabilities to the soldier will be detailed.

2. Terms and Abbreviations

The following terms and abbreviations are used throughout this report:

AAT	Acute Acoustical Trauma
ANR	Active Noise Reduction
CF	Canadian Forces
CIC	Completely-In-Canal hearing aids
dB	Decibel
dBA	dB measured using the A-weighted network with a slow meter response.
GELP	God's Eye Localization Pointing
HPD	Hearing Protection Device
HRFT	Head Related Transfer Function
ILD	Interaural Level Difference
ITD	Interaural Time Difference
JND	Just-Noticeable-Difference - The smallest difference in sensory input necessary to be perceived fifty percent of the time.
MRT	Modified Rhyme Test
NHR	Natural Hearing Restoration
SA	Situation Awareness
SIL	Speech Interference Level
SIS	Sound Identification Score
SNR	Signal-to-Noise Ratio
SPL	Sound Pressure Level
TJR	Target-to-Jammer Ratio
TTS	Temporary Threshold Shift

3. Auditory Needs

The auditory sense contributes valuable information to the dismounted infantry soldier's overall situation awareness. The snap of a twig, the click of a rifle safety being released, the rumble of a truck engine, and the whisper of a command can all contribute to a soldier's situation awareness on a variety of levels. A survey conducted after World War II and the Korean conflict noted that enemy personnel were most often detected by sounds they, or their equipment, made (Katzell, Thomson, Zalkind, & Lange, 1952 as cited in Price & Hodge, 1976).

The following section is not intended to be a comprehensive review of the auditory system but rather outline how the dismounted soldier might use the sense of hearing to maintain situation awareness. Auditory needs are discussed in terms of detection, recognition, localization, and speech intelligibility.

3.1 Detection

Detection of the presence or absence of a signal is the most basic level of perception. Auditory detection can alert the soldier of the presence of others. The just-noticeable-difference (JND) of the auditory system has been established through psychoacoustic studies. The absolute threshold for detection of sounds in the mid-frequencies is of the order of 0 dB SPL (Mershon, 1997). The JNDs in duration, frequency, and level are on the order of 10% reference duration, 3% reference frequency, and 1 dB respectively (Mershon, 1997; Moore, 1997). The JNDs presented here represent listening in ideal laboratory conditions, without the presence of competing signals that may mask the target signal. These absolute thresholds provide a benchmark performance goal for future restorative hearing systems. The sensitivity of the auditory system makes it an ideal system to alert the soldier of targets and events. Therefore preserving, and potentially augmenting, a soldier's auditory detection ability is highly desirable when wearing hearing protection and communication devices.

3.2 Recognition

The nature of a target can be recognized by the characteristics of the sound it emits. For example, one can imagine the ease with which sound characteristics from a helicopter could be differentiated from a Light Armoured Vehicle (LAV). In this way auditory recognition serves to inform the soldier of the nature of the sound source and can provide the soldier with valuable information about the types of targets in the environment. Furthermore, auditory information can potentially allow the soldier to make friend-foe identifications. For example, different tanks have different noise signatures, potentially allowing the soldier to identify the tank as friend or foe prior to visual information being available. Similarly, all personal and crew-served weapons have a distinctive noise signature. Recognizing this signature will alert the soldier to the type and nature of the weapon and may signal the size of the enemy forces. Therefore, another goal of a restorative hearing system would be to minimize any alterations of sound characteristics caused by the hearing protection.

3.3 Localization

Spatial localization of sound sources also contributes to a soldier's sense of situation awareness. For example, when on stealthy reconnaissance the ability to localize the source direction of a faint rattling of equipment can mean the difference in survival. Human listeners localize sound using interaural cues and spectral cues. Small differences in the time of arrival (interaural time difference, ITD) of the stimuli arriving at each of the ears are created by the differences in the distance the sound must travel to reach the different ears – see Figure 1 (Middlebrooks & Green, 1991). ITD is one of the more important localization cues, dominant over other cues for stimuli with frequencies below 1500 Hz (Wightman & Kistler, 1992; 1997). Similarly, small differences in the sound level (interaural level difference, ILD or interaural intensity difference, IID) at each ear are created by the shadowing effects of the head (Middlebrooks & Green, 1991). Together, ITD and ILD are referred to as interaural, or binaural, cues.

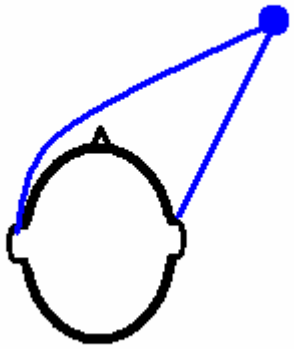

Figure 1: Illustration of interaural differences

Interaural cues alone are insufficient to uniquely specify a sound source location (Oldfield & Parker, 1984a). The range of possible positions which could account for a given pattern of interaural differences have been theorized to distribute themselves on the surface of a cone, centred about the interaural axis – see Figure 2 (Wallach, 1939). This is a simplification of actual distribution in that it assumes a spherical head, an interaural axis through the centre of the sphere, and no external ears, however it provides a useful depiction of the generalized confusion patterns (Oldfield & Parker, 1984a). The position-dependent changes to a waveform caused by the pinnae, head, and torso are referred to as spectral cues (or spectral colouration) (Middlebrooks & Green, 1997). It is believed that these spectral cues are crucial in identifying source elevation and location as in front of or behind the head (Oldfield & Parker, 1984a). The relative contribution of the different localization cues is dependent on a variety of factors, such as stimulus dynamics, source familiarity, listener expectations, and cue plausibility (Wightman & Kistler, 1997). The composite of ILD, ITD, and spectral cues are captured in a mathematical expression called a Head Related Transfer Function (HRTF). An HRTF can be used to recreate directional cues.

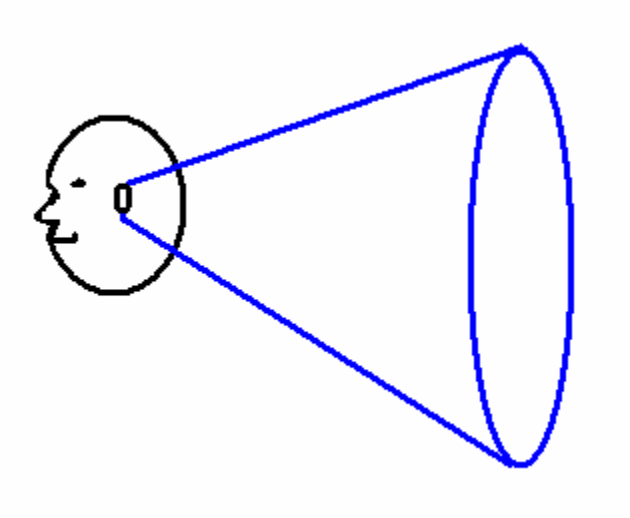

Figure 2: Illustration of cones of confusion

Measures of a sound source spatial location are typically expressed in an azimuth (or horizontal) angle, an elevation (or vertical) angle, and distance. Localization in azimuth and elevation are defined by angles from the median and horizontal planes of the listener's head respectively. The acuity of localization varies greatly with the location relative to the head position. For source localization in azimuth near the median plane (vertical plane through the middle of the head from front to back) the JND is approximately 2^o however near the interaural axis (vertical plane from ear to ear) the JND is on the order of 20^o – see Figure 3 (Middlebrooks & Green, 1991). Similarly for sound source localization in elevation near the horizontal plane in front of the listener the JND is approximately 3.5^o however as the source location deviates from the horizontal plane the JND increases to approximately 20^o (Middlebrooks & Green, 1991). Elevation localization primarily utilizes the spectral pattern of the sound stimulus (Roffler & Butler, 1968).

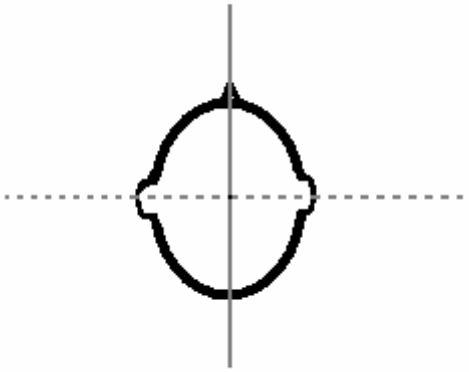

Figure 3: Top view illustration of median plane (solid) and interaural axis (dotted)

Occasionally a listener will confuse the spatial quadrant of a sound source location. Front/back confusions occur when the listener localizes a sound source in rear which is actually in the front or vice-versa. The azimuthal component of a stimulus in front/back confusion tends to be identified

in a location of mirror symmetry about the interaural axis to the actual location (Middlebrooks & Green, 1991). Confusion of sources in front being identified as being to the rear is the more common type (Wenzel, Arruda, Kistler, & Wightman, 1993). The spectral pattern of the sound stimulus is used to resolve the ambiguity resulting from purely interaural cues, however these confusions still occur in normal listening (Oldfield & Parker, 1984a).

The primary cues used in judgement of sound source distance are intensity and reverberation (Middlebrooks & Green, 1991). Sound source distance is relatively poorly identified unless the listener has prior knowledge of the stimulus intensity at the source (Mershon, 1997; Middlebrooks & Green, 1991).

Sound source localization is a complex process that plays an important role in a soldier maintaining situation awareness. Due to the complexity of the localization process, restoring all of the necessary cues to localization will be a significant challenge for restorative hearing systems.

3.4 Speech Intelligibility

The dismounted infantry soldier uses speech for both face-to-face and radio communications. Speech intelligibility is defined as "the extent to which the transmitted message is understood by the listener." (McCormick & Sanders, 1982, pp. 157). Several standardized tests have been developed to measure speech intelligibility. The ability of the soldier to accurately decipher speech is crucial to communications, both with comrades and other people encountered in the combat area (e.g. civilians, combatants, etc.). Intelligibility can be a critical issue when interacting with civilian and coalition forces. It is particularly critical when a foreign language is used as poor intelligibility can lead to greater confusion and misunderstanding. Furthermore, battlefield noise and other occlusive elements (e.g. wind) can degrade the intelligibility of free-field and radio speech. Therefore, speech intelligibility will also be a vital metric in evaluating restorative hearing systems.

3.5 Auditory Needs Conclusion

The dismounted infantry soldier requires auditory capabilities for detection, recognition, localization, and speech understanding on the battlefield. Sound is often used as an early warning system, alerting the soldier of potential threats. Extracting the nature of a sound source by the auditory signature and thereby inferring further information, provides the soldier with valuable strategic information. Accurate localization of nearby sources can be the difference in survival and therefore must be of paramount concern in restorative hearing systems. Speech signals must be understandable for verbal communication to be effective. Hearing is a vital component of the soldiers' sensory system and as such, degradation to any aspect of the soldiers' auditory capabilities will adversely affect their performance effectiveness.

4. Noise Hazards

The dismounted infantry soldier is exposed to a range of noise hazards in normal operations. Noise exposure can damage hearing causing a temporary threshold shift (TTS) that is gradually recovered in a quiet environment or permanent irreversible sensory hair cell loss (Abel, 2005). Hearing loss has serious operational consequences, including difficulty detecting, localizing, and identifying acoustic sources, thereby reducing operational efficiency and security of the soldier (Dancer & Buck, 2005). In peace time, acoustic trauma is the leading cause of morbidity in the military (Dancer & Buck, 2005).

