**UNIVERSITY OF SOUTHAMPTON**

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Institute of Sound and Vibration Research

# AUDITORY FITNESS FOR DUTY:

# LOCALISING SMALL ARMS GUNFIRE

by

Zoë Leanne Bevis

Thesis for the degree of Doctor of Philosophy

March 2016

**UNIVERSITY OF SOUTHAMPTON**

# ABSTRACT

FACULTY OF ENGINEERING AND THE ENVIRONMENT

INSTITUTE OF SOUND AND VIBRATION RESEARCH

Thesis for the degree of Doctor of Philosophy

**AUDITORY FITNESS FOR DUTY: LOCALISING SMALL ARMS GUNFIRE**

Zoë Leanne Bevis

Locating the source of small arms fire is deemed a mission-critical auditory task by infantry personnel (Bevis et al. 2014; Semeraro et al. 2015). Little is known about the acoustic localisation cues within a gunshot and human ability to localise gunshots. Binaural recordings of 'live' gunshots from an SA80 rifle were obtained using a KEMAR dummy head placed 100 m from the firer, within 30 cm of the bullet trajectory and with 13 azimuth angles from 90° left to 90º right. The 'crack', created by the supersonic bullet passing the target, produced smaller interaural time and level differences than the 'thump', created by the muzzle blast, for the rifle at the same angle. Forty normal-hearing listeners (20 civilian, 20 military personnel) and 12 hearing impaired listeners (all military personnel) completed a virtual azimuthal localisation task using three stimuli created from the recordings (whole gunshot, 'crack' only and 'thump' only) plus a 50 ms broadband noise burst convolved with KEMAR impulse responses. All listeners localised all stimuli types above chance level. Average localisation error increased in the order of: noise burst < thump < gunshot < crack, for all cohorts. Military personnel (regardless of their hearing level) performed significantly worse than civilians for all stimuli; they had a higher tendency to select the extreme left and right sources, resulting in an increased lateral bias. The difference between military and civilian participants may be due to their understanding of the task or military training/experience. Mild to moderate bilateral symmetrical sensorineural hearing loss did not have a significant impact on localisation accuracy. This suggests that, providing the gunshot is clearly audible and audiometric thresholds are equal between the ears, binaural cues will still be accessible and localisation accuracy will be preserved. Further work is recommended to investigate the relationship between other hearing loss configurations and small arms gunshot localisation accuracy before considering gunshot localisation as a measure of auditory fitness for infantry personnel.

# Table of Contents

# List of Tables

# List of Figures

# DECLARATION OF AUTHORSHIP

I, Zoë Leanne Bevis declare that this thesis entitled "Auditory fitness for duty: localising small arms gunfire" and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:

Bevis, Z. L., Semeraro, H. D., van Besouw, R. M., Rowan, D., Lineton, B. & Allsopp, A. J. (2014) Fit for the frontline? A focus group exploration of auditory tasks carried out by infantry and combat support personnel. *Noise and Health*. 16 (69). 127-135.

Semeraro, H. D., Bevis, Z. L., Rowan, D., van Besouw, R. M. & Allsopp, A. J. (2015) Fit for the frontline? Identification of mission-critical auditory tasks (MCATs) carried out by infantry and combat support personnel. *Noise and Health*. 17 (75). 98-107.

Signed: ..........................................................................................................................

Date: ..............................................................................................................................

# Acknowledgements

Firstly I need to thank Adrian Allsopp, Ben Lineton, Daniel Rowan and Rachel van Besouw for the academic support throughout the PhD process. You inspired, guided and confused me in equal measure!

Thank you to my examiners Paul White and Bill Whitmer, your insights helped to pull together the frazzled threads at the edge of this thesis. To the coding geniuses of Carla Perkins and Falk Martin Hoffman, thank you for your MATLAB expertise in times of need. Also, thank you to the individuals at ISVR, INM and ITDU who helped with participant recruitment and the infantry personnel who took part in my research studies.

To the friends outside of the office and my colleagues at USAIS I am grateful for the hugs and the much needed distractions. Thank you to the squad members - Anne, Cherith, Noura, Lucy, Giorgos, Tobi, Xin and Alan – that marched in step throughout the process. You are all a constant source of inspiration.

A special mention to my two favourite AFFD researchers and comrades Hannah and Matt. You've both seen the best and worst of me during this project and I am unbelievably grateful for your friendship and moral support through the wonderful highs and the challenging lows.

Thank you to my family – Mum & Mike, Dad & Michele, Nanny and Grandad OTF, Nanny and Grandad Bevis and Jason – for your unwavering support and belief that I'd make it through to the other side. I couldn't have done it without you.

And last but by no means least, a special mention for George – thank you for your patience and commitment. You'll be happy to know that I can't use the PhD as an excuse to avoid the housework/hiking in the rain any more!

*"One of the advantages of being disorganised is that one is constantly making exciting discoveries'* - Winnie the Pooh

# List of Abbreviations

AFFD – Auditory fitness for duty

ANOVA – Analysis of Variance

C – Unsigned error/bias error

CIPIC – Centre for Image Processing and Integrated Computing

dB – Decibel (SPL – sound pressure level, HL – hearing level or C - C weighted)

DFO – Department of Fisheries and Oceans

E – Signed constant error

EAM – External auditory meatus

HCP – Hearing conservation programme

HCT – Hearing critical task

HINT – Hearing in Noise Test

HRTF – Head related transfer function

HTL – Hearing threshold level

IHC – Inner hair cell

ILD – Interaural level difference

INM – Institute of Naval Medicine

ITD – Interaural time difference

ITDU – Infantry Trials and Development Unit

JSP – Joint service publication

KEMAR – Knowles Electronic Manikin for Acoustic Research

LPC – Lateral percent correct

LSO – Lateral superior olive/olivary complex

MAA – Minimum audible angle

MAE – Mean absolute error

MATLAB – Matrix Laboratory

MCAT – Mission critical auditory task

MNTB – Medial nucleus of the trapezoid body

MoD – Ministry of Defence

MSO – Medial superior olive

NIHL – Noise induced hearing loss

OHC – Outer hair cell

PRR – Personal role radio

PTA – Pure tone audiometry

R – References (used in study 1 only)

RCMP – Royal Canadian Mounted Police

RE – Random error

RMS – Root mean square

S- Sources (used in study 1 only)

SA80 – Small arms rifle 1980

SD – Standard deviation

SIM – Source identification method

SLM – Sound level meter

SME – Subject matter expert

SNR – Signal to noise ratio

SOC – Superior Olivary Complex

TFS – Temporal fine structure

TTS – Temporary threshold shift

XTC – Cross-talk cancellation

# Chapter 1: Introduction

## 1.1 Introduction

In order to be operationally effective military personnel need to be able to communicate with each other whilst maintaining awareness of their surroundings. A significant threat to the deployability of service personnel is noise induced hearing loss (NIHL) (Patil and Breeze 2011) and the extent of this is measured using Pure Tone Audiometry (PTA). The decision regarding a soldier's deployability is then based upon four discrete classifications of hearing loss: the 'H' categories. This system can be traced back to the 1970s, but there is no evidence to suggest that it correlates with functional hearing ability in military environments (hearing abilities required to perform occupation specific auditory tasks).

Despite increased awareness of hearing loss in the military, new legislation and hearing conservation programmes, the prevalence of NIHL is high amongst personnel. A preliminary study was conducted in 2008 by Surgeon Commander Pearson (at the Institute of Naval Medicine (INM), Gosport) to determine the incidence of NIHL during an operation in Afghanistan. The results showed that 42% of personnel had a measurable increase in hearing thresholds compared to their pre-deployment audiogram (Pearson 2011). The relationship between an individual's pure tone audiogram and their safety and effectiveness during operational duties is not clearly defined. Therefore, use of the current hearing standards may lead to the redeployment of personnel that are not capable of performing their role to an acceptable level or the medical downgrading of personnel that are still able to perform the tasks required of them.

Auditory fitness for duty (AFFD) describes an individual's ability to hear the essential sounds required for safe and effective job performance (Tufts et al. 2009). Auditory fitness for duty measures should be based upon the specific auditory skills required for the job, but prior to the current research, there was no documentation of the auditory tasks carried out by infantry personnel on operational duties (Le Prell and Henderson 2012). Identifying these job-specific auditory tasks was the initial focus of the current body of research.

Tufts et al. (2009) carried out a review of international AFFD measures for hearing critical occupations and found that occupational auditory tasks could be divided into three categories; sound detection and identification, speech communication and sound localisation. The latter of these is the focus of the current research. Localisation ability is generally not incorporated into AFFD protocols as few validated localisation tests exist, and the facilities to carry out freefield source localisation tasks are often unavailable in workplaces or occupational health clinics (Punch et al. 1996). Localisation of small arms gunfire was identified as an auditory task carried out frequently by infantry personnel on operational duties (Bevis et al. 2014). Relatively little is known about human listeners' ability to locate gunfire and only one published study measuring small arms gunfire localisation accuracy with human listeners currently exists (Talcott et al. 2012).

Before incorporating a localisation task in the UK military AFFD protocol, three conditions must be satisfied: 1) localisation of small arms gunfire must be possible (normal hearing personnel must be able to perform this task to a degree of accuracy greater than just selecting sources at random), 2) small arms localisation ability must be affected to some degree by military relevant hearing loss (to ensure the task is dependent on the sense of hearing), and 3) performance must be statistically independent from an individual's pure tone thresholds (if it is not, performance could be accurately predicted from threshold levels and the current AFFD protocol may be able to assess localisation ability). As the answers to these questions were not found in the literature, the current body of work was designed and implemented to explore these gaps in knowledge.

## 1.2 Research questions and aims

### 1.2.1 Research questions

This thesis intends to answer the following general research questions (more detailed research questions are introduced at the start of the relevant chapters):

1. What are the mission critical auditory requirements of UK infantry personnel?
2. What localisation cues are available within a live small arms gunshot?
3. How accurately are normal hearing military personnel able to localise a small arms gunshot?
4. Is small arms localisation ability sensitive to military specific hearing loss?

### 1.2.2 Aims

This thesis has the following aims:

1. Explore the auditory requirements of UK infantry personnel on operational duties, including their acoustic environment. Identify the tasks they are required to perform and any circumstances that decrease their performance on auditory tasks.
2. Investigate how the auditory components of a small arms gunshot contribute to a human listener's ability to localise this complex stimulus.
3. Develop a method of measuring localisation accuracy using a small arms gunshot stimulus for normal hearing and hearing impaired listeners.
4. Measure the localisation accuracy of normal hearing military personnel using a small arms gunshot stimulus.
5. Determine whether there is an effect of military specific hearing impairment on localisation accuracy of small arms gunfire.

## 1.3 Thesis structure

The current chapter has introduced the topic and summarised the main aims and research questions of the thesis.

*Chapter 2* describes the impact of noise on the auditory system, highlighting the problems experienced by military personnel who are exposed to excessive occupational noise. This chapter also discusses the limitations of the current UK military protocol for assessing AFFD.

*Chapter 3* presents the results of two qualitative studies. The studies identified and prioritised MCATs for representation in new AFFD measures. In addition, the attitudes and behaviours of infantry personnel towards hearing protection and noise exposure were explored.

*Chapter 4* narrows the focus of the thesis to localisation of small arms gunfire, a high priority MCAT. This chapter reviews the wider literature, examining the mechanisms for human sound localisation more generally. Following this, the literature surrounding localisation of gunfire is discussed and gaps in knowledge are identified.

*Chapter 5* describes the process of recording live small arms gunfire using omnidirectional and binaural microphones. These recordings were analysed to investigate the acoustic characteristics of a small arms gunshot and the findings of these analyses are presented in chapter 5.

*Chapter 6* details the development of a virtual source identification task using the gunfire recordings. Four studies were carried out with civilian and military participants to determine the localisation accuracy of normal hearing and hearing impaired listeners using a gunshot stimulus. The findings of these studies are presented and discussed in chapter 6.

*Chapter 7* concatenates the findings of the qualitative research studies presented in chapter 3 with the quantitative studies in chapter 6. This chapter outlines the wider implications of the research and considers the next steps to be taken in developing localisation AFFD measures for infantry personnel.

## 1.4 Original contributions to knowledge

Six contributions to knowledge have been made by the current research:

The qualitative work presented in chapter 3 resulted in the following contributions:

1. A list of 17 MCATs carried out by infantry personnel on operational duties. Prior to this, there were no published studies outlining the hearing requirements of UK infantry personnel.
2. Four reasons for reduced performance on infantry auditory tasks. Participant comments provided a novel insight into the complex auditory environments experienced by British infantry personnel during training exercises and operational duties.
3. A detailed record of infantry personnel’s attitudes and behaviour towards hearing protection and hearing health. This built upon the research carried out by Okpala (2007) and highlighted further reasons for non-compliance with hearing protection protocols.

The quantitative studies presented in chapter 6 resulted in the following contributions:

4. A 360º set of dummy-head recordings of live SA80 gunfire at a miss distance of 30 cm and 100 m downrange. These were used during studies 3-6 and have been made available for use by students and other researchers.
5. Interaural time and intensity analyses of the binaural gunshot recordings within the frontal horizontal plane. These were used to form hypotheses about the localisation mechanisms used by human listeners to determine the source of small arms gunfire.
6. Experimental data indicating that normal hearing civilian and military listeners were able to determine the source of a single SA80 gunshot to within 33.7º RMS error, using a virtual source identification task. This was considerably more

accurate than the RMS error associated with selecting sources at random (56º± 4º at 0º azimuth). It was also evident that military personnel were able to complete the task with a significantly lesser degree of accuracy than civilians; this was due to the higher lateral bias present in the responses from the military participants.

## 1.5 Publications

Aspects of this thesis have been presented at national conferences (see Appendix A) and published in the following peer-reviewed journal articles:

1. Bevis, Z. L., Semeraro, H. D., van Besouw, R. M., Rowan, D., Lineton, B. & Allsopp, A. J. (2014) Fit for the frontline? A focus group exploration of auditory tasks carried out by infantry and combat support personnel. *Noise and Health*. 16 (69). 127-135.
2. Semeraro, H. D., Bevis, Z. L., Rowan, D., van Besouw, R. M. & Allsopp, A. J. (2015) Fit for the frontline? Identification of mission-critical auditory tasks (MCATs) carried out by infantry and combat support personnel. *Noise and Health*. 17 (75). 98-107.

# Chapter 2: Auditory fitness for duty

## 2.1 Introduction

In order to maintain their operational effectiveness, and ultimately their survival, military personnel need to be able to communicate directly with each other, or via communication equipment, whilst also maintaining situational awareness. Situational awareness as described by Endsley (1995) as *"the perception of the elements in the environment within a volume of time and space and the comprehension of their meaning"*. In military terms, this equates to personnel using all sensory modalities to create knowledge of their environment in order to make informed and appropriate decisions. If one of these sensory modalities was removed, it is likely that situational awareness would be compromised.

One of the greatest threats to the deployability of service personnel (principally Royal Marines and infantry personnel) is NIHL and the extent of this is measured using PTA (Patil and Breeze 2011).

The current chapter contains background information about NIHL and the impact of hearing loss on military personnel. The suitability of the current tool used by the armed forces to measure hearing is also discussed in this chapter, alongside the literature surrounding other auditory fitness measures and employment standards.

## 2.2 Effects of excessive noise on the auditory system

After the Second World War our knowledge of NIHL increased exponentially as government organisations funded large quantities of research to reduce exposure levels in the workplace (Axelsson et al. 1996). This section focuses on the public significance of NIHL and the biological/ physiological mechanisms of noise damage to the ear.

Hearing loss is typically attributed to noise exposure if the configuration of the audiogram is 'notched' and the patient reports a history of noise exposure (Le Prell and Henderson 2012). The most common definition of an audiometric notch is defined by as a 10 dB increase in thresholds at 3 and/or 4 kHz when compared to 1 or 2 kHz and 6 or 8 kHz (Osei-Lah and Yeoh 2010). However, patients may have an audiometric notch without a history of exposure to noise and equally may have been noise exposed but do not present with a notch in thresholds (Hong 2005, Osei-Lah and Yeoh 2010). Osei-Lah and Yeoh (2010) found that, during a large scale study of 149 outpatient adults, 39.6% had a high frequency notch not attributed to noise. Whilst this data was collected from only one audiogram per patient, if a test-retest audiometric error of 10 decibels (dB) was taken into account, a significant notch greater than 10 dB would still be present in 28.4% of ears (Osei-Lah and Yeoh 2010). This study demonstrates that a large number of individuals may have a naturally occurring audiometric ‘notch’ usually considered characteristic of NIHL.

The following sections (2.2.1 and 2.2.2) describe the changes occurring to the auditory system when damaged by prolonged or excessive noise exposure. Although there is no dispute that excessive noise causes damage to the auditory system, it can be difficult to confidently diagnose NIHL as the individual’s pure-tone thresholds may be similar to other hearing aetiologies such as presbyacusis.

### 2.2.1 Physiological changes to the auditory system

The characteristic ‘notch’ often found on the audiogram of an individual suffering from NIHL is thought to stem from the acoustic resonant properties of the external ear (Rabinowitz et al. 2006). The average human external auditory meatus (EAM) has a resonant frequency of 3200 Hz ‘amplifying’ sound as it passes from the entrance of the EAM to the tympanic membrane (Rabinowitz et al. 2006). The resonant characteristics of the EAM help to determine the amount of acoustic energy that is delivered to the cochlea, with an increase of up to 20 dB in the mid-frequency range.

It has been suggested that the wide variation in acoustic transfer characteristics of the EAM may be responsible for the variability in an individual’s susceptibility to noise damage. Hellstrom (1996) investigated the relationship between ear canal volume, ear canal length, sound transfer function and susceptibility to temporary threshold shift (TTS). He stated that his findings indicated that the sound transfer function is an important variable in predicting NIHL for younger individuals, but that the relationship becomes less clear among older individuals. This study used a large number of participants (>100) and reports clear and controlled repeats of the experiment on separate occasions and with randomised stimuli. Hellstrom’s findings agree with earlier work by Caiazzo and Tonndorf (1977), who artificially controlled ear canal length and found a direct effect on the level and frequency of an individual’s TTS.

Two studies speculate that the middle ear mechanics contribute significantly to susceptibility to NIHL (Rosowski 1991, Rabinowitz et al. 2006). It is well documented that there are variations in the size of the ossicles and middle ear space but there are currently no direct data concerning the relationship between these variables and NIHL. Many experiments have been carried out to show how the stapedius muscle contributes to protection from TTS. Zakrisson et al. (1980) investigated individuals with an existing facial nerve weakness (Bell's palsy) and found that TTS was significantly higher on the paralyzed side. Zakrisson et al. continued this study on animal subjects to investigate the effect of the stapedius muscle on permanent threshold shift and found a similar result; the weakened side had a much greater threshold shift, particularly in the low frequencies. Zakrisson's findings have been confirmed by other researchers (Borg et al. 1982, Colletti and Sittoni 1985). Colletti and Sittoni's retrospective paper provided an insight into the importance of the acoustic reflex in an industrial setting. Workers were classified according to the 'efficiency' of their acoustic reflex (strong contraction, low threshold). Those with 'sluggish' reflexes were found to have greater threshold shift than those with efficient reflexes. Whilst this study used only a very small number of participants, the findings were statistically significant and may indicate that the strength of the acoustic reflex could affect NIHL susceptibility.

The external and middle ear affect the level of NIHL in a relatively predictable way governed by the mechanical and acoustic properties of the tympanic membrane and ossicular chain. However, the effect of excessive noise on the complex biological systems within the inner ear are less well understood.

Traumatic noise exposure can fundamentally alter the metabolism of sensory cells within the cochlea; the cellular architecture is changed and the function of the cell is impaired. Changes to cells within the cochlea can be seen using animal subjects and electron microscopy. It has been found that outer hair cells (OHCs) are more severely affected by noise exposure than inner hair cells (IHCs) (Kujawa and Liberman 2009). They are more vulnerable due to the direct force they receive at their stereocilia (delicate hair-like structures on the apical surface of the hair cells) compared to IHCs that are stimulated by viscous drag; they are also unsupported by neighbouring cells. Secondly, the OHCs are closest to the maximum point of basilar membrane displacement.

The first noise-induced changes within the cell are metabolic. Alterations to the organelles within the cell cause ionic regulation to be impaired, resulting in disintegration of the membranes or complete destruction of organelles. Even if the reticular lamina remains intact, further loss of sensory cells is possible due to the intermixing of cochlear fluids

(Bohne and Rabbitt 2000). Increasing threshold shifts have been observed many hours after noise exposure and can be significantly greater than that measured soon after the exposure (Kujawa and Liberman 2009).

As the intensity of the noise increases, the alterations within the cochlear move from metabolic to primarily mechanical. High level acute trauma to sensory cells causes wide spread fracture of the cell junctions of the organ of Corti (Roberto and Zito 1988). Stereocilia are similarly damaged by high level noise. They have a complex structure and are among the first elements to be affected by excessive movement (Wang et al. 2002). Studies have shown that some of these ciliary changes are reversible and may be responsible for the recovery following TTS (Saunders and Flock 1986, Saunders et al. 1991).

Beyond the cochlea, if exposure is significant (enough to lead to loss of IHCs and inner pillar cells) there can be a deterioration of eighth nerve fibres. This can be seen from morphological changes in the ascending neural pathways (Morest 1982).

A reduction in hearing thresholds associated with the physiological changes caused by excessive noise can have a large impact on audibility of important signals such as speech. Other perceptual changes to hearing caused by noise damage are well documented in the literature. It has been noted that these additional symptoms of noise exposure may have a greater impact on quality of life and are more difficult to manage clinically (Axelsson and Prasher 2000).

### 2.2.2 Noise damage beyond the audiogram

Kujawa and Liberman (2009) state that it is "sobering to consider that normal threshold sensitivity can mask ongoing and dramatic neural degeneration in noise exposed listeners, yet threshold sensitivity represents the gold standard for quantifying noise damage in humans". From a wealth of studies using animal and human subjects it is clear that noise exposure causes progressive neuropathology that is likely to have profound long-term consequences for the listener (e.g. Kujawa and Liberman 2009, Humes et al. 2005).

This damage may manifest itself in a range of ways including tinnitus, hyperacusis and other perceptual anomalies. The mechanisms of these problems are still unclear but they are thought to arise from a combination of cochlear sensory cell damage together with the loss of afferent nerve terminals and delayed degeneration of the cochlear nerve (Irvine et al. 2001). Damage to cochlear neurons can lead to changes in brainstem circuitry; these changes are likely to decrease the robustness of stimulus coding (important for understanding speech in noise or extracting spatial cues from sound) in low signal to noise environments (Irvine et al. 2001).

Tinnitus and hyperacusis has been associated with other secondary psychological conditions such as anxiety, depression, sleep disturbances and disruptions to working memory (Yankaskas 2013). These illnesses have a large effect on quality of life and ability to carry out daily activities at home and in the workplace (Axelsson and Sandh 1985). It is likely that the psychological and emotional impacts of tinnitus (such as lack of concentration and sleep) would impact on the day-to-day performance of military personnel, especially when carrying out critical operational duties. The impact and prevalence of NIHL hearing loss amongst military personnel is discussed below in section 2.3.

## 2.3 Hearing loss in the military

### 2.3.1 The impact of noise induced hearing loss

It seems surprising that, considering the first documented discussion of NIHL dates back at least 300 years (Ramazzani's De Morbis Artificum 1713; translated into English and republished 2001), the physiological and functional impact is not yet fully understood. The effects of noise are not limited to hearing loss; some evidence suggests cardiovascular irregularities, stress disorders and sleep disturbance can all be caused by high levels of noise (Passchier-Vermeer and Passchier 2000).

Many individuals have attempted to estimate the prevalence of NIHL in the UK and these range from 509,000 (Palmer et al. 2001) to 81,000 people, according to the Self-reported Work-related Illness survey in 2003-2004 (Health and Safety Executive 2004). The number of individuals claiming disablement benefit for NIHL each year has barely changed since the late 1990s, following a long term decline since the early 1980s (Thorne 2007).

Even with policy and regulations in place to restrict the amount of noise that employees are exposed to, noise in the workplace is still a significant problem. The UK Health and Safety Executive (2004) reported that 1.7 million workers are regularly exposed to noise at work that is above the levels considered safe. From those that stated they worked in a noisy environment, 3% of women and 6% of men reported that they were left with tinnitus or a temporary feeling of deafness at least once a week, 2% of women and 3% of men reported that this sensation was felt daily. Despite the general decline in NIHL claims relating to workplace exposure over the past 30 years (Thorne 2007), work-related noise continues to be a prominent occupational issue in the UK.

Military personnel (more specifically the roles of infantry personnel and Royal Marines) are exposed to high levels of noise, both in the form of sudden blasts and continuous exposure, causing a high incidence of NIHL (Ylikoski and Ylikoski 1994). In other industrial sectors this would not be considered a safe working environment and steps would be taken to reduce levels of hazardous noise. However, the Crown Proceedings (Armed Forces) Act 1987 includes a doctrine of combat immunity. This means that there is no duty on the Ministry of Defence (MoD) to maintain a safe working environment on the frontline (an impossible task) (The National Archives 1987).

The Majority of noise exposure within the armed forces falls into two categories; 1) impulse noise from weapons fire and 2) continuous noise, similar to that found in an industrial environment. The dominant cause of NIHL in military personnel is small arms fire, with a shorter duration and higher peak level causing quickly progressing mechanical damage to hair cells (Cain 1998).

Table 2.1 shows some examples of peak pressure levels from weapons in use in 1988 (many of these are still in regular use by the UK armed forces). It is clear that all of these weapons could cause rapid damage to the auditory system if used without adequate hearing protection.

*Table 2.1 Peak sound pressure levels of military weaponry (Powell and Forrest 1988)*

| **Weapon** | **Peak Pressure (dB SPL)** |
|---|---|
| Thunderflash | 200 |
| 84mm Anti-armour weapon | 188 |
| Medium Mortar | 188 |
| Medium artillery | 180 |
| SA80 rifle at firer's ear | 160 |
| Tank gun inside closed down tank | 154 |
| Multiple launch rocket system crew position | 145 |

Many academics claim that there is an obvious association between small arms fire and hearing loss based on the measurable asymmetry in hearing thresholds, with right handed firers having the greatest deficit in the ear closest to the muzzle (left) (Collee et al. 2011, Ylikoski and Ylikoski 1994, Chung et al. 1983, Cox and Ford 1995).

All personnel are required to pass a hearing assessment before joining the armed forces. This means that the prevalence of hearing impairment amongst new military personnel is much lower than that in the general population. Consequently, many statistics about hearing loss prevalence in the armed forces underestimate the scale of the NIHL problem.

The exact number of military personnel affected by NIHL is unknown. Recent data on the prevalence of NIHL within the UK armed forces is scarce but it has been reported by the Royal British Legion (2014) that veterans under the age of 75 are 3.5 times more likely to report difficulty hearing than the general population. Patil and Breeze (2011) state that hearing loss is currently the second most common cause of military medical compensation claims (both in the UK and US). In December 2008 it was approximated that 15% of UK service personnel returning from operation Herrick in Afghanistan were unfit for redeployment or promotion due to NIHL (Patil and Breeze 2011).

Cox and Ford (1995) is a widely cited investigation of hearing thresholds of 225 soldiers. The authors found that for 66% of those with hearing loss, there was a greater than 10 dB asymmetry between the ears at 4 kHz. Noise exposure varied between participants and only those that had sustained blast injuries or suffered from underlying audiological pathology were excluded from the study. No pre-exposure thresholds were recorded. There was no indication whether all participants were right handed, although the authors do make a note of the significance of handedness, discussing that most standard issue rifles are now right hand-fire only (in agreement with worse hearing thresholds in the left ear). The authors discuss the possibility of spurious thresholds but decide that 'well motivated service-personnel have little to gain from producing exaggerated thresholds' (Cox and Ford 1995, pg 293). The conclusions made in this paper are based on assumptions of the participants' right handedness and symmetrical hearing before noise exposure despite evidence to suggest that hearing thresholds are rarely perfectly symmetrical (Pirila 1991).

In a further investigation of hearing impairment and military auditory performance Peters and Garinther (1990) found that speech intelligibility over headphones decreased from 93.5% to 7.1% during a tank skills training exercise. This decreased personnel's ability to hit a target using a single round from 90% to 62%. This, in turn, increased rates of friendly fire from 7% to 28% potentially increasing risk to life and decreasing mission success (Peters and Garinther 1990). Whilst it is clear that hearing loss would have a detrimental effect on military performance, Le Prell and Henderson (2012) state that there is no known database of sounds critical to troop survivability and lethality available for research purposes.

### 2.3.2 Hearing testing in the military

The UK military hearing conservation programme is used as a guide for medical personnel on the requirements of hearing testing, interpretation of the audiogram and the action required when deterioration in thresholds is identified. It also contains guidelines on the amount of hearing protection or occupational restriction required to avoid further noise induced hearing impairment. The Joint Service Publication 950 (JSP 950, MoD 2013) is the latest version of the chearing conservation programme.

The JSP 950 describes two types of hearing test, the first is an automated PTA procedure carried out as a screening measure pre-employment and annually during service. The second is a clinical measure, carried out by trained personnel if a noticeable change in hearing thresholds is detected during the screening test.

The thresholds measured on the clinical audiogram are categorised into acuity grades, commonly called hearing grades or H grades. These categories are calculated for each ear separately and are formed from the sum of low frequency and high frequency thresholds. The highest value (either low or high frequency sum) is used to determine the H grade. The individual is classified based upon the H grade of their worst hearing ear (MoD 2013). The pure tone thresholds for the H grades are outlined in table 2.2 and examples of H2, H3 and H4 audiograms are given in figure 2.1.

The H grades can be traced back to the 1960's (origin unknown) and are believed to have been developed as guidelines for hearing conservation. They appear to be based on medico-legal definitions of handicapping hearing loss; they were not developed to be used as predictors of functioning hearing ability (Tufts et al. 2009).

*Table 2.2 H Grade classification for military pure-tone thresholds (MoD 2013)*

| **Grade** | Low frequency sum (0.5, 1, 2 kHz) (dB HL) | High frequency sum (3, 4, 6 kHz) (dB HL) | Functional Level |
|---|---|---|---|
| **H1** | ≤45 | ≤45 | Good hearing |
| **H2** | ≤84 | ≤123 | Acceptable hearing |
| **H3** | ≤150 | ≤210 | Impaired hearing |
| **H4** | >150 | >210 | Poor hearing: subject to further assessment |
| **H8** | >150 | >210 | Poor hearing: incompatible with continued service* |

*H4 and H8 have the same audiometric criteria. H4 is given if the individual is allowed to remain in service (this will depend on their role) and H8 is given if they cannot continue in service.

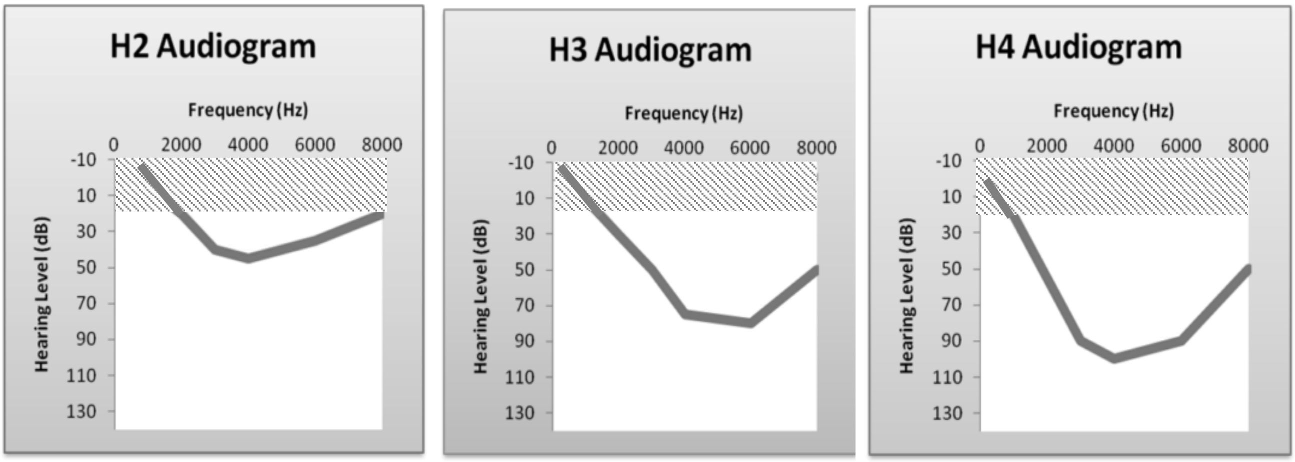


*Figure 2.1 Audiograms to show example hearing threshold levels for H2, H3 and H4 military hearing classifications. An individual with H1 hearing should have normal thresholds at all frequencies (≤20 dB HL) as shown by the shaded area*

As shown in Figure 2.1, the high frequency sum is greater than the low frequency sum to take into account the average configuration for NIHL. Military personnel with H2 hearing will be informed of the risk of hearing damage from their role and will be advised on additional hearing protection (although no exact guidelines on this currently exist; Biggs and Everest 2011). A H2 individual would not be restricted from performing their role fully.

A H4 grading is believed to indicate a 'functional loss' of hearing that may impact a personnel's ability to perform specific duties (the exact duties have not been identified). The individual and their line manager would be informed of the grading and would be required to implement strict noise safety guidelines (these are also undocumented in the literature and subject matter experts seemed unaware of a protocol for this guidance). A H4 grading would result in operational restrictions for the individual, to avoid further hearing damage, this would usually involve prohibition from front-line duties (Biggs and Everest 2011).

H8 hearing has very significant career implications. Specialist referral and guidance will still take place (as for H4) but personnel will no longer be able to deploy abroad and duties may be severely restricted in the UK. In most cases, this grading would ultimately result in medical discharge from the armed forces (Biggs and Everest 2011).

The JSP 950 (MoD 2013) describes the use of the H grades in terms of four key areas. Further assessment is carried out to compare the hearing thresholds with role-specific guidance. The results of the assessment determine whether an individual receives a Hearing Conservation Programme (HCP) 'pass' or a HCP 'referral'. As outlined in JSP 950, the four areas of this assessment are as follows:

1. **Fitness for role**

   This assessment could be considered a basic measure of auditory fitness. Each individual role within the armed forces has an associated service guidance document (not publically available) that outlines the physical and mental requirements for the role. The service guidance contains a recommended H grade that should be associated with the role and this enables the medical practitioners to dictate whether personnel can continue to perform their role (HCP pass). If there is a difference between the individual's measured H grade and the guidance H grade then this would be considered a HCP referral.

2. **Sudden hearing loss**

   JSP 950 defines a sudden hearing loss as a difference of 30 dB HL between the high frequency sums of audiograms measured within three years. This can be difficult to monitor if records are not kept over a prolonged period. If no sudden loss is recorded, then the individual receives a HCP pass. If personnel are found to have had a sudden loss, they should be referred to the Defence Audiology Service (DAS).

3. **Unilateral hearing loss**

   Asymmetric hearing thresholds are defined within the JSP 950 as a difference in average pure tone thresholds (at 1, 2, 3, 4 and 6 kHz) for each ear of 45 dB HL or greater. Similar to a sudden hearing loss, if asymmetric thresholds are observed then a HCP referral to the DAS is made.

4. **Age and gender weighted hearing acuity**

   In addition to the H categories, referrals are also made based upon gender and age specific hearing requirements. Table 2.3 shows the hearing thresholds that would require a warning (recommendations for greater levels of hearing protection, for example) or referral to the DAS, based upon age and gender.

*Table 2.3 Military age and gender specific hearing threshold referral criteria (MoD 2013)*

| Sum dB HL at 1, 2, 3,4 and 6 kHz | | | | |
|---|---|---|---|---|
| **Age (years)** | **Males (dB HL)** | | **Females (dB HL)** | |
| | **Warning** | **Referral** | **Warning** | **Referral** |
| 18-24 | 51 | 95 | 46 | 78 |
| 25-29 | 67 | 113 | 55 | 91 |
| 30-34 | 82 | 132 | 63 | 105 |
| 35-39 | 100 | 154 | 71 | 119 |
| 40-44 | 121 | 183 | 80 | 134 |
| 45-49 | 142 | 211 | 93 | 153 |
| 50-54 | 165 | 240 | 111 | 176 |
| 55-59 | 190 | 269 | 131 | 204 |
| 60-64 | 217 | 296 | 157 | 235 |

It is worth noting that the assessment criteria presented in JSP 950 are not linked to any particular source or evidence base (MoD 2013). The current grading system can have very serious implications for personnel serving in the UK military and it is of paramount importance that decisions regarding an individual's employment are supported by a documented evidence base.

## 2.4 Auditory fitness for duty (AFFD)

### 2.4.1 What is AFFD?

For some occupations, hearing impairment may place the hearing-impaired employee and others at risk of injury and death (Vaillancourt et al. 2011, Tufts et al. 2009, Laroche et al. 2003). For example, military personnel need to be able to communicate directly with each other whilst maintaining situational awareness in order to ensure their operational effectiveness and survival (Killion et al. 2011, Breeze et al. 2011). They are also at high risk of NIHL (Yankaskas 2013, Abel 2005, Patil and Breeze 2011, Cox and Ford 1995, Muhr and Rosenhall 2011, Biggs and Everest 2011), which could interfere with their ability to detect and interpret sounds (Killion et al. 2011, Yankaskas 2013). In addition to the detrimental effect of NIHL on the quality of life of service personnel, NIHL also poses a significant threat to their deployability. Removing skilled personnel from operational duties is costly considering the investment made by the employer to train personnel and maintain their operational effectiveness (Saunders and Griest 2009). It is important, in order to optimise levels of safety and efficiency, to allocate job tasks to hearing impaired personnel based on the hearing requirements of the task and the individual's functional hearing ability.

Auditory fitness for duty describes an individual's ability to hear the essential sounds required for safe and effective job performance. This is of paramount importance in occupations where the work is physically hazardous or involves the safety of others (such as firefighting and military occupations).

At its most basic level AFFD is tested using PTA at selected frequencies at the start of employment or on an on-going basis. The employee may then be found either (a) capable of performing their job with no restrictions (b) capable of performing the job with restrictions/accommodations or (c) incapable of performing the tasks required for safe practice and will subsequently be restricted from these or all activities in the workplace.

Hearing loss is a known liability in military tasks internationally and this has been largely proven in a controlled environment (Hodge and Price 1976, Peters and Garinther 1990, Vaillancourt et al. 2011). Hodge and Price (1976) simulated 24 US military auditory tasks (including detection of an AK47 magazine insertion click and footfall on coarse gravel) and found, not surprisingly, that hearing loss impaired a soldier's ability to hear enemy movement and therefore reduce the hypothetical warning time available for approaching enemy personnel. All of the stimuli used by Hodge and Price (1976) were quiet sounds (indicating enemy activity) and would have been below the hearing threshold level of individuals with even a mild hearing loss so it is unsurprising that they found a high correlation between task performance and hearing levels. However, Garinther and Peters (1990) carried out a similar study using varying communication conditions and a target identification task. The findings were in support of those reported by Hodge and Price (1976) and the stimuli were considerably louder (conversational speech at approximately 65 dB A). Hodge and Price also found that task performance decreased as hearing loss increased and as a result, the number of correctly identified targets decreased. The implications of incorrect target identification were an increase in friendly fire and increase in civilian 'casualties'. These investigations illustrate the importance of good functional hearing for military employees.