There are two primary types of noise hazards to the infantry soldier; continuous noise from sources such as vehicles (wheeled and tracked) and aircraft (rotary and fixed wing), and impulse noise typically from weapons. A survey of noise exposure in CF personnel in peace-time operations revealed a peak impulse level of 150 dB and an average continuous sound level of approximately 87 dBA for infantry soldiers (Massel & Kumagai, 2003).

4.1 Continuous Noise

Continuous noise refers to a consistently present sound level in an environment, typically at a constant frequency and level. Infantry soldiers can be exposed to continuous noise when operating near vehicles and during transport. The A-weighted noise levels of land-vehicles range from as low as approximately 71 dBA in the quietest cargo vehicles to approximately 120dBA in heavy tanks (Dancer & Buck, 2005). The majority of land-vehicles surveyed produce interior noise levels greater than 85 dBA, the suggested equivalent exposure level over 8 hours (Dancer & Buck, 2005). Noise levels from a range of different Indian army vehicles have been measured between 117.5 and 123.5 dB (Srivastava, Chaturvedi, & Singh, 1997). The Speech Interference Level (SIL) of these vehicles indicated a concentration of sound energy in speech frequencies (Srivastava et al., 1997). Continuous noise in these frequencies can damage the range of human hearing critical to verbal communication.

4.2 Impulse Noise

Impulse noise consists of a brief air pressure disturbance, as would be caused by the detonation of explosive material or impact of two objects (Patterson & Johnson, 1996). The hearing risk posed by impulse noise from weapons is well recognized as a severe hazard in the military environment, with peak levels measured as high as 185 dB SPL and above (Abel, 2005; Christiansson & Wintzell, 1993; Dancer, Grateau, Cabanis, Barnabe, Cagnin, Vaillant, & Lafont, 1992; Mrena, Salvolainen, Pirvola, & Ylikoski, 2004; Patterson & Johnson, 1996; Pelausa, Abel, Simard, & Dempsey, 1995). This hazard can be so severe that it is a limiting factor in the use of some weapons (Dancer et al., 1992). Hearing conservation programs developed for noise encountered in industrial settings may not be adequate for a military environment, as evidenced by the prevalence of moderate hearing loss in spite of HPD use (Abel, 2005; Pelausa et al, 1995).

Military noise exposure from small arms, mortar, and artillery fire range from approximately 140 dB to over 190 dB (McKinley, 2000). Noise levels from a range of different Indian army weapons has been measured between 147.8 and 180.0 dB, and the equivalent level at 6m from the source as between 162.8 and 189.2 dB (Srivastava et al., 1997). Peak pressure from a 120 mm mortar at the

loader's ear is 185 dB and from a .50 caliber sniper's rifle at the shooter's ear is 175 dB (Dancer & Buck, 2005). From small arms fire, the noise level at the firer's ear varied between 153 and 166 dB (Srivastava et al., 1997). Finnish measures of impulse noise peak sound pressure from assault rifles and other small firearms range from 155 to 168 dB (Paakkonen, Lehtomaki, & Savolainen, 1998). Gun crews of a howitzer are exposed to peak pressure impulses of between 175 and 176 dB (Dancer et al., 1992).

The impulse noise associated with even small calibre weapons fired in the free field may induce permanent threshold shifts with repeated exposure if no HPD is used (Dancer et al, 1992). The most common cause of Acute Acoustical Trauma (AAT) in the Finnish Defence Forces is the firing of an assault rifle (80.8% of cases in 2000), yet in only one-third of the cases (31.9%) had the soldier sustaining the AAT been the one actually firing the weapon (Mrena et al., 2004). In the vast majority of cases (87.5%) of AAT in the Finnish Defence Forces, no HPD was in use at the time of the AAT (Mrena et al., 2004). For infantry personnel shooting right handed, the left ear is more at risk (Pelausa et al., 1995). The difference in hearing between ears for infantry personnel has been measured to be 7 dB at 4 kHz and 6 kHz after 3 years of service (Pelausa et al., 1995).

4.3 Hearing Loss

In a survey of hearing loss among different groups of the CF, a deterministic relationship between hearing loss in combat arms personnel (infantry, artillery, armour) and length of service has been established (Forshaw, 1973). Moreover, the regression line relating length of service and percent of personnel with normal hearing for combat personnel is significantly different (ie. greater rate of hearing loss) from the same line for minimum noise-exposed personnel in the CF (Forshaw, 1973). A retrospective assessment of exposure to gunfire noise among Finnish soldiers concluded that it was dangerous enough to cause severe hearing deterioration early in the soldier's career if HPDs were not worn at all times during shooting exercises (Ylikoski, 1994).

A survey of CF personnel found that 50% of infantry soldiers believed HPD would interfere with their ability to hear during soldiering tasks and auditory impairment to free field hearing was concluded to be a major impediment to HPD usage (Abel, 2005). Twenty-eight percent of infantry soldiers felt that HPD would often or definitely pose a danger at work (Abel, 2005). Approximately eight percent of 36-45 year old infantry soldiers were found to have moderate to severe hearing loss at 4 kHz (Abel, 2005).

Despite the existence of a hearing conservation program since the 1950s, the cost of noise-induced hearing loss in the CF is rising (Abel, 2005). It was concluded that the current hearing conservation program does not provide sufficient training in the hazards of noise exposure, the selection of HPD, and HPD use (Abel, 2005). Further problems with the current hearing conservation program affecting HPD use were identified in discomfort with extended use, incompatibility with other equipment, and communication difficulties in noise (Abel, 2005).

While it is widely recognized that noise-induced hearing loss degrades sound detection and recognition ability, it also has a large adverse effect on the ability to localize sound sources, both in terms of localization acuity and frequency of front-back reversals (Ericson & Staley, 2003). Mild hearing loss primarily affects localization in elevation while moderate hearing loss degrades both azimuth and elevation acuity (Ericson & Staley, 2003). While head motion is normally an effective strategy in improving localization acuity, individuals with moderate hearing loss no longer benefit from head movement (Ericson & Staley, 2003).

4.4 Noise Hazards Conclusion

Due to the overwhelming threat to hearing posed by both continuous and impulse noise in military environments, it is imperative to protect the soldier's hearing. Therefore any restorative hearing system must provide sufficient protection against both continuous and impulse noise hazards, be comfortable to wear for extended periods, be compatible with other equipment, and not create communication difficulties in noise, while restoring auditory awareness of ambient sounds and non-radio communications.

5. Implications of Hearing Protection

In protecting the soldier from the noise hazards present in the military environment, the utility of the auditory sense in maintaining situation awareness is degraded. Hearing protection not only suppresses all sounds, including both noise and useful sounds, but also distorts the sound field (Bronkhorst & Verhave, 2005).

> Soldiers are very often obliged to wear cumbersome and uncomfortable hearing protectors, sometimes incompatible with other headgear, which can isolate them from their comrades and from the acoustic environment with potentially far more dangerous consequences than the hazard to hearing. (Dancer et al., 1992, pp. 1687).

A survey of infantry soldiers indicates that 92% believe that HPDs will interfere with hearing, 47% believe that HPDs may pose a danger at work, and 95% believe that HPDs cause some difficulties understanding orders in a noisy room (Pelausa et al., 1995). The implications of hearing protection will be considered in terms of protection afforded and three areas of auditory sensory degradation: detection, localization, and speech intelligibility.

5.1 Protection

Performance of a Hearing Protection Device (HPD) in protecting against continuous noise may be drastically different from protection against impulse noise (Johnson & Patterson, 1993). Attenuation provided by a HPD varies widely between devices. Furthermore, variations in fit of the HPD to the user's head will have significant impact on the attenuation provided. In a study of HPDs modified to simulate a poor fit, the incidence of temporary threshold shifts when using a perforated earplug was significantly higher than when using a modified earmuff (Johnson & Patterson, 1997).

The manufacturers' specification of attenuation provided by earplugs range from 23dB to 58dB and is dependent on the device and the frequency of the noise (Abel, Krever, Giguere, & Alberti, 1991; Bolia, D'Angelo, Mishler, & Morris, 2001). For earmuffs, manufacturers' specifications of attenuation range from 16dB to 41dB (Abel et al., 1991; Bolia et al., 2001).

5.2 Detection

Any loss of hearing sensitivity is unlikely to be acceptable in situations such as patrol and sentry activities where the auditory sense is a crucial detection system, yet the potential consequences of not protecting combat personnel from temporary threshold shifts is potentially as dangerous as the attenuation of a HPD (Forshaw, 1973).

The very nature of HPDs is to attenuate sound as it travels to the ear. Therefore, the detection abilities of the soldier are directly impacted as the hearing protection level is increased. However the relationship between attenuation provided by the HPD and detection abilities is not as simple as it may intuitively seem.

In a quiet environment, conventional HPDs have been shown to increase the detection threshold (Abel et al., 1991). However, in a noisy environment little difference in detection thresholds are observed between unoccluded and HPD conditions (Abel et al., 1991). Some research has

suggested that in a noisy environment HPDs will lower the detection threshold, as compared to unoccluded listening (Casali, Robinson, Dabney, & Gauger, 2004). These discrepancies may be the result of differences in the noise of the environment and the attenuation characteristics of the HPDs tested.

5.3 Localization

There have been a number of studies investigating the effects of HPDs on sound source localization. Abel and Armstrong (1993) found that conventional HPDs reduced localization accuracy by 20%. The detrimental effect on sound localization may be dependent on the frequency of the sound stimulus (Abel & Hay, 1994). Other studies have independently found that earplugs and earmuffs increase azimuth error by approximately 5^{o}, elevation error by approximately 15^{o}, and front-back confusions by 24-27% (Bolia et al., 2001; McKinley, 2000). Left-right reversals have been demonstrated to increase when earmuffs or earplugs are worn (Atherley & Noble, 1970). While azimuth errors normally vary as a function of elevation, where sources near the horizontal plane of the listener's ears are located with higher accuracy, the use of a HPD removes this relationship (Bolia et al., 2001).

In general, earmuffs have larger adverse effects on signal localization than earplugs, particularly in the horizontal plane and in terms of front-back confusions (Abel & Giguere, 1997; Abel & Hay, 1994; Noble & Russell, 1972). This is understandable as the disruption of spectral cues created by the pinna is much greater with earmuffs than earplugs. However, even earplugs are considered to dramatically reduce the ability to localize sound sources (Dancer et al., 1992). Gardner and Gardner (1973) systematically increased occlusion of the pinnae cavity and found that localization ability decreases with increasing cavity occlusion. Localization ability was also found to improve with increasing frequency of stimuli and with broadband noise (Gardner & Gardner, 1973).

Exploratory head movements help to restore localization ability lost due to a HPD; however they do not fully restore localization ability (Noble, 1981). Brungart and colleagues (Brungart, Kordik, & Simpson, 2002) found that the length of the stimuli was an important factor in localization ability with a HPD, where continuous stimuli allowed moderately good localization performance but short stimuli did not. This is consistent with the finding that head movements improve localization ability. They also investigated the use of double hearing protection and found that double protection reduced localization to the chance level for short stimuli and near chance for continuous stimuli (Brungart et al., 2002; Brungart, Kordik, Simpson, & McKinley, 2003). This led to the conclusion that double protection reduces air-conducted signals to the point that interaural differences are disrupted by bone and tissue conducted signals (Brungart et al., 2002).

In a more applied task, HPDs have a small, but significant, effect on reaction time in an aurally aided visual search task (Bolia & McKinley, 2000; McKinley, 2000). While the presence of an audio cue normally had a huge effect on reaction time, wearing a HPD reduced this effect (Bolia & McKinley, 2000).

5.4 Speech intelligibility

In normal hearing subjects, HPDs have been demonstrated to not impact speech intelligibility in quiet or noisy environments (Abel, Alberti, Haythornthwaite, & Riko, 1982; Abel, Armstrong, & Giguere, 1993). In a review of findings it has been shown that for normal listeners, there are no differences in speech understanding performance with HPD vs. unoccluded (Abel & Giguere, 1997). However, if the listener is hearing impaired, wearing a HPD will be a significant detriment

to intelligibility (Abel & Giguere, 1997). In normal listeners, no differences in consonant discrimination have been found between conventional HPDs and unoccluded listening in quiet environments, but word recognition suffers when a HPD is worn (Abel et al., 1991). In noisy environments, HPDs have shown slightly enhanced consonant discrimination and word recognition as compared to unoccluded listening (Abel et al., 1991).

Earplug HPDs do not have much of an effect on speech intelligibility in quiet environments, however in noise the Signal to Noise Ratio (SNR) and overall speech levels were lower with earplugs (Tufts & Frank, 2003).

5.5 Hearing Protection Conclusion

Due to the isolation effects of hearing protectors, in practice most soldiers do not use hearing protectors during military operations (Dancer et al., 1992). Any restorative hearing system must first ensure that detection capabilities in all environments are restored to the soldier. Studies of the impact of HPDs on the auditory sense collectively point to sound source localization as the primary area of degraded sensory awareness. Therefore restoring localization ability to the hearing protected soldier will be a key goal in any restorative hearing system.

6. Issues in Restoring Hearing

In attempting to restore hearing capabilities to the protected soldier there are many issues to consider. Any system that does not appropriately consider all of the issues will lead to user dissatisfaction and likely will not be used.

6.1 Comfort and Compatibility

The comfort afforded by the HPD and its compatibility with other headgear must be considered, in addition to the protection provided by a HPD (Dancer et al., 1992). Earmuffs are commonly considered unsuitable (too heavy, hot, bulky) for long-duration training or operational conditions (Dancer et al., 1992).

The compatibility of HPDs with other mission equipment must also be considered. For example the attenuation provided by an earmuff is significantly decreased when worn in combination with safety glasses and/or a half-mask respirator, with a larger decrement in attenuation in the lower frequencies (Abel, Sass-Kortsak, & Kielar, 2001). Equipment not purposefully designed to protect hearing (gas mask and hood) have been demonstrated to significantly increase the detection threshold and reduce speech intelligibility (Letowski, Ricard, & Greives, 1997). While the use of a kevlar helmet has not been shown to degrade localization acuity, the combination of helmet with earplugs has shown additive effects to the decrease in localization acuity as compared to just earplugs without the helmet (Vause & Grantham, 1999).

Therefore any potential restorative hearing system must not only meet the auditory performance requirements but also be comfortable to wear and compatible with other equipment.

6.2 Detection

Little scientific research has examined the level to which auditory signals need be restored; however the assumption is that any restorative system must return detection thresholds, in both quiet and noisy environments, to that of an unprotected listener. Furthermore, the potential for a supernormal listening ability is easily foreseeable by extending the mechanisms used to restore ambient sounds to a higher level and spectral based aural focusing (e.g. Letowski, Ricard, Kalb, Mermagen, & Amrein, 1997)

6.3 Localization

The restoration of localization is perhaps the most important challenge in creating restorative hearing systems. As illustrated by the review of the impact of wearing a HPD, the primary detriments to auditory awareness are in sound source localization. The following subsections detail some of the issues to be considered in restoring localization ability to the protected soldier.

6.3.1 Head Movements

Individuals prone to front-back confusions have been shown more apt to use head movements for resolving confusions than listeners who less frequently make such errors (Wightman & Kistler, 1998). Therefore it is imperative that any restorative system present a spatially stable auditory

image to allow the listener to make exploratory head movements. Any delays introduced by the system must not interfere with the listener's ability to use head movements to resolve the sound source location. With the integration of head orientation tracking, the extension of short stimuli on demand could potentially increase the utility of head movement for signals to which head movement would normally be of little value.

6.3.2 Head Related Transfer Functions

In an early study recognizing the role of the pinna in localization it was found that head movement can compensate for the lack of the spectral filtering in the absence of pinnae but when head movement is restricted even artificial pinnae allowed better localization performance than no pinnae (Fisher & Freedman, 1968). Pinna-based spectral cues are thought to specify the quadrant, front or rear, of the horizontal plane from which a sound source originates and promote accuracy of localization within a given quadrant (Musicant & Butler, 1984). Pinna based spectral cues are of particular importance for localization in the vertical plane (Roffler & Butler, 1968) and resolving front-back confusions (Oldfield & Parker, 1984b).

The use of generic HRTFs will generally lead to a significantly higher rate of front-back confusions as compared to both free-field listening (approximately quadruple) and simulation with personalized HRTFs (approximately double) (Arrabito & Mendelson, 2000; Wenzel et al., 1993; Wenzel, Wightman, & Kistler, 1991; Wightman & Kistler, 1989). Similarly, up-down confusion rates also increase significantly with virtual sources as compared to free-field listening (Wenzel et al., 1993; Wenzel et al., 1991). However, there are several strategies to reduce the negative impact of generic HRTFs.

Feedback following each localization trial (Shinn-Cunningham, Durlach, & Held, 1998), training and practice localizing with the generic HRTF (Wenzel et al., 1993), using a HRTF from a 'good' localizer (Wenzel et al., 1993), scaling the generic HRTF in frequency (Middlebrooks, 1999a, b), and tracking the changes of interaural cues during head motion (Begault, Wenzel, & Anderson, 2001; Wenzel et al., 1993) can all reduce error in localizing with generic HRTFs. The confusions resulting from the use of a generic HRTF tend to diminish with experience (Asano, Suzuki, & Sone, 1990; Wenzel et al., 1993). Head movement or source movement under the listener's control will significantly reduce front-back reversals caused by the use of a generic HRTF (Wightman & Kistler, 1999). A listener's accuracy in judging source elevation can be predicted from the acoustic characteristics of the outer ear and the pattern of errors caused by these characteristics transferred from one listener to another in simulated sounds (Wenzel, Wightman, Kistler, & Foster, 1988). The detriment associated with use of a generic HRTF can be reduced by approximately 50% by scaling the generic HRTF in frequency (Middlebrooks, 1999b). With confusions resolved, the accuracy of source localization with generic HRTFs is comparable to free-field listening (Wenzel et al., 1993). Furthermore, there are no definitive differences in variability of localization accuracy for free-field vs. sounds synthesized with generic HRTFs (Wenzel et al., 1993; Wightman & Kistler, 1999). Finally, the existence of free-field reversals indicates that the problem is not entirely the result of the simulation; however the high rates of confusion remains a problem (Wenzel et al., 1993).

One study actually found better localization of sound sources using generic HRTFs than individualized HRTFs, however this study stands in contrast to a large body of evidence to the contrary (Savick, 1998). When localizing speech sources, most listeners can localize in azimuth with generic HRTFs as accurately as with individualized HRTFs (Begault et al., 2001; Begault & Wenzel, 1993). This finding can be explained by the fact that, for speech, interaural cues are more

significant than spectral cues due to the frequency region of most of the spectral energy (Begault et al., 2001). In the opinion of some researchers, the possible performance detriment associated with generic HRTFs is a limiting factor preventing real-world application of synthesized 3D audio (Arrabito & Mendelson, 2000), however this is not a universal consensus.

While measurement of an HRTF can be complicated and resource intensive, research results indicate that localization accuracy in the horizontal plane is independent of the different HRTF measurement techniques (Arrabito & Mendelson, 2000). However, the number of spatial positions measured in a HRTF can affect listener performance (Arrabito, 2000).

6.3.3 Distance

One of the acoustic cues in the perception of source distance is reverberation (Shinn-Cunningham & Brungart, 2001). Thus, in restoring hearing the natural reverberant characteristics of the listener's environment should be maintained.

6.3.4 Calibration and Adaptation

Retino-visuomotor feedback is constantly used to recalibrate a listener's auditory space and maintain stable spatial alignment of location percept from audition and vision (Lewald, 2002a). Studies of blind individuals indicate that azimuth recalibration is possible by substituting audiomotor feedback for retino-visuomotor feedback; however, elevation recalibration is more reliant on visual information (Lewald, 2002a; 2002b). The innate relationship of inter-aural cues to the head median plane is suggested to explain these findings (Lewald, 2002a; 2002b).

The capability of the human auditory system to adapt to altered spectral cues has been demonstrated (Hofman, Van Riswick, & Van Opstal, 1998). This ability is contingent on a sufficiently rich set of spectral cues, visual feedback, and active head movements (Hofman et al., 1998). The ability to adapt to different representations of spectral cues and create new filter sets does not preclude maintaining the filter set of normal listening, but rather multiple sets of transfer functions can be maintained (Hofman et al., 1998). Furthermore, after-effects commonly observed in analogous visual adaptation to sensory realignment are not present following auditory adaptation (Hofman et al., 1998). Studies have shown that humans have the ability to completely adapt, with short-term training, to linear transformations of auditory space (Shinn-Cunningham, Streeter, & Gyss, 2001). Therefore, it appears that with the appropriate conditions, listeners should be able to adapt to slight alterations in localization cues presented by a restorative hearing system.

6.3.5 Signal Bandwidth

Studies of 3D audio displays have shown that band-limiting the signal presented to a listener will limit the listener's perceptual spatial resolution (King & Oldfield, 1997). Results suggest that frequencies from 0 to at least 13 kHz are necessary in order for listeners to accurately localize the sound source (King & Oldfield, 1997). However other research has found that broadband stimuli are not localized significantly better than frequency restricted (3 kHz low-pass) stimuli (Arrabito & Mendelson, 2000). It is important to note that this study measured only localization in the horizontal plane, in which spectral cues are believed to play a minimal role in sound localization (Arrabito & Mendelson, 2000). Other researchers have concluded that frequencies above 4 kHz are not used to locate sound in the correct quadrant of the horizontal plane (Musicant & Butler, 1984). The higher frequencies are particularly important for localization in the vertical plane

(Roffler & Butler, 1968). Therefore the signal bandwidth has important implications for restorative hearing systems in that a large range of frequencies must be faithfully replicated in order to restore localization ability in both azimuth and elevation.