Pure tone audiometry forms the backbone of hearing testing in the military and is used to broadly predict an individual's ability to perform the auditory tasks necessary for safe and effective practice. It is widely recognised as the gold standard of hearing testing, giving the best compromise between threshold accuracy and time efficiency, available in mainstream audiology clinics. An audiogram is often used to inform the programming of hearing prostheses and has an important part to play when diagnosing hearing disorders. However, PTA measures monaural, peripheral auditory function in quiet, while good functional hearing requires the listener to have spatial awareness of speech and sounds, often in a background of complex noise (Laroche et al. 2008). Laroche and colleagues (2008) reported on the development of occupational hearing standards and have spent many years consulting subject matter experts to determine the hearing requirements of a range of hearing critical occupations.

From the literature it appears that an individual’s ability to perform hearing critical tasks (HCTs) may not be adequately predicted from the audiogram alone (Marshall and Carpenter 1988, Jones and Hughes 2000). Marshall and Carpenter analysed the audiograms of 416 sonar technicians, finding that there was a mismatch between level of hearing loss and performance on job-specific auditory tasks. The general findings of this study are of interest as it presents an early case for the need for auditory fitness tests; however the methodology has some obvious flaws. Audiograms were measured using an automated audiometer and the hearing of the non-test ear was not appropriately masked. The authors only use personal communication with the sonar technicians as a measure of task performance which was not reported or analysed. Giguere et al. (2008) predicted that PTA underestimates a hearing impaired individual’s ability to carry out functional hearing tasks in the workplace. Employees are often able to overcome a mild hearing deficit using experience and familiarity with the task and knowledge of the typical communications or warning signals given in the workplace (Jones and Hughes 2000).

In many workplace environments a pre-existing hearing impairment (detected using PTA) is not sufficient to deny an individual employment due to The Equality Act (2010). The act states an employer must prove that an individual cannot perform the task required (after reasonable adjustment) using a test that accurately represents the task before exclusion. A case was taken to court in Canada when an employee from the Department of Fisheries and Oceans (DFO) felt they were unfairly denied employment due to the inappropriate hearing testing they received (Laroche et al. 2003). This case resulted in a large amount of compensation paid from the DFO to the individual. Whilst frontline soldiers employed by the UK Armed Forces are exempt from The Equality Act (UK Parliament 2010), this type of legal case has sparked a rise in AFFD research (five studies published between 1990-1999, compared to eleven from 2000-2009; Tufts et al. 2009).

There are functional hearing 'abilities' common to most (if not all) HCTs. Laroche et al. (2003) state that a task is hearing-critical if it can be performed 'to a specified level of accuracy by a normal hearing individual using the sense of hearing alone' and not supplemented by job experience or non-auditory cues. Hearing critical tasks require the ability to identify and locate sounds and understand speech; these categories are discussed in more detail below. Laroche et al. (2008) and Cook and Hickey (2003) refer to these as 'functional hearing abilities' and this definition will be used here. This definition is key in emphasising the *use* of hearing and not the psychoacoustic phenomena associated with detection of pure tones or frequency and temporal resolution (Tufts et al. 2009). Further to this, the term mission critical auditory task (MCAT) will be used throughout this thesis to describe HCTs that are vital for the safe and effective job performance of military personnel on operational duties.

**Sound identification**

In almost all hearing dependent jobs the basic necessity to detect and identify a sound is fundamental. Without this, localisation and understanding of speech or other sounds cannot happen. Pure tone audiometry plays a significant part in testing sound detection for AFFD and often the widely accepted clinical categories for mild, moderate, severe and profound hearing loss (definitions of these categories can be found in appendix B) are used as a guide to determine if an individual's ability to detect sounds is adequate for the job in consideration (Tufts et al. 2009). If the HCT only requires detection of a sound in quiet, PTA has high face validity and can accurately predict an individual's level of performance on that task (Kamm et al. 1985). A detection task in noise, however, requires the consideration of more factors than simply pure tone thresholds. It is widely reported that a patient with a sensorineural hearing deficit may experience greater difficulty in noisy situations than normal hearing individuals or those with a conductive hearing loss (Plomp 1978, Feston and Plomp 1990, Vermiglio et al. 2012). They also typically require a greater signal to noise ratio (SNR) due partly to varying patterns of outer and IHC loss or damage (Moore 2007). Signal detection in noise is not currently part of AFFD testing within the UK military, despite its importance in everyday and combat situations.

Beyond detection, identification of sounds is required for individuals in hearing critical occupations (Tufts et al. 2009). Sound identification requires a combination of skills. The sound must be detected (requiring hearing acuity) and then classified (requiring auditory memory and other cognitive processes). It is therefore reasonable to assume that an individual's ability to identify important signals is not comprehensively assessed by a sound detection task such as PTA.

**Speech recognition**

Understanding speech should be considered separately from sound identification as it presents many unique challenges to the individual. In some occupations (and this is true of many military roles) speech may need to be understood without visual cues such as via radio, mobile telephone or in low visibility/darkness. Personnel may be expected to understand speech cues that are distorted, incomplete or spoken with a foreign accent (Cook and Hickey 2003). According to Plomp (1978) it is not appropriate to assume that if a speech signal is presented at an audible level, that it will be understood by the hearing impaired listener due to distortion and diminished frequency selectivity. This is often referred to as SNR loss (Killion and Niquette, 2000) and is difficult to measure due to the large variation between individuals with the same threshold levels.

Understanding speech in noise is vital for safe and effective work performance in hearing critical occupations (Giguère et al, 2008). It is known that even with a clinically normal audiogram, the individual may suffer some difficulty understanding speech in noise due to a central auditory disorder, temporal resolution deficit (or language barrier) (Stach 2000). Recently developed AFFD protocols have recognised the importance of detecting individuals with speech processing difficulties and have included a speech in noise test (Forshaw et al. 1999, Giguère et al. 2008, Laroche et al. 2008). Validated speech in noise tests (that are suitable for this purpose) exist but the AFFD protocols that recommend speech testing do not stipulate which tests are to be used or the pass-fail criteria (Tufts et al. 2009). It is key to notice that even if an individual passes a clinical speech in noise test there is not satisfactory evidence to prove, or disprove, that they have sufficient hearing abilities for the HCT they are required to perform (Tufts et al, 2009). It seems likely that all UK military personnel require a level of speech in noise understanding to perform their role safely and effectively; at the most basic level, personnel need to understand important commands in noisy environments. Three questions remain unclear: 1) which speech perception tasks are they required to perform in their role, 2) what level of functional hearing ability do they require for these tasks and 3) is there an existing clinical test that adequately predicts their ability to perform these tasks?

**Sound Localisation**

Identifying a sound source has been listed as a common HCT amongst hearing dependent occupations (Tufts et al. 2009) and the ability to localise is important (if not vital) to the safe and effective working of military personnel (Biggs and Everest 2011). Biggs and Everest (2011) stress the importance of identifying the location of a sound source as a critical skill needed for survival in the battlefield. Localisation is defined by Cook and Hickey (2003) as "the ability to gauge the direction and distance of a sound source outside the head" and in addition to this, some HCTs require the localisation of a sound source in background noise or require the individual to track a moving sound source.

It is widely reported that hearing loss can adversely affect an individual's ability to localise a sound (Moore 2007, Lorenzi et al. 1999, Sabin et al. 2005, Abel and Hay 1996, Simpson et al. 2005, Scharine and Letowski 2005). This correlation is not straightforward; localisation is affected by threshold asymmetry between the ears and the type or degree of hearing loss. As sound localisation in military environments is the focus of this thesis, a more detailed review of the relationship between hearing impairment and localisation is presented in chapter 4.

### 2.4.2 Testing AFFD

Physical tests and standards have historically been used by organisations to assess whether personnel are capable of performing demanding occupations (Bilzon et al. 2002). This becomes particularly important in military occupations where it is widely acknowledged that individual capability can directly influence the lethality and survivability of the whole team of personnel. Just as physical strength and fitness are vital for military personnel, so are adequate hearing threshold levels. Without a certain level of 'functional' hearing, individuals may be putting themselves and their colleagues in danger by not performing their job with the required level of efficiency or effectiveness. The current arbitrary standards of hearing required for military deployment (as outlined in section 2.3.2) may lead the organisation to employ individuals that are not physically able to perform the job required, or equally as important, may unnecessarily discriminate against capable personnel.

In adopting an appropriate test of hearing ability/acuity and set of employment standards, objective criteria must be used to ensure that the occupational requirements are valid, fair and legally defensible. Further to this, the standards and pass criteria must reflect the demands of the task and only incorporate or reflect its essential components (Tufts et al. 2009). For the test to be used by clinicians, the results must provide valid and reliable information to enable appropriate decisions to be made about an individual's ability to perform a set task or series of tasks. The literature raises concerns about the usefulness of the current hearing assessment protocol and calls for a greater evidence base for tests developed in future (Innes and Straker 1999, Abdel-Moty et al. 1996)

Creating a new set of employment standards and developing a valid and reliable test of these standards is a lengthy and complex process. This section aims to outline and review two papers that discuss this process to better understand the theory behind test development and how that theory can be applied to the current problem.

A detailed literature search was carried out to identify any studies that discussed the development of AFFD tests for the UK military population. A number of key words were used to search Pubmed, Web of Knowledge, Google Scholar and TDNet (the University of Southampton's library database), as well as backward and forward citation searches, and no papers discussing this specific problem were found. Personal communication with a research officer and ear nose and throat surgeon from the INM Gosport did not uncover any published research and only hearing conservation articles were unearthed when the military library database (containing confidential and historical documents) was searched. Therefore, it was necessary to review investigations that developed AFFD tests for other occupational activities. From the identified papers two clearly outlined the stages implemented in developing an AFFD test for occupations that require good hearing ability for safe and effective working.

The first study outlines the process of developing auditory fitness standards for the Department of fisheries and Oceans (DFO). The approach adopted by Laroche et al. (2008) was to use a well-established speech perception test with pre-defined psychometric properties and normative values as a measure to screen employees. This approach was devised to avoid using a simulated task-based test on all employees; this would have proven costly and time inefficient. The authors discuss the statistical modelling applied to predict performance in workplace environments from the speech perception test.

The first stage of this process was consultation with subject matter experts (SMEs) to identify the critical auditory tasks that employees are required to perform and the acceptable levels of performance in these tasks. The authors have excelled at reporting the procedure used to determine which tasks are most important and the exact acoustic environments that these tasks are performed in. The article contained a comprehensive list of all the tasks and the distance between talkers, vocal effort, minimum acceptable intelligibility, level of background noise and whether the speech is able to be repeated in the workplace. This provides the reader with all the information needed to critique the assumptions reported by the investigator.

Whilst the initial stages of the study were carried out in a clear and methodical way, when it came to choosing the most suitable hearing in noise test to use for screening the hearing abilities of personal Laroche et al. (2008) were restricted in their choice due to the language requirements of the test. A combination of French and English speaking employees work for the DFO and therefore a test that was validated for both languages was needed. In an ideal situation, a number of speech tests would be used to determine the test that gave the most accurate representation of the workplace task. Despite this shortfall, the authors report a close relationship between the simulation tasks and the Hearing in Noise Test (HINT) and deem it appropriate for use as a hearing screening measure in place of hearing threshold testing. The main advantage of this approach is the calculation that allowed each task to be assigned a minimum HINT score necessary for safe and effective performance (although there is no description of what constitutes a safe and effective performance in each task). This calculation is beneficial for potential employees with hearing loss. It allows an individual to be matched appropriately to a certain role or responsibility (an ideal attribute of an AFFD test) and may allow a hearing impaired employee to work in an area where only certain auditory tasks (that they were able to perform) are necessary.

The problem addressed in the Laroche et al. study has many similarities to the problem of AFFD in the military. They both involve complex auditory tasks in site specific background noise and both the DFO and military employees are at risk of serious injury or loss of life if tasks are not completed correctly (Laroche et al. 2003). There are also a number of differences between developing an AFFD test for the DFO and for military populations. Laroche et al. (2008) report that the single most important auditory task for DFO workers is understanding speech in noisy environments and have therefore chosen to concentrate purely on testing speech perception. It is expected that military personnel have to perform other types of auditory task such as localisation of enemy signals and therefore may require a battery of tests to accurately predict AFFD.

The second paper identified in the literature search had similar aims to the Laroche study but used a different approach. Vaillancourt et al. (2011) reported on the assessment of Royal Canadian Mounted Police Officers (RCMP) wearing hearing aids in speech recognition and sound localisation tasks. Whilst the study used hearing impaired employees it still aimed to quantify individual performance on the necessary components of AFFD.

The RCMP allows hearing aids to be worn by employees when completing tasks such as surveillance, pursuit, court testimony and criminal investigations (Vaillancourt et al. 2011). In accordance with this, hearing aids are also worn by personnel during AFFD testing. Similar to the UK military, the RCMP currently uses PTA to classify its officers with a similar system to the H grades and the study aimed to establish supplementary criteria based on functional assessment tools for hearing impaired employees. In some ways the task discussed by Vaillancourt et al. (2011) was more complex than the one faced by Laroche et al. (2008). Mounted police officers have to be able to perform more complex auditory tasks such as localisation of speech signals and require more acute situational awareness than the DFO employees.

Vaillancourt et al. (2011) state that creating a comprehensive AFFD protocol involving all of the auditory tasks required for safe and effective practice is a lengthy and costly undertaking. Hence, the investigation sought only to create an ‘interim’ protocol including aided and unaided sound field measures of basic speech recognition, sound detection and localisation. The investigation involved testing 57 hearing aid users (sampled from the RCMP and only including individuals that had been medically downgraded due to their hearing) on speech recognition and localisation with numerous parameters. Some individuals performed better than expected and it was recommended that their hearing classification was relaxed to allow them to perform their original roles within the RCMP. This further demonstrates the PTA may not give a true representation of functional hearing ability on occupational auditory tasks.

Vaillancourt et al. (2011) conclude that ‘further steps [needed for the development of AFFD measures] include: job analysis with SME’s, detailed descriptions…of HCTs and linking of job specific hearing standards to outcome measures using functional tests’. It is clear that this study was in its very early stages and there were many uncertainties that needed to be investigated before suitable recommendations could be made.

From the two studies reviewed it appears that the process of developing an AFFD test is not straightforward. The first approach, where a detailed job analysis was completed before considering the types of test needed, appeared to be a more robust method. Approaching the problem in that way guided the researchers in selecting an AFFD test that closely matched the requirements of the original auditory tasks identified. The second method was advantageous in gathering a solid understanding of the effect of hearing loss on tests that were thought to broadly represent the auditory tasks in the workplace. However, without evidence to support the relationship between the generic tests and the workplace environment, the recommendations made by Vaillancourt et al. (2011) should not be used to inform the medical grading of hearing impaired employees. The recommended grading may overestimate an individual's hearing ability and this could result in harm to the employee or the general public if auditory tasks are performed incorrectly. In an attempt to create robust and representative AFFD measures for UK military personnel a job analysis was completed in the first instance.

## 2.5 Summary and knowledge gaps

### 2.5.1 Summary

Noise induced hearing loss is a significant threat to the safety and deployability of military personnel (Patil and Breeze 2011). This acquired hearing deficit affects, not only their ability to carry out MCATs but their general quality of life, often causing secondary health conditions such as tinnitus and depression. The current AFFD protocol used by the UK military, PTA, is known to be a poor predictor of performance on complex tasks such as speech discrimination in noise. There are studies outlining the development of representative and appropriate AFFD measures for the DFO (Laroche et al. 2008) and RCMP (Vaillancourt et al. 2011) and these can be used to inform the development of more suitable measures to assess performance on military auditory tasks.

The military is a large and complex organisation, constructed from many varied occupations. Creating AFFD measures that are appropriate for all military disciplines would require generic tests of auditory ability that may not be specific enough to assess performance on any particular aspect of operational duty. As a starting point, AFFD measures for infantry personnel will be developed; the infantry carry out the most fundamental of all military tasks and all personnel from the Army, Navy and Air Force are trained first and foremost as infantry soldiers before developing specialist skills specific to their role. Personnel are classified as infantry if they perform a role in which they are expected to engage, fight and defeat enemy in face-to-face combat (predominantly on foot). For the purposes of this thesis, combat support personnel will also be included under the umbrella term 'infantry' as they work closely with those in infantry roles during training exercises and on the frontline.

In order to fully research infantry AFFD, a dedicated research group at the University of Southampton was formed. The Hear for Duty team continue to develop AFFD measures for infantry personnel incorporating the operational tasks that personnel are required to perform.

### 2.5.2 Knowledge gaps

From a review of the literature surrounding noise induced hearing amongst military personnel and AFFD, the following knowledge gap was identified:

- **There is no documentation of the MCATs carried out by infantry personnel on operational duties. AFFD measures should assess performance on MCATs.**

In order to perform hearing critical occupations to an acceptable standard is it likely that an individual requires auditory skills in sound identification, speech recognition and sound localisation. Le Prell and Henderson (2012) state that there is no known database of sounds critical to troop survivability and lethality available for research purposes. A thorough job analysis is required to identify MCATs and develop new measures of auditory fitness that accurately assess the auditory skills required on operational duties.

# Chapter 3: Identifying mission critical auditory tasks

## 3.1 Introduction

Chapter 3 outlines the two-stage process used to identify MCATs carried out by infantry personnel. The first study comprised 16 focus groups with infantry personnel to identify auditory tasks carried out on operational duties. The author designed and implemented study 1 together with colleague Hannah Semeraro. Analysis of the focus group transcripts was carried out solely by the author. Study 2 comprised a questionnaire used to determine which of the auditory tasks from study 1 could be described as MCATs. Whilst the author acted in an advisory capacity during the design of the questionnaire, Semeraro conducted all of the data collection and analysis independently. Both studies are reported and discussed in this chapter as they form the basis of the research carried out throughout this thesis. Studies 1 and 2 were published in the peer-reviewed journal Noise and Health (Bevis et al. 2013; Semeraro et al. 2014).

As discussed in chapter 2 use of the British military's current PTA-based AFFD protocol may lead to the redeployment of infantry personnel who are not capable of performing their role to an acceptable level, or the medical downgrading of personnel who are still able to perform the tasks required of them. The first step in developing new AFFD standards that are representative of the tasks that infantry personnel are required to perform is to carry out a thorough job analysis.

It is important to note that all quotes included in this chapter are individuals' perceptions regarding their hearing health and auditory job requirements and should not be interpreted as fact. Opinions of personnel do not necessarily reflect the views of the UK Armed Forces.

**Research question:** What are the MCATs carried out by UK infantry personnel on operational duties?

**Hypothesis:** Infantry MCATs are similar to HCTs carried out by other hearing-dependent occupations (the DFO and RCMP, for example); including sound identification, speech communication and sound localisation tasks.

## 3.2 Study 1 – Focus group job analysis

### 3.2.1 Introduction

Section 3.2 describes the focus group data collected from 80 infantry personnel across the South East of England during October and November 2012. The study was carried out due to a gap in the literature, identified in chapter 2. A review of job analysis techniques was carried out (appendix C) and the appropriateness of these techniques was discussed with subject matter experts (psychologists at the INM, Gosport). The SMEs advised that, whilst individual interviews should gain all the necessary information, they would not be as beneficial as focus groups. This opinion was based on past experience and the understanding that personnel are often reluctant to talk openly on their own, intimidated by the formality of the situation.

Focus groups allow participants to raise relevant issues, discover areas of agreement and disagreement and reflect on past experiences (Pearn and Kandola 1988). A focus group format can facilitate articulation of perceptions that a participant may not feel comfortable discussing on a one-to-one basis (Kitzinger 1995). Some personnel returned from theatre as little as 48 hrs before the study commenced and may have found it difficult discussing sensitive and potentially distressing subject matter. Every effort was taken to ensure that participants felt comfortable discussing their experiences and potentially sensitive subjects were avoided where possible.

### 3.2.2 Aims

Study 1 aimed to:

- Gain a greater understanding of the hearing requirements of infantry personnel.
- Gather information about auditory tasks carried out by infantry personnel on operational duties and the environment in which these tasks were performed.
- Investigate the underlying attitudes and behaviour of personnel towards noise exposure and use of hearing protection devices.
- To determine any conditions, other than reduced hearing thresholds, which may cause military personnel to no longer be able to perform hearing dependent tasks.

### 3.2.3 Method

The focus group guideline consisted of seven open-ended questions (table 3.1) that were developed in consultation with SMEs at the INM, Gosport. The questions were designed to elicit information about auditory tasks performed whilst on operational duties, sources of background noise and hearing protection. The questions were open-ended to encourage discussion whilst maintaining enough structure to ensure that all the research aims were addressed.

Two researchers were present, one to act as facilitator – encouraging all members of the group to participate and guiding discussion; the other to take brief notes and check recording equipment during the meeting. The researchers were escorted onto military bases by a representative from the INM, this individual was present during the focus groups but did not contribute to the audio taped discussion.

Data collection took place at the participants' normal place of work. A brief description of the research was given to the participants from their section commander at least 24 hours before data collection and they were informed that their involvement in the study was voluntary. Before the focus group discussion, participants were given an information sheet outlining the research aims and were reminded again that their participation was on a voluntary basis. Participants were asked to fill out a consent form and a questionnaire asking about their military rank, responsibilities and the number of tours of duty they had completed in their service career.

Focus groups began with a recap of the purpose of the study and introductions. Questions were asked in no particular order to maintain the flow of conversation. Participants were also asked to expand on their ideas during the interview using questions such as 'describe the situation you were in' and 'can you explain what you mean by that?' Discussion ended when all of the questions had been addressed and the participants felt that they had no further information to add to the conversation (usually after 30-45 minutes). The focus groups were audio taped and transcribed verbatim during October and November 2012.

*Table 3.1 Focus group questions*

1. Can you describe the types of noise you were exposed to whilst on duty?
2. Describe any situations whilst performing your job in which you think having good hearing is critical.
3. Can you recall any time when you have been unable to hear clearly when performing your role?
4. Can you recall a situation when you were unable to make yourself heard?
5. Can you describe the impact, if any, that your hearing protection has on your ability to hear whilst on duty?
6. How do you communicate important signals with each other?
7. Can you describe any situations where determining the location of a sound source was important?

**Ethical considerations**

Ethical approval was gained from the University of Southampton (Ref: 5872) and the MoD Research Ethical Committee (Ref: 359/GEN/12) (Appendix D). All data collected were treated confidentially and transcripts were anonymised so that any quoted material could not be attributed to an individual participant.

**Participants**

The study consisted of 16 semi-structured focus group interviews. Eighty British Army personnel were purposely recruited from five infantry regiments across the South of England. Recruitment of participants was terminated when no new content categories (codes) were derived from the latest interview transcripts during the analysis process (i.e. when data saturation was reached, as judged by the author). All participants had experience of active service and had returned from an operational tour of duty abroad within two months of the study commencing. The participants were selected to represent a range of ranks and infantry occupations (table 3.2 and figure 3.1). The mean number of participants per group was five, with a range of three to six.

*Table 3.2 Study 1 participant characteristics*

| **Characteristics** | **Number of participants % (n)** |
|---|---|
| **Gender** | |
| Male | 97 (78) |
| Female | 3 (2) |
| **Rank** | |
| Private | 60 (48) |
| Lance Corporal | 19 (15) |
| Corporal | 15 (12) |
| Sergeant | 4 (3) |
| Warrant Officer | 1 (1) |
| Second Lieutenant | 1 (1) |
| **Role** | |
| Formation reconnaissance | 38 (30) |
| Armoured role infantry | 16 (13) |
| Armoured engineers | 25 (20) |
| Vehicle based artillery | 21 (17) |
| **Number of tours of duty** | |
| 1 | 45 (36) |
| 2 | 31 (25) |
| >2 | 24 (19) |

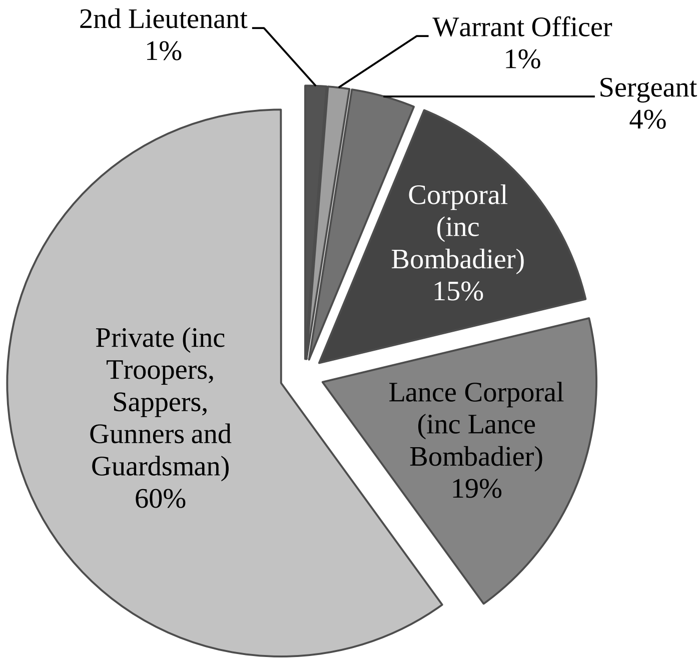


*Figure 3.1 Distribution of participants by rank*

**Data Analysis**

A qualitative, descriptive method was selected for analysis since emerging themes and ideas were of interest as well as the number of times a particular idea was mentioned. The analysis followed a typical content analysis procedure (Moretti et al. 2011). Content analysis is a systematic, replicable technique for reducing large text data to fewer content categories based on a set of coding rules (Krippendorff 2004). The technique was ideal for the data set as it can be used to isolate the information of interest from large amounts of unstructured data (Downe-Wamboldt 1992). In this study, content analysis was used primarily to identify qualitative themes but also to statistically represent the data. This method was well suited to the aims of the study - drawing out important details about infantry auditory tasks and the acoustic environment, whilst also exploring the attitudes and underlying behaviour of participants.

A piece of qualitative analysis software NVivo 10 (QSR International Pty Ltd. 2012) was used as an aid for content analysis of the raw data (see figure 3.2). Transcripts were read thoroughly to aid familiarisation before the analysis was completed. Sentences that described a certain idea or opinion were highlighted and notes were made about the common ideas and opinions. This process was continued through the first five focus groups. At this point a list of codes was determined based on themes that emerged. The following 11 transcripts were then analysed, with key ideas assigned to the preliminary codes (the number of preliminary codes was 39 and total number of coded units was 1177). After the initial coding process the codes were discussed (by the author and Semeraro) to determine whether any could be consolidated or discarded. This discussion led to changes in the coding hierarchy and drew out two themes and seven sub-themes.

To examine the reliability and objectivity of the coding process a second, independent coder was asked to re-code a sample of the data (five focus group transcriptions, 341 coded units) using the original coding descriptions. The second coder had experience of qualitative research and working with military personnel, but had not been involved with the present study. Cohen's Kappa was calculated to provide a measure of inter-rater agreement. Cohen's Kappa is a measurement of agreement between two raters when the coding is on a categorical scale, taking into account the likelihood of chance agreement (Weber 1990, Rourke et al. 2000). Strong agreement between coders was achieved ($\kappa$ = 0.795). The discrepancies observed were most often between the codes 'stress' and 'attention difficulties'. The coding descriptors were then adapted to clarify which code was most appropriate. References were deemed to be relating to 'stress' when the interviewee discussed an emotional reaction to a difficult or demanding situation and 'attention difficulties' was considered the appropriate code when the interviewee discussed performing more than one task concurrently.

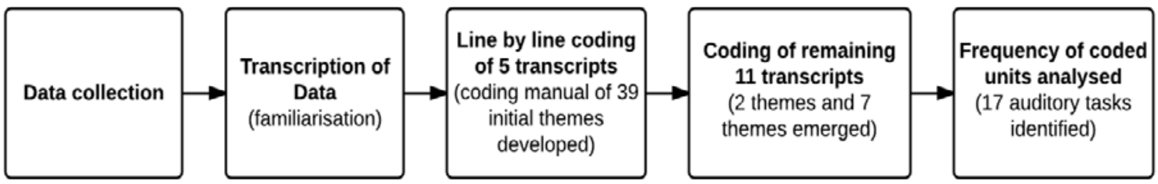


*Figure 3.2 Content analysis flow diagram*

**Reporting of results**

The number of references made to a particular idea is indicated (R= references), together with the number of focus groups the idea was mentioned in (S= number of sources). For instance: ‘negative references to hearing protection (15R, 4S)’ demonstrates that there were 15 negative comments made about hearing protection devices, and that these comments were voiced in four focus groups.

### 3.2.4 Results

Content analysis of the focus group data resulted in two main themes (table 3.3). The first theme describes the auditory tasks that infantry personnel are expected to perform as part of their operational duties. From within this theme 17 auditory tasks carried out by infantry personnel whilst on operational duty were identified. Many of the tasks identified were carried out in the presence of background noise or using radio communication systems (table 3.4). The second main theme revealed four factors that personnel believe compromise their performance on auditory tasks.

Sub-themes that emerged from the data either illustrated and explained the types of auditory tasks that personnel are expected to perform (sub-themes 1.1-1.3) or described situations where personnel felt that their hearing ability was reduced or hindered in some way (sub-themes 2.1-2.4). These sub-themes are further explored below to demonstrate the differing views and to provide context.

*Table 3.3 Themes and sub-themes of focus group dialogue*

| Theme | Sub-theme |
|---|---|
| 1**. Auditory tasks** | |
| | 1.1 Sound detection and identification |
| | 1.2 Speech communication |
| | 1.3 Sound localisation |
| 2. **Reasons for reduced performance** | |
| | 2.1 Background noise |
| | 2.2 Hearing protection devices |
| | 2.3 Stress |
| | 2.4 Attention difficulties |

*Table 3.4 Auditory tasks carried out by infantry personnel on operational duties*

| Auditory task |
|---|
| Hearing commands in a casualty situation |
| Hearing grid references |
| Hearing directions on patrol |
| Hearing directions in a vehicle |
| Hearing fire control orders |
| Hearing stop commands |
| Hearing the briefing before a foot patrol |
| Communicating through an interpreter |
| Locating a small arms firing point |
| Locating an artillery firing point |
| Locating the moving sound source of a motorbike |
| Locating the moving sound source of footsteps |
| Locating enemy movement in maize fields |
| Locating a talker |
| Identifying the type of weapon system being fired |
| Determining talker identity |
| Detecting a malfunction in an item of machinery |

**Theme 1: Auditory tasks**

**Sub-theme 1.1: Sound detection and identification**

All of the auditory tasks described by personnel involve an initial element of sound detection. In addition to detection of the sound (a skill common to both speech communication and sound localisation), the personnel were expected to identify the type of sound and whether it was a threat to their safety or the safety of others. It was the identification component of these tasks that separated sub theme 1.1 from the other sub-themes.

Personnel felt that they needed to detect weapon fire and then to determine the type of weapon being fired (22R, 10S). The most common reference referred to small arms fire and the supersonic ‘crack’ followed by the ‘thump’ sound that is generated.

*“Rifles, and when a bullet goes over your head it sends a crack and it is knowing, and things like that are really important because if you don’t hear them then there is no point being there because you’re useless really”*

Situational awareness was unsurprisingly regarded as very important by most personnel (39R, 12S). This code incorporated sounds of enemy and civilian activity.

*“Listening out for the rustling, the trees moving, the crops”*

*“Even the local nationals walking past if they’re talking I want to know how they are talking, does it sound aggressive or if they are shouting/normal”*

**Sub-theme 1.2: Speech communication**

This sub-theme incorporated comments about the ways in which speech was communicated; the distance and level of communication and the equipment used to aid conversation between personnel. Approximately 50% of the communication references referred to face-to-face communication (94R, 15S) and the other 50% to radio communication (92R, 16S).

**Face-to-face communication between personnel**

Personnel felt that the average distance over which speech was communicated was 5-10 metres and discussed how this distance reduced or increased during certain operations, often determined by the type of terrain or whether the mission takes place during the day or at night.

*"There is no set distance, it depends upon the situation you are in, the type of grounds you are on and the briefing you've got that day"*

Personnel also described how the level of their voices also varied depending on the type of mission (64R, 12S). The largest number of references (34R, 12S) indicated that voices were often raised and the participants felt this helped to make a command clearer and emphasise its importance.

*"Everyone is screaming and shouting at the top of their lungs so that you can hear everything"*

**Communication equipment**

Infantry personnel use a number of different pieces of equipment to aid communication. The equipment mentioned during data collection falls into two categories: 1) Radio, referred to as 'comms' by the majority of personnel and used to communicate between base camp, vehicles and guard positions 2) Personal Role Radio (PRR), a personal radio headset designed to allow the members of a unit to communicate more effectively with each other.

Personnel felt that the main radio was easier to use than the PRR and the signal received was usually clearer without obvious distortion (6R, 3S).

*"But regards radios and stuff, no it is fine, can hear 100%."*

*"if you are listening there is only ever one person talking but he finishes someone else can start all the time so you can't listen to three people at the same time, it is only ever one"*

Discussion of the PRR generated predominantly negative comments. Personnel felt that they were not robust enough and remarked that some devices broke very early on during the tour of duty or that the signal received was of poor quality (16R, 7S). Many chose not to communicate via PRR.

*"The PRRs they aren't very good, the way the headphone shuts on your ear you'd think it would hear a lot more. Yeah it's shit."*

*"I think we had three PRRs to a section and it's like, that's insane."*

It was apparent during the focus groups (from their comments, but also the tone of their voice and their body language) that personnel were frustrated by the difficulty caused by broken or poor quality radio signals, admitting that they favour face-to-face conversation whenever feasible.

**Commands**

The code with the most references in this sub-theme was ‘commands’ (187R, 16S). This included either a demonstration or a description of the command given. It also contains references that state when commands are important. Five command ‘situations’ were highlighted by personnel: casualty situations, directions, fire control orders, grid references and stop commands.

*“We need to know that everyone is ok so I will communicate back to them to make sure that the rest of the section is alright”*

*“Target indication and the firing point things like that, anyone that’s seen the enemy, the main ones that are needed.”*

**Communicating via an interpreter**

Personnel commented that using interpreters to talk to civilians provided an additional challenge when communicating (9R, 4S). Some personnel felt that the interpreters were well trained and useful, whereas others claimed that they were more of a hindrance than a help.

*“Like when your interpreter is trying to talk to you as well, it is hard enough to understand them anyway sometimes.”*

*“Depends on how good they are, some are really good, some not so good”*

**Sub-theme 1.3: Sound localisation**

Localisation was mentioned in all 16 focus groups. One of the questions in the focus group guideline aimed to address whether personnel needed to localise sounds, but participants often discussed this without being prompted (188R, 16S). From this sub-theme it was clear that locating a small arms firing point was of high importance for the safety of unit members and the effectiveness of the mission.

This sub theme was further coded into 5 secondary sub-themes; 1) how accurately personnel felt they were able to localise a sound source, 2) how a decision was formed within a unit about the location of the enemy, 3) the sounds that they were required to localise, 4) the pre-deployment training they received and 5) the equipment that can be used to help with localisation of firing points.

The accuracy of localisation was strongly debated in some focus groups. Some personnel felt that they were extremely skilled in locating a firing point whereas others disagreed. Most felt that they became more skilled with ‘practice’.

*“If it’s open ground you usually know where it is coming from, you might see some dust you might not. If it is a built up area it is hard, you get an echo, and you are not going to get a precise direction from it”*

*“Most of us had a pretty good idea it was in that sort of direction, not necessarily the range”*

*“You’d have other people thinking they were being shot at from fucking behind”*

*“Yeah it is coming from over there and it was coming from completely the opposite direction and even the commander of the force protection got it in completely the wrong direction. There were only three of us that could see the whole area that actually knew where the firing point was. And that’s what we need.”*

From the discussion of accuracy it was apparent that personnel were not always able to make an independent decision about the location of a sound source. This led to references about decision making. Many commented that the unit would discuss the location of the enemy before returning fire whereas others took immediate action even if unsure.

*“Whoever hears it can direct someone else onto it”*

*“Yeah, everyone will have a quick little discussion, “we think it is over there” and then… yeh”*

*“It’s just a case of looking out to wait and see if they do it again”*

*“Some people just pluck it out of the black”*

A large number of references (52R) described the sound that was being localised. The overwhelming majority state that a small arms firing point needs to be detected from a 'crack and thump' stimuli (38R). There were a small number of references (6R) stating the importance of tracking a moving sound source, for instance a motorbike.

*"Small arms fire. If you are under contact you need to know where it is coming from so you can locate it."*

*"you hear a crack and thump, crack you ignore and then you hear a duller thud and that will be the actual sound of the explosion of the weapon system and you can fire onto that and that is where the chap usually is"*

*"Did really need to do it, 'cause I was on an Op and we were getting shot by a sniper and we really needed to know where that were coming from. If you could not hear that… well… you're dead"*

*"The thump there is a time between the crack and the thump, that will determine the distance and then from the thump you can determine the direction."*

Some of the younger personnel had received training in localising a firing point at Sandhurst Military Academy or Stanton Morley. This involved a 30 minute exercise to highlight the acoustic stimuli that personnel should listen out for in order to determine the location of an enemy firing point. There were mixed opinions about the usefulness of this.

*"Literally, they would shoot something and ask right where do you think that is coming from?"*

*"You do a stupid little stand don't at Stanton its good but because they've got a battle group there its... you don't get much training value out of it cause there's that many people on the lesson. It's about 5 seconds long (all laugh)"*

*"There was not substantial training."*

*"We touched on it but it was about an hour, not even that, we just sat in a field for an hour and touched on it. We could have done more. It was good what we got"*

For personnel working on vehicles there is equipment available (Boomerang) that is able to detect the location and distance of an enemy firing point. Those that had access to the device were impressed with its accuracy but many stated it was not robust enough.

*"Boomerang, oh yeah, we had Boomerang on our wagon. Until we went through a bush and ripped it off! But yeah Boomerang was good"*

*"I broke it as soon as I got it. Literally it is like a polystyrene rod coming out the top of your wagon and I just snapped it straight off"*

*"They are supposed to be good though from what people have been telling us, they are supposed to be good and really reliable"*

There were several comments about the nature of the localisation tasks. Participants discussed scanning the horizon in front of them looking for likely enemy hiding places, using visual cues to confirm auditory cues. They also mentioned communicating an enemy location by using a clock face system. '12 o'clock' referring to a point on the landscape directly in front of their position. These comments suggested that locating a small arms firing point is predominantly a frontal horizontal localisation task during foot patrols, requiring personnel to note the perceived azimuth of the sound source.

*"you gotta look for a point on the ground… where they might be… 'enemy at 3' (hand gesture pointing 90˚ to the right)"*

**Theme 2: Reasons for reduced performance**

**Sub-theme 2.1: Background noise**

The background noise sub-theme contained any references to a sound that interfered with an auditory task; these fell into two clear categories 'continuous noise' (vehicle noise or other constant background noise) and 'intermittent noise' (any sound that was impulsive or appeared in short bursts such as gunfire or people talking).

**Continuous (74R, 15S)**

The number of references was the most interesting characteristic of this code as it helped to ascertain the most prominent acoustic environment experienced by personnel. Types of noise were grouped together and included: generators (13R), radio noise (3R), wind noise (7R), machinery (noise from engineering works) (2R), engine noise (29R) and helicopters (8R). The most commonly mentioned engine noise was from the Warrior armoured vehicle.

*"The turbo on a CVRT is really loud and it whistles, that would damage your ears after a while, constant noise."*

*"There will be an engine running or something all the time"*

**Intermittent (55R, 16S)**

This code contained mainly references to weapons or a specific weapon system. Some other examples of intermittent background noise included call to prayer, dogs barking and improvised explosive devices detonating.

*"Artillery that is just constantly firing"*

*"I was in Bastian so obviously we had the ranges where we are so I would hear everything from mortars to small arms fire."*

**Sub-theme 2.2: Hearing protection devices**

The overwhelming majority of comments (107 out of 127 comments about hearing protection) were negative and only three personnel admitted to wearing the devices regularly. Participants felt that they had reduced situational awareness and were not able to hear commands as clearly with the devices in their ears. Many complained that they were uncomfortable, made them feel claustrophobic and 'a hassle' to insert and remove.

*"So you won't know what is going on around you, you can't hear nothing"*

*"We never got issued them"*

*"Never wore them once."*

Two personnel admitted that they had been asked to remove hearing protection by a senior colleague during an artillery training exercise.

*"I did a defensive shoot on a range and they told us not to wear ear defence so we weren't shocked by the sound of it in real life and for a good half an hour afterwards I had that whiney noise in my ear"*

**Sub-theme 2.3: Stress**

Personnel felt that they were unable to hear during combat situations, not because of their hearing levels, but due to some other factor described as panic, shock or stress (31R, 9S).

*"[Participant claps loudly] that's how I'd put it, you don't know when it's coming, you can't explain it. It's just what the fuck was that? You're looking around and you've got to*

*shout is everyone all right, yeah. I think like anything if you're not ready for it's going to be a shock, you're going to be shocked yourself"*

*"In a contact when every ones flapping, but you're running over there because you can't hear and you're a headless chicken and you're scared"*

**Sub-theme 2.4: Attention difficulties**

On many occasions personnel mentioned that they found it difficult to hear people talking or maintain situational awareness when they were trying to concentrate on more than one task at once (43R, 10S).

Often the tasks described by personnel involved listening to more than one competing talker, listening to a talker and watching for a visual signal or listening and talking simultaneously.

*"you can't focus on what you are meant to be hearing, it is nothing to do with your hearing, you just can't process everything; take everything in, do you see what I mean? You can't do it"*

*"Talking in the radio, telling your boy to do something, telling him to do something and can't, you see what I mean, struggling to take it in, you miss something with your hearing"*

### 3.2.5 Discussion

Study 1 was conducted to gather information about auditory tasks carried out by infantry personnel on operational duty and the environment these tasks were being performed in. Content analysis of the focus group data resulted in two themes. Theme one: auditory tasks - describes and explains the types of auditory tasks that infantry personnel are expected to perform as part of their operational duties. From within this theme 17 auditory tasks carried out by infantry personnel were identified. Theme two: reasons for reduced performance - revealed four aspects of the participant's state of mind or environment that they believed compromised their performance on these auditory tasks.

The auditory tasks identified from the first theme fell into three sub-themes; sound identification, speech communication and sound localisation. As expected, these sub-themes support the auditory tasks reported by Laroche et al. (Laroche et al. 2008) and Giguere et al. (2008) and are common to all hearing critical occupations. However, whilst auditory tasks carried out by infantry personnel can be categorised in this way, the participants emphasised that specific tasks were often complex and carried out in diverse and changeable environments.

All of the auditory tasks described by personnel begin with the detection of a sound or signal, whether it is speech, weapons firing or the rustling of movement through a maize field. The first sub-theme - sound identification - documents tasks associated with good situational awareness (hearing enemy movement and vehicles moving) but also identification of specific sounds such as the type of weapon system that was being fired. It can be assumed that satisfactory performance on these tasks requires good hearing thresholds together with knowledge of environmental and battlefield sounds.

The second sub-theme - speech communication - was felt by personnel to be vital on all operations. Participants reported that they were often expected to understand speech without visual cues such as in low visibility situations or darkness and when using the radio. The comments from participants support the view held by Tufts et al. (2009) and Cook and Hickey (2003) that speech must be understood even when incomplete, distorted, or filtered, as with commands and conversation communicated via radio. Comments such as “if blokes can’t understand what you want them to do… its life or death” and “if you can’t hear a command, there is no point you being there” emphasise the perceived importance of infantry personnel being able to hear and understand speech on the frontline.

The third sub-theme - localisation - contained conflicting statements from participants. Whilst personnel agreed that they needed to determine the source of small arms fire, they were unsure how accurately they were able to do this. Some participants commented that they needed visual confirmation of a firing point before they were sure of its location, while others were confident that they had correctly identified the location from the sound alone. Further research is required to determine how skilled personnel are at localising a sound source and whether it is necessary to incorporate a test of localisation into a military AFFD protocol.

The level of hearing acuity required to carry out the tasks identified cannot be determined from the focus group data; it is unlikely that these tasks can be performed using job experience and other sensory modalities alone. Tufts et al. (2009) define tasks of this type as ‘hearing critical’. It was also not possible to conclude whether poor performance on a task would compromise the safety and/or efficiency of a mission. In short, it is not yet known whether any of the auditory tasks described by personnel are ‘mission critical’.

The three auditory task sub-themes (speech communication, sound detection and sound localisation) were discussed at length in all of the focus groups. It appears that, regardless of role or rank, all infantry personnel may be expected to perform these fundamental tasks during operational duties. It is also clear that certain roles encounter particular auditory tasks more often than others; for instance, senior personnel and mounted infantry soldiers are more likely to communicate via radio than dismounted soldiers or lower ranking personnel. Those working in engineering roles commented that they rarely had to localise a sound source but they were often expected to identify potential vehicle faults from the sound of the engine. Due to this, there are limitations in the generalizability of the information gathered about each auditory task, assuming that only some personnel perform a specific task on a regular basis. In addition, the generalisability of these data to other military cohorts (such as the Royal Navy and the Royal Air Force) is likely to be limited due to the varied nature of military occupations.

Theme two - reasons for reduced performance - consisted of references to poor performance on auditory tasks and the reasons for this. The most commonly mentioned, and perhaps most obvious, reason for reduced hearing ability was the introduction of background noise. Participants discussed the types of noise that interfere with auditory tasks and whilst some of these were expected, for example weapons firing and engine noise; others were less expected, such as noise from electricity generators and wind noise interfering with radio communication. The present study has provided a detailed and unique representation of the challenges faced by personnel on operational duties with regards to interfering noise. The effects of background noise on task performance will need to be considered when ascertaining whether personnel have the necessary auditory skills for infantry job roles.

The second most commonly mentioned reason for reduced performance on auditory tasks was the use of hearing protection devices. In general, personnel were knowledgeable about the need to wear hearing protection and the effect of prolonged or excessive noise exposure on their hearing. In spite of this, only three personnel reported wearing hearing protection devices on a regular basis. Whilst not within the scope of this study, the focus group transcripts serve as a record of infantry attitudes towards hearing protection. The adjectives and emotive language used by participants was indicative of a group that are concerned about their hearing and their ability to safely perform the job required of them. Understandably, personnel showed greater concern for maintaining their situational awareness and ultimately their survivability. Personnel cited similar reasons to those reported by Okpala (2007) for not using hearing protection: predominantly lack of situational awareness, the perceived inability to hear commands and discomfort. Other reasons not previously reported included feelings of claustrophobia and the inconvenience of using the devices.

The final sub-themes (stress and attention difficulties) address two aspects of operational duties that personnel felt affected their ability to complete auditory tasks to a satisfactory standard. Participants felt that in stressful environments (predominantly when in contact with the enemy) their ability to maintain situational awareness and understand speech was compromised. This was reported in addition to the difficulties caused by any associated background noise. This sub-theme had a significant amount of overlap with the sub-theme of attention difficulties. Participants described situations where they were expected to complete more than one auditory task (or an auditory and a written task) as particularly stressful. An increase in cognitive load (induced by a stressful environment or by increasing the number of tasks personnel must perform) has been shown to decrease performance on auditory tasks (Scharine and Letowski 2005, Pashler 1994). The focus group data highlights a need for further research into this area as the actual effect of increased cognitive load on military auditory tasks is unknown.

The present study has several possible limitations. The development of the coding scheme and its administration was completed by the same member of the research team. Krippendorf (2004) notes that this is less than ideal and can lead to coder bias. However in order to reduce any effect of coder bias, the inter-rater reliability was measured and there was found to be strong agreement between coders. A second limitation is that the inter-rater reliability was calculated using broad categories (e.g. ‘speech communication’, ‘stress’, background noise’). It was after this process that the lead author continued to divide these codes further into smaller categories (e.g. ‘face-to-face communication’ and ‘communication equipment’). Inter-rater reliability was not measured for these smaller content categories.

The participants were all army personnel and for the study to be truly representative of the infantry as a whole, personnel from the Royal Marines should have been included. However, Royal Marines (whilst technically infantry personnel) often have very specific roles and responsibilities that are not carried out by the majority of army personnel. If AFFD measures were to be designed specifically for Royal Marines it may be appropriate to carry out a further job analysis.

### 3.2.6 Conclusions

The current qualitative study provided an important and novel insight to the complex auditory environment experienced by British infantry personnel on operational duties abroad, identifying 17 auditory tasks. Comments made by participants have also highlighted four reasons for reduced performance on these auditory tasks. Due to the qualitative nature of the data collected the actual consequences of performing military auditory tasks incorrectly could not be determined. Personnel, on occasion, alluded to the failure of a task resulting in serious injury or fatality and have also stated that a colleague would be ‘useless’ or ‘redundant’ without certain hearing abilities. Without knowing the consequences of unsatisfactory performance it is not possible to determine whether or not these tasks are in fact vital to the success and safety of the mission (and therefore considered to be MCATs). Without this further information it is still clear that personnel regard their hearing as vital within an infantry role and that they strongly believe a hearing impairment would decrease job performance. The auditory demands highlighted in this study are important considerations for researchers developing AFFD protocols, both for military personnel and other hearing critical occupations.

### Summary

In accordance with the aims, study 1 has:

- Gathered information about the hearing requirements of infantry personnel.
- Identified 17 auditory tasks carried out by infantry personnel during operational duties as well as providing information about the environments these tasks are performed in.
- Highlighted attitudes and behaviours of personnel towards noise exposure and the use of hearing protection devices.

Beyond the aims, the study has also:

- Identified important knowledge gaps that will form the foundations of further research into cognitive load during military tasks, AFFD and hearing protection design and implementation.
- Documented a methodology for job analysis where auditory skills are of interest; a method that could be applied to other occupations and cohorts where AFFD is important.

## 3.3 Study 2 – Task questionnaire

### 3.3.1 Introduction

A further qualitative study was conducted by Semeraro to determine which of the auditory tasks carried out by infantry personnel could be described as MCATs (Semeraro et al. 2014). The author of this report did not conduct this study and was only involved in an advisory capacity during the design stage. A brief overview of the aims, methods and results are presented below due to the significant impact of the findings on the research questions and experimental work presented in this thesis.

A questionnaire was designed to gather information about the auditory tasks in table 3.4. By definition, an MCAT must be hearing dependent. Tasks were deemed to be hearing dependent if they could not be completed using job experience or other sensory modalities alone. Using these criteria it was decided that all 17 auditory tasks met this initial criterion and were therefore included in the questionnaire.

MCATs must also have negative consequences if performed poorly. The negative consequence may take any form, but often it compromises the safety or effectiveness of a mission or task. The questionnaire aimed to determine which tasks could have negative consequences if not completed correctly and quantify the severity of this negative outcome.

It is also illogical to incorporate a task that is A) only carried out infrequently or B) by a small number of personnel, into the AFFD test battery. Therefore the questionnaire gathered information about the frequency of tasks performed during operational duties and who they are performed by.

To summarise, three pieces of information about each auditory task were required in order to determine which of the tasks are mission-critical and which should be represented by a measure of AFFD:

1. The consequences of poor performance on the task,

2. Which ranks and roles perform the task, and

3. How frequently the task is performed.

### 3.3.2 Aims

Study 2 aimed to:

- Identify which of the auditory tasks carried out by infantry personnel can be defined as MCATs
- Which MCATs should be represented by a measure of AFFD for infantry personnel

### 3.3.3 Method

The 17 auditory tasks from study 1 were included in the questionnaire. For each task, participants were asked to give a scale rating concerning:

1. The significance of the consequences of poor performance

2. Whether the task is carried out by all, some or no infantry personnel

3. How frequently the task is performed during a training exercise or when serving on a tour of duty.

See table 3.5 for questionnaire items and 3.6 for the list of auditory tasks with their corresponding questionnaire reference number.

**Participants**

Participants were recruited from four regiments across the south of England. The questionnaire, with a covering letter, were sent to 11 senior personnel who were involved in study 1. They were asked to distribute the questionnaire within their normal place of work. Eighty-seven questionnaires were received and 79 of these were suitable for analysis (eight were rejected as they were incomplete or completed incorrectly). All participants had experience of infantry roles either during training exercises or during an operational tour of duty. The participants represent a wide range of ranks and roles.

*Table 3.5 Task questionnaire items*

| Consequences of poor performance | Who performs this task? | Frequency of task |
|---|---|---|
| In your opinion how significant are the consequences of poor performance on this task? | In your opinion, during a training exercise or when serving on a tour of duty is this task carried out by all infantry personnel, some infantry personnel or no infantry personnel? | In your opinion, how frequently is this task performed during a training exercise or when serving on a tour of duty? |
| 1 = No Consequence<br>2 = Minor<br>3 = Moderate<br>4 = Major<br>5 = Critical | 1 = No infantry personnel<br>2 = Some infantry personnel (indicate which roles)<br>3 = All infantry personnel | 1 = Seldom or yearly<br>2 = Occasionally or monthly<br>3 = Regularly or weekly<br>4 = Frequently or daily<br>5 = Continuously or several times per day |

*Table 3.6 Infantry auditory task list with task numbers*

| No. | Task |
|---|---|
| T1 | Accurately hearing commands in a casualty situation |
| T2 | Accurately hearing grid references |
| T3 | Accurately hearing directions on patrol |
| T4 | Accurately hearing direction in a vehicle |
| T5 | Accurately hearing fire control orders |
| T6 | Accurately hearing ‘stop’ commands |
| T7 | Accurately hearing the briefing before a foot patrol |
| T8 | Communicating accurately through an interpreter |
| T9 | Locating a small arms firing point |
| T10 | Locating artillery firing point |
| T11 | Locating the moving sound source of a motorbike |
| T12 | Locating the moving sound source of enemy footsteps |
| T13 | Locating rustling of vegetation and leaves |
| T14 | Locating a person talking |
| T15 | Identifying the type of weapon systems being fired |
| T16 | Identifying talker identity |
| T17 | Identifying a malfunction of an item of machinery |

### 3.3.4 Results

**Consequences of poor performance**

The responses to question 1 (consequences to poor performance) show that for all 17 tasks the mean consequence score is above 3, moderate consequence. The top three tasks are all speech communication tasks (T1, T6, T5, see table 3.6 for the task list). The sound localisation task with the highest mean consequence score is T9, locating a small arms firing point. All three sound identification tasks were deemed to have minor or no negative consequences due to poor performance.

**Who performs the task?**

There was general agreement amongst all participants that all of the tasks were performed by the majority of personnel. The results show that 80% of the tasks were deemed to be carried out by all infantry personnel. Only T8 (communicating via an interpreter) was not deemed to be a generic task and therefore this task was removed from any further analysis; it does not need to be actively represented during the development of a new AFFD protocol.

**Frequency of task performance**

The final question addressed how frequently an auditory task was performed. None of the tasks had a mean frequency rating of 5 (continuously or several times per day). Three tasks (T3, T2 and T4) had a mean frequency rating of 4 (frequently or daily). Twelve tasks (T1, T5, T6, T7, T8, T9, T11, T12, T13, T14, T15 and T16) had a mean frequency rating of 3 (regularly or weekly) and two tasks (T10 and T17) had a mean frequency rating of 2 (occasionally or monthly).

In the consequence-frequency matrix (table 3.7) colour coding is used to show high risk (black), medium risk (grey) and low risk (white). The tasks in the black area should, ideally, be represented by an AFFD protocol. The cut-off point between the grey and black area is subjective. This was chosen in order to include the tasks with either a frequency or consequence score in the top two categories. From the matrix it is possible to generate a list of MCATs which ought to be represented in a measure of AFFD for infantry personnel; these are listed in table 3.8.

*Table 3.7 Consequence/ frequency matrix (Key *speech communication, ~sound localisation, $sound detection). Calculated using the mean consequence and frequency ratings of each task. The tasks in the black shaded area were deemed to be high risk and should be prioritised in measures of AFFD.*

| | | Consequences of poor performance | | | | |
|---|---|---|---|---|---|---|
| **Frequency of task performance** | | **No consequence** | **Minor** | **Moderate** | **Major** | **Critical** |
| | **Seldom or yearly** | | | | | |
| | **Occasionally or monthly** | | | **T17$** | **T10~ T12~** | |
| | **Regularly or weekly** | | | **T11~ T13~ T14~ T16$** | **T15$** | **T1* T6* T9~** |
| | **Frequently or daily** | | | | **T2* T3* T4* T7*** | **T5*** |
| | **Continuously or several times per day** | | | | | |

*Table 3.8 List of MCATs to be prioritised in measures of AFFD for the infantry*

| **Speech Communication** |
|---|
| T1: Accurately hearing commands in a casualty situation |
| T2: Accurately hearing grid references |
| T3: Accurately hearing directions on patrol |
| T4: Accurately hearing direction in a vehicle |
| T5: Accurately hearing fire control orders |
| T6: Accurately hearing ‘stop’ commands |
| **Sound Localisation** |
| T9: Locating a small arms firing point |
| T12: Locating the moving sound source of enemy footsteps |
| **Sound Identification** |
| T15: Identifying the type of weapon systems being fired |

### 3.3.5 Discussion

The primary aim of study 2 was to identify which auditory tasks from study 1 could be classified as mission critical. A secondary aim was to determine which tasks should be represented by a measure(s) of AFFD.

The results indicate that all of the 17 auditory tasks can be deemed MCATs; they are all dependent on the individual having some level of hearing and all have some level of negative consequence when performed below a certain standard. The data also enabled prioritisation of those MCATs that should be assessed in some way by an AFFD measure. This does not necessarily mean that the most appropriate AFFD measure is a replica or simulation of the task itself; simply that the auditory skills required to carry out the task are assessed in some way to determine the skill level of the individual. This is particularly important when the individual has some level of hearing deficit that may impair their performance level.

Study 2 was not without limitations. For some tasks, participant responses about frequency and consequence were highly varied, particularly for those tasks that fell in the 'low risk' area of the frequency-consequence matrix. This may have been due to the varied roles and responsibilities of the participants; for some roles certain tasks will have been performed more frequently and have a much higher level of responsibility attached to the task. There were a few unexpected responses from individual participants such as stating that no infantry personnel had to hear directions on a foot patrol or that there were no negative consequences to mishearing grid references. Whilst these responses made only a very small percentage of the total number of responses, it raises questions over whether participants understood the questionnaire. It is also likely that some individuals answered the questions based on their role and not with respect to the infantry as a whole.

### 3.3.6 Conclusions

Study 2 provided a valuable insight into the way in which auditory tasks are carried out by infantry personnel on operational duties and the consequences of performing these tasks incorrectly. The study has built on the data collected from study 1 to identify mission critical hearing tasks and prioritise them for inclusion into AFFD measures.

**Summary**

In accordance with the aims, Study 2 has:

- Identified that all of the 17 auditory tasks carried out by infantry personnel can be defined as MCATs
- Created an objective, evidence-based shortlist of 9 tasks. All of these tasks are carried out frequently, by the majority of personnel, and have a major or critical consequence if performed below an acceptable standard. The auditory skills required for the completion of these tasks ought to be assessed by a measure(s) of AFFD.

## 3.4 Summary and knowledge gaps

### 3.4.1 Summary

It is argued that using PTA alone (without further testing) may not give a comprehensive measurement of ability on occupational auditory tasks (Vaillancourt et al. 2011, Tufts et al. 2009, Tufts 2011). British infantry personnel are required to carry out complex listening tasks in their everyday work environment and any measure of AFFD needs to directly assess the skills required to carry out the MCATs identified through studies 1 and 2.

Over 150 personnel contributed to these comprehensive studies, identifying 17 MCATs that are vital to the safety and efficiency of infantry missions on operational duties. Currently, no other studies of this type have been carried out for UK military personnel. The studies also uncovered infantry attitudes and behaviours towards noise exposure and hearing protection. Further to this, the qualitative data collected provided a much needed insight to the challenging acoustic environments and stressors encountered by infantry personnel working in war zones abroad.

The nine MCATs prioritised for representation by measures of AFFD fall into three categories: speech communication, sound localisation and sound identification. Six out of the nine tasks were speech communication tasks and whilst appearing varied, are likely to require similar auditory skills (i.e. hearing and processing speech face-to-face or via a radio system, in quiet or a background of noise). A speech discrimination measure of AFFD is therefore being developed and evaluated by the Hear for Duty team at Southampton University (Semeraro 2015).

Beyond speech communication, the most frequently performed MCAT with the most critical negative consequences when performed incorrectly was task T9; localising a small arms firing point. Prior to considering an AFFD measure representative of this task, it is first necessary to determine how well individuals with normal hearing are able to perform this task. Some personnel were confident in their ability to perform the task; others relied on visual cues and the support of colleagues. As there appeared to be a range of abilities for this task, it called into question whether all personnel are able to localise gunfire. It would not be appropriate to assess localisation accuracy as a component of AFFD if only a small percentage possessed this ability. This second key question forms the basis of the research in the remainder of this thesis.

### 3.4.2 Knowledge gaps

Before AFFD measures can be developed three key questions require answering:

1) Can normal hearing infantry personnel carry out the localisation MCAT?

It is not known how well personnel with normal hearing are able to carry out these tasks. It is possible that, even with unimpaired hearing, personnel's skill level on certain tasks is low or varies significantly between individuals. In either of these cases it may be inappropriate to allow performance on these tasks to dictate an individuals overall auditory fitness level.

2) Is task performance affected by hearing loss?

It is not known to what extent a hearing impairment would impact on an individuals ability to carry out one of the shortlisted tasks. If level of hearing only has a mild impact on task performance it is possible that personnel are relying on other sensory modalities or memory to aid their performance. In this instance it may be necessary to assess other skills in conjunction with auditory fitness.

3) Is performance on the shortlisted MCATs statistically independent to results observed from the current measure of AFFD?

It would not be necessary to implement a large battery of very specific auditory tests if one (or more than one) test was able to predict performance on a number of MCATs.

It was not known whether these questions represented true gaps in knowledge. A thorough search of the literature was conducted to identify whether answers to the questions were already in existence. This literature review is presented in chapter 4.

# Chapter 4: Localisation background and literature review

## 4.1 Introduction

Localising the source of small arms fire is an MCAT carried out by infantry and combat support personnel on operational duties abroad (Bevis et al. 2014, Semeraro et al. 2015). Chapter 4 outlines the mechanisms of human sound localisation and discusses the literature surrounding localisation accuracy of both generic and gunshot-like stimuli. Based upon the findings of the focus groups and questionnaire study, it was clear that personnel felt they performed the gunshot localisation MCAT with varying degrees of success. The current chapter reviews the factors that are known to hinder human localisation accuracy (section 4.4) and highlights gaps in the existing knowledge base. Further to this, it reviews the current methods of measuring localisation performance (section 4.3); this evidence was used to inform the experimental design developed and implemented throughout the following chapters.

## 4.2 Fundamentals of human localisation

In order to localise sound, humans rely on information from their acoustic environment and the effects of their head and body on the signals received. As this thesis is primarily focussed around the localisation of small arms fire in an open area (identified as a predominantly horizontal localisation task in section 3.2.4), this section will focus on the models of sound localisation in the horizontal plane. Kulkarni and Colburn (1998) give a detailed review on determining the elevation of a sound source.

In the most basic condition, a sound source emits a signal that propagates through a given environment and is received by a human listener with two ears. The relative locations of the listener and the source, the shape and size of the receiver (their head, body and external ear) together with the environment characteristics, determine the differences between the original signal and the signal received by the listener. As described by Colburn and Kulkarni (2005) the listener uses attributes of the received signal to determine the location of the source and these attributes, or localisation 'cues', must A) vary with the location of the source and B) be detectable by the human auditory system.

Whilst humans are able to locate a sound source to a degree of accuracy using only one ear, the dominant method of localisation requires the comparison of two signals arriving at spatially separate ears. Whilst the individual signals do not contain explicit spatial information, the lower auditory pathway is able to compute and compare the physical parameters of the sound (Grothe et al. 2010). This comparison of signals from the horizontal plane takes place in the superior olivary complex (SOC). The lateral superior olive (LSO) and medial superior olive (MSO) are responsible for processing binaural cues from the excitatory input received from the left and right cochlear nuclei (ipsilaterally and contralaterally). A map of the auditory pathway and the location of the SOC can be seen in figure 4.1.

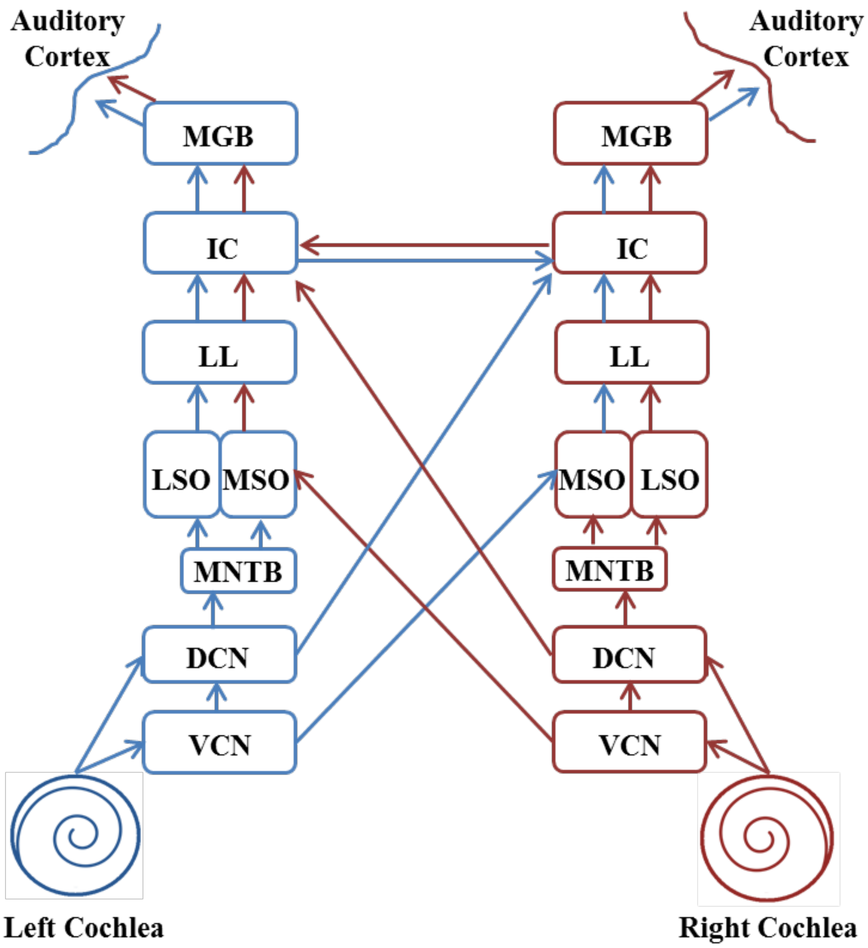


*Figure 4.1 The central auditory pathway from cochlea to cortex. DCN = dorsal cochlear nucleus, VCN = ventral cochlear nucleus, LSO = lateral superior olive, MSO = medial superior olive, MNTB = medial nucleus of the trapezoid body, LL = lateral lemniscus, IC = inferior colliculus, MGB = medial geniculate body.*

### 4.2.1 Binaural cues and the duplex theory

Binaural cues detected within the SOC are the interaural level difference (ILD) and the interaural time difference (ITD) respectively. Rayleigh (1907) was the first to explain that localisation was based upon the differing path lengths between the sound source and the listener’s individual ears. The ILD is a comparison of the intensity levels of the sound arriving at each ear and the ITD is a comparison of the time taken for a signal to arrive at each ear (Moore 1989).

Computing of the ITD begins in the MSO and time differences are greatest for low frequency sounds (Tollin 2003). MSO cells receive excitatory input from the ipsilateral and contralateral cochlear nuclei. The input sounds may differ in latency and the MSO cells responds to a time difference in sound onset or a difference in cycles of ongoing sounds. Different MSO cells are responsible for ‘detecting’ different ITDs and the majority of cells respond to low frequency ITDs. This is not unexpected; ITDs are mainly produced by low frequency stimuli as the wave length is greater than the maximum time delay between the ears; this causes a phase difference between the sounds arriving at each ear (Moore 1989).

Complex sounds such as speech or warning sounds in a battlefield environment are made up of a number of amplitude modulated signals. Temporal information from each of these signals can be separated into 1) the temporal fine structure (TFS): fast changes in amplitude around the centre frequency or the pattern of phase locking to the waveform and 2) temporal envelope; the slow oscillations in firing rate over time (Hopkins and Moore 2010, Cheng and Wakefield 2001). These two types of temporal information are shown in figure 4.2.

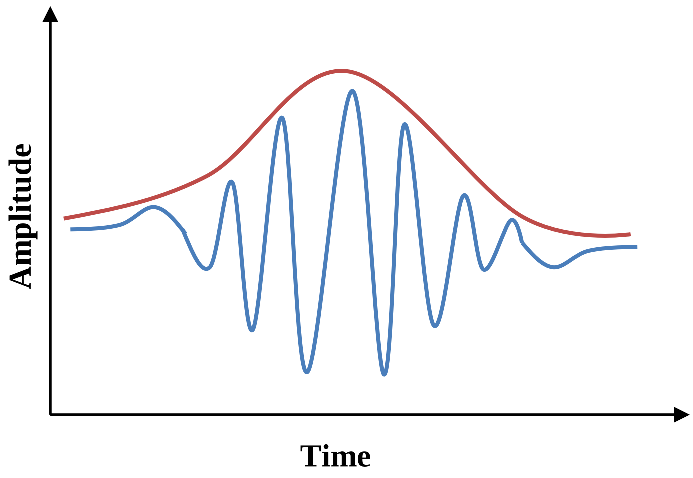


*Figure 4.2 Diagram to show temporal fine structure (blue) and temporal envelope (red)*

There is more than one theory describing how the auditory pathway is able to extract reliable spatial cues from complex sounds such as a click, particularly in the presence of reverberation and competing sounds (Dietz et al. 2013). It would seem possible that humans are able to glimpse spatial information from the very start of a stimulus, ignoring conflicting cues from later-arriving or modulating portions of the sound. The dominant cue in determining the ITD is the TFS; normal hearing listeners are able to discriminate ITDs of 10-20 µs for low frequency tones (Zwislocki and Feldman 1956). For unmodulated sounds or short duration stimuli this is of particular importance; a human listener is forced to utilise information gathered at the start of the stimulus as they are unable to wait for any later envelope modulations in the signal (Brungart and Simpson 2008). Conversely, envelope cues are predominantly used for localising and spatially separating highly modulated stimuli such as speech from other stimuli (Apoux et al. 2013). Sensitivity to TFS is known to degrade with hearing impairment and increasing age (Grose and Mamo 2010).

Whilst the ITD is generally considered to be more effective for low frequency stimuli (below 1.5 kHz) (Hawkins and Wightman 1980), Kuhn (1977) reported that humans do not utilise ITD cues as much as expected for low frequency stimuli. Wightman and Kistler (1992) conducted a localisation study using broadband stimuli with either natural ITD cues or ITDs that had been made artificially constant across frequency and found that the accuracy of localisation in both conditions was the same. However, although localisation accuracy remained constant, participants made a higher number of front back errors when ITD cues were kept at a constant level. Whilst it is known that ITDs are the dominant cue for localisation of a wideband stimulus, for any given ITD value there are a number of potential source positions. ITD and ILD cues are only marginally useful for front-back differentiation. This is because of the spatial ambiguity caused by head symmetry and is described in the literature as the ‘cone of confusion’ (Letowski and Letowski 2011). As shown in figure 4.3, sound events originating from any point on the circumference of a cone give identical ITDs, causing listeners to sometimes localise the sound to the incorrect position around the base of the cone (incorrectly guessing source B instead of source A, for instance) (Hartmann et al. 1998).

Wightman and Kistler (2005) noted that humans require the use of other localisation cues (ILDs and spectral cues) to determine the direction more accurately on the cone of confusion that can be caused by relying upon ITDs alone. This type of ambiguity is also observed when ILDs are used independently of other localisation cues (Bronkhurst 1995).

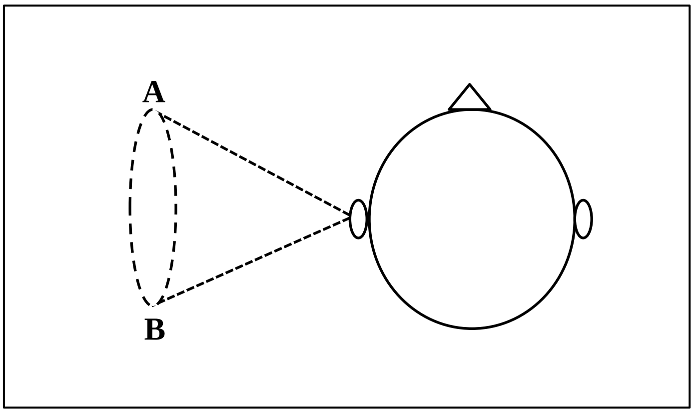


*Figure 4.3 Cone of confusion. 'Front-back errors' occur when a listener incorrectly perceives a sound from source A instead of source B. Sound sources that fall on the circumference of the cone have identical ITD and/or ILD values.*

For a given source position the peaks and troughs in the transfer function (caused by reflections from the head and torso of the listener) will differ in frequency (Wightman and Kistler 2005). Further to this, the ILD is small at frequencies below 1.5 kHz as the low frequency wavelengths are relatively large compared to the dimensions of the head (Rayleigh 1907) which means that sound waves are able to diffract around the head. This diffraction results in the signal reaching both ears at a similar intensity.

Stevens and Newman (1936) supported the theories outlined above in a localisation experiment with normal hearing listeners. Participants were asked to determine the angular location of a source (a loudspeaker mounted on a 12 foot long boom). The results showed that broadband click and noise burst stimuli were localised with considerable accuracy but sinusoidal stimuli resulted in multiple front back confusions and errors within the frequency region 1500 -3000 Hz. Middlebrooks and Green (1991) suggested that this was due to the stimuli being too high in frequency to produce useful ITD cues and too low in frequency for useful ILD cues.

The LSO is the primary area for computation of ILD cues (Tollin 2003). LSO cells receive an excitatory input from the cochlear nucleus of the ipsilateral ear – similar to the mechanism for ITD cues. Further to this, the LSO also receives an inhibitory input from the medial nucleus of the trapezoid body (MNTB; shown in figure 4.1) from the contralateral ear (Tollin 2003). The output of the LSO cells is a direct result of the combined depolarising and hyperpolarising effect of the inputs. Similar to the MSO, cells in the LSO respond to specific interaural level differences.

### 4.2.2 Head related transfer functions

While the relationship between ILD, ITD and spatial location of a sound source is well documented, there is not yet a clear association between spectral cues and perceived location. The direction-dependent free-field frequency response of the ear is called a head related transfer function (HRTF). This is normally measured by first presenting a wideband signal from a loudspeaker and recording the response first with a listener present (with the microphone placed in the ear canal) and absent (with the microphone placed at an equivalent distance from the source) (Cheng and Wakefield 2001) in anechoic conditions. Then, with the responses in the frequency domain, the HRTF can be calculated by dividing the ear canal response by the loudspeaker-only response (Wightman and Kistler 2005). The diffraction and reflection properties of an individual’s pinna, head and torso varies giving rise to HRTFs that vary from person to person. A signal received by each individual ear is made up of the original sound (entering the ear directly) together with many copies of the signal that have been reflected and filtered by the shape of the head and pinna, all differing slightly in terms of amplitude and frequency (Wenzel et al. 1993). These signals overlap, causing certain frequency bands to be enhanced and others reduced due to phase cancellation. The brain is able to detect these peaks within the final signal and make comparisons with known directions of sound (Hofman et al. 1998). HRTFs also vary depending on the reflective properties of an individual's clothing and hair and human listeners are able to adapt to the variations relatively rapidly (Hofman et al. 1998). The listener uses these direction-specific properties to help determine the location of the sound source, particularly in the vertical plane (Blauert 1997).

HRTF cues occur primarily in the frequency range above 4 kHz due to the small size of the geometric features of the pinnae in comparison to the wavelength. Therefore, the more high frequency content a sound has, the more useful the monaural cues. There is also a significant peak in HRTFs around 3 kHz due to the natural resonance of the ear canal (Wightman and Kistler 2005). Humans are able to localise sounds using only one ear, but without the use of level and time differences, localisation errors increase from approximately 3˚ to over 30˚ for broadband stimuli (Scharine and Letowski 2005).

The HRTF can be used to help pinpoint a source location within the 'cone of confusion' described earlier (where ILD and ITD cues give a range of potential source locations). To prove that the brain relies on this 'internal calibration' (formed from spatial feedback from other sensory systems), Hofman et al. (1998) disrupted pinna cues by fitting four individuals with outer ear moulds. They found that localisation accuracy was impaired immediately after fitting but performance improved steadily as the participants' 'recalibrated' to their new HRTFs. The authors note that they are unsure of the origins of this adaptation as the participants did not receive feedback during the experiment.

In addition to utilising pinna cues, a person can move their head to help resolve front-back confusions. In turning their head, an individual is able to make better use of ILD and ITD cues by moving the sound source out of the cone of confusion or by 'mentally comparing' the original HRTFs with those present after the head movement (Iwaya et al. 2003).

### 4.2.3 Distance perception

Whilst this thesis is not focussed upon auditory distance perception, locating the source of small arms fire in operational environments would likely incorporate an element of distance estimation. Due to this, a short introduction is provided here and further information can be obtained from Scharine and Letowski (2005). During the focus groups conducted in study 1, personnel mentioned distance cues when discussing small arms fire; "*The thump, there is a time between the crack and the thump, that will determine the distance and then from the thump you can determine the direction.*". This suggests that personnel may be able to make use of distance cues contained within the gunshot stimulus.

Estimating auditory distance requires a combination of cues together with a visual frame of reference. Humans are generally not skilled at predicting the distance between themselves and a sound source, with accuracy errors of approximately 20% (Zahorik et al. 2005). Distance perception is a research topic still in relative infancy with the majority of recent literature based on the observations of Coleman (1962).