6.3.6 Supernormal Localization

Introducing digital processing of auditory signals between the environment and the listener gives the potential for application of supernormal auditory localization cue concepts, such as those proposed by Durlach, Shinn-Cunningham, and Held (Durlach, Shinn-Cunningham, & Held, 1993; Shinn-Cunningham, Durlach, & Held, 1998a; Shinn-Cunningham, Durlach, & Held, 1998b). These supernormal auditory cue concepts include creating localization cues representative of an enlarged head for increased directional resolution, remapping normal space filters, and exaggerating distance cues (Durlach, Shinn-Cunningham, & Held, 1993; Shinn-Cunningham, Durlach, & Held, 1998a; Shinn-Cunningham, Durlach, & Held, 1998b).

A binaural linear microphone array can be used to restore hearing to a listener and extend the detection range of low-level signals (Letowski et al., 1997). By having the listener rotate the array such that the aural image is centred between the ears (equalizing interaural differences), localization performance equal to that of unaided, unobstructed listening can be achieved (Letowski et al., 1997).

6.3.7 3D Audio Display

The utility of 3D audio presentation is dependent on the listener's ability to localize and discriminate between sound sources (Arrabito, 2000). The utility of a 3D audio system in increasing situational awareness for dispersed teams has been partially demonstrated (Bryden, 2000 as referenced by Arrabito, 2000). Compass instability and latency to head movements were two primary limitations of this preliminary investigation into 3D audio for radio communications. The implementation of a 3D audio system for real-world applications will depend on many factors, such the HRTF used, characteristics of the sound stimulus, and head tracking (Arrabito, 2000). The components necessary for inclusion of a restorative hearing system in future soldier concepts may create synergies for the inclusion of a 3D audio display (e.g. HRTF use, binaural signal presentation).

6.3.8 Aiding Visual Search

Spatialized audio cues have been shown to significantly reduce reaction time in a visual search task, for both simple and complex search fields (McKinley, 2000). Even 3D sound fields synthesized with a generic HRTF have been demonstrated to provide a considerable advantage for visual search tasks (Perrott, Cisneros, McKinley, & D'Angelo, 1996). Thus spatialized audio cues can facilitate visual localization, thereby demonstrating an advantage of auditory information in maintaining situation awareness.

6.3.9 Aiding Speech Intelligibility

A listener's ability to detect and understand the content of a sound stimulus is improved if it is spatial separated from interfering (masking) sounds through a phenomenon known as spatial unmasking (Shinn-Cunningham, 2003). Multiple simultaneous talkers from the same source location will sound jumbled. Spatial separation situates and segregates the talkers spatially

enabling the listener to distinctly decipher individual talkers. The advantages of spatialized audio in improving speech intelligibility become apparent when the number of simultaneous talkers increases beyond two (Arrabito, 2000; Ericson & McKinley, 1997). However, even with just two overlapping messages, spatialization has been shown to improve recognition accuracy (Campbell, 2002; Brungart & Simpson, 2005). Therefore, the focus of restorative hearing systems on localization may further facilitate speech intelligibility,

6.4 Speech intelligibility

The intelligibility of speech will be a crucial metric of a restorative hearing system. This is an area where much could be learned from the contributing mature technology of hearing aids not detailed in this report. One area that has been explored is obtaining speech intelligibility gains by improving noise attenuation through active means.

6.4.1 Active Noise Reduction

Active Noise Reduction (ANR) is an electro-acoustic technique of measuring sound in the ear canal, reversing the phase of the noise, and introducing this out of phase signal back into the ear canal to partially cancel the original sound (Crabtree, 1996). ANR is best suited to lower frequencies (below 1000 Hz) and strongly depends on the fit of the HPD delivering the ANR (Crabtree, 1996).

Abel and Giguere (1997) conducted a literature review of the feasibility of integrating ANR and binaural technology into communication headsets. ANR was found to increase detection threshold by 10 dB at 0.25 kHz compared to a similar device with no ANR, however ANR may improve detection of signals of frequencies above the ANR operating bandwidth by preventing or reducing forward masking (Abel & Giguere, 1997).

The use of ANR has shown substantial intelligibility gains over normal passive protection (McKinley, 2000). There is some evidence to suggest the speech intelligibility gains created by ANR are lost when other equipment, such as a CB mask and spectacles, are worn (Mozo & Murphy, 1998).

Clearly, there are benefits of ANR in both attenuating noise and improving speech intelligibility. If ANR and restorative hearing systems are to be used together, extensive integration of these systems will be necessary to ensure both are performing their intended function without interfering with the other.

7. Means of Restoring Hearing

From the discussions of the auditory needs of, and noise hazards to, the dismounted soldier, a number of characteristics for an ideal solution can be deduced. The ideal solution will protect the soldier from hazardous auditory signals while providing the soldier the full benefit of his/her auditory system. In other words, protection from dangerous impulse and continuous noise will not interfere with the soldier's normal auditory situation awareness. This can be measured in the protection, detection, localization, and speech intelligibility framework used throughout the report. Furthermore, the ideal solution will allow for extensions of the auditory system in areas such as supernormal auditory detection, aural focusing, supernormal auditory localization, and enhanced speech intelligibility. Finally, the ideal solution will create synergies in the implementation of advanced display concepts such as 3D audio displays and spatialized radio communications. Additional considerations critical in the implementation of any solution include comfort, ballistic protection, chemical and biological threat protection, energy requirements, compatibility with other equipment, maintenance, and cost.

Hearing can be restored to the protected listener using many different mechanisms. The following section details research efforts, starting with the simplest passive systems and culminating with the fully electronic transparent hearing systems. Only scientific evaluations of potential solutions will be presented. Refer to Annex A for a listing of commercially available restorative hearing systems. Each type of system will be discussed in terms of protection afforded, detection ability, localization, and speech intelligibility issues.

7.1 Passive Feed-Through / Level-Dependent

Passive feed-through, or level-dependent, hearing protectors use mechanical means, such as a small aperture or baffles, to limit the level of sound passing through. In this way the wearer is protected from high-intensity noise, while still being able to hear ambient sounds. Because these systems rely on passive mechanisms to limit the sound level and do not electronically reproduce the sound, any radio communications would have to be accomplished through an alternative communication device. The auditory display would need to be independent from the HPD, possibly through the use of bone conduction.

7.1.1 Protection

The Gundefender earplug consists of a standard earplug with the core removed and replaced with a small metal disk with an aperture drilled through the disk (Mosko & Fletcher, 1971). The aperture allows low-intensity waves to pass relatively unimpeded while the turbulent characteristics of high-intensity waves cause them to be attenuated as they pass through the aperture (Mosko & Fletcher, 1971). The effectiveness of this device has been evaluated against a wide range of impulse noise threats. One of the earliest evaluations of this earplug tested the magnitude of TTSs when using the Gundefender compared to a standard earplug and unprotected ears (Mosko & Fletcher, 1971). Twelve participants with normal hearing were repeatedly exposed to M-14 rifle impulse noise (172 dB) in the unprotected condition until a TTS was induced. Participants were then tested with the two types of earplugs (Gundefenders and standard) in a counterbalanced order using the same number of noise exposures as in the unprotected condition and additional exposures of three times the number of rounds to determine the upper limits of the ear protection devices. The Gundefender

earplugs were found to be as effective as the standard earplugs in the reduction of TTS (Mosko & Fletcher, 1971).

Dancer and colleagues (Dancer et al., 1992) found the Jrenum LP3, EAR ER-20, and Gundefender earplugs effective against Howitzer impulse noise. They also tested the EAR Ultrafit modified with 1-1.5 mm diameter hole and 0.5 mm diameter tube creating passages to the ear canal and found some, but not a significant number of temporary threshold shifts with rifle, antitank, and howitzer impulse weapon noise (Dancer et al., 1992). These earplugs were considered sufficient for protecting from infrequent field firing exercises, as encountered in training (Dancer et al., 1992). The nonlinear acoustic phenomena of the small openings of these HPDs are thought to enable the level of protection (as measured by frequency of TTSs) despite the low attenuation values when measured at low levels (Dancer et al., 2002). The authors offer the opinion that perforated earplugs represent the best solution to protecting the soldier from impulse noises without restricting the operational abilities of the soldier (Dancer et al., 2002). The protection provided by the Gundefender earplug to impulse noise from an anti-tank weapon was found to be no different than the protection given by a conventional earplug; however neither plug was sufficient for extended, repeated exposure (Hughes, 1972).

7.1.2 Detection

Passive level-dependent HPDs cause an increase in detection thresholds in quiet environments but are no different from unoccluded listening in noisy environments (Abel et al., 1991).

Lindley and colleagues (1997) tested identification ability while wearing commercially available level-dependent earplugs. The two earplugs tested were the passive level-dependent Sonic II earplugs and the active feed-through SoundScope. Eighteen participants with normal hearing made identifications of seven possible sounds recorded at four distances under three listening conditions of open ears, Sonic II, and SoundScope. The seven sounds consisted of a crow call, a deer call, a duck call, a goose call, an owl call, a turkey call, and a person talking while walking. Distances tested were 25, 50, 75, and 100 yards.

Results are reported using a sound identification score (SIS) representing the percent of correct identifications in the given condition. Significant effects of listening condition and distance were found, as well as a significant interaction (Lindley et al., 1997). However, upon examination of the interaction effect it is evident that all of the main effects are caused by differences in the 100 yards condition, while across all other distances and listening conditions within the other distances the SIS's do not vary (approximately 100%) (Lindley et al., 1997). At 100 yards, significant differences were observed between all listening conditions with the best performance in the open ears condition, followed by the SoundScope and Sonic II respectively (Lindley et al., 1997).

7.1.3 Localization

No experimental test data on a listener's ability to localize sound while wearing any type of passive feed-through HPD is available.

7.1.4 Speech Intelligibility

An early study of the Gundefender earplugs also tested speech intelligibility with the Gundefender earplugs, standard earplugs, and open ears under a variety of noise levels and SNRs (Mosko & Fletcher, 1971). Ten participants with normal hearing were tested with the Modified Rhyme Test

(MRT) at SNR of 0 dB and +4dB, under no noise, 70 dB noise, and 100 dB noise. The Gundefender earplugs demonstrated advantages in speech intelligibility scores in the no-noise and low noise conditions for both SNRs, as compared to the standard earplugs condition, with performance similar to that of open ears (Mosko & Fletcher, 1971). However in the high-noise conditions, performance with the standard earplug was comparable to that of open ears, both of which were superior to the Gundefender (Mosko & Fletcher, 1971).

7.2 Active Feed-Through

Active feed-through HPDs selectively pass sound through the hearing protection at a safe level by powered means. Devices are typically non-linear, providing different levels of attenuation to sounds of different frequencies. Some active feed-through devices go further to provide amplification of sounds below 85 dB, in an attempt to improve the detection threshold.

7.2.1 Protection

Limited data is available on the level of protection provided by active feed-through HPDs. Several commercial earmuffs equipped with active feed-through have been demonstrated to provide sufficient attenuation of the impulse noise from a Finnish assault rifle (Paakkonen, Lehtomaki, & Savolainen, 1998).

7.2.2 Detection

There is some evidence that HPDs with active amplification of sounds below 85 dBA may prevent an increase in the detection threshold for most frequencies, as compared to unoccluded listening, in quiet environments (Abel et al., 1991). However, in noisy environments the amplification of the HPD may work against the listener, increasing the detection threshold for certain frequencies (Abel et al., 1991).