Sound intensity is the most established cue. It is well documented that in ideal conditions intensity decreases by 6 dB when the distance between the source and the receiver is doubled. Using intensity as a cue requires either the listener to move towards or away from the source to create a frame of reference, or have a knowledge of the sound's original loudness (Zahorik et al. 2005). However, even if one has a frame of reference, the relationship of distance to attenuation varies due to changes in the temperature and humidity of the air (Coleman 1962).

If the sound source is not in an open area then distance perception is affected by reverberation from reflective surfaces. The decrease in sound intensity follows the usual 6 dB rule until the energy from room reflections exceeds the energy from the sound source. The point where these energies are the same is called the critical distance and within this area distance perception is unaffected due to the precedence effect (Scharine et al. 2009). The further away from the sound source and the more reflective surfaces in the environment, the less accurate a listener's distance perception (Blauert 1997).

Reverberation is not necessarily a hindrance to distance perception. Reverberated sounds last longer and decay slower than an original sound, so for sounds originating far away from the listener reverberant energy may be greater than the original sound energy (Scharine et al. 2009). In this instance a listener may be able to use the reverberation to determine the distance of a sound source depending on their familiarity with a given space, the size of the space and the position of the sound source relative to the reflective surfaces (Scharine and Letowski 2005). Conversely, reverberation coming from an unseen and unfamiliar space may provide no useful distance information (Middlebrooks and Green 1991, Mershon and King 1975).

Humans are also able to use changes in sound quality (spectral changes) to help determine the distance between listener and source. The spectrum is affected by the absorbent properties of air (attenuating high frequencies by as much as 4 dB per 100 m) and the acoustic properties of any surrounding reflective surfaces. However, in the near field, these spectral changes are likely to be very small and Zahorik et al. (2005) suggest that, for short distances (defined by Zahorik as less than 15 m), they may not provide reliable or useful information for the listener. Coleman (1962) was the first to implicate the use of spectral cues for distance perception and this was further investigated by Little et al. (1991) who found that high frequency content decreased more rapidly than low frequency content as distance increased. Participants were able to use this and other spectral changes (that were not described by Little et al.) to determine auditory distance fairly accurately, even when loudness cues were removed. However, studies such as Coleman (1962) and Little et al. (1991) were conducted with few participants and in conditions (on a frozen lake covered in snow in Coleman's case) that would have made it difficult to keep other distance perception cues constant and to eliminate confounding variables.

## 4.3 Measuring localisation accuracy

### 4.3.1 Methods of measuring localisation accuracy

There are two psychoacoustic measurements often used to study human sound localisation. The minimum audible angle (MAA) is a discrimination task requiring the listener to detect small angular separations between sources (Letowski and Letowski 2011). Whilst MAA is a good measure of spatial acuity, the task may be solved by utilising a single acoustic parameter (such as ITD) without the listener needing to create a spatial image of their surroundings. The source identification method (SIM) requires a listener to identify a single sound source from their immediate surroundings. Although this task is often confined to the vertical or horizontal plane and a set of fixed source locations, it is able to assess a combination of auditory capabilities and is more applicable to a real-world localisation scenario (Makous and Middlebrooks 1990). For these reasons the SIM is an appropriate method to measure localisation accuracy on the complex MCATs identified in chapter 3. The following section will discuss the specific approaches to the source identification method.

Accurately reproducing a sound so that spatial cues are preserved can be difficult. This is particularly important when the stimulus contains complex spatial cues such as those present in a gunshot. The literature surrounding absolute auditory localization generally utilises one of two measurement methods; 1) a freefield speaker array placed horizontally or vertically around the participant with the speakers either visible or hidden from view, 2) a virtual localisation system, where stimuli containing HRTF information are presented binaurally to the listener. Both systems have advantages and disadvantages, some of which are discussed in this section.

**Freefield**

Freefield speaker arrays provide a versatile measure of localisation accuracy. Placing individual speakers around a participant in an anechoic room allows multiple stimuli to be presented to any listener from any angle. The speaker array can be visible to provide the listener with identifiable source locations or hidden to allow the listener to choose a point anywhere in between the speakers as the perceived stimulus origin. This system is advantageous when the participant requires listening prostheses; hearing aids or cochlear implants for example, and it leaves the individual free to move their head or body without disrupting the perceived source location (Bogaert et al. 2006, Verschuur et al. 2005).

Human listeners are able to localise using a free field source identification task with very high degrees of accuracy. Recanzone et al. (1998) report that for absolute localisation tasks human listeners are generally accurate to within 30º of the target (and often much more accurate), dependent on the type of stimulus. Whilst free field measurement systems leave the listeners' HRTFs intact, avoiding the need to convolve stimuli with individually measured HRTFs or average HRTFs, it is not practical for stimuli with complex/varying directional cues (Bronkhurst 1995). In this instance a greater number of recordings from multiple angles would need to be presented simultaneously through speakers in both the horizontal and vertical plane. This system has been used by some but is time consuming, costly and does not allow precise control over the stimuli (Wightman and Kistler 2005).

**Virtual sound reproduction over earphones**

To overcome some of the problems associated with freefield measurement systems, researchers have turned to presenting virtual sound sources to human listeners via headphones or insert earphones (Cheng and Wakefield 2001, Kulkarni and Colburn 1998, Wenzel et al. 1993, Wightman and Kistler 1992). This system can be advantageous; it is lightweight, portable and allows precise systematic control over the stimulus delivered to the listener (Wightman and Kistler 1989). It also allows the complex spatial cues contained within some stimuli, such as the conflicting origin of the projectile and muzzle blast within a small arms gunshot, to be preserved.

As binaural recordings are often created using microphones placed at the eardrums of a dummy head with average human proportions, the HRTFs are not matched to those of the listener when the recordings are played back. This can lead to internalisation of the sound or an unrealistic sound image perceived by the listener, causing front-back errors. These errors can be reduced or removed by measuring an individual's HRTFs (a process that can be time consuming) and mathematically applying them to the signal (Wightman and Kistler 2005). The issues described above are affected by the size and shape of the participant's head, torso and pinnae. If the participant's shape closely matches the dummy then internalisation and front back errors will be minimised (Roginska et al. 2011).

One of the main problems with measurements of localisation accuracy using a virtual auditory space is the effect of participant head movement. When a human moves their head in the presence of a continuous sound, the origin of the source will appear to move in the opposite direction to the head. When a sound is presented to a participant over headphones the source moves together with their head and in the same direction. This phenomenon causes greater internalisation for virtual sounds and can lead to source identification errors if the participant does not remain still during the sound presentation (Brimijoin et al. 2013). The effect of head movement on localisation accuracy depends on the type of signal used. If a short duration signal is presented to the listener (for example a single click) then it is unlikely that a head movement will take place during the presentation time; forcing the participant to make a source identification judgement after the stimulus offset.

It is possible to reduce the effects of head movement by incorporating a head tracking system (Begault et al. 2001, Iwaya et al. 2003, Brimijoin et al. 2013). This system tracks the movement of the person using cameras or motion sensors and alters the virtual sound source location to stabilise the auditory space, stopping it from moving with the listener. Using a head tracking system has been shown to reduce localisation errors and increase externalisation by up to 50% for stimuli presented at 0º azimuth (Brimijoin et al. 2013). Whilst head tracking has been shown to be beneficial for virtual localisation experiments the majority of researchers advocating its use were investigating horizontal and vertical localisation accuracy using a long duration or speech stimulus in a 360º array (Wightman and Kistler 1989, Macpherson and Middlebrooks 2000, Simpson et al. 2005, Brimijoin et al. 2013). For studies that only utilise a 180º array of sources and short duration noise burst or click stimuli, the potential for front back errors is eliminated and the introduction of errors due to head movement is greatly reduced (Bronkhurst 1995)

A further consideration when measuring localisation accuracy using virtual sources is the type of HRTF that is applied to the signal. Using individual HRTFs, measured with in ear microphones, can result in participant accuracy scores that are equal those measured in a free field array (Bronkhurst 1995). However, personalised HRTFs are time consuming, invasive to measure and impractical if the localisation test is to be used for large numbers of participants (Zotkin et al. 2003). In this instance it is possible to use generic HRTFs by applying an average HRTF to the signal or by measuring the original sound using a dummy head with human proportions (such as Knowles Electronic Manikin for Acoustic Research, KEMAR). It is widely reported that using generic HRTFs increases localisation errors by a measurable amount and the extent of this increase has been thoroughly investigated (Wightman and Kistler 1989, Wenzel et al. 1993, Bronkhurst 1995, Moller et al. 1996, Begault et al. 2001 and Zotkin et al. 2003). A summary of studies comparing the use of individualised and non-individualised HRTFs is presented in table 4.1.

*Table 4.1 Overview of the literature investigating localisation accuracy for individualised and non-individualised HRTFs*

| Study | Type of HRTFs | Stimulus | Azimuth Error (MAE in degrees) | Knowledge contributions | Limitations of study |
|---|---|---|---|---|---|
| Wightman and Kistler (1989) | Individualised | Eight 250 ms bursts of Gaussian noise (20 ms cosine-squared onset-offset ramps), 300 ms silence between bursts | 17.9 Freefield, **21.5 virtual** (front, middle elevations). 16.1 freefield, **15.1 virtual** (side, middle elevations). | First study to compare free field with simulated stimuli. Found only subtle differences in performance for middle elevations, therefore, they were successful in creating simulated stimuli that could be localised well. Used 15 degree intervals in azimuth. | Surprisingly high azimuthal errors considering participants had approximately 10h training and individualised HRTFs were used.<br><br>Errors may have been introduced by the participant response system (naming co-ordinates may have been difficult for some) |
| Wenzel, Arruda, Kistler and Wightman (1993) | Non-individualised (based upon one 'average' participant from Wightman and Kistler 1989) | Same as Wightman and Kistler (1989) | Mean unsigned error – Does not report actual values (values taken from graph). Low elevations – 20 freefield, **22 virtual**. High elevations – 26 freefield, **29 virtual**. | Reports that there is significant variation between 'good' and 'bad' localisers.<br>For 'good' localisers, simulated stimuli using non-individualised HRTFs were comparable to free field results. | Does not give exact error values – values reported here are from figure 6 of the article.<br><br>Does not report information about the HRTFs used to create the headphone stimuli – or how closely this represented the participants' HRTFs. |
| Bronkhurst (1995) | Nonindividualised (HRTFs from other randomly selected participants were used) | Harmonic signal, fundamental frequency of 250 Hz and upper frequency from 4 to 15 kHz. Maximum presentation time of 15 sec. | 5 freefield and **5 virtual** for head pointing task during long duration stimulus.<br><br>Error rates not reported for short duration stimulus but 'percentage of confusions increased from 21% to 41% from free field to simulated' | The first study to implement head tracking to allow head movements.<br><br>The authors conclude that non-individualised performance is variable and 'mostly poorer' than individualised. | Very low error rates observed as participants were able to move their head until 'centred' on the source location, making the task considerably easier.<br><br>The use of other participants' HRTFs meant that no 'average' HRTF data was used and this makes it difficult to draw conclusions from the data. The small sample size may have meant that, by chance, the HRTFs were very similar amongst the group. |

| | | | | | |
|---|---|---|---|---|---|
| Moller, Sorenson, Jensen and Hammershoi (1996) | Individualised and non-individualised (HRTFs chosen from another participant at random) | 5 sec speech stimulus | Azimuthal error not reported. Errors increased from 15.5% incorrect for individual HRTFs to 33.8% incorrect for non-individual | Shown that there is a significant increase in error rates for non-individualised HRTFs compared with individually measured. | By using another participants HRTF data the authors have increased the variability of error scores (it is difficult to compare scores between individuals – some may have HRTFs that match their new HRTFs whereas others could differ greatly). No azimuthal data is reported, stopping any meaningful comparison between this study and others. |
| Begault, Wenzel and Anderson (2001) | Individualised and non-individualised (based on KEMAR measurements packaged as a room modelling software, by the University of Aachen – no further details provided) | 3 sec segments of speech stimuli presented at 60 dB(A) – no further details provided | Significant effect of HRTF found. Despite this, the difference observed between individualised and generic was very small (individual MAE – 20, **KEMAR – 22.5**) | It appears that when participant head movements are tracked accurately throughout it is possible to perform with similar levels of accuracy regardless of the HRTFs used.<br>The authors note that head tracking was particularly important when using a stimulus with a longer duration. | The article lacks detail with regards to the method of stimulus creation and the generic HRTFs used.<br><br>The effect sizes have not been reported and it can be assumed with a small sample size (n=9) that the significant difference found may not necessarily be true of the wider population. |
| Zotkin, Hwang, Duraiswami and Davis (2003) | Individualised, personalised and non-individualised (from KEMAR, CIPIC database, small pinnae). | 3 white noise bursts – 93 ms in length with 93 ms pauses in between. | MAE =Individualised – 13.8, **KEMAR – 16.06**<br><br>RMS = Individualised – 17.91, **KEMAR – 19.62** | All conditions used a head tracker. This study demonstrates (similar to Begault et al. 2001) that there are small but measurable differences between localisation accuracy using generic and individualised HRTFs. | Similar to Begault et al. (2001), Zotkin et al. had a small sample size (n=8) but did report the methods in detail including the method for HRTF personalisation. Two subjects showed no improvement with measured HRTFs and the authors stated no significant difference between individual and KEMAR HRTFs when head movement was compensated for. |

As shown in table 4.1 there is a consistent deterioration in localisation accuracy when virtual localisation methods are used (compared with freefield) and a further deterioration when non-individualised HRTFs are utilised to create the virtual sound sources. The increase in error scores from freefield to virtual sources is between 1 and 4º azimuth and an extra 2 to 3º of error is added when generic HRTFs were used. Whilst this difference is consistent and was statistically significant in one instance, it is only a very small increase in error between a freefield paradigm and virtual sources created using non-individualised HRTFs.

The wide range of methods and the differing statistical tools used to analyse data made it almost impossible to compare the findings of the individual studies in table 4.1.

### 4.3.2 Analysing localisation judgements

Previous localisation studies in the wider literature use a variety of differing performance measures (Lorenzi et al. 1999, Noble et al. 1994, Bogaert et al. 2006, Majdak et al. 2011). Assuming that participant responses have a normal distribution, the mean and standard deviation (SD) can be used to describe the data set. Ideally the mean response would correspond to the actual source location; however, any bias in responses may result in a difference between the mean response and actual source; this is described as a constant error. The second main type of error to consider when measuring localisation ability is called random error (RE). This is a descriptor for the variability in listener perception and changes in listening conditions; or in other words the precision of participant responses. Figure 4.4 demonstrates the concepts of constant error (accuracy) and RE (precision).

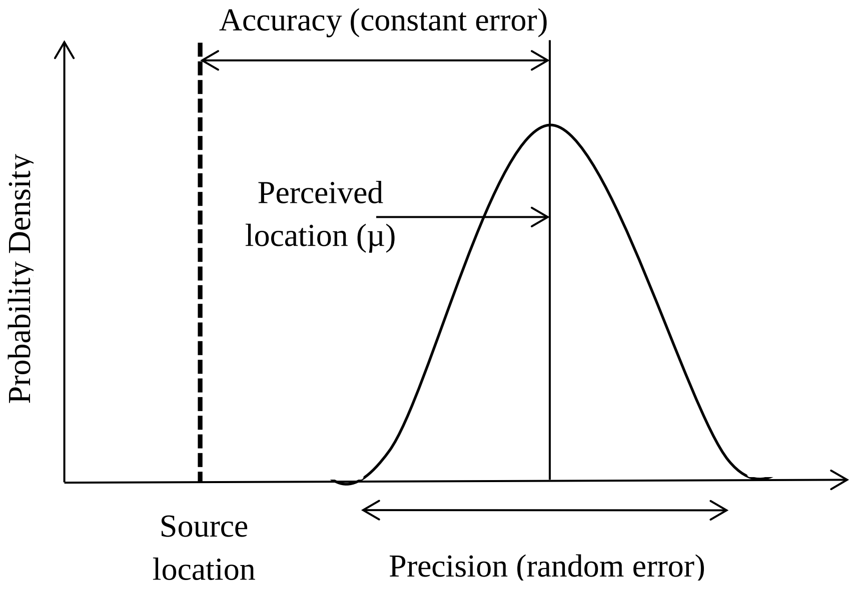


*Figure 4.4 Concepts of random error and constant error in localisation judgements*

The Mean Absolute Error (MAE) is commonly used in the localisation literature as it represents constant error (Letowski and Letowski 2011). In accordance with the literature, the absolute error is calculated as the difference between the participant's response and the correct source location (perceived vs actual location). To determine the MAE for a particular azimuth, mean error is calculated from all of the presentations at that azimuth. Additionally, to create a single MAE value for each stimulus condition, all azimuth MAE values are summed and divided by the total number of source locations. It is worth noting that in some publications the MAE is referred to as the Mean Absolute Deviation or the Mean Unsigned Error.

For the purpose of this thesis, MAE is defined as:

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|x_i - \eta|$$

The second commonly used measure of localisation error is the Root Mean Square (RMS) error. Calculated as the square root of the average squared error, this incorporates RE and constant error to give a single figure estimation of total localisation error. There are divided opinions as to whether MAE or RMS best characterises localisation error.

Letowski and Letowski (2011, p67) criticize RMS as it includes the Mean error but is more difficult to interpret as it is influenced by the distribution of the squared errors. Hartmann (1983) stated that for the same reason RMS is the most meaningful single measure of localisation performance. Linear localisation statistics that use RMS values are able to highlight differences in the patterns of participant responses. Two listeners may have identical MAE scores for a particular stimulus but one listener may have been biased towards the central source locations and the second may have been biased towards the end source locations in the frontal horizontal plane (-90 and 90°). To understand localising behaviours in humans, it is important to analyse bias (a tendency to localise centrally/laterally or towards the left/right) as well as constant error (absolute error towards the left or right). The RMS allows differences in bias to be highlighted but does not provide evidence about the nature of the bias. Further measurements are required to compare patterns of localisation error between conditions.

For the purpose of this thesis, RMS error is defined as:

$$\text{RMS error} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \eta)^2}$$

The SD is the simplest measure of variation in responses. It is a measure of RE and represents the range of variability around the mean; 2/3 of responses fall within ± 1 SD. A large SD value indicates that participant responses were not closely clustered around the mean and that there was more variability in responses. This measure is useful as it shows whether the mean value is a good representation of the data points.

The constant error (E) (referred to as signed constant error) shows the degree of consistent directional bias (Hartmann 1983). If a listener consistently picks a source location 15º to the right of the actual source location, E would equal +15º. Likewise if they consistently perceive the source location to be 10º to the left of the actual source, E would equal -10º. This is an important measure when assessing the spatial fidelity of recordings in virtual localisation systems; if listeners all show a significant deviation to the left or right, there may be errors in the binaural cues of the stimuli.

The final measure of localisation accuracy is the unsigned error or bias error (C). This represents the magnitude of errors irrespective of direction (Makous and Middlebrooks 1990). A large C value indicates that listeners were biased towards the lateral source locations or towards the centre; a value of zero would indicate the listener's responses were evenly distributed amongst the source locations. However, a low C score does not mean that the listenerguessed the source correctly every single time; if they randomly guessed the source location (giving a very large RMS and SD value) they would exhibit no lateral or central bias, appearing highly accurate.

It is also possible to determine localisation ability for areas of source locations. For example, if a soldier was walking clockwise around the perimeter of a dangerous area it may only be sounds from their right hand side that require accurate localisation. To assess their ability to perform this particular task it is not sensible to only present sounds from the right as this would be an easier task; instead, an array of sound sources could be used but only correct identifications of the right hand sources would be of interest. During the focus group investigation (chapter 3) personnel discussed the need to turn their bodies or heads to the left or right to search for a visual cue in some localisation scenarios. An individual's ability to correctly identify sources laterally can be presented as a percentage score of correct responses (lateral percent correct score or LPC) for specific sets of source locations to the left or right hand side.

For the purposes of this thesis, a range of accuracy measures will be reported throughout for ease of comparison with the wider literature.

## 4.4 Factors affecting localisation accuracy

### 4.4.1 Hearing impairment

Military personnel are at a high risk of NIHL (Yankaskas 2013, Abel 2005, Patil and Breeze 2011, Cox and Ford 1995, Muhr and Rosenhall 2011). Hearing impaired personnel may not be able to carry out job-specific auditory tasks, such as localising small arms firing points. As yet, the relationship between hearing loss and localisation ability has not yet been thoroughly investigated. The following section reviews the literature surrounding hearing loss and localisation ability.

Localisation is defined by Cook and Hickey (2003) as "the ability to gauge the direction and distance of a sound source outside the head" and in addition to this, some HCTs require the localisation of a sound source in background noise or require the individual to track a moving sound source. As described during the focus groups in chapter 3, infantry auditory tasks included tracking the sound of moving motorbikes and locating a talker in a background of engine noise.

**Early studies**

It is widely reported that hearing loss can adversely affect an individual's ability to localise a sound (Moore 2007, Lorenzi et al. 1999, Sabin et al. 2005, Abel and Hay 1996, Scharine and Letowski 2005). This relationship is not straightforward; localisation is affected by threshold asymmetry between the ears, the type of hearing loss as well as the degree of loss. Durlach et al. (1981) reviewed 14 studies of localisation and hearing impairment written between 1929 and 1975. In the very early studies (Bergman 1957, Greene 1929; both discussed in Durlach 1981) the focus was placed on the type of hearing loss; Greene compared an 'otologic' group, which appeared to be mainly middle ear disease with a 'neurologic group' (those with sensorineural impairment). The methods were rudimentary and participants were allowed to move their heads whilst determining the location of the sound source in the source array (it is now known that this increases an individual's ability to localise (Begault et al. 2001)). These basic studies did highlight the following key principles: (1) that the type of loss affects localisation ability; those participants with sensorineural losses performed better than those with conductive or mixed components and (2) even when a sound is clearly audible to those with sensorineural hearing loss, performance is still not equal to that of normal hearing listeners. The exact cause of this second observation is not clear. It is believed that the widely reported 'distortion' experienced by individuals with a sensorineural hearing impairment may explain some of the difficulty they experience even when the sound presented is suprathreshold (Plomp 1978, Tonning 1975). More recent studies have confirmed these findings in a more controlled environment under stricter test conditions (Noble et al. 1994, Abel and Hay 1996).

Durlach et al. (1981) reported from their systematic review that subjects with a unilateral hearing loss tended to perform poorly on localisation tasks. An early study by Viehweg and Campbell (1960) investigated the effects of unilateral hearing loss using an eight loudspeaker, 360 degree speech-signal localisation task. All participants had normal speech reception thresholds in the better ear and at least a 30 dB asymmetry between ears (at the audiometric frequencies tested, 0.5, 1, 2, 4 and 6 kHz). The authors reported five key observations: (1) unilaterally impaired listeners had a decreased ability to localise when compared to normal hearing listeners, (2) localisation was best on the side of the better ear and in front, (3) performance was worse for unilaterally impaired individuals with sensorineural deafness when compared to conductive losses, (4) high frequency loss in the better ear did not impair performance and (5) performance was independent of whether the loss was acquired or congenital, suggesting that compensation for the deficit does not take place over time. These results contradict results from earlier studies and Durlach et al. suggested that observation (4) may be due to head movement (even though subjects were instructed to keep their head still). Observation (3) is also in disagreement with the results reported by Bergman (1957) and Greene (1929).

**Unilateral deafness**

Nordlund (1964) performed a free-field localisation experiment in the horizontal plane on individuals with a variety of aural pathologies. He reported MAE and SD of responses. A participant's performance was judged to be abnormal overall if it was abnormal for at least one of the five conditions (500, 2000, 4000 Hz pure tones, low-pass noise and head fixed in low-pass noise). Percentage of abnormalities increased in the following order: vestibular lesions< cochlear lesions< brain lesions< cochlear and suspected central lesions< middle ear lesions< auditory nerve and pons legions< unilateral deafness. Only one of the participants with bilateral cochlear legions performed abnormally compared to 7% of unilateral (Nordlund 1964). The author reports no statistically significant correlation between measured audiometric thresholds and performance in the localisation conditions but this may have been due to the small number of repeats carried out for each condition resulting in large variability of responses.

Nordlund's findings are supported by the work carried out by Roser (1966) and Tonning (1975). However, the poor quality data presented in Tonning's study do not fully support the conclusions. Tonning (1975) states that unilateral deafness need not completely destroy localisation ability; it was found that whilst 65% of participants with a mild unilateral loss did not perform as well as normal hearing listeners, some were still able to localise to near normal levels but there was considerable variation between participants. Tonning also reports (without clear support from the data collected in this study of 80 hearing impaired participants) that neither the pure tone audiogram nor the duration of deafness can be used to predict the performance of an individual in a localisation task.

Whilst most of these early investigations report that unilateral hearing impairment is detrimental to localisation performance it remains unclear whether the deficit in performance can be correlated to the level of hearing loss or the degree of asymmetry (Durlach et al. 1981).

**Degree of hearing loss**

The effect of level of hearing is more difficult to quantify than the effect of unilateral loss and there are significant gaps in the literature regarding the ability to correlate an individual's audiogram with their localisation performance. There are very few studies that compare a participant's degree of hearing loss with performance on a horizontal localisation task in quiet and often the authors have not provided all the necessary information for direct comparison between experimental designs. Rosenhall (1985) performed audiometry on 50 participants and found that those with symmetrical bilateral sensorineural impairment of 40 dB HL or less showed normal directional hearing and those with thresholds greater than 40 dB HL at 500 Hz had abnormal directional hearing. Whilst the author does not speculate about the reasons for these abnormal results, they may be due to the participants' poor low frequency hearing levels and therefore lack of ITD cues (present at frequencies below 1.5 kHz). Unfortunately Rosenhall did not analyse the data collected in finer detail than the very broad categories described above and therefore it is not possible to draw any further conclusions other than low frequency hearing loss may have a detrimental effect on localisation performance due to loss of sensitivity to TFS.

Butler (1970) compared horizontal and vertical localisation performance between normal hearing listeners and those with a high frequency bilateral hearing impairment. It was found that impaired listeners performed virtually at chance levels for the vertical localisation task, yet were able to localise successfully in the horizontal plane. Participants with high frequency hearing impairment would have been less able to make use of spectral cues. This would have had a greater impact on their vertical localisation ability, where additional information from ITDs and ILDs would not have been available. These findings were in accordance with the theories of earlier researchers and led to further reviews of the literature comparing horizontal and vertical localisation performance. Butler and Humanski (1992) reported on the role of binaural cues as an aid to vertical plane localisation, suggesting that good binaural hearing is required for vertical localisation tasks. Nordlund (1964), Hawkins and Wightman (1980) and Durlach et al. (1981) all concluded that there is insufficient evidence to suggest that localisation ability in the horizontal or vertical plane can be predicted from the audiogram.

Studies published in the early 1990s aimed to redress the problem of predicting localisation performance from audiometric data. Proschel and Doring (1990, discussed in Noble et al. (1994) as unable to access paper in English) were the first to show a firm relationship between degree of hearing loss and horizontal localisation performance, using groups of hearing impaired individuals. They found a significant difference between groups, with normally hearing participants performing better than the mild impairment group (>20 <40 dB hearing threshold level (HTL) 0.25-6 kHz) and the mild group performing better than the group with HTLs greater than 40 dB.

Noble et al. (1994) set out to separate the effects of degree of hearing loss from the type of hearing loss and discuss theoretical reasons for the differences in performance observed. Eighty-seven bilaterally hearing impaired subjects were studied in the horizontal plane and vertical plane, laterally and frontally using a 20 speaker array. Noble et al. found that there were associations between vertical discrimination and high frequency hearing loss, and front-back discrimination with mid to high frequency loss. These observations (similar to those noted by Butler (1970)) are likely to be due to the lack of high frequency spectral cues available to the hearing impaired listeners. Whilst moderate correlations were observed between hearing loss configuration and performance level, the authors felt that the results were not conclusive enough to state that audiometric thresholds could be used to predict localisation performance. Noble et al. questioned the unexplained variance in their results; measurement error may well have played a part in this together with the variation found in normal populations. Although not examined directly, they speculate that attenuation may only contribute a small amount to the difficulties experienced by hearing impaired individuals (providing that the signal is still audible) and that other aspects of hearing loss (such as distortion – as reported by Plomp (1978)) may be to blame for this variation in localisation ability.

From the evidence reviewed above, it is difficult to draw any firm conclusions concerning an individual’s ability to localise a sound in relation to their hearing impairment. Only limited comparison can be made between investigations due to varying stimuli used, differences in hearing impairment categories and data processing. Even when aspects of the results can be compared, the findings often appear contradictory. All of the studies reviewed concluded that in general, localisation is degraded by unilateral impairment and bilateral asymmetry; that conductive impairment has a greater effect on performance than sensorineural impairment and that performance cannot be easily or accurately determined from audiometric data. Considering AFFD, the level of predictive accuracy needed from the audiogram would depend on the pass-fail criterion of the MCAT. If a task must be completed with a high level of accuracy, then a very good prediction of localisation ability would be needed to distinguish between personnel who were able to perform the task and those who were not. The evidence outlined above demonstrates that further studies are required to determine the impact of hearing impairment (and more specifically hearing impairment caused by exposure to high levels of noise) on generic localisation tasks. Advances in this area would help to determine the levels of hearing required for military personnel to be considered ‘fit for duty’, with regards to all localisation tasks encountered on operational duties.

### 4.4.2 Other characteristics of the listener

Beyond hearing impairment, there are other listener characteristics that may affect localisation accuracy.

**Age**

It is known that peripheral and central auditory function changes as a function of age, regardless of the level of hearing impairment measured by a pure tone audiogram. There are few studies discussing these changes in relation to localisation ability, but those that do provide a useful insight into an otherwise ‘hidden disability’.

Dobreva et al. (2011) tested 42 participants of varying age (20-81 years) on their ability to identify sound sources placed along the horizontal and vertical axis, 10º apart. A range of stimuli was used and they were all presented at a clearly audible level. The authors reported a significant decrease in localisation precision with increasing age for broadband, low pass and high pass noise; stating that this was consistent with peripheral and central auditory aging. Dobreva et al. used measures of accuracy and precision to show how the patterns of errors change with increasing age (greater variability in responses for older participants). The authors commented that these deteriorations in precision are likely to be due to changes in binaural cue processing in the brainstem and the decline in temporal acuity and high frequency sensitivity in older listeners. It is difficult to definitively conclude that the results were due to aging alone; all of the older adults had some level of hearing impairment and in some cases this was as much as an 80 dB HL deficit at high frequencies. To investigate the effects of increasing age without hearing impairment for elderly participants is difficult and therefore it was acceptable to use listeners with age-appropriate hearing levels. However, it is the young and middle-aged population that is of particular interest when investigating infantry auditory fitness and Dobreva et al. (2011) appear to show a significant deterioration in localisation precision between these groups.

Whilst there are very few studies investigating the direct effect of age (without hearing impairment) on localisation accuracy; it is possible to make hypotheses based upon studies assessing other auditory abilities as a function of age. Grose and Mamo (2010) found that sensitivity to binaural TFS (measured using an interaural phase difference discrimination task) decreased with increasing age for normal hearing listeners at 750 Hz and 1000 Hz. Interestingly no significant difference was found for the lowest frequency stimuli (250 and 500 Hz). Similar findings to Grose and Mamo (2010) have been reported by Helfer and Vargo (2009), Pichora-Fuller and Schneider (1992) and Strouse et al. (1998).

This decline in neural synchrony between young and middle-aged adults suggests that as age increases there may be changes in localisation accuracy or precision, particularly in the mid to high frequency range. It is therefore sensible to consider the possibility of age effects when measuring human localisation accuracy.

**Gender**

There is evidence of physiological and psychophysical differences in the auditory systems of men and women. In terms of localization, men have been shown to have slightly increased ability to discriminate small differences in ITD and ILD (McFadden 1998). Langford (1994) measured ITD and ILD discrimination and found that whilst males required on average 86 µs or 3.1 dB of difference, females required 113 µs or 4 dB. This difference was stable and significant, but only equates to a very small change in azimuth if applied to a real world listening task (approximately 1-2º azimuth). McFadden (1998) suggest that this may be due to the male auditory system being better able to more precisely compare the binaural signals in the auditory cortex.

**Handedness/Eye dominance**

Handedness and eye dominance are two of the most obvious cerebral functional asymmetries in humans. Left handers (and left eye dominants) are more likely to show right hemisphere superiority and this has been linked to significant differences between right and left handers for spatial processing tasks (Corballis 2003). It is believed that these differences arise, not from a perceived shift in sound source location, but from an inability to visually bisect a horizontal line (demonstrated by Bowers and Heilman 1980). Bowers and Heilman found that most listeners tended to have a leftward bias (consistent with the right hemisphere dominance observed for most of the population) but that this bias was shifted a relative distance to the right when the task was completed by lefthanders. The few studies discussing cerebral asymmetry and spatial perception are all in agreement that handedness influences the left/right bias of responses.

Ocklenburg et al. (2010) sought to discover whether this bias was also evident for auditory space perception tasks. Using a horizontal source identification task with 21 source locations from -80º left to 80º right they assessed the localisation accuracy of 33 right handers and 20 left handers. They found no significant differences in overall accuracy between left handers and right handers, but did find a significant difference in the signed constant error. Right handers showed a constant bias towards the left hand sources and left handers showed a similar bias towards the right. These observed differences were only significant when the response method was a hand point; no significant differences were found when a head pointing system was used (Ocklenburg et al. 2010). The authors stated the importance of choosing a response method for localisation experiments that does not introduce translational errors. Similar findings were reported by Dufour et al. (2007) during an auditory midline task where listeners had to adjust the level of two stimuli to make the perceived fused sound originate from the midsagittal plane.

Less conclusive results have been found for the effect of eye dominance (and other cerebral asymmetries such as foot dominance). Ocklenburg et al. (2010) found no effect of general lateral preference on localisation accuracy or bias; both right and left lateral preference showed a slight bias towards the left of the midline. Interestingly, during a neuroimaging study it was noticed that humans have right hemisphere superiority for auditory spatial processing (Fujiki et al. 2002) and this may explain the tendency for leftward bias in all listeners regardless of handedness or general lateral preference.

### 4.4.3 Characteristics of the signal

In everyday life it is rare for a human listener to need to locate the source of a simple, single noise burst or pure tone-type stimuli. Often ‘real life’ stimuli are complex and listeners are required to make a single judgement based upon more than one sound in difficult listening environments. Determining the source of small arms fire is one such task; infantry personnel described using the two sounds created by a single gunshot to detect the firing point (see chapter 3 for a more detailed explanation of the task) often in noisy or stressful environments. There is a wealth of evidence discussing the effect of stimulus type on localisation accuracy and precision; this section outlines the complications associated with locating a single source associated with multiple signals.

Whilst there are no studies investigating how the specific characteristics of a gunshot affect localisation accuracy, it is possible to use the wider literature to consider how a similar stimulus may be localised. It is known that a single gunshot is made of two sounds of different amplitude and origin (Beck 2011) similar to the acoustic signature created by a single source in a reverberant environment (the sound made by the supersonic projectile is not always audible, see page 86 for explanation). In the latter case the first sound heard by the listener would be the highest in amplitude and would be followed by a series of reflections or echoes that are lower in amplitude. For a gunshot the first sound (the crack made by the supersonic projectile) would similarly be the highest in amplitude, but it would not originate from the source. The second distinguishable sound (the muzzle blast) may be the most useful for localisation purposes as it comes from the weapon itself (Mallock 1908).

In order to identify a single source from multiple spatially separate stimuli a human listener must 'rank' the stimuli in terms of their importance. It is not yet clear exactly how these decisions are made in the auditory system (Blauert 1997) but there are some well documented perceptual phenomena that can explain spatial judgements in specific cases.

The precedence effect describes a binaural psychoacoustic effect, which aids in spatial decision making in reverberant environments. When the original sound is followed by a subsequent echo, separated by a sufficiently short time delay, the listener hears a single fused sound. The auditory system is able to suppress the location of the second wave-front and the perceived spatial location is then dominated by the first arriving sound (Hawley et al. 1999). The original stimuli and echo are only perceived as a single auditory event if the lag time between them is below 5 ms; the boundary between one fused sound and two perceptually separate sounds is called the echo threshold (Blauert 1997).

Locating a firing point may not take place in a reverberant area, but it is theoretically possible for the shockwave from the projectile to be perceptually fused with the muzzle blast. This would occur if the delay between shockwave and blast was less than 5 ms; only possible if the listener was placed < 25 m in front of the weapon (calculated from the gunshot measurements presented in chapter 5). Not only would this be a rare occurrence on operational duties, it would appear likely that, at this close proximity, visual cues would prove more useful to locate a firer. For the purpose of this thesis, only gunshots measured >50 m from the firer are used; it can therefore be assumed that the precedence effect does not influence the perceived spatial location of the firer.

Similarly to a stimulus and its echo in a reverberant environment, the first sound measured from a gunshot is significantly more intense than the second. At 50 ms from the firer the shockwave from the bullet can be as loud as 160 dB(C) (peak sound level) and the muzzle blast up to 140 dB(C) (Beck 2011). At this distance the sound levels experienced by an individual without hearing protection are far above those deemed to be safe (HSE 2006). It is likely that a listener would experience a TTS due to changes in the mechanical sensitivity of the outer hair cells from acoustic over-stimulation (Patuzzi 1998).

It is incredibly difficult to determine whether this TTS would have an impact on the spatial perception of the firing point. It is possible that the decrease in hearing sensitivity caused by the projectile shockwave could confound the individual’s ability to hear and subsequently localise the muzzle blast.

Ghasemi et al. (2012) conducted a study to investigate the impact of TTS on 40 military personnel in Tehran. Each participant was exposed to 20 rounds of ammunition at approximately 114 dB SPL and hearing thresholds were measured pre and post exposure. Ghasemi et al. found that 3 hours post exposure HTLs were elevated bilaterally for 40% of the cohort and 70% self-reported tinnitus symptoms. One participant suffered from a tympanic membrane perforation as a result of the study. This highly unethical research demonstrated that exposure to high levels of impulse noise is likely to affect hearing function for prolonged periods. TTS would be at its most severe immediately after the impulse noise, but the study did not measure participants hearing until 3 hours post exposure. Due to this, it is likely that the effect of the noise on the participants was even greater than reported.

The speed of TTS onset is difficult to measure, but is likely to be faster than the arrival of the muzzle blast due to its origin within the peripheral auditory system. The temporary disruption caused to the organ of Corti within the cochlea would be almost instantaneous; such is the speed of a waveform travelling through the auditory system (early auditory evoked potentials can be recorded < 10 ms from stimulus onset (Plourde 2006)).

Although Ghasemi et al. (2012) do not give any insight into the effect of TTS on the perception of subsequent sounds; it is likely that the shock of the first impulse paired with probable TTS and tinnitus would draw the listener's attention away from localising the second impulse sound even if it is still clearly audible.

## 4.5 Localisation in the military

### 4.5.1 Locating a small arms firing point

Locating a small arms firing point is the most frequently occurring and critical localisation task carried out by infantry personnel on operational duties abroad (Bevis et al. 2014, Semeraro et al. 2015).

The descriptor 'small arms' is used to describe any infantry weapon that can be carried by an individual soldier, including revolvers, pistols, carbines, rifles, shotguns, submachine guns, assault rifles and general-purpose machine guns. It does not include combat support weapons, heavy machine guns or mortars. This group of weapons is also characterised by the sound they create. The distinct sound is the result of two events: The bullet leaving the muzzle of the gun (thump) and the shockwave created by the bullet moving through the air (crack) (Sherwin and Gaston 2013). The critical angle of the ballistic supersonic crack sound is reported to be approximately 60˚ from the shooter to the left and the right of the target line for some small arms projectiles (Beck 2011). Due to this, the crack sound can only be heard if the listener is within this critical angle relevant to the target. If the shooter fires away from the listener, the crack will not be heard. Figure 4.5 demonstrates the waveform created by a rifle shot, showing the crack and thump sounds explained above.

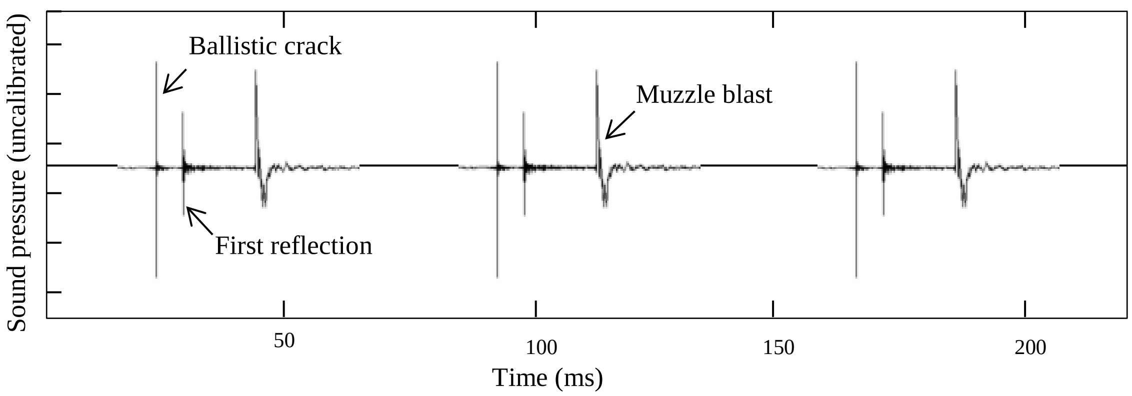


*Figure 4.5 Waveform showing three shots from an assault rifle with ballistic crack (caused by the supersonic bullet), the reflection of the crack from the ground and the muzzle blast.*

By locating the source of weapons fire, infantry personnel can greatly improve their situational awareness and operational effectiveness. This allows them to react appropriately to a combat situation, defend themselves efficiently and avoid potential 'friendly fire' situations (Fluitt et al. 2010).

Very little research has been conducted to date, to determine whether normal hearing humans are able to determine the origin of a gunshot. The literature in this area has been largely conducted by commercial enterprises interested in developing military equipment and has, so far, focussed on determining the effect of hearing protection on localisation ability or the development of automatic gunshot localisation equipment.

Over 100 years ago Mallock (1908) made a set of brave observations at a military firing range in England.

"*I noticed that when standing in a position in front of the gun and not far from the line of fire, the sound thus heard seemed to come, not from the firing point, but from some point considerably in advance of the gun"*

He explained that he believed this was due to the wave front of the projectile; a phenomenon not previously documented due to the slower projectile speeds of weapons before the 1900s. Mallock investigated (using his own, probably noise damaged, ears) whether this new sound could be localised by drawing an arrow towards the perceived firing point on a piece of paper next to him. He used these arrows to draw a map of the firing range and match his observations to the actual locations of the firers.

Whilst Mallock's method was somewhat rudimentary, he was able to locate firing points to within 'a few degrees of accuracy' and make some valuable observations about the way in which he felt this novel sound was perceived. He claims that the sound of the projectile caused confusion for the listener and when he was positioned close to the gun the difficulty in making localisation judgements increased due to the overlap of muzzle blast and projectile.

Since 1908, to the best of the author's knowledge only one study has been conducted to investigate human localisation ability using a small arms gunshot. Talcott et al. (2012) aimed to determine the impact of four hearing protection devices on localisation accuracy of blank cartridges fired in an open area with and without the addition of 82 dB A military vehicle noise. The study consisted of 13 participants (nine normal hearing, four with bilateral, mild to moderate, high frequency, sensorineural hearing loss) with varying levels of experience of firearms. The study was conducted on a large shooting range with the participant placed in the centre of a clearing surrounded by 16 numbered target signs at 22.5˚ of separation. Blank cartridges were fired from a pistol 150 ft away from behind eight of the target signs, with the participant selecting a number that corresponded to the perceived location of the shooter. This was then repeated with the introduction of engine noise presented through a loudspeaker adjacent to the participant.

Talcott et al. found that hearing protection devices decreased localisation ability in most conditions. The MAE and percentage of correct responses for the open ear condition were 22º (± 14º) and 55% respectively. The statistics reported for the open ear condition are the results from the normal hearing and hearing impaired participants combined. The authors did not separate the two groups for the main analyses. There was no significant effect of background noise.

Somewhat surprisingly, the introduction of background noise did not significantly change localisation performance with or without hearing protection (when averaged across all five conditions) and hearing impaired listeners did not perform significantly worse than normal hearing listeners (although the figures to suggest this are not reported in the paper). The results do not agree with the literature written about hearing impairment and localisation ability (see section 4.4.1) but this may have been due to the experimental design. The authors admitted that the small number of hearing impaired participants and their varied audiometric configurations make this result difficult to interpret in a meaningful way. It is also likely that the participants' varied military and firearm experience levels may have influenced their localisation ability as the study did show some learning effects. Further to this, there were a very small number of trials for each listening condition (n=16) causing the relative impact of a single incorrect response to increase.

It would have been beneficial for the study to incorporate another stimulus that had been more widely discussed in the literature. Using only a gunshot sound stops the reader forming conclusions about the effect of the stimulus itself.

Despite the limitations in the methodology, the study did highlight that human listeners may not be highly skilled at localising a gunshot from the muzzle blast alone and that certain types of hearing protection may affect localisation accuracy. Talcott et al. (2012) called for more research to be carried out to determine the associations between impaired hearing (whether due to hearing loss or hearing protection devices) and localisation of gunshot sounds to ultimately create hearing protection devices that are able to replicate or even enhance normal hearing. It is also important to consider that the sound made by the weapon (fired at the listener) in this study is not truly representative of infantry operational duties as the ammunition was blank. If live ammunition had been used, the stimulus would contain the supersonic shockwave as well as the muzzle blast.

Whilst Talcott et al. (2012) are currently the only researchers to investigate localisation accuracy using a small arm stimulus specifically, there are other studies in the wider literature that are able to provide peripheral information about this subject and can be used to inform hypotheses.

Simpson et al. (2005) conducted an earlier study concerning localisation using auditory and visual stimuli to determine the effect of hearing protection devices on localisation accuracy. Seven normal hearing participants took part in a visual search task stood within a 4.3 metre geodesic sphere surrounded by 277 loudspeakers. Each loudspeaker was attached to a cluster of 4 LEDs. A visual ‘target’ was defined as two or four lit LEDs, whereas a visual ‘distractor’ had one or three lit. The auditory stimulus used was a continuous broadband pink noise, presented at 30-35 dB sensation level (with hearing protection), at the location of the visual target. Five listening conditions were tested; unoccluded, no auditory cue, earplugs, ear defenders and ear defenders plus earplugs. Participants were able to localise very well in all conditions (94-99% correct). However, search time increased dramatically in the double hearing protection and no auditory cue conditions. In accordance with the speed of response, head movement also increased in the double hearing protection and no auditory cue conditions. There was no significant difference between the speeds of response or amount of head movement for the unoccluded, earplug and earmuff conditions. The increased head movement and slow response times indicate that participants are relying heavily (or entirely) on the visual stimulus, instead of using the auditory stimulus to locate the target LEDs. It would be of interest to repeat this experiment using a gunshot stimulus, as the low amplitude broadband stimulus is not ecologically representative of a military auditory task and the long duration allowed participants to use head movements to increase localisation accuracy.

Whilst the present research is concerned with the effect of hearing loss on localisation ability in a military context (not investigating the relationship between hearing protection and localisation ability), it seems likely that hearing impaired listeners would perform similarly to those wearing hearing protection or double hearing protection, depending on the level of their hearing loss. An increase in reaction time and the need to search for visual confirmation of a sound source could be costly for hearing impaired personnel in a combat situation. According to the anecdotal evidence collected from infantry personnel during the focus group study, every second wasted in a combat situation is likely to decrease survivability and lethality.

Beyond the scope of the current research, the localisation abilities of those using hearing protection is of continuing interest to the MoD; the ultimate aim is to develop hearing protection devices that preserve natural human situational awareness and localisation performance. Research in the field of hearing protection is often a catalyst for further localisation studies using important military stimuli.

Whilst not specifically investigating localisation accuracy, Sherwin and Gaston (2013) conducted a study using electroencephalography to determine the brain regions involved in the rapid decision making process that military personnel face when detecting and reacting to small arms fire. They aimed to contribute to the limited behavioural literature for the perception of small arms firing events. Sherwin and Gaston (2013) used 11 participants all with extensive military experience and recorded two audio stimulus using an M4 carbine. Recordings were made at microphone locations 16 m directly in front of the shooter and 16 m perpendicular to the shooter. This set of stimuli was used to simulate two conditions: 1) the participants being ‘shot at’ and in this condition the acoustic ‘crack’ is present (as though being attacked by the enemy) and 2) the shot was fired away from the participant and did not contain the crack sound. The second condition was used to simulate a ‘friendly fire’ situation (see figure 4.6 for experiment design).

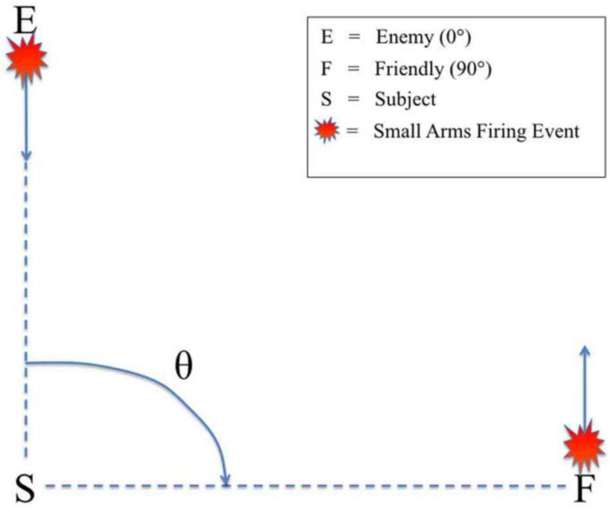


*Figure 4.6 Experiment diagram demonstrating the virtual environment that participants were asked to imagine. Enemy shots sounded as though they were fired towards the subject (from E towards S), and friendly shots appeared to be fired from 90˚ right and the bullet trajectory was away from the subject (from F, away from S) (Reproduced with permission, Sherwin and Gaston 2013).*

The stimuli were presented via two loudspeakers placed in front and to the side of the participant. Overall accuracy was determined to be 93% and 94% for 0˚ events and 90˚ events respectively. The authors found that specific neural markers are used for determining the location of the sound source and that neural activity increased leading up to the decision making process, suggesting that participants use an evidence gathering process to determine location. This study also found that there was activation in the Brodmann area of the brain (associated with visual processing) during the decision making process, signifying that participants might have mapped the auditory stimuli visually in order to localise accurately. Sherwin and Gaston (2013) speculate that this may be due to the experience level of the listeners and propose that a novice population may be less able to utilise this spatial mapping process due to their lack of 'real world' firearms experience. However without conducting further research in this area this proposed relationship cannot be determined.

This study raises interesting questions regarding the effects of experience and the use of visual memories to aid the localisation of a small arms firing event. However, the low error rates may not have been a result of the participant utilising ITD and ILD cues and may instead have been due to pitch or level differences between the two recorded stimuli. The 'friendly' stimuli were always presented from 90˚ and 'enemy' from 0˚ so the participant may simply have listened for the lack of the ballistic crack within the stimulus to aid their response. This experiment is a two alternative forced choice task using different, easily audible stimuli, spatially separated by 90˚; it is therefore surprising that participants did not perform better than the 93-94% accuracy observed. Sherwin and Gaston (2013) do not discuss the reasons for less than perfect performance.

There are currently no localisation studies using recordings of gunfire with live ammunition (only blank ammunition). The acoustic signature of live ammunition contains an additional sound from the bullet as it passes through the air at supersonic speed. It is also known that the muzzle blast waveform from blank rounds is different from the muzzle blast waveform from live rounds due to the amount of gunpowder contained within the cartridge (Mazerolle et al. 1999). For these reasons, there may be limited generalizability from localisation experiments using blank gunfire stimuli.

## 4.6 Summary and knowledge gaps

### 4.6.1 Summary

Humans are able to use monaural and binaural cues to locate sound sources in the horizontal plane. This ability is affected by both the characteristics of the listener and the signal. With regards to listener characteristics, hearing impairment has the greatest impact on accuracy; conductive hearing losses and asymmetrical sensorineural impairments have a significant effect on accuracy and precision of localisation judgements. Symmetrical sensorineural hearing losses have been shown to affect localisation but the literature surrounding this interaction is not comprehensive or conclusive.

None of the currently available measurement methods are perfect for measuring human localisation accuracy. However, the advantages of a more portable system that does not involve measuring individual HRTFs and maintains the complex auditory cues within the stimuli far outweighs the disadvantage of slightly increased error scores. For these reasons a virtual localisation paradigm using non-individualised HRTFs was used throughout this body of work to assess localisation performance.

Human localisation of gunshot stimuli is a relatively untouched area of research. Only one (underpowered) study exists to quantify human localisation accuracy using a gunshot stimulus and this used blank ammunition. Further investigation into the mechanisms of localisation for live gunshot stimuli is required to determine whether military personnel (with or without a hearing impairment) are able to perform the task. Without this information it is not possible to ascertain whether a test of localisation is needed as part of an auditory fitness test battery.

### 4.6.2 Knowledge gaps

From the studies discussed in section 4.5.1, and the wider localisation literature, it is clear that research determining localisation accuracy with small arms stimuli is scarce and incredibly varied. In addition to the knowledge gap identified in chapter 2 and addressed in chapter 3, two main knowledge gaps remain:

- **For a 'live' small arms gunshot, the localisation accuracy of normal hearing listeners is not known.**

Talcott et al. (2012) reported that normal hearing military personnel were able to correctly identify the source of gunfire out of 8 potential source locations 55% of the time - a relatively basic measure of accuracy compared with other generic localisation experiments. Further research is required to determine the level of accuracy in greater detail to reflect the level of skill required by infantry personnel when detecting and neutralising an enemy threat. According to subject matter experts at the Infantry Training Defence Unit (Warminster), infantry personnel use a clock face grid system (12 markers, 30˚ apart) to pin point and communicate the location of an enemy threat. Normal hearing humans are able to accurately localise to within 30º of the target using a transient stimulus such as a click, virtual localisation paradigm and non-individualised HRTFs (Wenzel et al. 1993, Wightman and Kistler 1989, Begault et al. 2001, Zotkin et al. 2003).

**Research question:** How accurately are normal hearing humans able to localise a small arms gunshot?

**Hypothesis:** Ability to localise small arms gunfire will be similar to other transient stimuli such as clicks and noise bursts (between 16º and 29º RMS error) measured using a virtual localisation paradigm and non-individualised HRTFs.

- **It is not known whether there is a relationship between an individual's audiometric thresholds and their ability to localise a small arms gunshot**

The number of hearing impaired participants in Talcott et al.'s (2012) study was too small, and the configurations of hearing loss too varied, to determine the effect of hearing impairment on localisation performance. A larger study with clear and defined groups of hearing impaired subjects is needed to determine the relationship (if any) between hearing impairment and localisation accuracy of small arms gunfire.

**Research Question:** How does hearing impairment (specifically NIHL) impact localisation accuracy using a small arms stimulus?

**Hypothesis:** There is a relationship between degree of hearing loss and localisation accuracy. Individuals with a mild sensorineural symmetrical hearing impairment (20 – 40 dB HL hearing thresholds) may only show a small reduction in accuracy. However, those with greater symmetrical hearing impairment (>40 dB HL) will show a significant reduction in localisation accuracy as shown by Proschel and Doring (1990) and Rosenhall (1985).

# Chapter 5: Recording live small arms gunfire

## 5.1 Introduction

There is a wide body of literature on the acoustic nature of projectiles that travel at supersonic speeds and their resulting shockwaves (Snow 1967, Maher and Shaw 2008). Despite this, the challenge of capturing and analysing the extraordinarily fast rise times, the high sound pressure levels and the very short duration of the acoustic signature is still present, even with modern equipment.

In order to measure localisation accuracy among military and civilian cohorts it was necessary to create a set of high quality audio recordings of small arms fire under controlled conditions. This chapter describes how the recordings were created and a detailed analysis of their acoustic properties in terms of amplitude, frequency content and binaural characteristics.

## 5.2 Recording details

Binaural recordings of SA80 gunfire were created over two days (13.01.14 and 12.03.14) at an outdoor firing range at the Infantry Training and Defence Unit (ITDU), Warminster, using a KEMAR. The author also made recordings using a Soundfield ST450 surround microphone 1.5 m to the right of KEMAR and at ear height. KEMAR and the Soundfield microphone were positioned downrange from the firer by 50, 100, 200 and 300 m (see figure 5.1 for recording set up).

In order to make the most of this measurement opportunity, Mike Lower (ISVR consulting) measured sound pressure levels and made recordings downrange (alongside and to the left of KEMAR) using a B&K 2250 sound level meter. Gurmail Paddan (INM, Gosport), together with Mike Lower, measured sound levels and made recordings at positions to the firers left which, in a battlefield environment, may be occupied by other firers.

The binaural recordings were of greatest interest for the purposes of this thesis, but the omnidirectional recordings created to the side of KEMAR provided a useful point of reference and so are also documented in this chapter. Some analysis of the omnidirectional recordings was carried out by Mike Lower and this is acknowledged where appropriate.

The Soundfield microphone recordings and the omnidirectional recordings made to the side of the firer were not used for any experimental work reported in this thesis and therefore are not described further here, but are detailed in Lower et al. (under review).

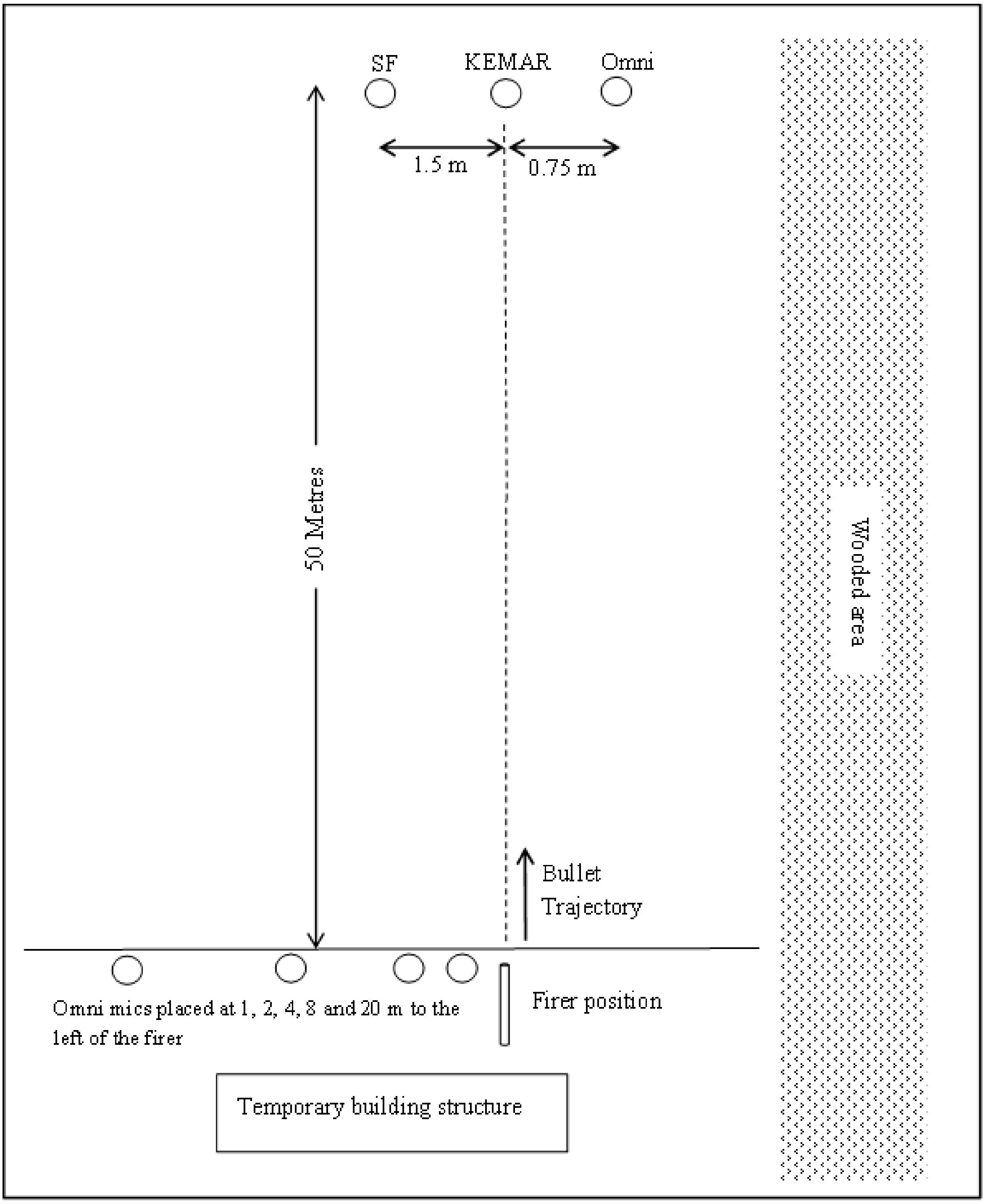


*Figure 5.1 Diagram to show positions of microphones in relation to firer and bullet trajectory at ITDU for the 50 m downrange recordings. SF- Soundfield microphone, Omni- B&K 2250 sound level meter.*

### 5.2.1 Weapon

An SA80 automatic assault rifle, 5.56 mm calibre, was fired manually (individual shots) by a uniformed member of the armed forces. The ammunition used was a NATO 5.56 x 45 mm standard shell. This particular weapon was chosen as it has been the standard issue rifle for the army since the 1980s and will be in continued use for at least a further 5 years (personal communication with Simon Archer, ITDU, 12.12.13). It was fired from a prone position on a raised platform (approximately 0.5 m above ground level). The firing position was approximately latitude 51.228610°, longitude -2.155515°. The firer aimed 30 cm above KEMAR, in line with the centre of its head. The firer was accurate to ±6 cm, measured when the weapon was calibrated using a target at 100 m.

### 5.2.2 Environment

The firing range was on predominantly flat ground with short grass. The conditions in January and March were mild (8ºC and 15ºC respectively) with little wind (light breeze of <3 m/s NW in March). Measurements were stopped on the 13.01.14 due to heavy rain in the afternoon and measurements could not be taken until fog had cleared at 1pm on the 12.03.14.

### 5.2.3 Binaural measurements

The G.R.A.S. KEMAR head and torso simulator was fitted with G.R.A.S. IEC 711 RA0045 ear simulators (including 40AG ½” microphones). These were connected via a G.R.A.S. 12AK 1-channel power module and RME Babyface 22-Channel soundcard to a Dell laptop running Adobe Audition (v3.0). KEMAR had been calibrated by a DANAK accredited laboratory within 3 months prior to the recording dates. All equipment was powered using a car battery and suitable power adapter.

KEMAR was placed on a turntable at 50, 100, 200 and 300 m down range from the firer. Including the turntable, KEMAR ‘stood’ at 175cm tall (measured from the ground to the top of its head), in concurrence with the average height of a man in the UK (British Broadcasting Corporation, 2010). The turntable was operated using the laptop and a Matrix Laboratory (MATLAB) programme written by Ferdinando Olivieri and adapted for this purpose by the author. Unfortunately the MATLAB programme for the turntable failed to operate correctly during the March recording day, causing the turntable to be manually operated for the recordings at 100, 200 and 300 m.When the turntable was used at the 50 m distance it was difficult to observe whether the automatic movements were correct and there was a concern that the final two 15º turns were not completed correctly (this is discussed in further detail on page 139). A total of 48 shots were recorded at each distance downrange; two shots per 15º turn of KEMAR.

Recording using KEMAR placed this close to the bullet trajectory created a number of challenges. The first was the peak pressure level. At a rough approximation the peak level at KEMARs eardrum microphones was in the region of 165 dB SPL, or approximately 3500 Pa peak pressure, with about 44 volts peak signal output assuming a sensitivity of 12.5 mV/Pa. The G.R.A.S. specification gives the upper limit of the microphones as 160 dB SPL for 3% distortion and as a result the initial test recordings were clipped and distorted. With the 12 AA power unit set at -20 dB (bringing the voltage peak down to 4.4 at the Bayonet Neill-Concelman connectors) we were able to record without clipping or noticeable distortion.

### 5.2.4 Omnidirectional measurements

Mike Lower used a Brüel & Kjær (B&K) type 2250 hand held analyser with a B&K 4938 “quarter-inch” pressure microphone to create the omnidirectional recordings to the side of KEMAR at 50, 100, 200 and 300 m downrange from the firer. The microphone and preamplifier were mounted on a tripod. The microphone was approximately 75 cm to the right of KEMAR and placed at ear height.

The microphone was fitted with a B&K foam wind screen. The calibration of the B&K 2250 meter and B&K 4231 sound level calibrator are traceable to a DANAK accredited laboratory. The B&K 4938 microphone was calibrated in house by ISVR Consulting. Forty-eight rounds were recorded at 50 m and 100 m downrange, while 26 rounds were recorded at 200 m and 300 m.

All recording equipment (KEMAR and omnidirectional microphone) was set to generate ‘wav’ files with 24 bit resolution and 48 kHz sampling rate.

### 5.2.5 Analysis techniques

**Analysis of general characteristics**

Frequency analysis was conducted and waveforms were synthesised using MATLAB.

All recordings were analysed using Adobe Audition 3.0 and MATLAB. C-weighted peak levels were obtained for the omnidirectional recordings by replaying individual gunshots through a Digital Audio Labs 'CardDeluxe' sound card into the line input of the B&K 2250 analyser. The C-weighted peak sound levels were measured for each individual gunshot, including crack and thump portions. The peak amplitude analyses of the omnidirectional recordings were conducted by Mike Lower.

In addition to the sound levels, the elapsed time between the peak of the initial shockwave of the bullet and the peak of the muzzle blast was determined for each shot at each distance by selecting and highlighting the time period in Adobe Audition and reading off the selected time to the nearest millisecond.

**Analysis of binaural measurements**

The binaural characteristics of the gunshots were determined to give an indication of the localisation cues that may be available to a human listener. Interaural time differences and ILDs were calculated for all binaurally recorded gunshots at 50 m and 100 m using a custom MATLAB programme. As no calibration tone was recorded using KEMAR during the recording days, the peak sound levels reported in section 5.4.2 are from the 50 m downrange omnidirectional recordings. The sound levels at KEMAR's eardrums (the placement of the microphones) would have been higher due to the closer proximity to the bullet shockwave and the natural resonance of the ear canal (closely matched by KEMAR's microphone couplers).

## 5.3 Analysis of gunshot recordings

### 5.3.1 Overview of gunshot characteristics

In a study conducted by Sherwin and Gaston (2013) recordings were created using omnidirectional microphones placed directly under the bullet trajectory of an M4 carbine weapon. The microphone placement was unusual (the majority of previous literature in this field create and use recordings off to the side of the bullet trajectory) and therefore provided a good set of comparison data to confirm the gunshot characteristics observed in the current set of recordings. Figure 5.2 (Sherwin and Gaston 2013) shows a burst of two small arms shots recorded 16 m from the firer.

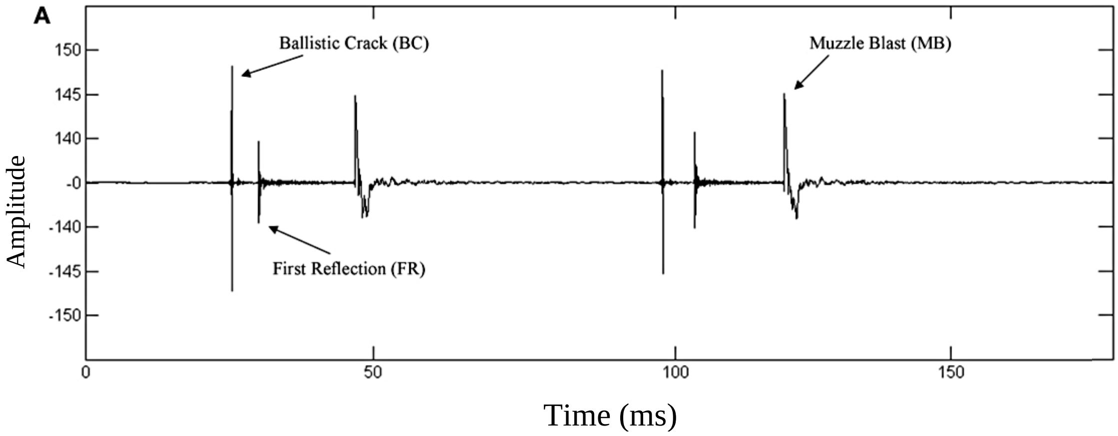


*Figure 5.2 A two round burst of fire from an M4 carbine (a type of small arms weapon) recorded under the bullet trajectory and 16 m from the firer (reproduced with permission, Sherwin and Gaston 2013). The term muzzle blast is referred to as thump in this thesis.*

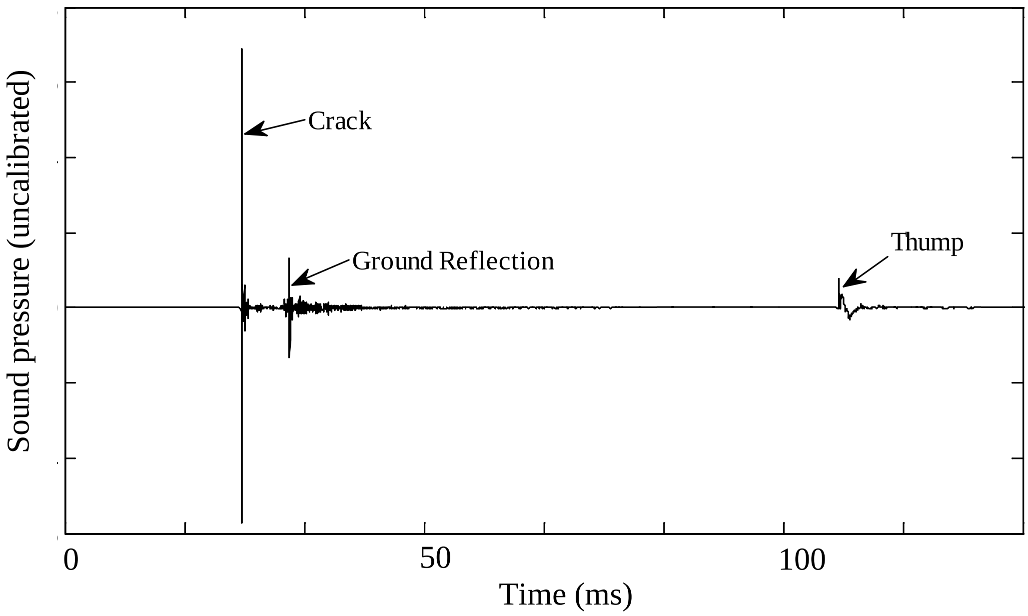


*Figure 5.3 Example waveform of an SA80 gunshot showing the ballistic shockwave (crack), ground reflection from the shockwave and the muzzle blast (thump), measured at 50 m downrange with an omnidirectional microphone.*

In a waveform taken from the current set of recordings, a very similar pattern of peaks can be seen. Figure 5.3 shows an example of a waveform recorded at 50 m downrange. The two components of the gunshot can clearly be seen in figure 5.2 and 5.3; the supersonic ballistic shockwave (crack) from the bullet and the muzzle blast (thump) following.

The ground reflection (called 'first reflection' in Sherwin and Gaston 2013) was measured approximately 80 ms after the crack in both recordings indicating that the height of the microphones was similar in both recordings. There are two main differences between the waveforms in figure 5.2 and 5.3. The first is the amplitude of crack and thump; Sherwin and Gaston measured the crack and thump to have similar amplitudes, whereas in figure 5.3 the thump is relatively much quieter. This is due to the distance between microphone and firer (50 m in figure 5.3 and 16 m in figure 5.2). The supersonic speed of the bullet allows the peak amplitude of the crack to remain constant over a greater distance, whereas the amplitude of the thump decays rapidly over distance (Beck et al. 2011). The evidence for this phenomenon is presented in section 5.4.2.

The second difference between the two waveforms is the time delay between crack and thump; the delay is 20 ms in figure 5.2 increasing to 94 ms in figure 5.3. This is likely to be due to the distance between microphone and firer: an increase in distance downrange causes an increase in delay between crack and thump. The atmospheric conditions and projectile speed (approximately 940 m/s for an SA80 rifle) may also have played a part in the differing lag time (Snow 1967).

Crack and thump are entirely different in terms of their resulting waveforms and frequency characteristics. Beck et al. (2011) have extensively analysed and modelled the behaviour of both crack and thump with varying firearms to create general mathematical principles that can be used by forensic and military communities. The authors place greater emphasis on the importance of the thump sound as it can be heard no matter what angle the microphone is placed in relation to the firer (see section 5.4.3 for further explanation of this). Beck et al. (2011) describe the muzzle blast as an 'explosive shockwave produced by propellant gases under extremely high pressure that expand rapidly as the bullet exits the muzzle'. The muzzle blast causes an almost instant rise in pressure followed by decay from peak to partial vacuum and back to ambient pressure levels. This results in a waveform (figure 5.4) that has a rise time of less than a microsecond (as measured by high speed recording systems, but not normally captured by audio recording systems due to the front-end low-pass filter response (Maher and Shaw 2008)). The fast rise time (at 4.5 ms) and negative phase duration (6 - 8 ms) can be seen in figure 5.4.

Beck et al. (2011) noted that, ideally, the phase of negative duration would return smoothly to an ambient pressure level, but that this is not the case in recordings of live gunfire. As can be seen in figure 5.4 the pressure oscillates for some time after the shockwave due to turbulence, inertia and aftershocks (Beck et al. 2011).

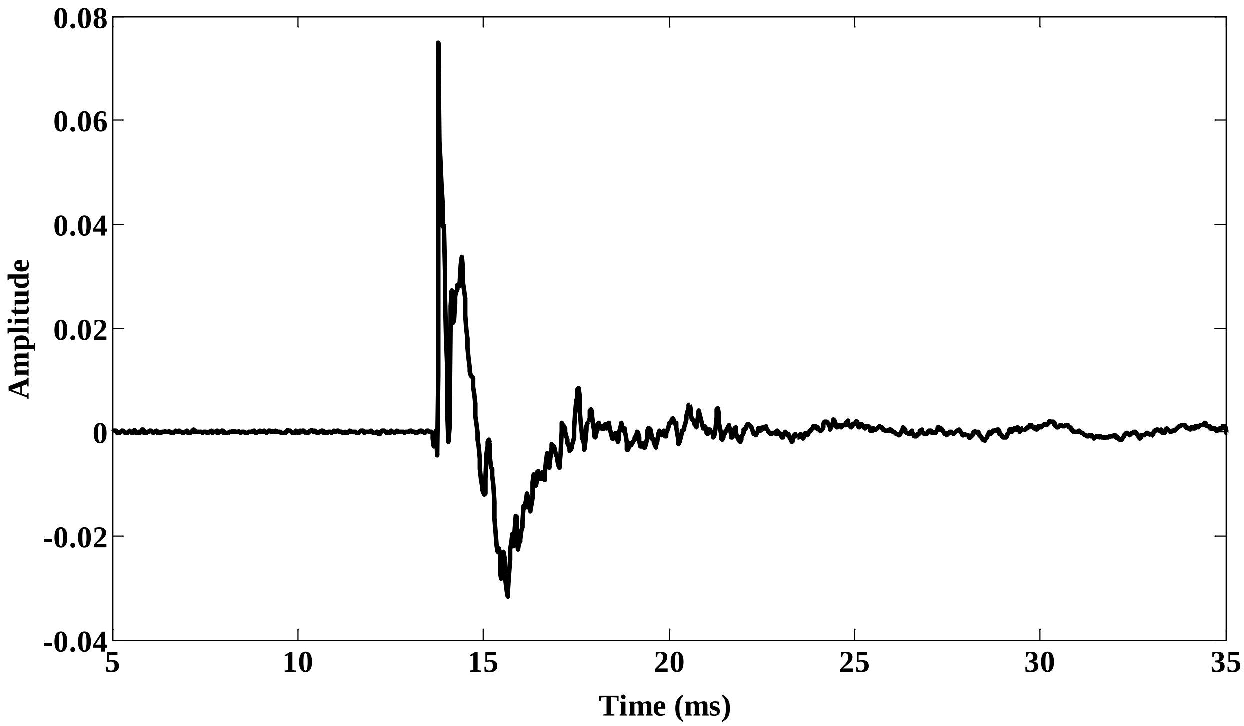


*Figure 5.4 Example waveform of an SA80 gunshot, recorded with an omnidirectional microphone, showing only the thump.*

The frequency spectrum of the thump varies from weapon to weapon (due to muzzle and ammunition size) so is not as easily characterised as the waveform (Maher and Shaw 2008). Maximum energy is generally seen in the 100-500 Hz frequency band (Donzier and Cadavid 2005), but is reported by Beck et al. (2011) to be as high at 650 Hz for some weapon types. This corresponds with the recordings in the current study; the peak amplitude of the muzzle blast was measured at 450 Hz (see figure 5.5) for a shot recorded 50 m downrange.