7.2.3 Localization

Level-dependent earmuffs with dichotic amplification do not improve sound localization over conventional earmuffs (Abel & Giguere, 1997). This finding is consistent with other studies finding that level-dependent earmuffs are no better than conventional HPDs for sound localization, and may cause more left-right confusions (Abel & Armstrong, 1993; Abel & Hay, 1994).

Two major research efforts in this area are summarized.

Air Force Research Laboratory / Sytronics Inc.

In an effort to determine the crucial design constrains and explore the engineering tradeoffs of active feed-through earplugs, Brungart and colleagues investigated the effect of microphone placement and transducer bandwidth on localization performance (Brungart, Kordik, Eades, & Simpson, 2003). The effect of moving the microphone away from the optimal placement for active pass-through earplugs of completely-in-the-canal (CIC), where HRTFs are created naturally, was explored. A series of custom-molded earplugs and active pass-through earmuffs were compared to open ears and a CIC hearing aid. Furthermore, components meeting the size and power requirements for use in a CIC design typically are not capable of producing the 13 kHz of bandwidth necessary to preserve sound localization performance or providing enough acoustic isolation to protect the listener to be used in a HPD. The effect of signal bandwidth was explored

by using devices of differing bandwidth and two open ears condition, one of broadband noise signal and one of a limited low-pass noise signal.

Two participant groups were used to test experimental conditions (Brungart et al., 2003). The first group of 4 participants was tested with the 5 custom-molded earplugs conditions varying microphone placement and 2 open ears conditions of broadband noise and 6 kHz bandwidth limited noise. The second group of 5 participants was tested with the CIC hearing aid, active pass-through earmuff, and the open ears condition with broadband noise. The earplug devices had a bandwidth measured to be 6 kHz, the CIC hearing aid had a manufacturer reported bandwidth of 7.4 kHz, and the earmuff bandwidth was not reported. All participants were screened for normal hearing and had previous experience in localization experiments.

The Air Force Research Laboratory's Auditory Localization Facility (ALF) was used to test localization ability (Brungart et al., 2003). The ALF consists of a geodesic sphere of 4.6 m diameter, with speakers at each of the 272 vertices giving 15 degrees of arc between adjacent speakers, in an anechoic chamber. The noise signal stimuli was presented at 70 dB SPL and was manipulated in two conditions; the short condition gave a 250 ms burst while the long continued the signal until the participant responded. In all conditions participants were free to move their heads. The participants provided responses by moving a head-slaved cursor to the perceive location of the sound source. Trial blocks consisted of 50 stimuli presentations from the 232 speaker locations above -45 degrees elevation. Participants in the first group completed one trial block in each listening condition for both short and continuous stimuli lengths, while participants in the second group completed three trial blocks for each listening condition for both short and continuous stimuli lengths.

Results were presented in terms of radial, frontal plane azimuth, median plane azimuth, and elevation error. Quadrant confusions are not reported. Statistical analysis revealed that the main effect of stimulus length was significant for all error measures in both groups, except elevation error in the second group (Brungart et al., 2003). The main effect of listening condition was significant for all types of error in both groups, except frontal plane azimuth error in the first group (Brungart et al., 2003). The authors offer a number of general observations about the results. Errors were generally lower in frontal plane azimuth than median plane azimuth or elevation for all listening conditions, as expected due to the dominance of robust interaural differences. Continuous stimuli allowed more accurate localization than short stimuli length due to the ability to use head motion to further resolve the sound source location. Median plane azimuth error was reduced the most in the continuous stimuli condition, as the length of the stimulus allowed the listener to rotate their head such that interaural differences could be more effectively utilized.

For the first participant group, another series of general observations of results are given. The open ears listening condition was significantly better than any of the 5 custom-molded earplug conditions for all error measures except median plane azimuth error (Brungart et al., 2003). Bandwidth limitations had the strongest effect on elevation accuracy. While the 6 kHz bandwidth limited open ears condition resulted in statistically significantly lower radial and elevation errors than the custom-molded earplug conditions, the size of this effect was small relative to the open ears broadband condition. This finding suggests that the earplugs were causing localization difficulties due to their limited bandwidth, not the HRTF distortions caused by the earplugs. The relatively few differences observed between the different earplugs further reinforces the finding that the HRTF distortion caused by the earplug, and therefore the relative placement of the microphone, was not the primary causal factor in the localization performance difficulties.

For the second participant group, performance was ordered from best to worst by open ears, CIC hearing aid, and earmuffs, with significant differences between conditions, except open ears and CIC hearing aid in frontal plane azimuth error (Brungart et al., 2003).

While statistical comparisons between participant groups are difficult, several general observations can be made. The CIC hearing aid condition performed as well as the custom-molded earplugs in every error dimension and possibly better in elevation (Brungart et al., 2003). This finding may have been caused by the slightly larger bandwidth of the CIC hearing aid (7.4 kHz) compared to the earplugs (6 kHz) and the fact that the CIC hearing aid should not have interfered with the natural HRTFs at all (Brungart et al., 2003). In the earmuffs condition, performance was substantially worse than any other condition tested in either participant group (Brungart et al., 2003). This finding suggests that a certain accuracy of HRTF must be maintained (Brungart et al., 2003). One notable piece of information missing from the report of this work is the bandwidth of the earmuffs. Therefore, while bandwidth appears to be the predominate factor for earplug type systems, earmuff type systems may have alternate relative importance of factors.

Army Research Laboratory

Scharine (2004) conducted a localization study examining the effects of various HPDs with some form of feed-through mechanism. Five HPDs were tested, consisting of 2 earmuffs and 3 earplugs, and a control condition of open ears. The two earmuffs tested were the Sordin earmuffs providing approximately 24 dB of passive attenuation and active hear-through via 2 frontally place microphones and the Sennheiser articulating earmuffs providing less than 2 dB of attenuation in open mode and transmission of ambient sounds by not entirely covering the ears. The three earplugs tested were the General Hearing (GH) earplugs providing 30 dB gain to restore hearing but compressing sounds above 90 dB SPL on a 4:1 ratio, the Terminal Attack Communications (TAC) earplugs providing 29 dB passive attenuation with 20 dB gain to restore hearing and limiting sounds greater than 85 dB, and the Communications Enhancement and Protection System (CEPS) earplugs providing 29.5 dB passive attenuation with 12 dB gain to restore hearing and limiting sound transmission greater than 125 dB SPL. All three earplugs are considered active feed-through devices as they utilize microphones to pick up ambient sounds and electronic circuitry to prevent the transmission of dangerous sound levels. Participants were allowed to adjust the levels of the HPD such that the stimulus appeared normal and comfortable, however these levels did not differ by more than 2 dB between participants.

Twelve speakers, located 30 degrees apart in azimuth at a single elevation, surrounded the listener (Scharine, 2004). Four participants with normal hearing indicated the perceived source of the stimulus via a computer interface. The stimulus was a female voice saying the word “Joe”, with peak presentation level of 75 dB, and duration of less than 250 ms.

Results indicated all of the HPDs caused higher average error than the open ears condition, but no significant differences were found between HPDs (Scharine, 2004). When quadrant confusions are corrected for, the error in all HPD conditions is reduced to approximately 5 degrees larger than the open ears condition, except for the TAC earplugs which showed average error approximately equal to the open ears condition (Scharine, 2004). The large reductions in average error seen when quadrant confusions are corrected indicates that the localization error induced by the HPDs was primarily due to an increase in quadrant confusions. It is interesting to note that the largest localization performance detriments were seen for the Sennheiser articulating earmuffs which do not employ any electronic means of feed-through (Scharine, 2004).

7.2.4 Speech Intelligibility

Very little research is available on speech intelligibility with active pass-through HPDs. Active pass-through HPDs have been demonstrated to be successful in restoring consonant discrimination and word recognition abilities in quiet environments to unoccluded listening levels, however in noisy environments these same devices are typically worse than unoccluded listening, and occasionally worse than conventional HPDs (Abel et al., 1991).

7.3 Hearing Aids

Hearing aids could also be considered restorative hearing systems because they provide ambient sound stimuli to the listener at an audible level. However, in this case the listener's hearing ability is reduced due to a degraded auditory system as opposed to a reduction in ability caused by hearing protection. Therefore, hearing aids will be discussed in terms of how this technology can contribute to restorative hearing systems and not the protection, detection, localization, and speech intelligibility framework.

7.3.1 Microphone Arrays

Adaptive microphone arrays used in hearing aids have been demonstrated to improve the target-to-jammer ratio (TJR) over conventional hearing aids that indiscriminately amplify the desired source (target) and background noise (jammers) (Greenberg, 1994). In this way, microphone arrays have been used to provide benefits in aural focusing. Further research has shown that microphone arrays can be designed to provide both the benefits of aural focussing and the natural sound localization and speech intelligibility benefits of a binaural system (Desloge, Rabinowitz, & Zurek, 1997; Welker, Greenber, Desloge, & Zurek, 1997). The use of microphone arrays in hearing aids has also shown improvements in speech intelligibility by improving the SNR (Luts, Maj, Soede, & Wouters, 2004).

7.3.2 Completely-In-Canal Hearing Aids

Completely-In-Canal hearing aid designs are thought to have advantages in auditory source localization by reducing alterations of the spectral characteristics of the sound (D'Angelo, Bolia, Mishler, & Morris, 2001). The Starkey Tympanettes CIC hearing aid was tested for localization performance compared to open ears in 6 normal hearing participants in the ALF (D'Angelo et al., 2001). The God's Eye Localization Pointing (GELP) technique developed by Gilkey and colleagues (Gilkey, Good, Ericson, Brinkman, & Stewart, 1995) was used to collect responses. Stimulus elevation positions were categorized in three regions; upper hemisphere for elevations greater than 15 degrees, peri-horizontal region between -15 degrees and 15 degrees elevation inclusive, and lower hemisphere for elevations less than -15 degrees. Stimuli of 750 ms broadband pink noise were presented at 70 dB SPL from the 272 loundspeakers in a randomized order. Participant's head position was fixed via a chin rest throughout the experimental trials. Participants were trained until performance no longer improved on several consecutive sessions.

Azimuth error was corrected for front-back confusions prior to presentation. Significant effects of listening condition and source elevation were observed, with a small but significant increase in azimuth error in the hearing aid condition and azimuth error significantly less in the peri-horizontal region than for other elevations for both the hearing and open ears conditions (D'Angelo et al., 2001). Similarly for percentages of trials in which a front-back confusion occurred, significantly

more confusions were made with the hearing aid and in the upper and lower hemispheres. Also, significantly more confusions were observed in the upper hemisphere than in the lower hemisphere. For elevation error, significant effects of listening condition, source elevation, and an interaction of main effects was observed. There was significantly higher elevation error in the hearing aid condition than in the open ears conditions. Significant differences in elevation errors were seen between the lower hemisphere, peri-horizontal region, and upper hemisphere, with the lowest error in the lower hemisphere and greatest error in the upper hemisphere. However the interaction of main effects showed this ordering of elevation regions true only for the hearing aid condition and not for the open ears condition where all elevation regions demonstrated roughly equal elevation error. Therefore, while CIC hearing aid design is considered optimal for localization performance, it still does not afford the same localization ability as unoccluded listening in normal hearing subjects (D'Angelo et al., 2001).

7.4 Transparent Hearing

Transparent hearing systems are very similar in form to active pass-through systems, in that external microphones pick up ambient sound and electronically transmit it to the listener's ear canal. One of the criticisms of existing pass-through systems is the failure to compensate for distortions of the sound field caused by the HPD (Bronkhorst & Verhave, 2005). Transparent hearing systems attempt to include the interaural and spectral cues of the listener's unoccluded listening environment in the restored sound stimulus.

Scanlon and Tenney (1994) have developed hearing augmentation devices to restore hearing to a listener wearing encapsulating headgear. Using head-mounted pinna attachments, HRTF are applied to incoming signals. This system purportedly provides "excellent restoration of omnidirectional hearing"; however limited performance data is available on this system (Scanlon & Tenney, 1994, pp. 1994).

Mueller and Karau (2002) developed a headphone using the concept of transparent hearing. In their design, binaural microphones mounted on the exterior of headphone ear cups are used to pass external audio inputs into the headphones (Mueller & Karau, 2002). However, the fidelity of this primitive system has not been demonstrated.

7.4.1 Protection & Detection

None of the studies of transparent hearing systems have included measurement of the level of protection afforded by the device or the detection capabilities of a listener wearing the device. Many prototypes build on existing HPDs and assume that the same level of protection as offered by the unaltered HPD would be maintained. Detection capabilities are assumed to be equivalent to unoccluded listening, however studies of level-dependent HPDs suggest that this is not a safe assumption.

7.4.2 Localization

Developing a transparent hearing system that restores the listener's localization ability has justifiably been the primary focus of the most extensive development efforts in the area. A number of systems, and the localization performance achieved, will be described. Comparison of performance across devices is difficult due to experimentation differences.

Netherlands Organisation for Applied Scientific Research (TNO)

One of the most developed transparent hearing systems is a microphone-array-based system by Bronkhorst and Verhave (2005). This system simulates the direction- and frequency-dependent acoustic properties of the open ear using two arrays of 3 microphones on the corners of an equilateral triangle at the ear on the exterior of an earmuff. Interaural differences and spectral features are simulated by passing the incoming audio through filters that convert the transfer functions of the microphone array to a human's HRTF and compensates for the characteristics of the speakers in the earmuffs.

Bronkhorst and Verhave (2005) performed a localization experiment to validate their system, testing five conditions: open ears, earmuffs with electronics switched off, earmuffs with a single microphone operating on each side, earmuffs with the microphone arrays and individualized filters, and earmuffs with the microphone arrays and generic filters. The open ears condition was always tested first, while the order of testing the other four conditions was counterbalanced. Eight blindfolded participants used a pointer to point to the perceived sound source by aligning the pointer to the imaginary line between their head and the source location. Forty-two stimuli were presented consisting of 500 ms bursts of pink noise at 75 dBA (increased to 85 dBA for earmuffs with electronics switched off condition) with two repetitions for each of twenty-one loudspeaker positions varying in azimuth and elevation.

Results indicated that sound localization performance was significantly better in the open ears condition than the other conditions for all of the three primary measures: azimuth error, elevation error, percentage of quadrant confusions – see Figure 4 and Figure 5 (Bronkhorst & Verhave, 2005). Reanalysis with the open ears condition removed shows that the individualized HRTFs conditions was significantly better in terms of elevation error and percent confusions, but not azimuth error (Bronkhorst & Verhave, 2005). There was a general trend towards better performance with the generic HRTFs over the passive muff and one microphone conditions; however these effects did not reach conventional significance levels. Furthermore, subjective differences of the microphone array system to open ears listening are smaller than differences created by passive muffs or a one microphone system, particularly in that background noise sounds more natural with the microphone array system.

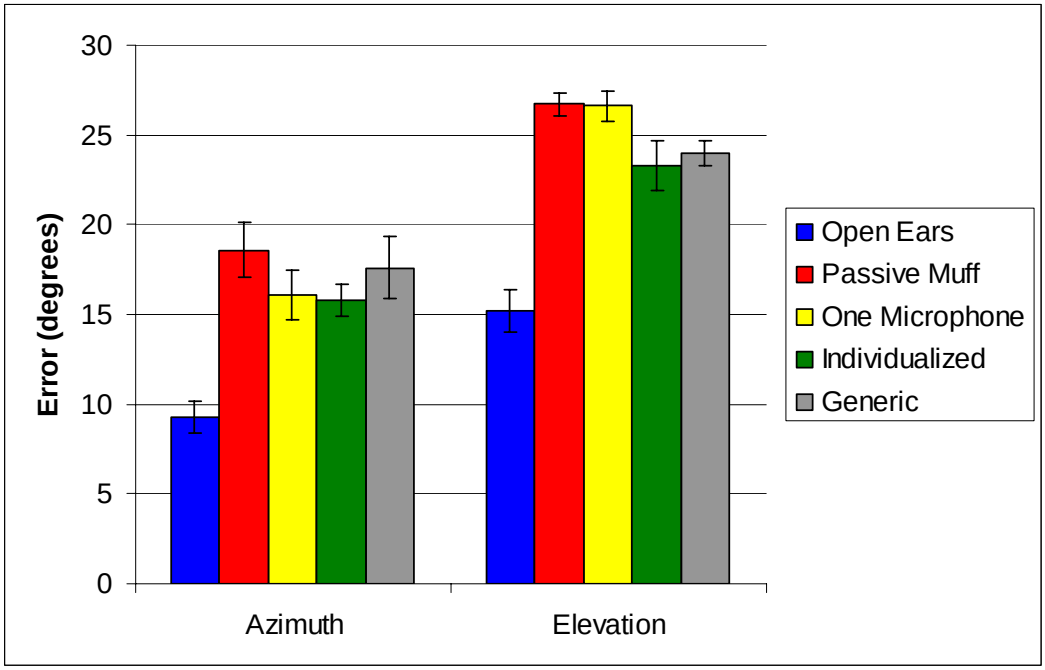

Figure 4: Azimuth and elevation error in sound localization (adapted from Bronkhorst & Verhave, 2005)

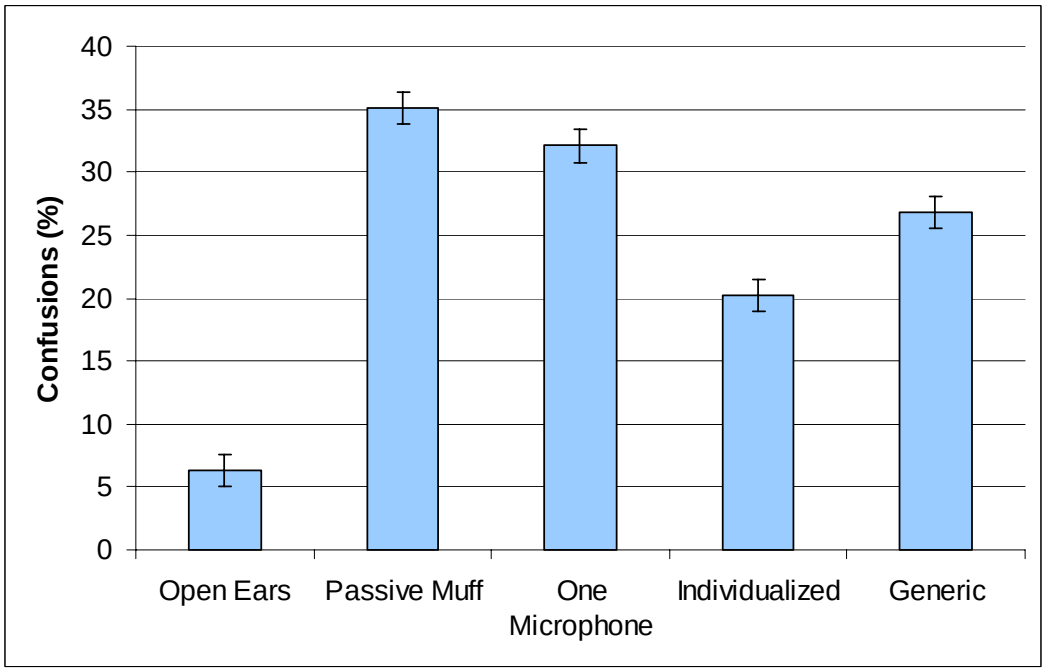

Figure 5: Quadrant confusions in sound localization (adapted from Bronkhorst & Verhave, 2005)

The results of localization tests on Bronkhorst and Verhave's (2005) system suggest that while a microphone array transparent hearing system affords better performance than passive muffs or

active pass-through systems, there remains significant work to bring performance to the level of open ear listening.

Adaptive Technologies / Virginia Tech

A group of researchers at Adaptive Technologies and Virginia Tech have developed a means of restoring hearing to a listener wearing encapsulating headgear, which they term Natural Hearing Restoration (NHR) (Goldstein, Johnson, Saunders, Vaudrey, & Carneal, 2004). The basic idea behind NHR is the same as a transparent audio system, which is to reproduce the sound pressures at the eardrums of the obstructed ears as would be perceived by a listener with unobstructed ears (Goldstein et al., 2004). This particular system was designed for a fully encapsulating helmet with external surface-mounted microphones and internal headphones. They approach the problem of resolving the audio signals of the microphones to the HRTF of the listener as a classic least squares problem. The error between the original and reconstructed HRTFs is dependent on the number of microphones used to reconstruct the HRTF. While preliminary measurements were made with a 24 microphone system, this number was considered impractical for real time implementation and the number of microphones was reduce to 4 on each side of the head (Goldstein et al., 2004; Johnson, Carneal, & Goldstein, 2004).

A localization study was performed to experimentally validate the efficacy of the NHR system (Johnson et al., 2004). Four hearing conditions were tested: open ears, with the helmet on but electronics of NHR turned off (occluded), a feed-through system using only one microphone, and the NHR system. Stimuli were white noise of unspecified length from one of fifty speakers arranged in a ten azimuth (-87, -67, -49, -29, -12, 10, 29, 49, 69, 88) by five elevation (-29, -16, 0, 16, 29) matrix (Johnson et al., 2004). Speakers were hidden from the participants by a visually opaque, acoustically transparent screen with position indicator on 5 degrees steps and angle labels every 10 degrees. Sixteen participants were asked to indicate the perceived location within 2.5 degrees using a laser pointer. Testing took place in an acoustically dead listening room. Localization was first tested without head movement in the four hearing conditions, in the order conditions are listed, then with head movements, in the same order. Each participant made 5 location judgements of randomly selected speakers per condition. The lack of experimental control of stimuli between hearing conditions and participants creates problems in interpreting results.

Results are presented in terms of azimuth, elevation, and radial (combined azimuth and elevation) error – see Figure 6 and Figure 7. Quadrant confusions are not reported. While the statistical procedures used are not clearly specified, it is evident that the feed-through and NHR offered substantial improvement in azimuth localization over an occluded condition (Johnson et al., 2004). No indication of the volume level of the stimuli was given, but it is indicated that in the occluded condition most participants could no longer hear the sound. Without head movement, azimuth error in the feed-through and NHR conditions were on the order of three times the open ears condition, however with head movements these differences are drastically reduced. The authors argue that the NHR system does not create as much bias as the feed-through system, but rather that overall average error of the NHR system is degraded by a few outliers (Johnson et al., 2004). However, as variability data is not provided, this argument is difficult to substantiate. Elevation error in all conditions except the open ears was near chance levels. Furthermore only the open ears condition appears to benefit from head movement in elevation localization.