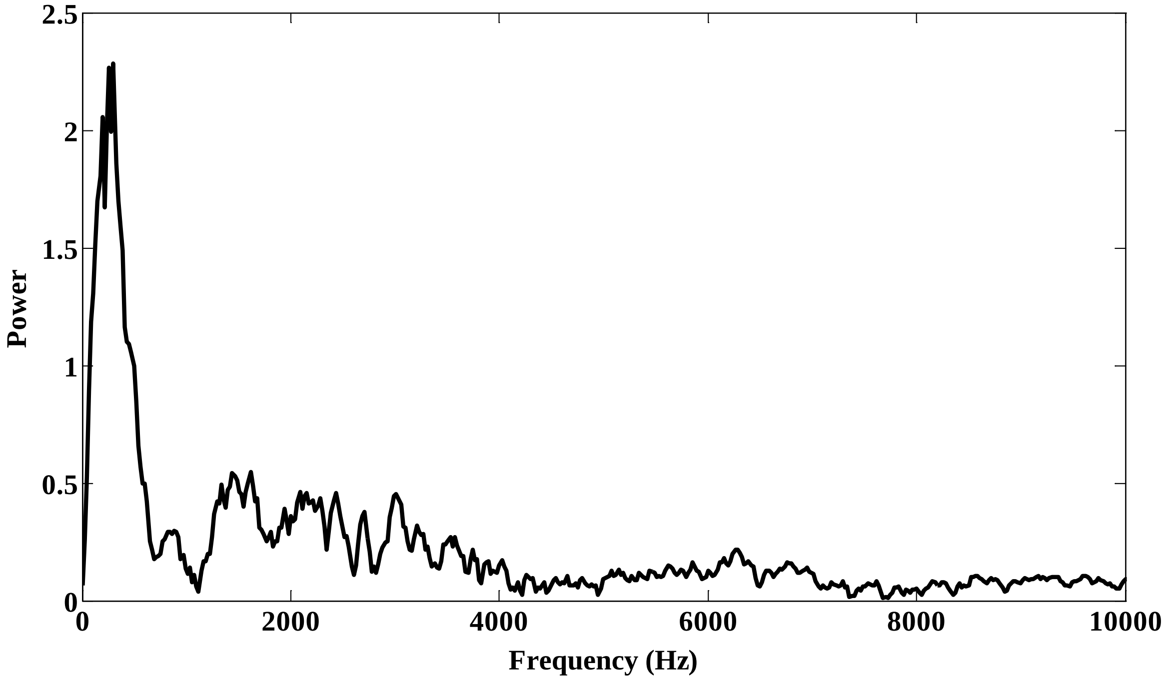


*Figure 5.5 The thump component in the frequency domain, with peak amplitude at 450 Hz. Measured using an omnidirectional microphone.*

A supersonic projectile causes a characteristic shockwave as it moves through the air. A conical wave follows the bullet with the wavefront propagating outwards at the speed of sound. This is captured by the microphone as a very rapid rise in pressure followed by a relatively slow ramp to an under pressure minimum (shown in figure 5.6). This is described in the literature as the “N” Wave and the time interval between maximum and minimum pressure is dictated by the size of the projectile (Snow 1967). A typical bullet of a few centimetres in length exhibits a time delay of less than 200 μs between pressure maxima and minima (Maher 2006).

If the microphone is placed near to a solid surface (buildings, pavements or grass covered ground) then the wavefront from the crack creates an echo as it hits the surface and returns to the microphone. In the current recordings a reflection of this kind has been measured approximately 9 ms after the crack for the KEMAR recordings.

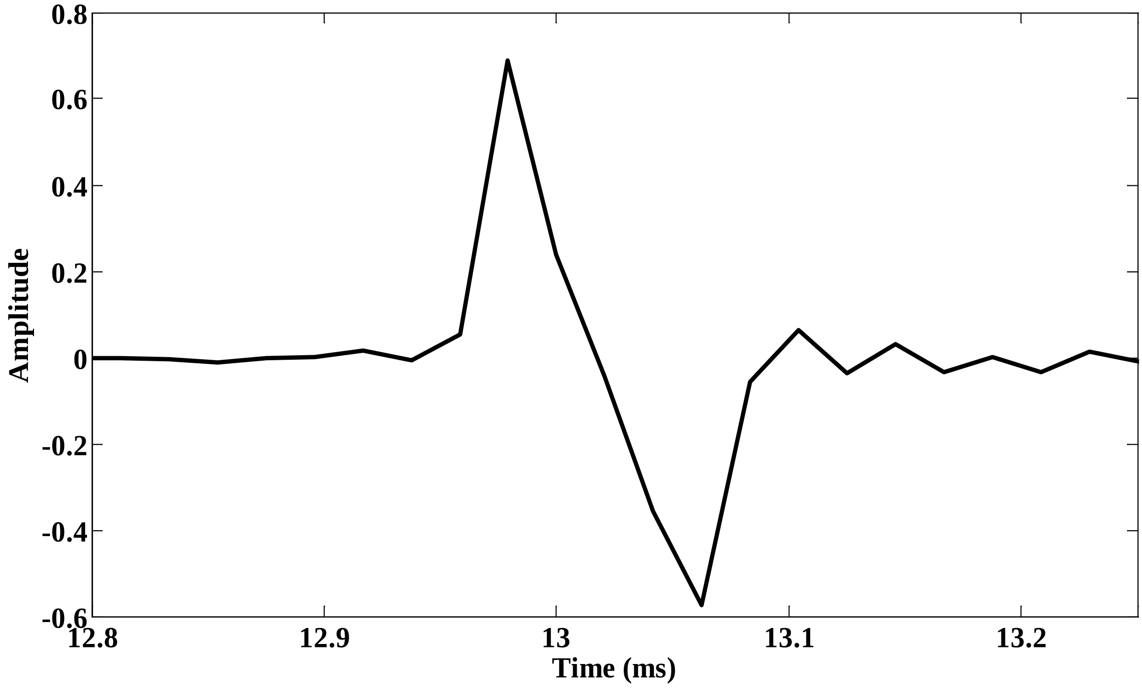


*Figure 5.6 N wave of gunshot as recorded by the omnidirectional microphone at 50 m. The fast rise in overpressure and corresponding minimum under-pressure can be seen.*

To demonstrate that this reflection was from a surface approximately the same distance away as the ground, the theoretical time delay for a sound wave to propagate from the bullet, hit the ground and return to the microphone was calculated. For the recordings measured at 50 m downrange the speed of sound in air was approximately 336 m/s (at 8ºC air temperature).

Figure 5.7 shows the theoretical position of the bullet when the crack is emitted at a point 30 cm above KEMAR (A) and the location of the omnidirectional microphone (B). The time delay between crack and ground reflection was calculated using the direct distance between A and B and the distance from A to B via the ground.

Direct distance A-B = b

Reflected distance A-B = 2d

Time taken for bullet to travel the direct distance = b/speed of bullet = 1.4 ms

Time taken for sound to travel reflected distance = 2d/speed of sound = 11.1 ms

Therefore, time taken between crack and ground reflection = 11.1 – 1.4 = 9.7 ms

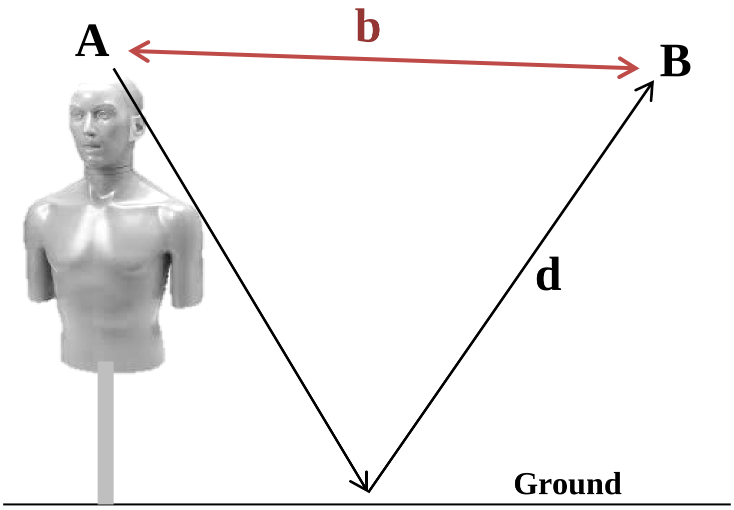


*Figure 5.7 Diagram to show how time delay between crack and ground reflection is calculated. A is the position of the bullet over KEMAR when the crack is emitted. B is the position of the omnidirectional microphone. d is the distance between ground and microphone/ bullet. b is the direct distance between the origin of the crack and the omnidirectional microphone.*

Whilst this is close to the measured time delay of 9 ms it is not exactly the same. This could be due to a greater than expected distance between bullet and microphone (due to inaccurate firing) or a slower speed of sound than expected due to atmospheric conditions (Beck et al. 2011). For this microphone set up there was no risk of the crack and reflection being superimposed as the microphone and source had a very small separation distance. Even with crack and reflection appearing as clearly separate peaks on the waveform they are not distinguishable as separate events by a human listener. For the purposes of further analysis and description of the signal, the ground reflection was considered to be part of the crack signal.

The crack component of the gunshot is typically characterized as a high frequency wave (Donzier and Cadavid 2005), but the frequency range of this is widely disputed and depends upon the type of weapon, the speed of projectile and the distance between firer and microphone. Donzier and Cadavid (2005) developed a small arms fire detection system and state that on average peak amplitudes are measured within 1-4 kHz. Snow

(1967) reports that due to its impulsive nature, the “N” wave is likely to be wide band in nature and this is demonstrated in figure 5.8 (the frequency spectrum of the crack, measured at 50 m downrange), where the highest amplitudes are measured between 3 and 8 kHz. Snow (1967) also noted that as distance increases, the energy above 10 kHz fell at a steeper rate due to the absorption loss of high frequencies. Due to the high frequency nature of the crack, it may be attenuated and distorted in human listeners with a bilateral high frequency sensorineural hearing loss (common in military populations due to high levels of noise exposure).

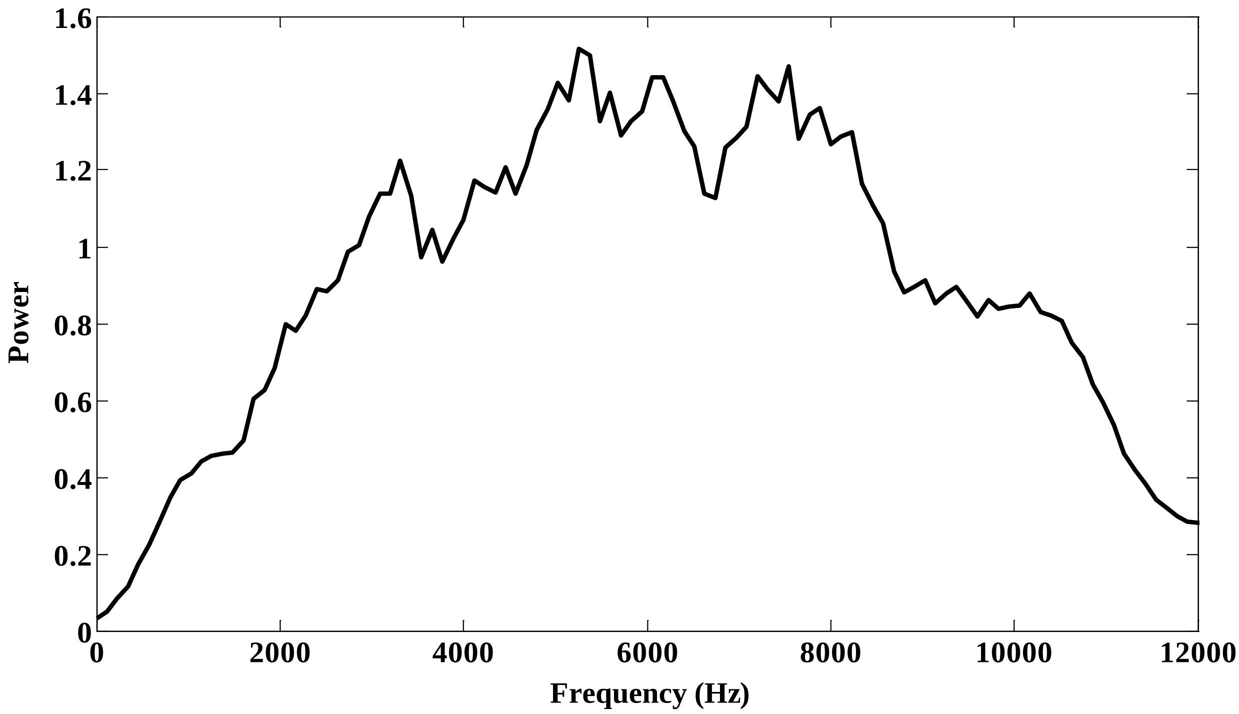


*Figure 5.8 Crack signal in the frequency domain. Peak amplitudes were observed between 3 and 8 kHz. Captured using an omnidirectional microphone.*

### 5.3.2 Amplitude as a function of distance

The distance between microphone and firer and the angle that they are placed at has a significant impact upon the gunshot waveform. With increasing distance between microphone and firer, the delay between crack and thump increases (as shown in table 5.1 and figure 5.10). It can be assumed that this trend would continue with increasing distance until the bullet slows to a sufficient degree for it to travel at the speed of sound and no longer create a shockwave.

The maximum peak level measured using the sound level meter and omnidirectional microphone for the crack was 150.1 dB(C) at 50 m downrange, above the peak sound exposure levels considered safe for humans (140 dB(C)) (Muhr 2010). This level decreased very little over distance, with only a 2 dB drop in peak levels between 50 m and 300 m downrange from the firer. Whilst the SA80 rifle has a reported ‘effective range’ of 600 m (Army technology, accessed online 02/02/15) it is clear from the bullet speed and measured peak sound levels that the ballistic shockwave would be heard for many hundreds of meters at potentially damaging levels. Conversely, the peak sound levels of the muzzle blast deteriorated fairly rapidly over distance (from 135.5 dB(C) at 50 m to 102.8 dB(C) at 300 m downrange from the firer). Even with this observed decrease in sound intensity (shown graphically in figure 5.9), the thump caused by the muzzle blast would remain at levels clearly audible to the human listener over a considerable distance. The thump is highly directional; the on-axis amplitude is much more intense than the levels recorded towards the rear or the side (Maher and Shaw 2008, Rasmussen et al. 2009).

*Table 5.1 Time delay between, and peak sound levels, of crack and thump measured downrange using the omnidirectional microphone (measurements carried out by Mike Lower)*

| **Distance downrange** **m** | Mean elapsed time between shockwave and muzzle blast ms | Time taken for sound of muzzle blast to reach measurement position (at 335.8 m/s if 15ºC) ms | Hence average speed of bullet between muzzle and measurement position m/s | Crack Peak sound levels, $L_{Cpeak}$ dB(C) | Thump Peak sound levels, $L_{Cpeak}$ dB(C) |
|---|---|---|---|---|---|
| **50** | 94.1 | 147.1 | 944 | 150.1 | 135.5 |
| **100** | 184.5 | 294.1 | 912 | 150.9 | 123 |
| **200** | 350.1 | 588.2 | 840 | 147.5 | 113.1 |
| **300** | 507.1 | 882.4 | 800 | 148.4 | 102.8 |

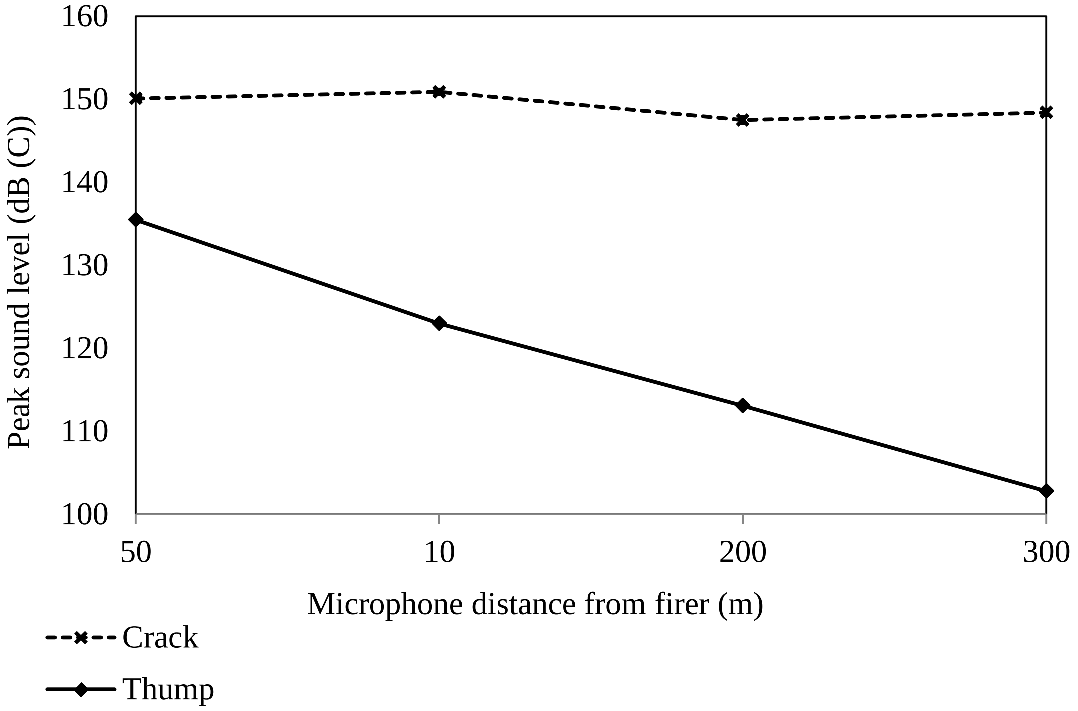


*Figure 5.9 Graph to show the average peak sound levels ($L_{Cpeak}$) of crack and thump as distance of omnidirectional microphone from firer increases*

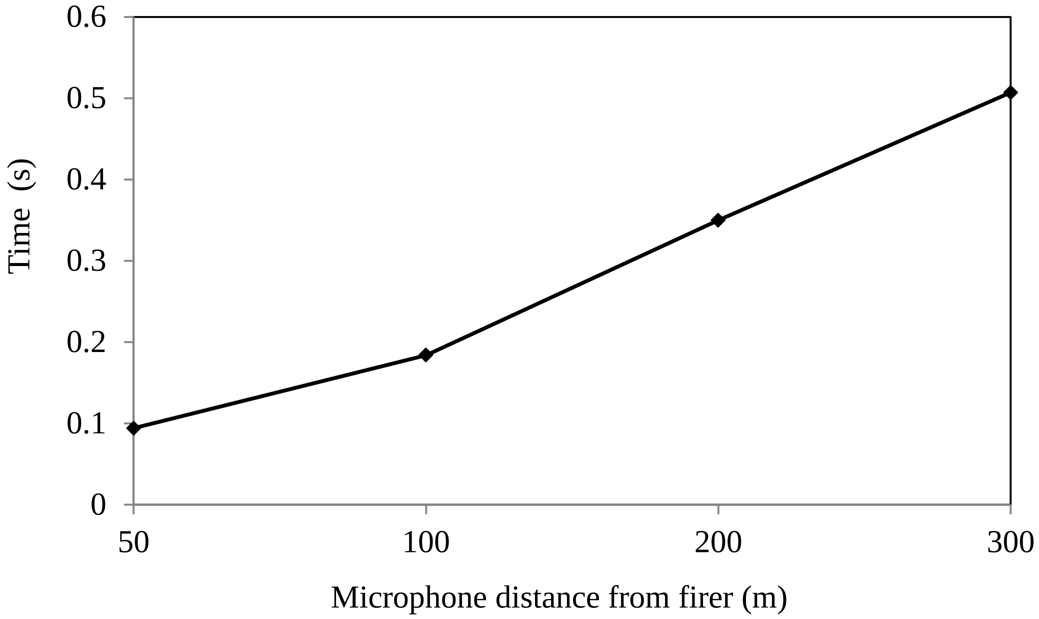


*Figure 5.10 Graph to show the average time delay between crack and thump as a function of omnidirectional microphone distance from firer.*

### 5.3.3 Bullet speed and trajectory

In order to understand how the sound created by the weapon would be heard by a human listener it is necessary to consider the geometry of the sound waves in relation to the binaural microphones in KEMAR. The crack and thump sounds reach the microphone via different geometric pathways and consequently it was believed that they may be perceived to have different origins by a human listener.

The thump sound is caused by the muzzle blast and follows a very simple path from weapon to the binaural microphones (when facing the direction of the firer). The muzzle blast travels at the speed of sound in a straight line through the air from the weapon to KEMAR. In a combat situation this would be heard by a human listener in KEMAR's place as a sound originating from the weapon at 0° azimuth. This is because the sound wave theoretically arrives at both ears at the same time and with the same intensity (evidence for this is presented in section 5.4.4).

The crack creates a conical shockwave with a wave front that propagates at the speed of sound away from the bullet (travelling at supersonic speed). The exact shockwave geometry depends upon the speed of the bullet, V, and the speed of sound within the specific environment, c (altered by air temperature, air pressure and humidity) (Donzier and Cadavid 2005). The calculation M = V/c is defined as the Mach number of the bullet and is greater than one for ammunition travelling at supersonic speeds. The angle between the bullet path and the resulting shockwave is termed the Mach angle, and this is given by:

$$\theta_M = \arcsin\left(\frac{1}{M}\right)$$

Mach angles vary depending on the speed of the projectile, ranging from 90º for bullets that travel just above the speed of sound to 30º or lower for bullets travelling at high velocities (Maher 2006).

Assuming that the temperature was 8ºC when the 50 m downrange recordings were created, the speed of sound in air (defined as:

$$C = C_o\sqrt{1 + \frac{T}{273}}$$

where $T$ is the air temperature in degrees Celsius and $C_o$ =331 m/s is the speed of sound at 0˚C) would be approximately 335.8 m/s.

The speed of the bullet was estimated from the elapsed time between crack and thump. The time taken (Tmb) for the thump signal to reach the measurement position was calculated assuming the speed of sound to be 335.8 m/s. The time taken for the bullet to travel the same distance was then estimated by subtracting the elapsed time from Tmb, and the speed of the bullet calculated by dividing the measurement distance by the time taken for the bullet to reach that point. No allowance was made for the fact that the shockwave trails the bullet so the shockwave at the microphone would be associated with a bullet position slightly further downrange than the microphone. This technique gives an estimated bullet speed of 944 m/s over the first 50 m, which agreed closely with the declared muzzle velocity of 940 m/s for the SA80 (Army technology, accessed online 02/02/15).

The Mach number was then calculated (M = 2.8) resulting in a Mach angle of 0.365 radians or 21 degrees (see figure 5.11).

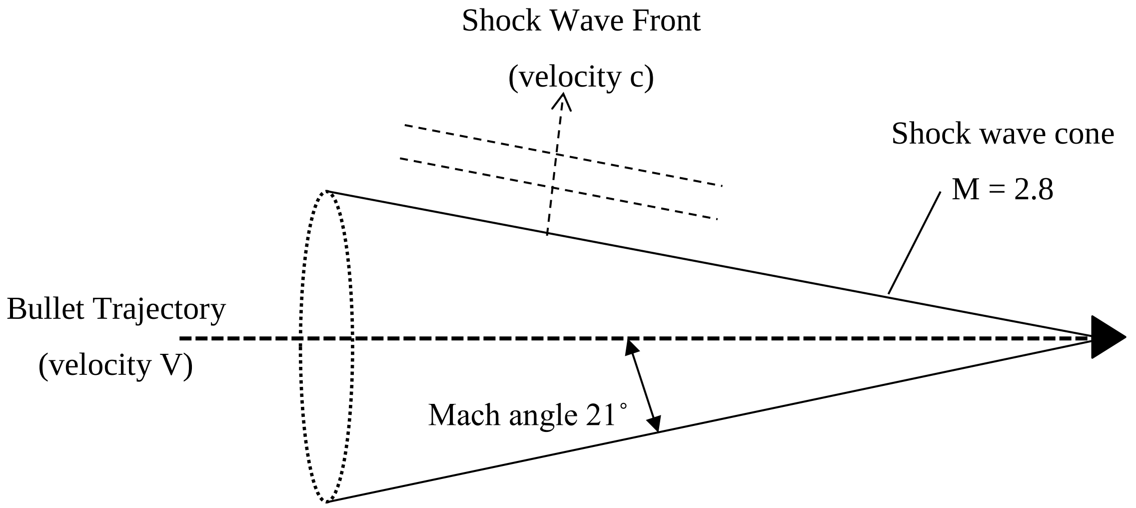


*Figure 5.11 Diagram showing the Mach angle of an SA80 gunshot in relation to the bullet trajectory*

This indicates that the ballistic shockwave created by the bullet from an SA80 rifle under the measured environmental conditions was very narrow (narrower than reported for other small arms projectiles, Beck (2011)) and that the crack sound recorded by KEMAR was a result of the wave front emanating at the speed of sound from the shock wave cone. Using this information it was possible to determine that the bullet, by the time the crack was recorded by KEMARs microphones, would have travelled downrange past KEMAR. The shock wave front trajectory (shown in figure 5.12) continued to propagate outwards from the conical shockwave, hitting the ground and causing a reflection to be measured by the microphone in very rapid succession of the crack sound (shown in figure 5.7 and described in section 5.4.1).

To the best knowledge of the author, no binaural recordings of live gunfire have been analysed in published literature. Donzier and Cadivad (2005) and Graves (2010) speculate that the angle of the shockwave (when the bullet passes over any given point) causes the resulting sound to originate from a position above that point. As a result of this, it was predicted that the crack signal contained little or no ITD or ILD information and would therefore be an unhelpful signal if used by a human listener to localise the position of a firer.

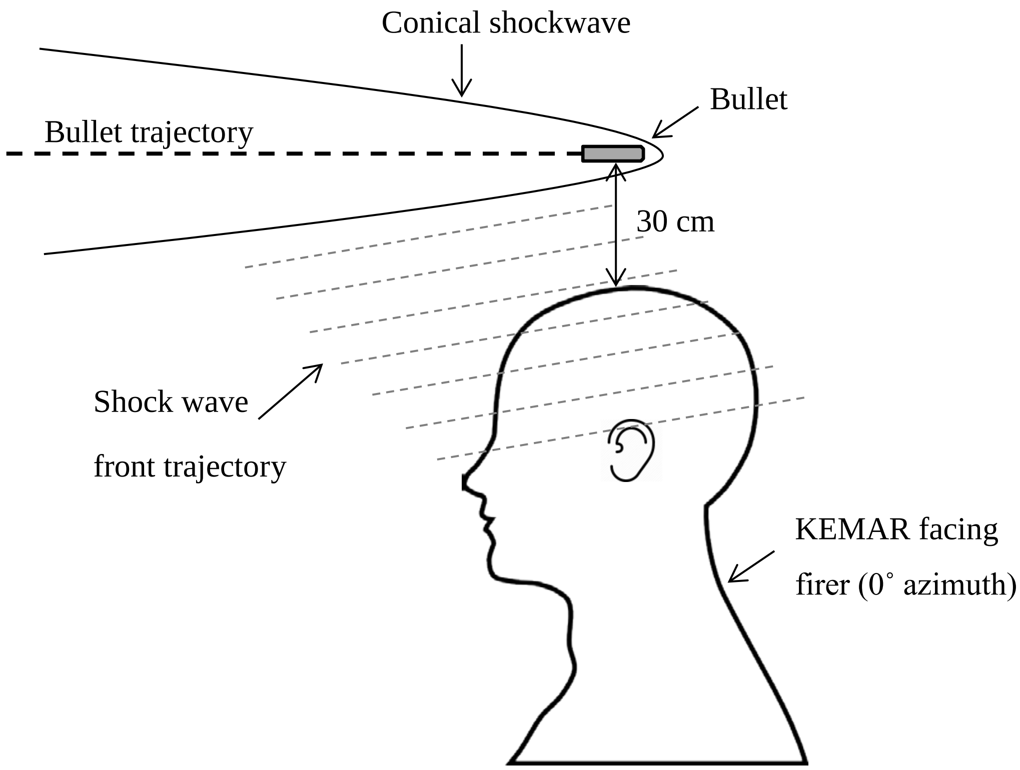


*Figure 5.12 Diagram to show the bullet shockwave and resulting wave front in relation to the KEMAR manikin*

Despite this, it was estimated that the crack signal may vary slightly in terms of binaural cues depending on the weapon position, angle of bullet propagation and miss-distance of the bullet (it can be seen from the theoretical diagram in figure 5.12 that there is a slight directionality to the propagating shock wave front as it reaches KEMARs ears).

From the evidence it is clear that the two components of a gunshot signal have the potential to provide conflicting localisation cues to a human listener. Based on the literature surrounding bullet propagation it is likely that the crack would provide fewer localisation cues to the human listener in terms of ILDs and time differences when compared to the muzzle blast. Further to this, the Mach angle dictates where the crack is audible. The larger the Mach angle, the greater the propagation of the sound from the bullet trajectory.

### 5.3.4 Binaural characteristics

In order to determine the binaural cues available to a human localiser within a gunshot, interaural differences were measured for the 50 m KEMAR recordings. The mean ILD and ITD of the two shots fired at each angle were used. Measurements were calculated using a custom-made MATLAB programme that compared the signals from the left and right ears. Level differences are measured using the RMS power differences between left and right ears over the whole duration of the signal (Brungart and Simpson 2002). Time differences were calculated by first using Hilbert transformation to realise the envelopes of the signals, followed by determining the maximum peak delay in the Hilbert transformations from both ears (as utilised by Aaronson and Hartmann 2010).

Two stimuli were used for the binaural measurements (i) the crack component of the gunshot (including the ground reflection) (ii) the thump component. These were then compared to the ILD and ITD values of a broadband noise stimulus presented using a Realistic Optimus Pro 7 loudspeaker mounted 1.4 meters from KEMAR (taken from a database created by Gardner and Martin 1995) as these were found to be the closest in recording set up to the gunshot KEMAR recordings (i.e. using KEMAR’s small ears G.R.A.S. IEC 711 RA0045 and similar analysis techniques to generate the ILD and ITD measurements).

From the theoretical data presented in section 5.4 it was predicted that the thump stimulus would behave similar to a broadband stimulus; originating from a point directly in front of KEMAR. Azimuth for both the gunshot and noise condition describes the position of the firer in relation to the binaural KEMAR measurements (zero degrees azimuth represents KEMAR facing the sound source). It was also expected that the crack stimulus would produce very small ITD and ILD cues and that these would vary less as a function of azimuth when compared to the thump.

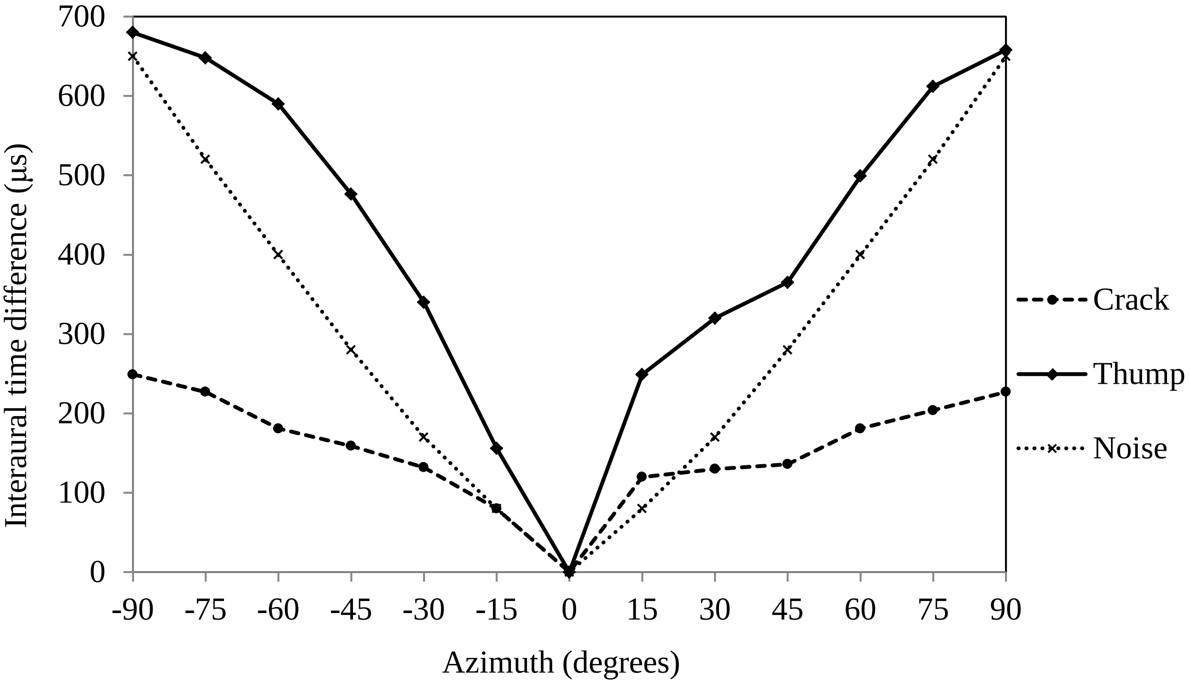


*Figure 5.13 Measured ITDs of the crack, thump (both recorded 50 m downrange from the firer) and broadband noise stimulus (from Gardner and Martin 1995). -90º azimuth describes KEMAR facing to the left and 90º to the right.*

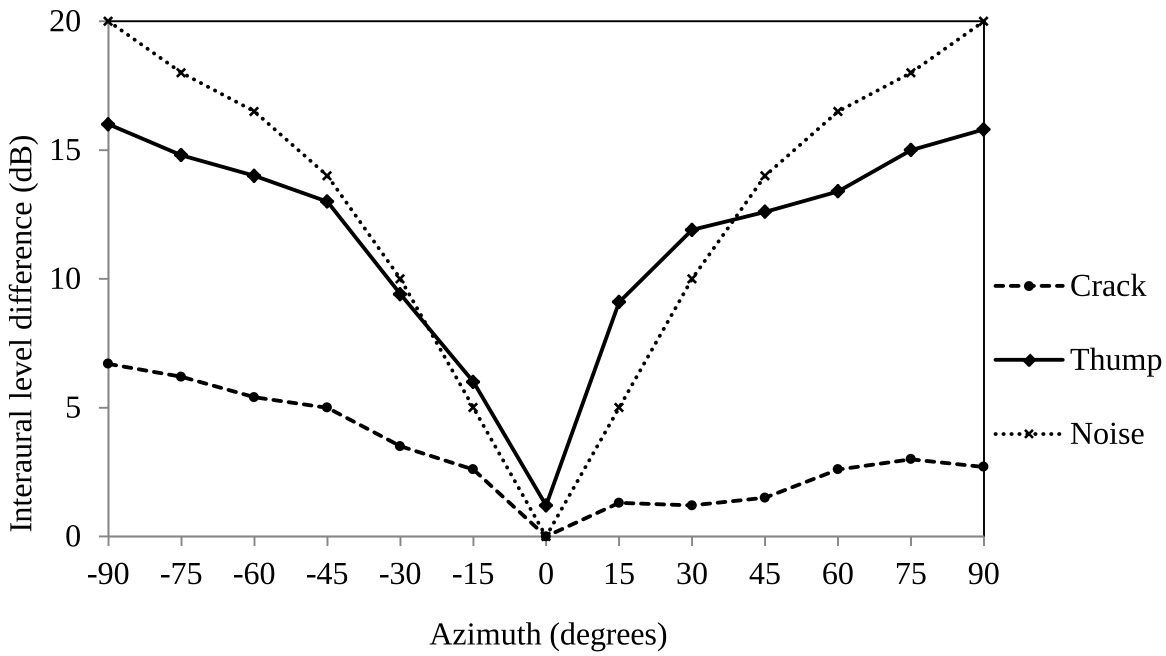


*Figure 5.14 Graph to show interaural level differences of gunshot components (recorded 50 m downrange) and broadband noise (from Gardner and Martin 1995).*

Figure 5.13 shows the measured ITDs of the three signals. The thump exhibits higher ITDs (particularly between -30 and -75) than the noise; this is likely due to the frequency content of the signal. It is known that lower frequency signals have higher ITDs and this is consistent with the findings of Roth et al. (1980). In contrast to the ITDs, the noise signal has higher measured ILDs (figure 5.14) than the thump and this is likely due to the greater high frequency content of the noise.

These measurements suggest that the thump would be localised by a human listener to a similar level of accuracy as the broadband noise stimulus; it is known that bandwidth has a significant effect on localisation accuracy (Middlebrooks and Green 1991) and therefore the broadband noise may provide more useful binaural cues than the thump stimulus. Furthermore, the higher ITD cues at each azimuth (compared with the noise stimulus) may cause a human listener to perceive the source of the thump more laterally, resulting in an increase in bias. An increase in bias would be most apparent between 15 and 60º to the left or right where the disparity between thump and noise ITD cues is greatest.

It is also apparent from figure 5.13 and 5.14 that the ITDs and ILDs measured for the crack signal are significantly lower than those measured for the other signals. This is particularly apparent at azimuths above 45º and below -45º where the ITD values change only very slightly between 15º intervals. This is likely to be due to the elevation as described in section 5.4.

If the crack originated from the same location as the thump it would have created the highest ILDs due to its high frequency nature.  This confirms (consistent with the theory presented in section 5.4) that the origin of the crack is not the weapon itself, but a point somewhere above the binaural microphones. It also demonstrates that a large movement of KEMAR results in a small alteration in ILDs and ITDs for the crack signal when compared to the thump.

Perceptually the crack stimulus should sound as though it originates from a central source, regardless of the actual gunshot source. It was therefore hypothesised that human listeners would exhibit a high central bias during a localisation task using the crack stimulus. Further to this, the confusing origin of the signal (containing some elevation cues as well as the sparse horizontal localisation cues) may result in higher overall RMS error due to an increase in random guessing.

Based on the predictions above it is possible to speculate how a human listener may localise the whole gunshot stimulus. As both crack and thump are audible, a listener could rely on the useful binaural cues contained within the thump and locate the whole gunshot with the same accuracy as the thump signal alone. Human listeners have a tendency to locate a sound source based on the first arriving sound (in order to ignore reflections, Bronkhurst (1995)) and this may increase participants' reliance on the crack portion of the signal. Listeners are likely to be divided between these two options; causing the overall error scores of the gunshot condition to fall in between that of the crack and thump individually.

The relationship between binaural cues and azimuth for the gunshot components is not totally linear and there are a few measurements that were unexpected (particularly at 15º and 30º for both ITD and ILD). This could have been due to changes in the bullet trajectory; the firer had no 'target' to aim for and the accuracy of the shot was not measured after the rifle was calibrated so there could have been some movement in the firing position and the proximity of the bullet in relation to KEMAR's head. Secondly, every shot fired was unique and would have varied slightly in bullet speed and therefore the frequency content of the signal for the crack. Thirdly, and most importantly, it was noted that the final two turns of turntable did not appear complete when viewed through binoculars and the turntable did not return exactly to 0º at the end of the 360º movement. This is discussed further on page 139.

From the binaural analysis of crack and thump it can be predicted that the thump signal provides greater cues for human localisation of the signal source. This, combined with the fact that the thump signal can be heard at any position around the firer suggests that it may be a very useful signal for military personnel to localise the source of gunfire. The ITD and ILD cues created by the crack vary only a small amount by azimuth and it is not yet known if it is possible for human listeners to utilise these cues to successfully identify the firer's position.

## 5.4 Summary and knowledge gaps

### 5.4.1 Summary

A novel set of recordings of live SA80 gunfire were created using binaural, omnidirectional and sound field microphones. The omnidirectional recordings were analysed to determine how distance affected the peak sound levels and delay between the supersonic crack signal and the muzzle blast.

The binaural analysis (to measure bullet trajectory and Mach angle together with ILDs and ITDs) allowed comparisons to be made with previous literature and the known acoustic characteristics of small arms fire. This in turn informed predictions about the likely success of a normal hearing human listener localising the source of small arms fire from the sound of a gunshot and its component parts.

### 5.4.2 Knowledge gaps

The detailed analysis of the recorded gunshots highlighted a fourth knowledge gap. This area of research (together with the knowledge gaps identified in chapter 4) is addressed in chapter 6 using the recorded gunshots in a source identification task.