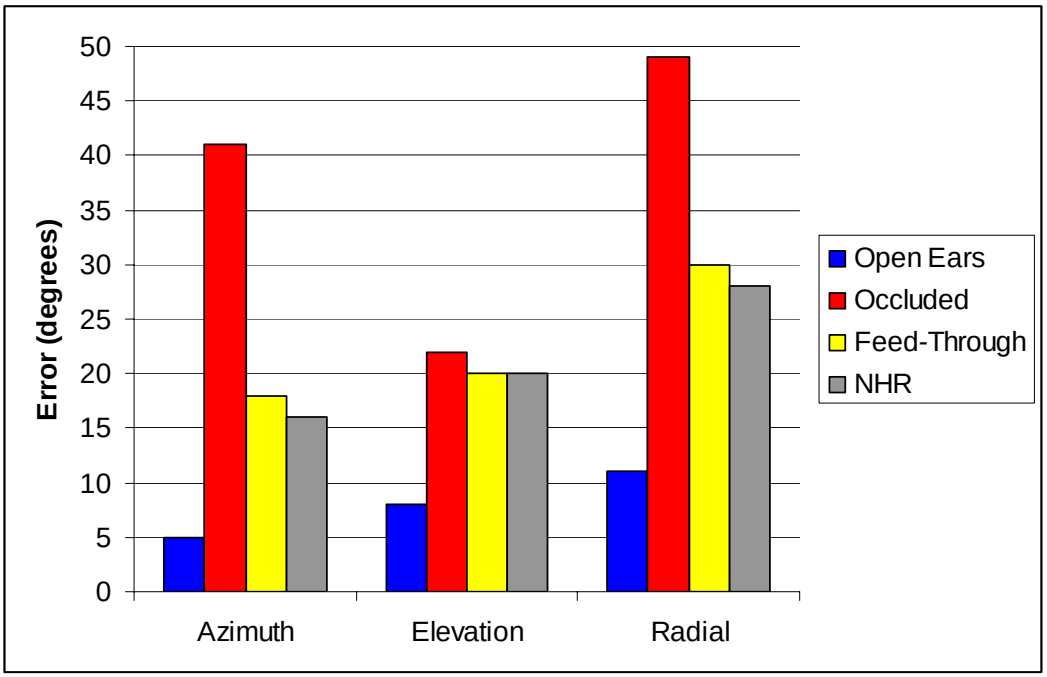

Figure 6: Azimuth, elevation, and radial error in stationary sound location (adapted from Johnson et al., 2004)

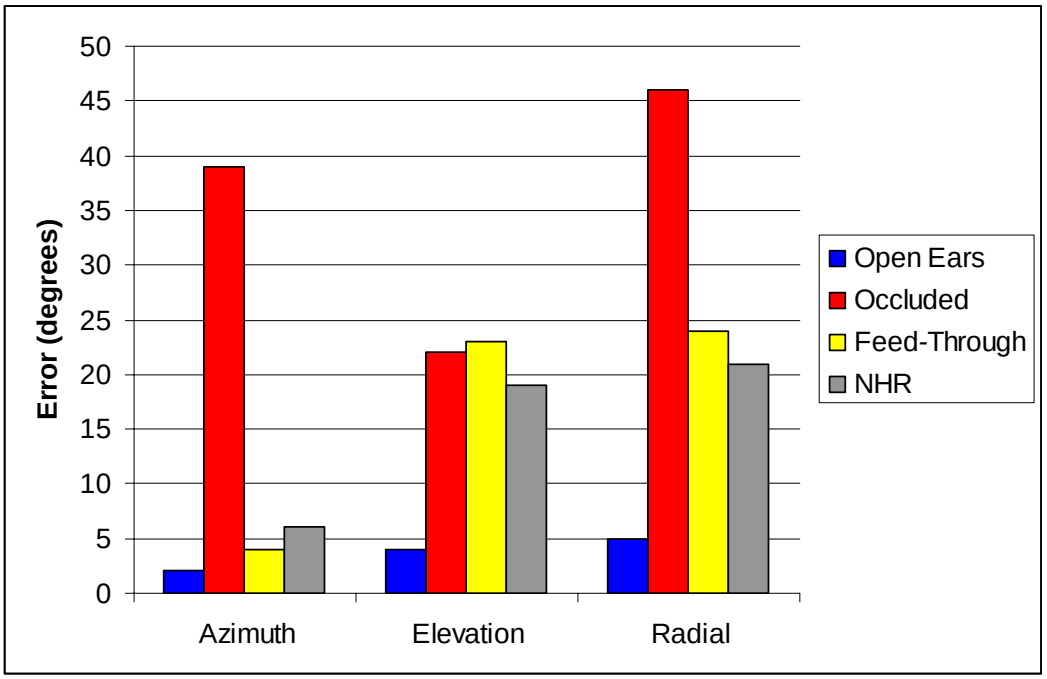

Figure 7: Azimuth, elevation, and radial error in sound location with head movement (adapted from Johnson et al., 2004)

Two further tests were conducted whereby the NHR and the feed-through system were qualitatively compared for white noise and human speech (Johnson et al., 2004). Participants were

free to move their head. It is not clear which speaker(s) were used in the white noise condition. In the human speech condition, an experimenter walked around the participant reading a script. The system identities were masked to the participant for these additional tests. The system was switched between NHR and feed-through until the participant reached a decision for three questions for each stimulus condition:

1. Which one gives a more precise indication of speaker location?
2. For which one does the sound seem to come from outside the helmet?
3. Which one sounds more like "natural" hearing?

Responses to the three questions tended to consistently identify the preferred system. In the white noise condition, the NHR system was preferred by approximately two-thirds of the participants, while between one-fifth and one-third of the participants preferred the feed-through system and the remainder indicating either both or neither (Johnson et al., 2004). However in the human speech condition, the feed-through system was preferred by approximately two-thirds of the participants, while between one-fifth and one-third of the participants preferring the NHR system and the remainder indicating both. The authors explain this result by suggesting that the relative low frequency of speech is outside of the design range of the NHR system (Johnson et al., 2004).

Despite the extensive work in applying HRTFs to the restored auditory signals, the NHR system appears to offer little advantage over a simple active feed-through system.

AuSIM

Extensive work on this concept was performed for the US Air Force Research Laboratory at Wright-Patterson Air Force Base and Natick Soldier Systems of the US Army (Chapin, Jost, Cook, Surucu, Foster, Zurek, Desloge, Beaudoin, Bolas, McDowall, Lorimer, Shinn-Cunningham, & Durlach, 2003). This project sought to reduce risk in future technology programs, establish metrics and evaluation methods, provide design guidelines, and estimate costs for future transparent hearing initiatives. A transparent hearing system is defined by these researchers as a system that "attenuates the direct, uncontrolled path to the point of psychoacoustic elimination and supplies an indirect, controlled path that supports transparent hearing." (Chapin et al., 2003, pp. 11). The goal of their transparent hearing system is not true transparency, as the system must selectively protect from acoustic trauma and the potential benefits of supernormal listening extend systems beyond true transparency (Chapin et al., 2003).

A solution space mapping of the approaches to achieving the spatialization of the transparent audio (both interaural cues and spectral cues) is given whereby solutions vary in geometric complexity and in electronic / computational complexity – see Figure 8 (Chapin et al., 2003). Point B of Figure 8 represents a binaural system, such as seen in many commercial muff style HPDs with active pass-through. Point P of Figure 8 represents geometric structures like the human pinna creating the spectral colouration. While many earplug style HPDs with pass-through rely on the listener's own pinna to create these spectral cues, it is possible to envision a system in which the geometric features surrounding the microphones recreate the spectral colouration naturally occurring from the human pinna. Point A1 of Figure 8 represents the other extreme of solutions, whereby an array of microphones is used to pick up the sound source and intensive computational processing is used to match the spectral cues of the microphone transfer functions to the HRTF of the listener. Point A2 in Figure 8 represents a trade-off of geometric and electronic complexity.

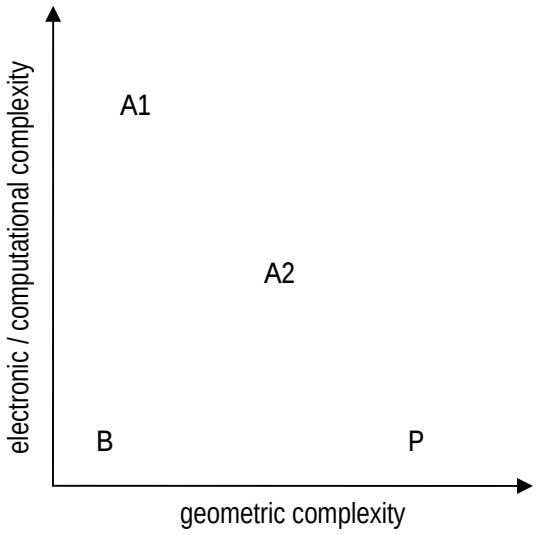

Figure 8: Solution space of transparent hearing systems in recreating spatialization cues (adapted from Chapin et al., 2003)

A number of solution approaches were pursued representing a range of points on the solution space outlined in Figure 8. These solutions included seven simulated pinnae systems and two general microphone array systems (Chapin et al., 2003).

A simplistic localization test was performed with 9 prototypes and 3 control conditions. The 9 prototypes consisted of 7 simulated pinnae systems varying the number and location of microphones and the digital filters, and 2 general microphone array systems with different number of microphones. The 3 control conditions consisted of open ears, open ears with helmet, and the Peltor AGC earmuff. Participants were tested using both KEMAR HRTFs and individualized HRTFs. An unknown number of participants gave verbal estimates of source locations with 500 ms low-pass 11 kHz white noise stimuli at sixteen possible locations (azimuth: 0^o, 45^o, 90^o, 135^o, 180^o; elevation: -45^o, 0^o, 45^o).

Results are reported in terms of overall, azimuth, and elevation error (Chapin et al., 2003). No indication as to the statistical treatment of results was given and as a result the confidence level of observed differences is unknown. As expected the smallest overall error was seen in the open ears and open ears with helmet conditions, while the largest overall error was in the Peltor earmuff condition. Performance with individualized HRTFs was consistently better than performance with KEMAR HRTFs, except in the general microphone array prototype systems. Performance of all experimental prototypes was roughly equal, although slight advantages were seen for one digital filter over another. The microphone array systems demonstrated better performance than any other condition in azimuth localization, but worse performance than all other experimental prototypes in elevation localization (Chapin et al., 2003). The frequency of front-back reversals was also recorded. The Peltor earmuff condition had the highest frequency of confusions, while prototype conditions exhibited roughly equal number of confusions as open ears control conditions (Chapin et al., 2003). While this study does not clearly identify an acceptable solution, it provides valuable guidance as to the most promising techniques for future research.