- **It has been shown that the component parts of a gunshot contain varying binaural cues. It is not known whether a human listener is able to localise the separate components of a gunshot (crack and thump) using the spatial cues available.**

**Research question:** Is there an effect of stimulus condition on localisation accuracy for the components of a small arms gunshot?

**Hypothesis:** It was hypothesised that there would be a significant effect of stimulus condition on localisation accuracy and that this would relate to the level of ITD and ILD cues present in the gunshot components as discussed in section 5.4.4. It was predicted that participants would have greater success in accurately localising the stimulus types in the order of broadband noise > thump > gunshot > crack.

# Chapter 6: Localising virtual gunshots

## 6.1 Introduction

Localisation of small arms fire in a combat environment is an MCAT carried out by UK infantry personnel (chapter 3, page 37). This task, in its most basic form, requires an individual to locate a firing point from a single small arms gunshot in a flat open area in front of them (ascertained from the focus groups in study 1 and personal communication with Major Simon Archer and Major Daniel Power, Infantry Trials and Development Unit, Land Warfare Centre, 15.02.2014). The source identification task described in the current chapter was developed as a simulation of the localisation MCAT to assess localisation accuracy for civilian and military listeners.

In the absence of a lightweight wearable device that is able to quickly identify the source of enemy fire, it is important to ensure that personnel with or without a hearing impairment are able to perform this task to a reasonable level (Vaillancourt et al. 2011; Biggs and Everest, 2011a; Scharine et al. 2014). To the best of the author's knowledge only one published study directly measured human localisation accuracy in the horizontal plane using a gunshot stimulus. Talcott et al. (2012) reported a localisation accuracy of 81-88% correct within 45º of the target; very poor accuracy compared to the wider localisation literature (where participants are able to locate a generic stimulus to within 30º of the target (Recanzone et al. 1998)). Furthermore, with the study's small sample size (nine normal hearing and four hearing impaired) and experimental design (as discussed in Chapter 4), it is only possible to draw very limited conclusions about levels of gunshot localisation accuracy from Talcott et al. (2012).

Other studies in this area incorporated hearing protection devices or helmets (Simpson et al. 2005; Abel et al. 2010; Scharine et al. 2014) and failed to provide quantitative measurements of localisation accuracy for normal hearing participants without hearing protection. The following chapter addresses this gap in the literature and presents four localisation experiments (studies 3-6) using civilian and military participants. Study 3 was a pilot study of 20 normal hearing civilian listeners designed to ensure that the virtual localisation method developed was robust and that the sound reproduction was accurate and true to the original source. Study 4 was a repeat of study 3 with a further 20 normal hearing civilian listeners after changes were made to the method and stimuli. The localisation accuracy of 20 normal hearing military personnel was assessed in Study 5 to determine if there were differences between civilian and military listeners. Study 6 was a preliminary study with 12 hearing impaired personnel to investigate the relationship between bilateral symmetrical hearing impairment and localisation accuracy within a military population.

### 6.1.1 Chapter 6 aims and hypotheses

The fundamental aim of the experimental work was to develop a suitable method for testing localisation accuracy in a controlled environment using the recorded small arms gunshots described in Chapter 5. A virtual localisation task was designed as a simulation of the MCAT identified during study 1 and aimed to assess whether small arms localisation is an auditory requirement for infantry personnel.

Development of the task involved the creation of a program to present the stimuli and collect participant responses, together with building a structure to give participants a visual frame of reference from which they could describe the source locations. Beyond this, there were four specific aims addressed by the studies throughout Chapter 6; these are presented below and again at the start of the relevant sections.

**Aims:**

**1)** To assess the localisation accuracy of normal hearing listeners for a small arms fire stimulus and to compare this to a stimulus that is well documented in the wider localisation literature.

**Research question:** How accurate are normal hearing human listeners in localising the source of small arms fire?

**Hypothesis:** It was hypothesised that normal hearing civilian listeners would be able to localise the source of small arms fire at level of accuracy better than that associated with selecting sources at random. Based upon the findings of Talcott et al. (2012) normal hearing listeners should have some level of success localising this stimulus, but the accuracy of this judgement is still unknown.

**2)** To investigate how the individual components of a gunshot contribute to a human’s ability to localise this complex stimulus. As outlined in Chapter 5 the gunshot sound is the result of two events: The bullet leaving the muzzle of the gun (‘thump’) and the shockwave created by the bullet moving through the air (‘crack’) (Sherwin & Gaston 2013). The crack sound produces much smaller ILD and ITD cues than the thump for the rifle at the same angle; it is not known how successfully humans are able to use these cues for localisation.

**Research question:** Is there an effect of stimulus condition on localisation accuracy for components of a small arms gunshot?

**Hypothesis:** It was hypothesised that there would be a significant effect of stimulus condition on localisation accuracy and that this would relate to the ITD and ILD cues present in the gunshot components as discussed in Chapter 5. It was predicted that participants would have greater success in accurately localising the stimulus types in order of broadband noise > thump > gunshot > crack.

**3)** To determine whether normal hearing military personnel and normal hearing civilians are able to carry out the small arms localisation task to the same degree of accuracy and precision.

**Research question:** Is there a significant difference between the small arms localisation accuracy of normal hearing military personnel and normal hearing civilians?

**Hypothesis:** It was thought that civilians and military personnel would perform the localisation task to a similar degree of accuracy providing other listener characteristics remained the same (for example age, handedness). It was hypothesised that military personnel may perform to a higher degree of accuracy due to their training and experience but that they may suffer from auditory processing issues associated with high levels of noise exposure. Hence, the net effect of these factors may not be apparent in their localisation accuracy.

**4)** To investigate the relationship between bilateral symmetrical hearing impairment and localisation accuracy within a military population.

**Research question:** Does degree of hearing impairment affect localisation accuracy on a virtual localisation task?

**Hypothesis:** From a review of the wider literature it was hypothesised that as bilateral hearing impairment increased localisation accuracy would decrease. This detriment in localisation accuracy will be most noticeable for participants with a >40 dB HL bilateral impairment (in accordance with the findings from Rosenhall; 1985).

## 6.2 Developing the virtual source identification task

This section describes the equipment and test procedure for the experimental work in this chapter. Where the methodology for a particular study differs from the general method, this is specified in the introduction of the relevant section. All experiments were approved by the University of Southampton Faculty of Engineering and the Environment Ethics Committee (REF: 9043), the INM Scientific Advisory Committee and the MoD Research Ethics Committee (REF: 636/MODREC/15) (see appendix D for approval documents).

### 6.2.1 Justification for virtual source identification task parameters

A comparison of localisation measurement methods is provided in chapter 4 (section 4.3.1) and the experimental method described in this section was developed based on the findings and recommendations of the literature reviewed. A virtual localisation paradigm was chosen to accurately reproduce the complex spatial cues within a gunshot stimulus. This ensured that the subtle binaural and HRTF cues from the gunshot stimulus and its component parts were maintained and allowed precise control over the stimuli presented to the listener. The virtual paradigm was appropriate for four reasons: 1) the short duration of the stimuli greatly reduced any effect of head movement on spatial perception 2) the rig and set up of the experiment was easily portable, allowing it to be moved around the university and to military bases across the South of England, 3) using non-individualised HRTFs meant that the stimuli remained constant throughout and testing time was kept to a minimum without the lengthy and invasive process of measuring individual HRTFs and 4) the complex cues contained within the supersonic crack component of the gunshot would not have been preserved using a loudspeaker array.

A letter-based visual framework was provided for participants to describe the chosen source location. This was designed based on the recommendations of Wenzel et al. (1993) who found that their complex numerical co-ordinate system may have affected task performance. They noted that a simpler system was needed to allow participants to easily describe the source. Whilst it was not possible to place the letter marker in the exact location of the virtual source (50 -100 m away from the listener) they were placed at eye-level so that the participant did not have to translate the location from a mark on the floor or a small screen in front of them. Participants were asked to say the letter out loud to avoid any translational errors that may occur from a head turn or a hand point (such as those found by Ocklenburg et al. 2010).

The number of source locations was chosen to reflect the current way in which military personnel communicate sound sources; using a clock face system (an enemy threat heard straight in front would be at 12 o'clock, for instance). However, using a single source for the hours on an analogue clock face would have only given seven sources in the frontal horizontal plane. With seven sources, the task may have exhibited ceiling effects so an extra source in between each one was added giving a total of 13 virtual source locations at 15° intervals. A similar 13 source array was used successfully by Wightman and Kistler (1989).

### 6.2.2 Equipment and apparatus

The experiment was carried out in a semi anechoic room with the dimensions 3.5 m wide, 4.5 m long and 2.5 m high. The participant was seated in the centre of a 125 cm diameter hoop positioned at eye level using three metal stands. There were 13 letter markers (A-M) attached in 15º intervals to the hoop corresponding to the azimuths of the stimuli sources. The letter A corresponded to a source at 90º to the left of the participants, M was 90º to the right and G was placed at 0º. The participant was sat facing 0º and their ears were in line with the furthest azimuth positions at +90º and -90º, as shown in figures 6.1 and 6.2. The stimuli, which were either recorded using a KEMAR manikin (as described in chapter 5) or digitally generated and convolved with KEMAR's HRTFs, were presented to the participant via Etymotic ER-2 insert earphones.

Stimuli were presented in random order using custom MATLAB (The MathWorks Inc., v.7.14) software and played to the participant through an RME Babyface audio interface and Apple Macbook Pro. The method used in this study was similar in design to that used by Zotkin et al. (2003) and Wenzel et al. (1993).

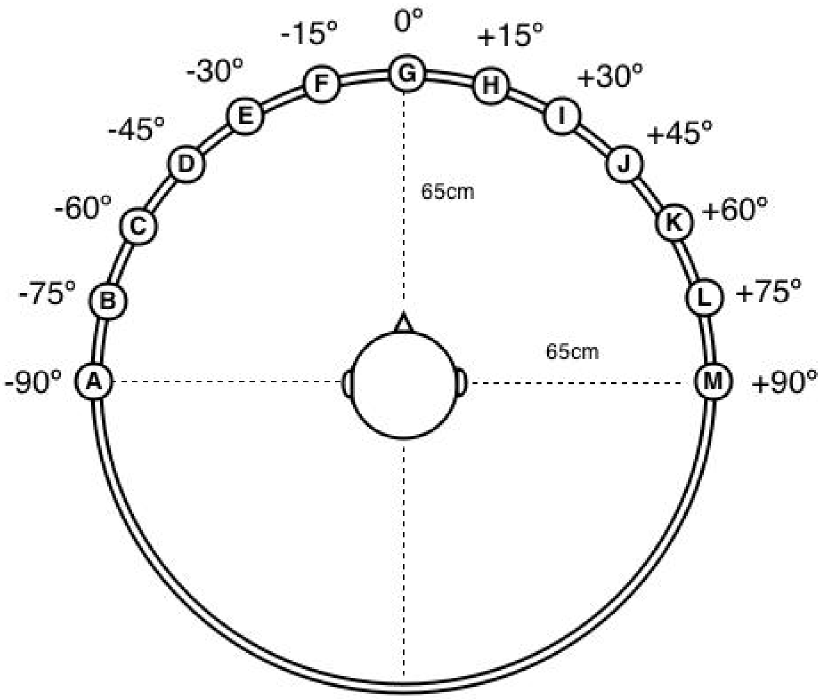


*Figure 6.1 Arrangement of participant and virtual source locations in plan view. The letter markers represent the source azimuth but do not represent the true distance between listener and source (either 50 or 100m).*


*Figure 6.2 Photograph of the experimental rig during study 3 at the Institute of Sound and Vibration Research at the University of Southampton.*

### 6.2.3 Stimuli

In accordance with the aims of this study, stimuli were chosen in order to measure the localisation accuracy of a whole gunshot stimulus as well as its component parts. A 100-10,000 Hz 50 ms Gaussian noise condition was also used to provide a comparison with previous studies of this design (Zotkin et al. 2003, Macpherson and Middlebrooks 2000) and to verify the experimental setup.

Reproducing an unprocessed recorded gunshot over insert earphones was not possible or ethical due to the high sound pressure levels. As all of the original recordings had a peak amplitude of over 150 dB SPL they needed to be attenuated significantly to ensure that the experimental stimulus was at a safe level. Reproducing the crack and thump separately introduced further complications. If the whole gunshot was attenuated and then split into crack and thump, the amplitude of the thump would have been considerably lower than the crack and may have been totally inaudible if the participant had even a mild hearing impairment. To avoid this, the amplitude of the crack stimulus was maintained and the thump components were amplified to an audible, comfortable level. Whilst this was not realistic of a real world scenario where crack and thump differ greatly in amplitude it aimed to keep the thump at a realistic level and to attenuate the crack to a safe level. A listener 100 m from the firer wearing a basic level of hearing protection such as the 3M EAR classic ear plug (attenuating the sound by approximately 18 dB (Berger 2013)) would hear the thump at approximately 105 dB SPL (peak sound level as measured by Lower and Paddan (under review)). Under the same conditions the crack would remain in excess of 132 dB SPL, a level that could cause damage to the auditory system.

**Gunshot, crack and thump**

Using a level adjust in MATLAB and the macbook sound level, the gunshot files were attenuated to a maximum peak amplitude of approximately 105 dB SPL (the calibration process is dicussed in section 6.2.4). The output was measured through insert earphones using an artificial ear and digital SPL meter; it was not appropriate to measure an average amplitude in dB(C) due to the impulsive nature of the stimulus. This attenuation did not change the relative amplitude of the gunshots; the peak amplitude of each gunshot varied between shots (at the same azimuth and as the azimuth changed). In order to closely simulate the original localisation MCAT the amplitude cues were altered as little as possible for the whole gunshot stimuli.

The gunshot recordings were then split using the Adobe Audition cut and paste tool into separate crack and thump files. The files were divided approximately half way between the offset of the ground reflection and the onset of the thump, an example of this can be seen in figure 6.3.

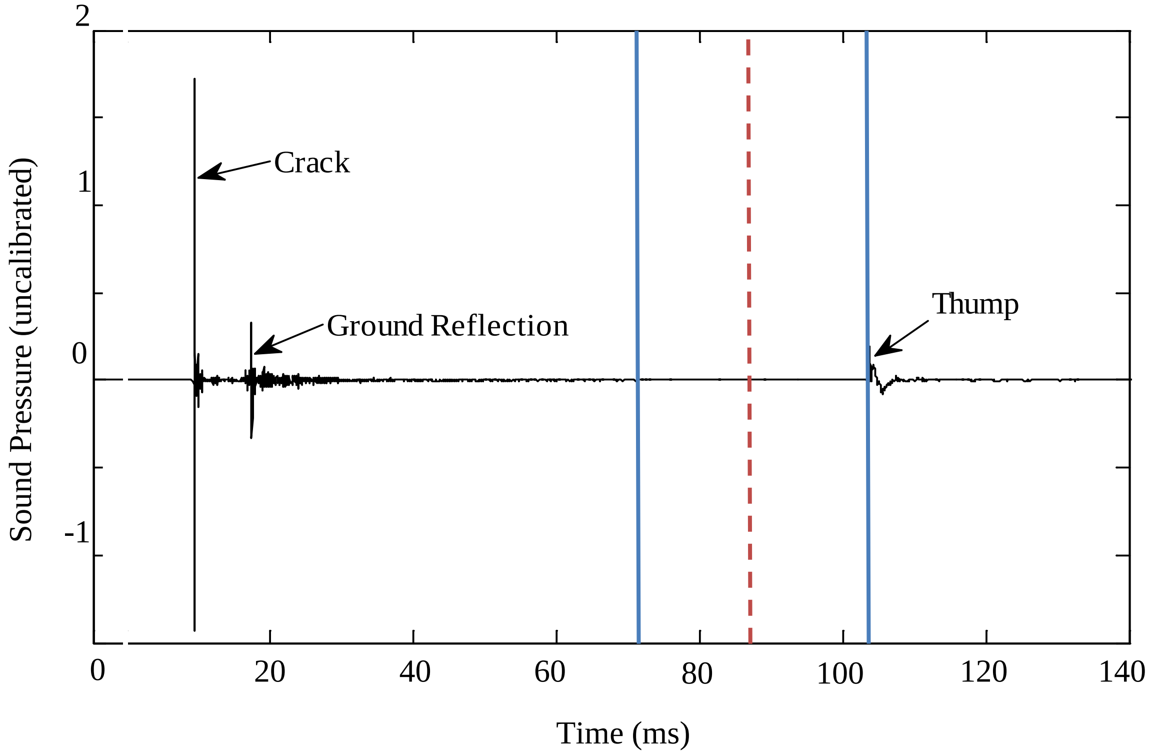


*Figure 6.3 Waveform showing the splitting of gunshot audio files into separate crack and thump components. The dashed red line indicates where the file was split and the blue lines are the offset of the crack and onset of the thump, shown either side.*

The separate thump files were much lower in amplitude than the gunshot and crack recordings; they were audible to a normal hearing listener but there was concern over their audibility to a hearing impaired listener. To overcome this, the thump recordings were amplified to a comfortable yet clearly audible level (equivalent to between -5 and -7 dB full scale) in adobe audition. As the thump stimuli were not formally calibrated, the absolute level presented to the listener is unknown (a limitation discussed in section 6.3.4). Similar to the crack and gunshot recordings, the peak level of the thump recordings varied between individual gunshots and azimuths.

The crack and thump files were increased in length to match the whole gunshot (approximately one second in length) by adding silence before and after the stimulus. To avoid any onset or offset cues that may have been created by abruptly cutting the files, a 5 ms onset/offset cosine ramp was applied between the added silence and the waveform.

**Broadband noise burst**

The aim was to include a stimulus condition that was well documented in the literature but that also shared characteristics with the gunshot in terms of duration and amplitude. For each trial unique 100-10,000 Hz band pass filtered Gaussian noise bursts were generated using a random number generator in MATLAB. This stimulus was similar to that used by Goupell et al. (2010), Zotkin et al. (2003) and Majdak et al. (2010). The duration was chosen to match the length of the individual gunshot components (approximately 50 ms). The sampling rate was 44.1 kHz and 5 ms onset/offset cosine ramps were added to decrease the chance of participants using onset or offset cues to aid localisation. In an attempt to match the amplitude of the noise to the gunshot components, the maximum peak output was set at 105 dB SPL in the MATLAB code; however, as the noise bursts were randomly generated, it was not possible to measure the peak output of every individual burst. When a sample of 10 generated noise bursts were measured using an SPL meter, the peak amplitude ranged from 102.2 – 105 dB SPL (after HRTF convolution, as described below).

The noise bursts were convolved using a custom MATLAB programme (developed by Daniel Rowan, see appendix E, part 1) with HRTFs of KEMAR (large pinnae: G.R.A.S. KB0065 and KB0066) from the Centre for Image Processing and Integrated Computing (CIPIC) database (Algazi et al. 2001). The intensity of the noise stimuli was roved by ± 5 dB to prevent participants from using absolute level cues to aid them in localisation (Byrne and Noble 1992).

There were two recorded gunshots (and therefore two crack and two thump components) for each azimuth and these were presented randomly. Each gunshot or gunshot component was presented an equal number of times over the stimulus trial.

*Table 6.1 Overview of stimulus characteristics*

| **Stimulus** | **Characteristics** |
|---|---|
| Gunshot | A 1 sec recording containing a single recorded gunshot of approximately 100 ms in duration. |
| Crack | A 1 sec recording containing the bullet shockwave (and ground reflection): approximately 50 ms in duration |
| Thump | A 1 sec recording containing the muzzle blast: approximately 50 ms in duration |
| Broadband noise | A MATLAB generated 100-10,000 Hz band pass filtered Gaussian noise burst, 50 ms in duration. This was convolved with HRTFs of KEMAR from the CIPIC database. |

#### 6.2.4 Calibration

To measure the peak level of the broadband stimulus a 20 sec signal was generated (from the angles of 270 and 90 degrees). This long duration signal was post-HRTF convolution and the 50 ms signals used for the experiment were equivalent to random excerpts from this signal. The signal was presented through the ER2 insert earphones and the sound pressure level (dB(A)) measured using an IEC 60318-4 occluded ear simulator and B&K 2270 sound level meter.

The amplitude within the MATLAB code was altered to give a maximum peak level of 105 dB SPL for the broadband signal; this gave a long term RMS level of 80 dB (A). As there was a level rove applied to the signal during the experiment (together with the HRTF convolution), the maximum output would have been 110 dB SPL (85 dB (A) RMS).

Calibration took place at the start of study 3, study 4 and study 5 (study 5 and 6 took place simultaneously). Identical transducers were used throughout and subjective listening checks were carried out daily to ensure the apparatus was working correctly.

The noise exposure levels for each testing session were within the daily exposure guidelines as outlined in the ISVR guide to experimentation involving human subjects (Griffin et al. 1996).

During calibration of a BSc student project in November 2015 it was noted that an identical sound card was overdriven when producing a pure tone signal at 96 dB SPL. This called into question whether any distortion was present in the broadband noise or gunshot stimuli used in studies 3-6. After further investigation (presented in appendix F, section 2) it was found that for the loudest stimuli some clipping of the signal may have occurred. The implications of this are discussed in Appendix F.

### 6.2.5 Test procedure

At the start of the test session participants were asked to complete the questionnaire to highlight any of the exclusion criteria and consent form (also a military experience questionnaire where appropriate). They were read the test instructions and asked if they had any questions or concerns. Otoscopy and a pure tone audiogram were carried out in accordance with BSA guidelines (BSA 2004). Prior to localisation testing a familiarisation trial took place. Familiarisation involved the participant listening (but not responding) to a 500 ms broadband noise signal presented from each of the source locations in sequence (with 500 ms gaps in between each burst) to allow them to acclimatise to the source locations and sound level. This was carried out twice for each participant. There was no training prior to the experiment and no feedback - negative or positive - given throughout testing to limit learning effects.

The stimuli were randomly presented using a custom-designed MATLAB program with a graphic user interface (GUI) controlled by the tester. After each stimulus presentation participants were required to respond by saying, out loud, the letter that corresponded to the perceived location of the sound source. This was then recorded by the tester on the MATLAB GUI. The participant was instructed to guess a letter if they were unsure of the source location.

For each stimulus condition there were 78 trials. For the broadband noise condition this comprised six unique stimuli generated for each of the 13 source locations, presented in random order. For the gunshot, crack and thump conditions there were three presentations of each of the two wav files for the 13 source locations (equalling 78 trials in total for each of gunshot, crack and thump).

The order of test conditions was partially counterbalanced by the use of an incomplete Latin square (Appendix G) as assigning condition order randomly may have introduced condition order bias due to the effects of learning or fatigue (Bradley 1958). The Latin square was incomplete as the number of participants and test conditions was not large enough to use all possible combinations of testing order. Using an incomplete Latin square gave some of the benefits of counterbalancing without testing more participants than required. The running order of the testing session is outlined in the flow diagram (figure 6.4); total testing time (excluding the hearing test screen) was between 60 and 75 minutes depending on the speed of participant responses.

The number of trials per condition/azimuth was chosen to ensure that there were sufficient repeats within a sensible time frame to minimize participant fatigue.

Participant responses were converted from letters (A-M) to azimuth in degrees (-90º to 90º). The MAE was automatically calculated for each set of responses and stored within the MATLAB software. MAE was calculated as the mean difference between actual source location and perceived source location for each stimulus condition. This measure is commonly used in localisation studies of this type (Letowski and Letowski 2011, Bogaert et al. 2006). Further analysis methods used are described below.

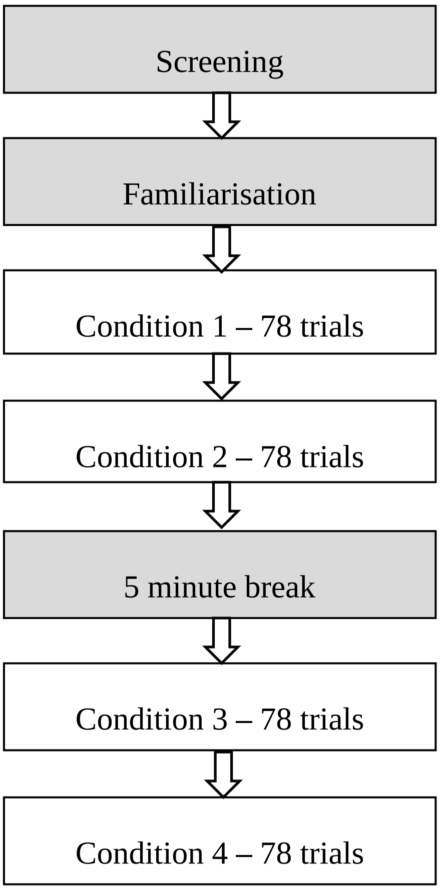


*Figure 6.4 Flow diagram to show the order of testing during the localisation experiment. Participants were allowed to take breaks at any point between conditions but one 5 min break was enforced.*

### 6.2.6 Analysis methods

Individual participant data for each stimulus condition were collated in a 13x6 matrix (six responses for each of the 13 source locations) and analysed using custom MATLAB code (Rowan and Lutman 2007). Further statistical analysis was carried out using SPSS (v22).

Methods of analysis for localisation judgements have been discussed in detail in chapter 4. A range of measures are reported in this chapter: MAE, RMS error, signed constant error (E), unsigned/bias error (C) and lateral percent correct (LPC) scores. These analysis techniques were chosen as they are collectively able to describe the distribution of participant responses and provided sufficient information to compare the current studies with previous localisation literature (eg. Zotkin et al. 2003, Begault et al. 2001). For further details see section 4.3.2 and the analysis MATLAB code in appendix E (part 4).

In order to ascertain whether participant localisation accuracy was better than chance, a Monte Carlo statistical simulation was used. If a participant was not able to localise then they would (in theory) select a source at random, without bias, for every stimulus presentation. A MATLAB program was written (by Ben Lineton, appendix E, part 5) to generate RMS error scores for 10,000 theoretical participants randomly selecting sources. The mean scores, together with the $5^{th}$-$95^{th}$ percentile, were calculated for individual source locations. If a stimulus was presented from the furthest left source (A), a randomly selected response source could range from correct (A) to incorrect by 180° (M). However, if a stimulus was presented from the centre source (G), a random response could range from correct (G) to incorrect by 90° (A or M). This causes the RMS error for selecting a source at random to vary between source locations, as shown in figure 6.7 (section 6.3.3).

### 6.2.7 General participant characteristics

Participant characteristics varied depending on the aims of the individual study and are therefore outlined at the start of each relevant section. Exclusion criteria remained the same throughout.

Participants were excluded if they:

- Had experienced any ear disease within 3 months (infections, discharge, pain)
- Underwent ear surgery within 3 months prior to the study
- Had a history of noise exposure within 48 hours of the test
- Suffered from hyperacusis
- Had excessive or occluding wax
- If they were considered unable to understand and/or complete the task

## 6.3 Study 3 – Piloting the virtual source identification task

### 6.3.1 Introduction

A pilot study of normal hearing participants was carried out to ensure that the experimental setup yielded results that were in concurrence with previous literature for the generic broadband noise stimulus. This pilot study was also to ensure that that the gunshot stimuli sounded external to the participants head and from a direction approximately in relation to the original recording. Further details and analysis of study 3 are presented in appendix H.

***Aim:*** To ensure that the virtual source identification task is able to appropriately assess localisation ability using a broadband noise stimulus and recorded gunshots.

### 6.3.2 Specific method and participants

The method used is outlined in section 6.2. Recordings created 50 m downrange from the firer were used and testing was carried out in a 3x3 m sound treated room at the University of Southampton. Twenty normal hearing university students were opportunistically recruited according to the exclusion criteria in section 6.2.7. All participants had normal hearing (thresholds in both ears below 20 dB HL at 0.25, 0.5, 1, 2, 4 and 8 kHz).

### 6.3.3 Results

Table 6.2 and figure 6.5 show both the RMS error and MAE data for the four stimulus conditions (to allow easy comparison with previous literature). There were varying levels of localisation accuracy between the conditions. RMS error and MAE were calculated from all participants and all azimuth repeats in each stimulus condition. Standard deviation was calculated from all data points across all participants within each stimulus condition.

*Table 6.2 Study 3: Root mean square, mean absolute error and standard deviation data. All values in degrees.*

| Stimulus condition | RMS error | RMS error SD | MAE | MAE SD |
|---|---|---|---|---|
| Gunshot | 28.2 | 6.2 | 19.2 | 7.2 |
| Crack | 33.1 | 7.7 | 24.4 | 7.0 |
| Thump | 22.7 | 5.8 | 17.0 | 7.4 |
| Broadband noise | 16.4 | 3.7 | 13.8 | 4.5 |

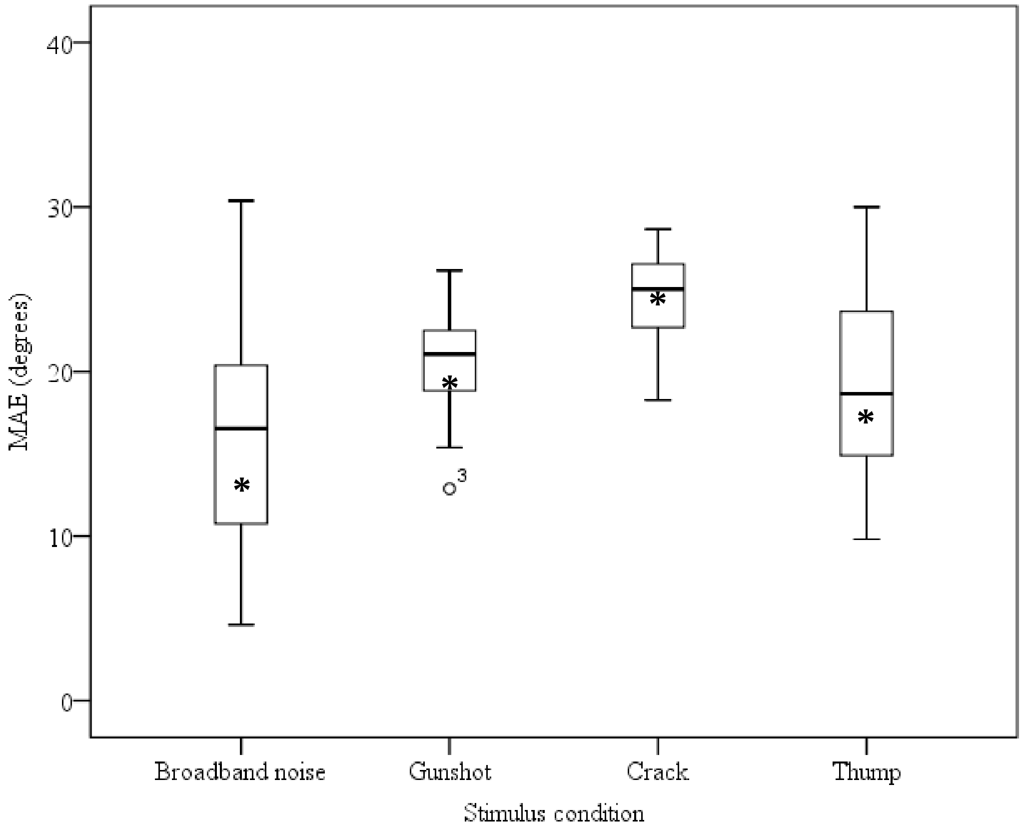


*Figure 6.5 Study 3: Box plot to show distribution of participant MAE for the four stimulus conditions (n=20). The central rectangle spans the first to the third quartile. The horizontal line through the box gives the median value and the 'whiskers' show the locations of the minimum and maximum response value. The star represents the mean value.*

As shown in figure 6.5, the greatest range of localisation accuracy scores was observed in the broadband noise stimulus (the most accurate score was 5º MAE and the least was 30.5º). The SD was smallest for the noise condition (MAE = 13.8, SD = 4.5), indicating that the majority of participant scores were clustered close to the mean.

Whilst scores were on average poorer for the gunshot and crack conditions, the spread of scores was small with all participants' achieving scores between 12º and 26º MAE. The SD of the gunshot condition was considerably larger than observed from the noise condition (MAE = 24.4, SD = 7.0) showing that the data points were spread further from the mean value.

To ensure that the stimuli were perceptually matched to their actual source location the RMS error rates for each azimuth were analysed. Figure 6.6 contains the RMS error scores from all participants for each source location.

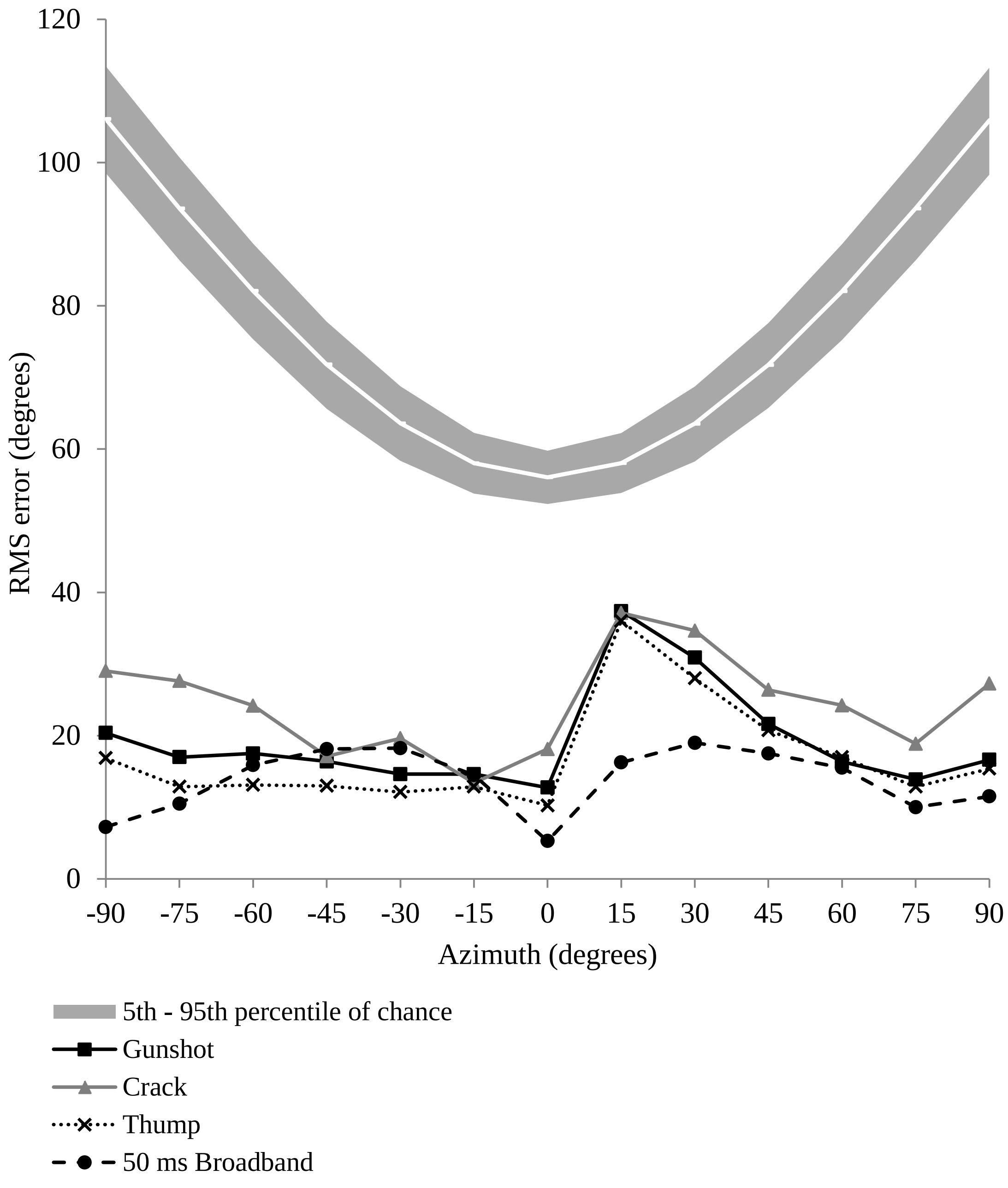


*Figure 6.6 Study 3: RMS error per azimuth (averaged from 20 participants). A large systematic error for the gunshot stimulus (and its component parts) can be seen between 15 and 45 degrees (with mean errors up to 37.4 degrees). The white line demonstrates mean RMS error of a participant selecting sources at random without bias as described on page 133 (grey shaded area shows 5$^{th}$- 95$^{th}$ percentile).*

From figure 6.6 it was clear that there was a consistent increase in error rates for the gunshot, crack and thump conditions between 15 and 45 degrees azimuth. This error was not present in the broadband noise condition indicating that the error was introduced in the recording, processing or presentation of the gunshot, crack and thump stimuli. This anomaly would have had a significant impact on the overall RMS values and therefore the differences between gunshot and broadband noise conditions.

### 6.3.4 Discussion

Notwithstanding the systematic errors found using the gunshot, crack and thump stimuli, participants were able to locate the source of the broadband noise stimulus to a similar degree of accuracy when compared to previous published studies. Zotkin et al. (2003) carried out a study to determine the effect of HRTF personalisation on localisation accuracy of various stimuli. One stimulus condition was created using KEMAR's small pinnae HRTFs (as opposed to individualised HRTFs) and localisation accuracy was measured virtually, using a 93 ms burst of white noise. Participants were required to look in the direction of the perceived sound source - any point between -90 and 90 degrees azimuth. Responses were measured using a head tracking system and the MAE (not reported in the article, but calculated from the reported means of all participant scores for that condition) was 16.07 (SD 6.4). This is similar to the MAE results reported for the broadband noise condition in the current study (MAE = 13.8, SD = 4.5). Participants may have been more accurate in their responses as the current study gave participants a frame of reference (in the form of 13 defined locations) whereas Zotkin et al. (2003) allowed participants to select (via a head turn) any point in the frontal horizontal plane. It is known that the response method has an effect on the localisation accuracy of normal hearing listeners (Brungart et al. 2000). It is also possible that the small sample size in the Zotkin study was not sufficient to achieve a representative mean; they recruited only eight participants and there were considerable variations in participant MAE scores (the highest score was 27.1º and the lowest 7.6º compared with 24.6º and 4.6º respectively for the current study). The final potential reason for the difference between the current study's findings and those of Zotkin et al. (2003) was the pinna size used for the HRTF convolution of the noise stimulus. Zotkin et al. used KEMARs small pinnae and the current study used large pinnae; if the large KEMAR pinnae closely matched the participants own pinnae then this could have improved participant performance in the current study.

The error measured at each source location for the broadband noise stimulus also follows the expected pattern when compared to previous literature. Participants found it easiest to locate the source when it was directly ahead (0º azimuth) or to the extreme left or right of the head (-90º and +90º). Participants couldn't select source locations beyond 90 degrees to the left and right and therefore, even if a sound had appeared to originate from behind them, they were forced to select the letter A or M as the closest available option. This 'end effect' is likely to be responsible for the low error rates observed at 90º and -90º.