A series of measurements were taken using an acoustic mannequin to quantify differences between reproduced sound characteristics and unoccluded sound characteristics (Chapin et al., 2003). These measurements suggested some differences between experimental prototypes however clear correlations with localization test results across devices were not evident (Chapin et al., 2003). This suggests that while acoustic measures may be useful as a preliminary evaluation technique, they cannot substitute for experimental trials with human participants.

7.4.3 Speech Intelligibility

The more developed transparent hearing systems of TNO, Adaptive Technologies, and AuSIM have not been systematically tested for speech intelligibility. The Adaptive Tech system testing included a brief, subjective measure of sound naturalness using speech stimuli however this can hardly be considered a test of speech intelligibility (Johnson et al., 2004).

Basu and Pentland (2001) developed a "Smart Headphones" concept in which speech sounds in the ambient environment are detected and selectively presented to the listener. This system works by using a speech-detection algorithm to discriminate speech from other input sounds of a 3 microphone, body-based array. The multiple microphones of the array allow the determination of the speech origin, allowing the user to set directional sensitivity for speech. This system is subject to an inherent delay due to the need to examine a certain amount of the signal to determine if it is speech prior to presentation (Basu & Pentland, 2001). Although no scientific examination of this system is available, the concept represents a potential means of restoring speech communication in noise hazardous environments.

8. Conclusions & Recommendations

The auditory sense is a vital tool to the dismounted infantry soldier in developing and maintaining situation awareness. Detection, localization, and speech intelligibility are important abilities to the soldier that need to be maintained on the battlefield. The noise hazards of the military environment necessitate protection from both continuous and impulse noise. However the isolation effects of hearing protection, real or perceived, limit hearing protector use due to loss of sound detection and recognition. Sound source localization is a primary area negatively impacted by the use of hearing protection. Further work examining the dismounted soldier's localization resolution requirements is needed before design tradeoffs can be confidently addressed. Practice with appropriate stimuli and feedback should allow listeners to adapt to slight alterations to their normal auditory cues.

Passive level-dependent systems represent a first step towards a transparent hearing audio system. Passive level-dependent earplugs have been demonstrated to be as effective in protecting the user as standard earplugs, yet neither is sufficient for extended repeated exposure. In noisy environments, detection ability with passive level-dependent HPDs is similar to unoccluded listening however recognition ability may be degraded. Speech intelligibility with passive level-dependent HPDs is also similar to unoccluded listening in both no noise and low noise conditions but not high noise.

Active feed-through systems represent a significant increase in complexity of the device in that electronics are now used to transmit and limit auditory signals. These devices typically excel in impulse noise protection and are commonly marketed for recreational shooters. While a certain accuracy of HRTF must be preserved, bandwidth limitations may more severely restrict the listener's ability to localize in elevation. The increased localization error associated with wearing these devices appears to be primarily caused by an increase in frequency of quadrant confusions rather than a drastic decrease in localization resolution.

Transparent hearing systems have focused on restoring localization ability with little attention given to protection, detection, or speech intelligibility. These systems are beginning to provide localization ability superior to that of passive hearing protection and active feed-through systems, however, much work is needed to bring performance to the level of unoccluded listening.

With the electronic restoration of ambient hearing abilities, extensions to supernormal listening abilities are easily foreseeable. For example, microphone arrays for hearing aids have been used for aural focusing.

From this review, key elements in the evaluation of future transparent hearing systems have emerged. The following factors must be considered in evaluating the fidelity, practicality, and advantage afforded by any transparent hearing system:

- Restore hearing abilities to the occluded listener, with specific consideration of:
    - Detection and recognition / identification ability.
    - Sound source localization. Acoustical measurements using a manikin cannot substitute for a localization test with human participants. The fidelity of the HRTF preserved / recreated and the bandwidth of frequencies transmitted are crucial in achieving good localization performance.
    - Speech intelligibility of both non-radio and radio communications.

- Hearing protection from continuous and impulse noise.
- Comfortable to wear for extended periods of time.
- Compatible with other equipment, not causing a loss of performance effectiveness of the transparent hearing system or any other equipment.
- Compatible with a large range of noise environments. Specifically, the system must not create any additional communication difficulties in noise.
- Requiring a reasonable amount of practice / adaptation to achieve expert performance.
- Facilitate the presentation of an auditory display and the addition of supernormal listening capabilities.

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Annex A: Survey of Commercial Systems

Passive Feed-Through	
Bilsom: Clarity (earmuff)	www.bilsom.com
Combat Arms Earplug	www.combatarmsearplugs.com
Deben: Hoppe's Earplugs	www.deben.com
E-A-R Ultra 9000 Earmuffs	www.e-a-r.com
EARinc: Acoustical Filtered Chameleon Ears (earplugs)	www.earinc.com
Etymotic Research: ER-20 (earplugs)	www.etymotic.com
Etymotic Research: Musicians Earplugs	www.etymotic.com
Peltor: PTL Muff H7 (earmuffs)	www.peltor.com
Jrenum Earplugs	www.jrenum.ch
North Safety Products: Sonic Ear Valves (earplugs)	www.northsafety.com
Remington Radians: Impulse Baffled Earplugs	www.radiansinc.com
Sennheiser: SLC 100	www.sennheiser.com
Silencio Super Sound Baffler Earplugs	www.silencio.com
Westone Style No. 39 (earplugs)	www.westone.com
Active Feed-Through	
Bilsom: Impact (earmuffs)	www.bilsom.com
Bionic Ear	www.botachtactical.com
Bose: Triport Tactical Headset (earmuffs)	www.bose.com
Deben: Slim Electronic Protection (earmuffs)	www.deben.com
Dillon HP-1	www.dillonprecision.com
DPI Sekur: Twin Active & Twin React (earmuffs)	www.dpisekur.com
EARinc: E.A.R. Digital Series (earplugs) E.A.R. MiniCanal (earplugs)	www.earinc.com
Electronic Shooters Protection: ESP-Digital Series & ESP-Elite (earplugs)	www.espamerica.com
Gentex: WolfEars	www.derry.gentex.com
Nacre: Quietpro	www.nacre.no
Nextlink: Invisio (earplugs)	www.nextlink.to
Peltor: Comtac II (earmuffs) Alert headset(earmuffs) Protac (earmuffs) Tactical 6 / Sound-Trap Slim Line (earmuffs) Tactical 7S Classic (earmuffs)	www.peltor.com
Pilot Communications: Enhancer & Explorer (earmuffs)	www.pilot-avionics.com
Racal Acoustics: Slimgard II (earmuffs)	www.racalacoustics.com
Remington Radians: R2000 Electronic Thin Muff	www.radiansinc.com
Ridgeline Pro-Ears: Dimension Series Predator Series	www.pro-ears.com
Sennheiser: WACH900 (earmuffs) SNG 100 (earmuffs)	www.sennheiserusa.com/sgs
Silencio: Falcon (earmuffs) NightHawk Tactical (earmuffs) Frontline Electronic (earmuffs) React Electronic (earmuffs)	www.silencio.com
Silver Creek Detectear	www.botachtactical.com

Terma: tbone Aviation Headset (earplugs)	www.terma.com
Walker's Game Ear, Inc.: Digital ITC (earplugs) Ultra Ear (earplugs) Game Ear (earplugs) Digital Game Ear (earplugs) Target Ear (earplugs) Tactical Ear (earplugs) Digital Quads (earmuffs) Range Ears Power Muffs (earmuffs)	www.walkersgameear.com

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(U) The auditory sense is a significant perceptual component of the dismounted infantry soldier's situation awareness. However, battlefield noise hazards necessitate the use of perceptually isolating hearing protection. This report seeks to review the progress made and key issues identified in developing a system to restore hearing capabilities to the protected listener. The auditory needs of the dismounted infantry soldier are described, followed by a description of the noise hazards encountered by the soldier. The implications of hearing protection and additional issues in restoring hearing are discussed. Scientific studies of restorative hearing systems are then detailed, starting from the simplest passive level−dependent systems and culminating in the most sophisticated transparent hearing systems, using a common protection, detection, localization, and speech intelligibility framework. Conclusions and recommendations for test criteria for future restorative hearing systems are given.

(U) L'ouïe est un élément sensoriel important de la perception globale d'une situation chez le soldat d'infanterie à pied. Mais à cause des dangers liés au bruit sur le champ de bataille, celui−ci doit porter une protection auditive qui l'isole sur le plan sensoriel. Le présent rapport tente d'examiner les progrès réalisés ainsi que les principales questions cernées lors de la mise au point d'un système visant à rétablir les capacités auditives de l'auditeur muni d'une protection antibruit. Nous décrivons les besoins auditifs du soldat d'infanterie à pied, ainsi que les dangers liés au bruit auxquels il fait face. Les répercussions de la protection auditive et d'autres questions touchant le rétablissement de l'audition sont abordées. Nous passons ensuite en revue les études scientifiques sur les systèmes de rétablissement de l'audition, allant des systèmes passifs les plus simples dépendant du niveau sonore jusqu'aux systèmes auditifs transparents les plus sophistiqués, en utilisant un cadre commun pour la protection, la détection, la localisation et l'intelligibilité vocale. Des conclusions et des recommandations concernant les critères d'essai des futurs systèmes de rétablissement de l'audition sont présentées.

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(U) SIHS TD, Soldier Integrated Headwear System; Restorative Hearing; situation awareness; hearing protection

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(U) The auditory sense is a significant perceptual component of the dismounted infantry soldier's situation awareness. However, battlefield noise hazards necessitate the use of perceptually isolating hearing protection. This report seeks to review the progress made and key issues identified in developing a system to restore hearing capabilities to the protected listener. The auditory needs of the dismounted infantry soldier are described, followed by a description of the noise hazards encountered by the soldier. The implications of hearing protection and additional issues in restoring hearing are discussed. Scientific studies of restorative hearing systems are then detailed, starting from the simplest passive level−dependent systems and culminating in the most sophisticated transparent hearing systems, using a common protection, detection, localization, and speech intelligibility framework. Conclusions and recommendations for test criteria for future restorative hearing systems are given.

(U) L'ouïe est un élément sensoriel important de la perception globale d'une situation chez le soldat d'infanterie à pied. Mais à cause des dangers liés au bruit sur le champ de bataille, celui−ci doit porter une protection auditive qui l'isole sur le plan sensoriel. Le présent rapport tente d'examiner les progrès réalisés ainsi que les principales questions cernées lors de la mise au point d'un système visant à rétablir les capacités auditives de l'auditeur muni d'une protection antibruit. Nous décrivons les besoins auditifs du soldat d'infanterie à pied, ainsi que les dangers liés au bruit auxquels il fait face. Les répercussions de la protection auditive et d'autres questions touchant le rétablissement de l'audition sont abordées. Nous passons ensuite en revue les études scientifiques sur les systèmes de rétablissement de l'audition, allant des systèmes passifs les plus simples dépendant du niveau sonore jusqu'aux systèmes auditifs transparents les plus sophistiqués, en utilisant un cadre commun pour la protection, la détection, la localisation et l'intelligibilité vocale. Des conclusions et des recommandations concernant les critères d'essai des futurs systèmes de rétablissement de l'audition sont présentées.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

(U) SIHS TD, Soldier Integrated Headwear System; Restorative Hearing; situation awareness; hearing protection