When ITD and ILD cues are 0 (as would be the case with sound presented from 0º azimuth) humans are very successful at locating the sound source (Middlebrooks and Green 1991). This can be seen from figure 6.7, participants were able to judge sounds from 0º azimuth to within 5º of the target. The highest error rate measured for the broadband noise stimulus was between 60º and 15º (and -60º to -15º). This was consistent with the findings of Makous and Middlebrooks (1990) who documented larger localisation errors at angles between 40 and 60 degrees when compared to 0 degrees (6.1º error at 40º azimuth, 9.7º error at 60º azimuth compared with 2.2º error at 0º azimuth). Whilst the pattern of error was very similar to the current study, the error scores observed at all azimuths were much lower than the current study. This is because Makous and Middlebrooks used a freefield experimental design; participants are more successful identifying source locations in this paradigm compared to virtual stimuli with non-individualised HRTFs (Begault et al. 2001).

The localisation accuracy of the broadband noise stimulus would suggest that the experimental design is fit for purpose and the results concur with previous literature. However, some of the results from the gunshot conditions were concerning. As the increase in error rates at 15 and 30º were consistent throughout the gunshot, crack and thump conditions, it was clear that the problem was introduced in the recording of the gunshots. When re-inspecting the ILD and ITD measurements (discussed in chapter 5, figures 5.13 and 5.14) it was apparent that the interaural measurements were abnormally high at 15 and 30 degrees, causing them to fall at levels almost consistent with a shot fired at 45 degrees (figure 6.7).

It appeared that the most likely cause of this alteration in the shot source was an incorrect movement of the turntable; the final two turns (corresponding to the 15 and 30º recordings) appeared incorrect/incomplete during the recording session. This was confirmed when participant responses were inspected. The vast majority of incorrect responses at 15 and 30º were higher than the correct azimuth, with most individuals perceiving the stimuli to originate from 45º, 60º or 75º azimuth.

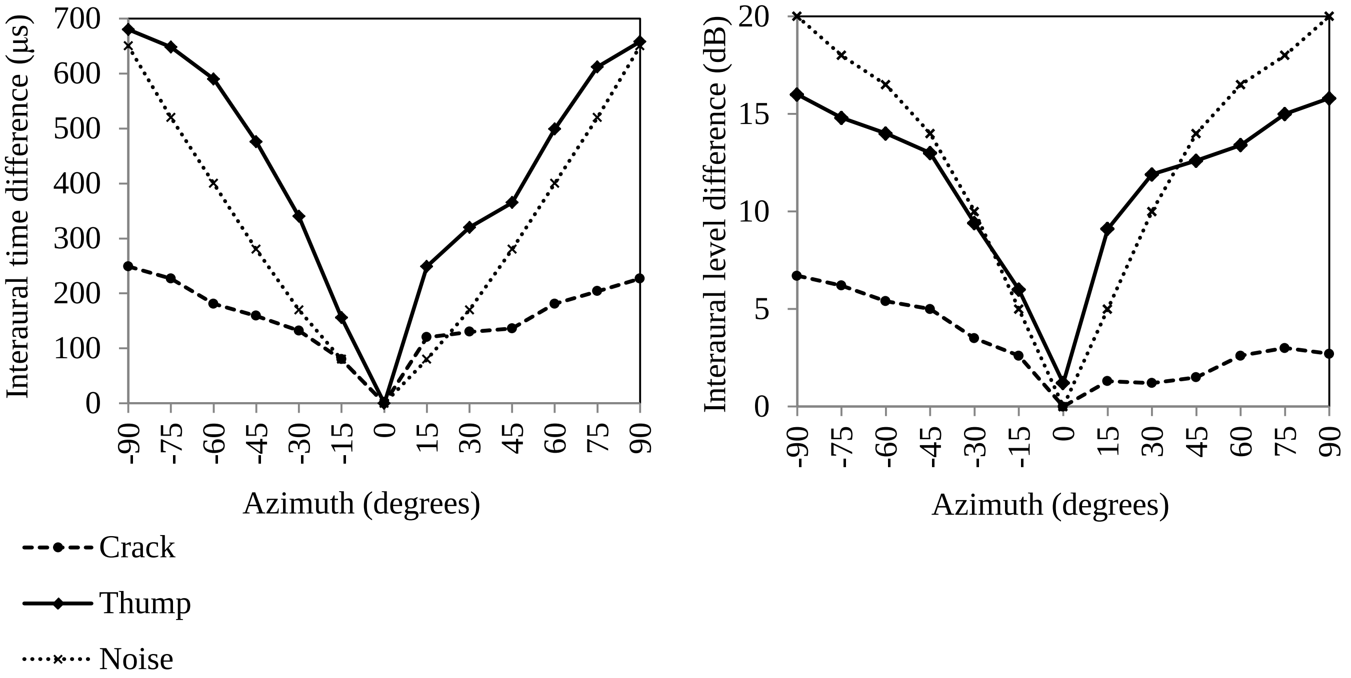


*Figure 6.7 (repeat of fig 5.13 and 5.14) Graphs showing ILD and ITD of crack and thump from 50 m downrange. At 15º and 30º the ITD and ILDs measured are higher than expected when compared with the measurements at -15º and -30º.*

### 6.3.5 Conclusions, knowledge gaps and justification for study 4

The findings of study 3 confirmed that normal hearing human listeners are able to localise a gunshot sound but the degree of accuracy remains uncertain due to systematic errors within the recordings used.

The localisation accuracy measured for the broadband noise stimulus was broadly similar to previous literature, suggesting that the localisation rig and the sound reproduction system are an appropriate way of measuring localisation accuracy for this stimulus.

**Justification for study 4**

The source identification task piloted in study 3 was able to accurately assess localisation ability using a broadband noise and gunshot stimulus. As there were other small arms recordings at distances further downrange available, it was possible to maintain the same successful study design and to change the recordings used. Study 4 was designed to address two knowledge gaps highlighted from the literature review:

- **For a 'live' small arms gunshot, the localisation accuracy of normal hearing listeners is not known.**
- **It is not known whether a human listener is able to localise the separate components of a gunshot (crack and thump) using the spatial cues available.**

## 6.4 Study 4 – How accurately can normal hearing civilians localise a small arms gunshot?

### 6.4.1 Introduction

Study 4 was carried out as a repeat of study 3 using a different set of recordings in order to remove the systematic error observed. In accordance with the original aim of study 3, study 4 was used to further determine whether the virtual localisation method was suitable to assess human localisation accuracy. This underlying aim was addressed by comparing the data collected with data from previous literature, reported in section 6.4.3. Gunshot recordings created at 100 m downrange were processed in the same way as the 50 m recordings (described in section 6.2.3). Before study 4 commenced, the recordings made at 100 m downrange were checked for any unusual patterns in ILDs and ITDs using the MATLAB programme described in section 5.4.4. Figure 6.8 shows that the ILDs and ITDs measured for the crack and thump stimuli were not exactly as expected but the ILDs and ITDs for azimuths either side of 0º were better matched than measured from the previous 50 m measurements. As the turntable was manually controlled for the 100 m recordings there were no concerns about incomplete turns. It is likely that variation in the 100 m ITD and ILD cues were due to off axis shooting or the changeable weather conditions. From the interaural data it was possible to form hypotheses about the expected localisation accuracy of the gunshot components.

**Aims:** The primary aim of Study 4 was to assess the localisation accuracy of normal hearing civilian listeners using a gunshot stimulus. Further to this, it aimed to determine the effect of the varying ITD and ILD cues contained within the gunshot components on localisation accuracy. It is important to ensure that all normal hearing listeners are able to locate the source of small arms gunfire to a satisfactory level prior to considering localisation as an important aspect of military AFFD.

**Research questions:**

1) How accurate are normal hearing human listeners in localising the source of small arms gunfire?
2) Is there an effect of stimulus condition on localisation accuracy for components of a small arms gunshot?

**Hypotheses:**

1) Normal hearing civilian listeners will be able to locate the source of small arms fire using a virtual localisation test to a degree of accuracy greater than selecting a source azimuth at random. Study 3, with the systematic error, demonstrated that normal hearing listeners were able to locate the source of small arms gunfire to within 28º RMS error. Assuming that Study 4 will not have the same error present, the RMS error should be lower indicating more accurate participant responses when averaged across the azimuths.
2) It was hypothesised that there would be a significant difference between localisation accuracy for different stimulus conditions owing to the varying binaural cues available to the listener (further justification for these hypotheses is provided in section 5.3.4).
    - It was predicted that the broadband noise would be most easily localised due to the readily available ITD and ILD cues and broadband nature of the signal.
    - It was hypothesised that the thump would cause higher RMS error scores (compared with the broadband noise) due to the narrower bandwidth of the signal. Further to this, the thump was expected to cause higher lateral bias due to the higher than expected ITD cues at any given azimuth, when compared with the broadband noise (as shown in figure 6.8).
    - It was predicted that the crack condition would cause a greater central bias in responses. The ILD cues (the predominant localisation cue for high frequency sounds) present in the crack were lower than those in the noise signal and this should cause listeners to perceive the source more centrally. Further to this, the confusing origin of the signal (containing some additional elevation cues) may result in a higher overall RMS error rates due to an increase in guessing.
    - As both crack and thump are audible, a listener could rely on the binaural cues contained within the thump and locate the whole gunshot with the same accuracy as the thump signal alone. However, human listeners have a tendency to locate a sound source based on the first arriving sound (in order to ignore reflections, Hartmann (1983)) and this may increase participants' reliance on the crack portion of the signal. Listeners may be divided between these two options; causing the overall error scores of the gunshot condition to fall in between that of the crack and thump individually.

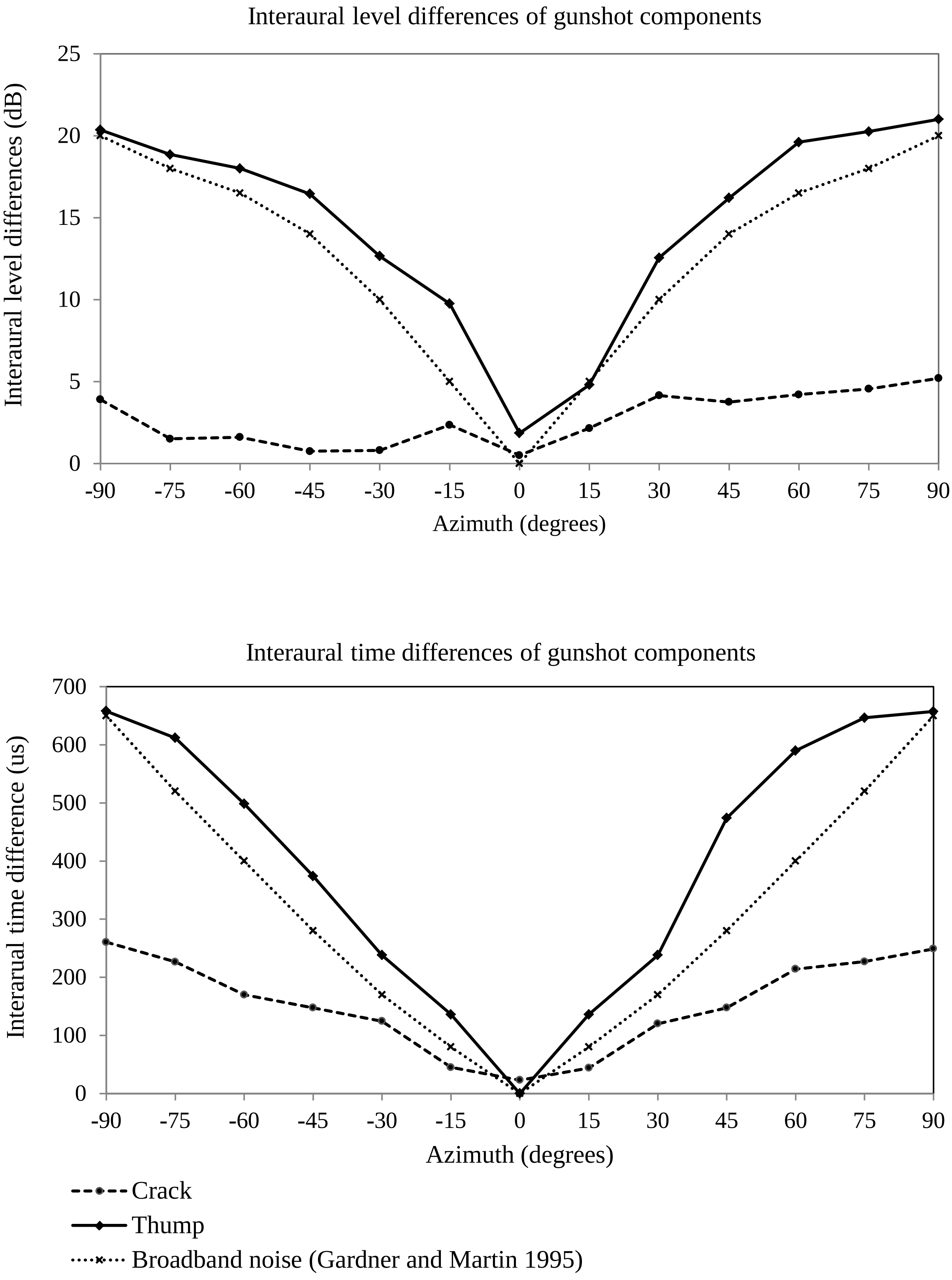


*Figure 6.8 Interaural level differences (top figure) and interaural time differences (bottom figure) of crack and thump at 100 m downrange. Broadband noise from Gardner and Martin (1995).*

### 6.4.2 Specific method and participants

The method used is outlined in section 6.2. Recordings created 100 m downrange from the firer were used.

Twenty normal hearing participants were opportunistically recruited according to the exclusion criteria outlined in section 6.2.3. Twelve participants took part in both study 3 and study 4, with four months in between testing sessions. The participant characteristics are in table 6.3.

The sample size was calculated based upon a null hypothesis of no significant difference in RMS error between stimulus conditions. Twenty participants were required assuming (from the pilot data) a least significant difference between the stimuli conditions of 5 degrees and a SD of 5.1 degrees, with the significance level of alpha set at 0.05 and a power of 85%.

*Table 6.3 Study 4: participant characteristics*

| **Characteristic** | **Number of participants** |
|---|---|
| Gender - M (F) | 9 (11) |
| Age - Mean (range) | 25 (19-35) |
| Handedness - R (L) | 18 (2) |
| Eye dominance - R (L) | 14 (6) |
| Experience with Firearms - Y (N) | 4* (18) |

*two participants had participated in recreational rifle shooting for <1 year, one had completed one hour of clay pigeon shooting and a fourth had conducted one year of national service in China.

### 6.4.3 Results

**How accurate are normal hearing human listeners in localising the source of small arms gunfire?**

On average, the normal hearing listeners were successful at locating the source of the gunshot to within 21º of the target (MAE) (27.5º RMS error) (table 6.4). The participant responses for the gunshot stimulus ranged between 16º and 46º RMS error.

*Table 6.4 Study 4: RMS and MAE values. All values are given in degrees.*

| **Stimulus condition** | **RMS error** | **RMS error SD** | **MAE** | **MAE SD** |
|---|---|---|---|---|
| Gunshot | 27.5 | 7.6 | 20.9 | 5.1 |
| Crack | 31.5 | 4.9 | 25.2 | 4.1 |
| Thump | 21.9 | 5.0 | 19.4 | 5.6 |
| Broadband noise | 17.0 | 4.8 | 16.2 | 3.3 |

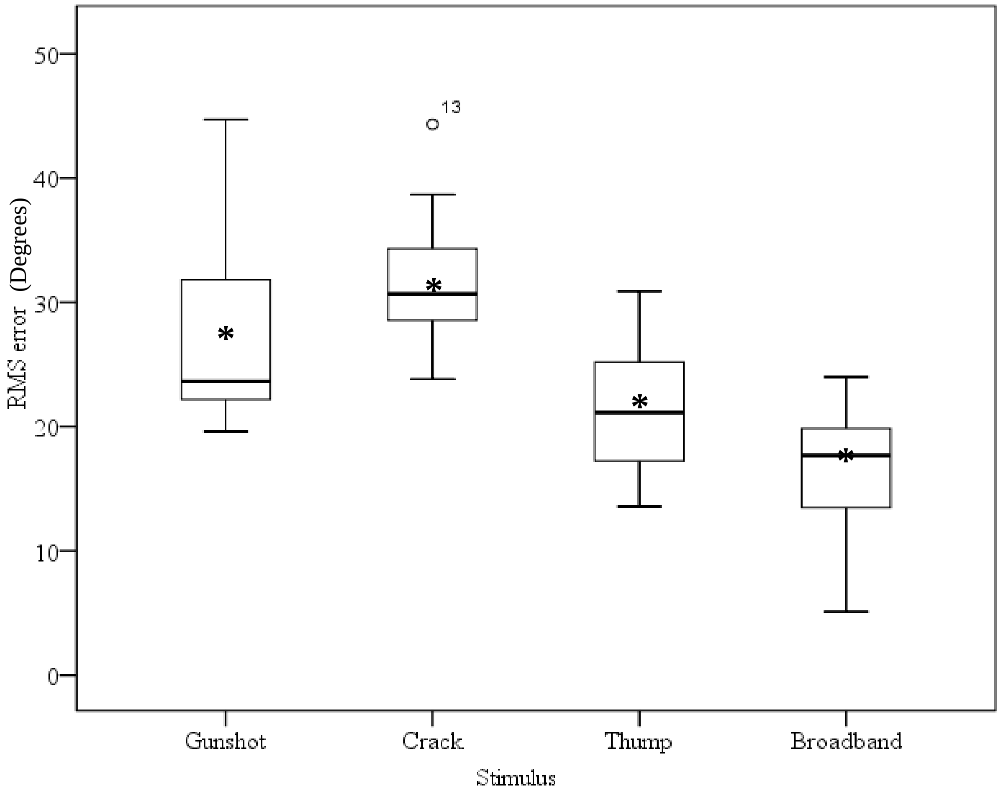


*Figure 6.9 Study 4: Boxplots to show the distribution of participant responses (in RMS error) for the four stimulus conditions (n=20). Star symbol represents the mean value. The RMS score associated with selecting a source azimuth at random is 56º± 4º when the actual source is 0º azimuth.*

Figure 6.9 shows that there was a large range of localisation accuracy scores across the four stimuli conditions. The greatest range of scores (and the largest SD) occurred in the gunshot condition, demonstrating that the participant scores were not closely clustered around the mean. The range of scores and standard deviations are similar among the other three stimulus conditions, despite the mean values differing considerably.

Figure 6.10 demonstrates that, at all azimuths, participants' RMS error scores were significantly lower than chance (shown by the white line). No single participant score, at any azimuth, crossed the line associated with selecting sources at random, indicating that all participants performed the task with some degree of success. No systematic errors were present, although the error rates were variable across source locations. Both the noise and thump conditions show a similar pattern of errors to each other with participants demonstrating greater accuracy at zero degrees azimuth and towards the lateral extremes. Further analysis was carried out to determine the differences in localisation accuracy between the gunshot components and to explore the way in which human listeners utilise the ITD and ILD cues present in the stimuli.

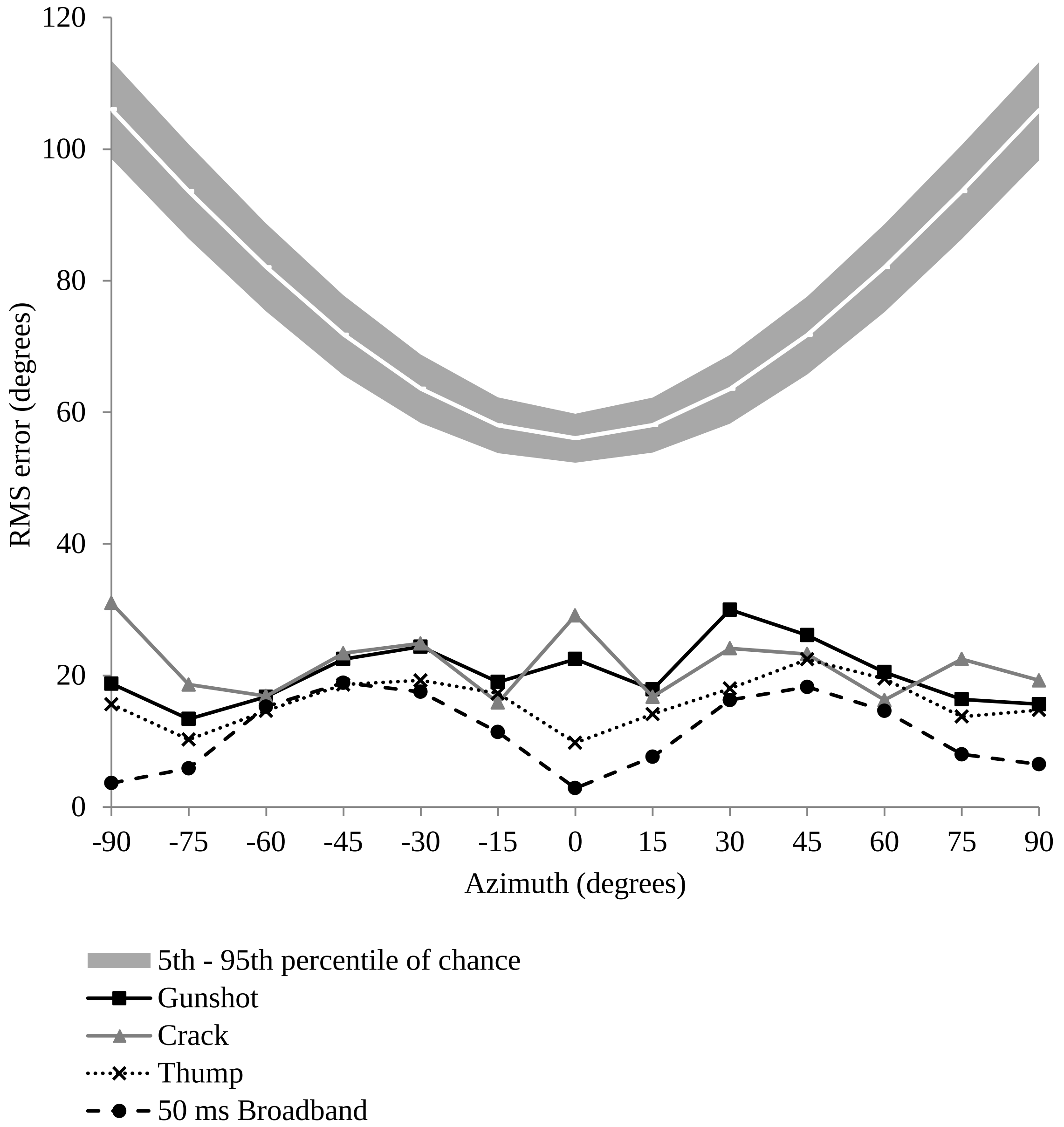


*Figure 6.10 Study 4: RMS error per azimuth. Error rates are variable across the source locations but no obvious systematic errors can be seen in the noise or gunshot stimuli. The white line demonstrates mean RMS error of a participant selecting sources at random (grey shaded area shows the $5^{th}$- $95^{th}$ percentile; analysis method is described on page 133).*

**Is there an effect of stimulus condition on localisation accuracy for components of a small arms gunshot?**

Table 6.4 shows RMS error and MAE values from study 4. There was a significant difference between stimulus conditions.

Repeated measures analysis of variance (ANOVA) showed significant differences between all stimulus conditions, indicating that normal hearing listeners consistently perform better using a broadband noise stimulus than a gunshot and that the varying ILD and ITD cues within the gunshot components appear to affect overall localisation accuracy.

All conditions were approximately normally distributed except for the gunshot condition as measured by Shapiro-Wilks test. ANOVA was used as it is somewhat robust to violations of normality. Mauchly's test indicated that the assumption of sphericity had been met $\chi^2$ (5) = 5.14, $p$= 0.398. The results show that there was a significant effect of stimulus condition on localisation accuracy (measured in RMS), $F(3,57) = 39.84$, $p < .001$. Post hoc tests (with Bonferroni correction applied to reduce the chance of type 1 error) indicated that there were significant differences in localisation accuracy between all of the conditions. Pairwise comparisons are shown in table 6.5.

*Table 6.5 Study 4: Pairwise comparisons of stimulus conditions (Bonferroni correction applied due to multiple comparisons).*

| **Condition** | Crack | Thump | Broadband noise |
|---|---|---|---|
| Gunshot | ✓ ($p$< .001) | ✓ ($p$= .013) | ✓ ($p$< .001) |
| Crack | | ✓ ($p$< .001) | ✓ ($p$< .001) |
| Thump | | | ✓ ($p$= .002) |

Whilst it was clear that there were differences in localisation accuracy between stimulus conditions, it was not known whether these were due to variations in the stimuli or a result observed due to random variation in the population. It was hypothesised that all individuals would perform with greater degrees of accuracy for the noise condition when compared to the gunshot, for example. Therefore, performance on the different stimulus conditions should correlate with each other; an individual who performed poorly in one condition might be assumed to perform poorly on others. Using Pearson's r it was possible to approximate this relationship; there was a moderate correlation between the broadband noise and gunshot stimulus (r = .55, n = 20, $p < .001$). This shows that over 30% of the variability in gunshot scores can be predicted from broadband noise scores. It is not possible to accurately predict localisation accuracy for the gunshot stimulus from the broadband noise scores alone. Whilst a participant who performed well during the noise condition was more likely to perform well during the gunshot condition it was also apparent that any two individuals with the same noise condition score could have performed very differently for the gunshot condition (as shown in figure 6.11).

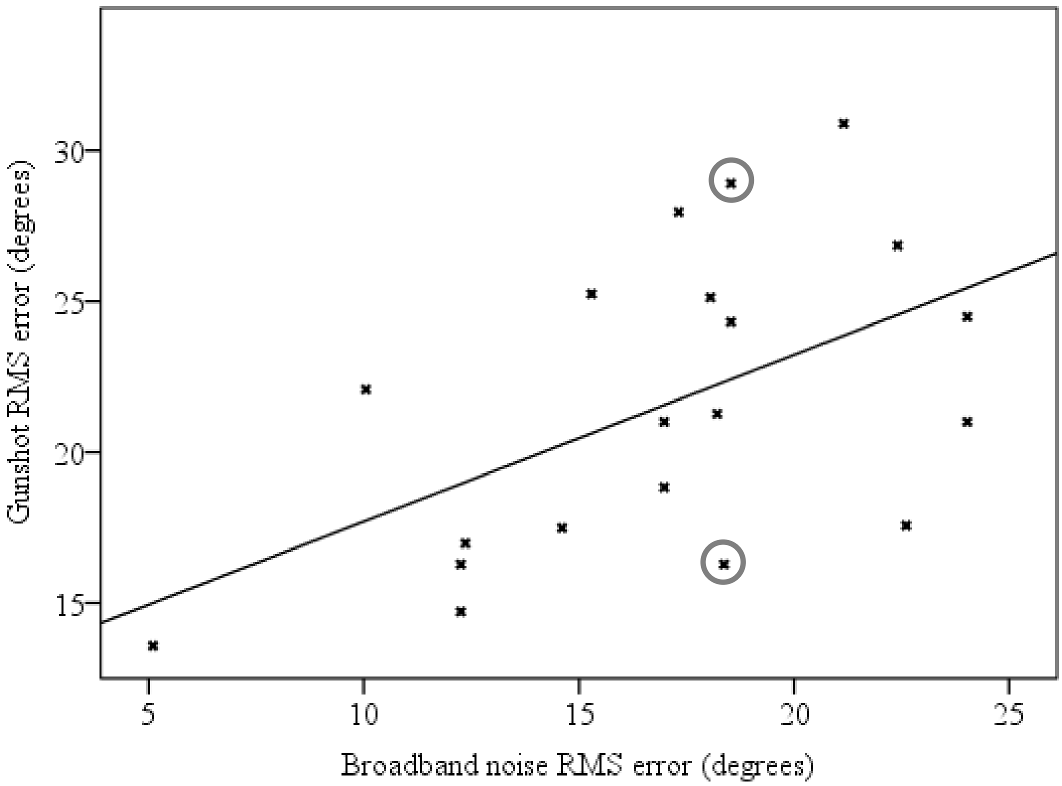


*Figure 6.11 Study 4: Correlation between localisation error for gunshot and broadband noise stimuli with regression line, $R^2 = 0.31$. Whilst there was a moderate correlation overall, two participants (circled) with the same RMS error for the broadband condition (18.5º) performed very differently for the gunshot stimulus (17º and 28.5º respectively).*

The differences observed between the stimuli conditions extended beyond overall error scores. The distribution of errors for each of the conditions was of interest as it was hypothesised that the availability of ILD and ITD cues would alter the way in which source azimuth was perceived. To examine this in more detail, bubble plots were created to illustrate the patterns of errors for each stimulus (shown in figure 6.12).

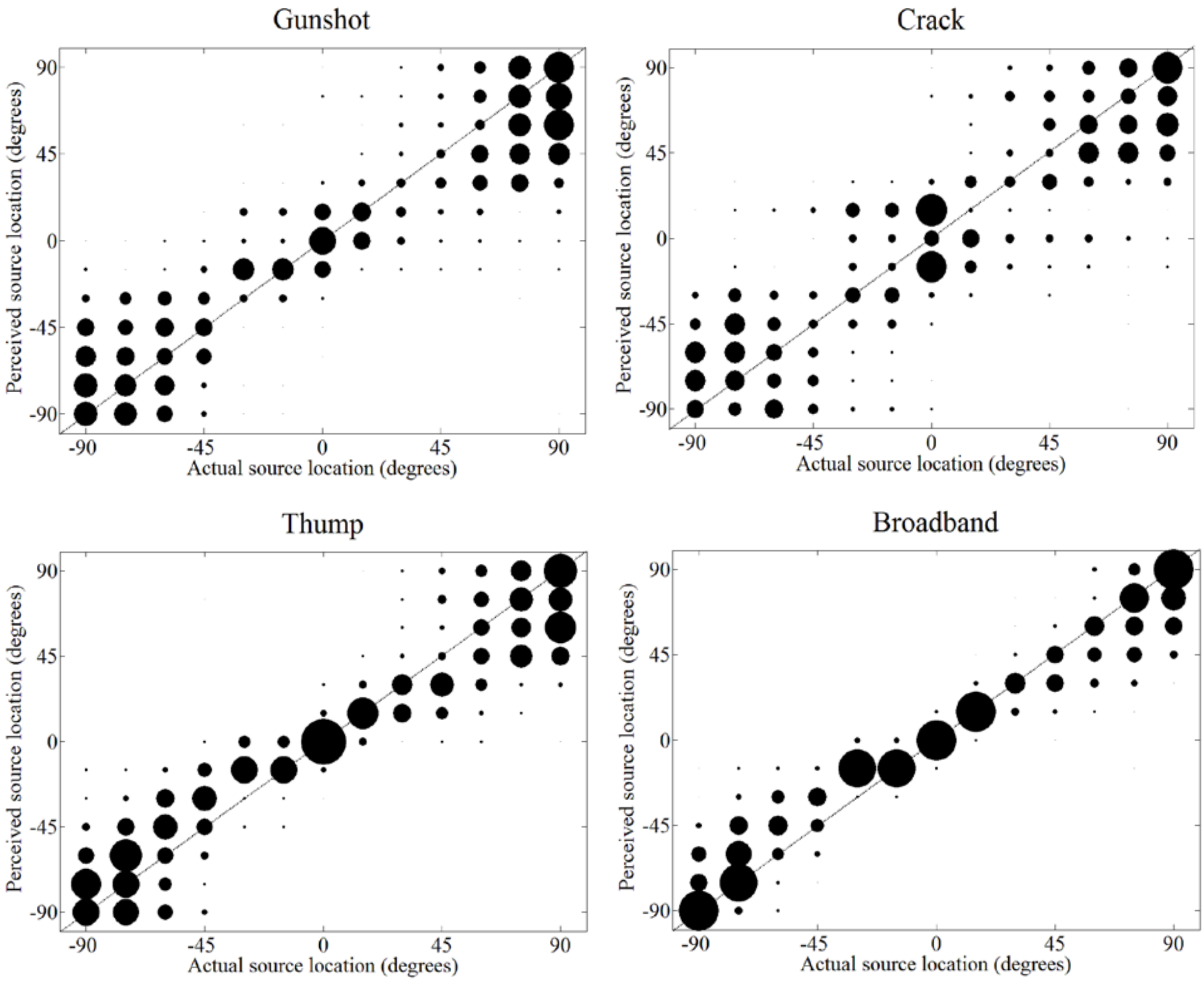


*Figure 6.12 Bubble plots to show the distribution of responses from all participants. The diagonal line represents a correct response and bubble area represents the number of responses. For example, 99 participant responses correctly pinpointed the broadband noise stimuli arising from 0° azimuth as opposed to only 43 for the gunshot stimulus. The largest bubble (0°, thump) represents 124 responses and the smallest bubbles represent 2 responses.*

The unsigned error (C, a measure of central or lateral bias described in section 4.3.2), RE and signed error (E, a measure of constant bias to the left or right) were measured and are reported in table 6.6.

*Table 6.6 Study 4: Measures of random error (RE), unsigned error (C) and signed error (E). All values given in degrees.*

| Condition | Random Error (SD) | Unsigned error (SD) | Signed Error (SD) |
|---|---|---|---|
| Gunshot | 19.4 (6.0) | 20.2 (7.9) | 2.4 (5.6) |
| Crack | 24 (5.0) | 22.2 (4.7) | 3.2 (6.3) |
| Thump | 13.7 (3.6) | 17.3 (5.1) | -0.2 (5.2) |
| Broadband noise | 11.9 (2.7) | 12.8 (4.9) | -0.6 (2.6) |

It was predicted that the broadband noise stimulus would elicit the smallest amount of random variation and bias as it contained the most useful interaural cues and had the greatest bandwidth of all the stimuli. Further to this, it was hypothesised that the thump stimulus would result in an increase in lateral bias. As shown in table 6.6, there was in increase in bias between noise and thump, however from figure 6.13 this would appear to be a central bias (most apparent at the sources from 30- 90º either side of centre).

It was predicted that the crack stimulus would exhibit high central bias and an increase in chance guessing. The results agree with the hypothesis. Table 6.6 demonstrates that the crack condition did cause participants to perceive the sound more centrally (bias was 22.2º for the crack condition compared with 12.8º for the noise) and the RE scores were also high.

The gunshot stimulus produced C and RE scores similar to, but a little better than, the crack stimulus. This agreed with the hypothesis that some listeners would localise using the binaural cues within the crack and some would use the thump, as both components were audible.

**Reliability of the test method**

The underlying aim of both study 3 and 4 was to create a reliable and robust virtual localisation test that could be used to measure localisation accuracy.

The broadband noise condition was used to compare the current test method with those used in the literature. Table 6.7 contains the results of the current study and previous studies using stimuli convolved with KEMAR HRTFs (Zotkin et al. used small pinnae and Begault et al. did not give details about the pinna size).

*Table 6.7 Study 4: Comparison of RMS and MAE data with previous literature.*

| Study | Stimulus | RMS (SD) | MAE (SD) |
|---|---|---|---|
| **Study 3** | 50 ms 0.1-10 kHz noise | 16.4 (3.7) | 13.8 (4.5) |
| **Study 4** | 50 ms 0.1-10 kHz noise | 17 (4.8) | 16.2 (3.3) |
| **Zotkin et al. (2003)** | 93 ms white noise | 19.6 (7.7) | 16.1 (6.4) |
| **Begault et al. (2001)** | 3 s speech burst | Not reported | 21.7 (7.8) |

The current study produced localisation accuracy scores better than those reported in the literature. This demonstrates that the current experimental design allowed participants to perceive the location of the virtual sound source with a reasonable degree of accuracy even though the HRTFs were not their own. Without data from a study using participants own pinnae it was not possible to calculate the decrease in accuracy caused by generic HRTFs.

Whilst these results are encouraging, they do not give an indication of the test reliability. A reliable behavioural test should give a similar result when used multiple times for the same individual. Ideally a study using a large number of individuals would be carried out to compare performance on two or more occasions; in the absence of these data it was possible to explore the test-retest reliability using data from the 12 participants that took part in both study 3 and 4.

Study 3 and 4 use different gunshot stimuli (recorded 50 m and 100 m from firer) so the gunshot conditions were not compared. The broadband stimulus remained the same throughout so a Pearson's correlation was used to determine the linear association between study 3 and 4 test scores.

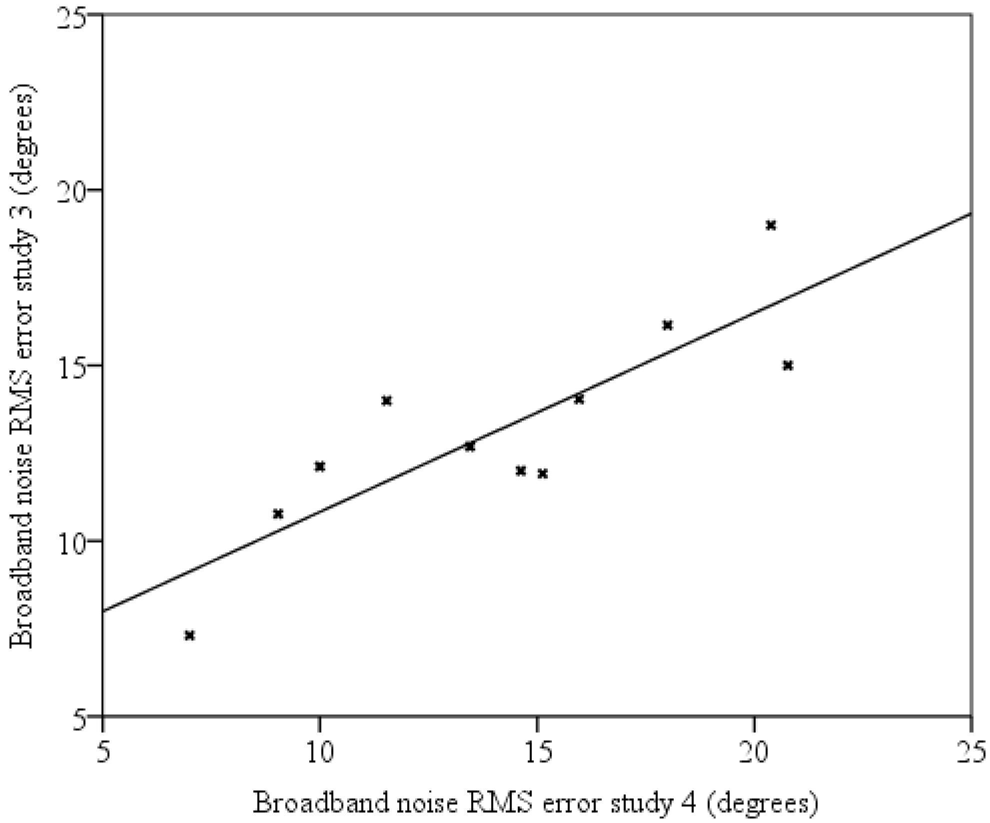


*Figure 6.13 Correlation between RMS error scores for study 3 and study 4. Linear regression line, $R^2$ = 0.78.*

A high correlation was found between the test scores from study 3 and 4 (r = .88, n = 12, $p$ < .01) (shown in figure 6.13). Correlation is a good indication of similarity between sets of scores but it is possible to achieve a high correlation without reliability if participants vary greatly but consistently across both tests. It was also useful to examine the difference in scores between the two tests for individual participants.

Figure 6.14 demonstrates that participants performed similarly on study 3 and 4 with 11 out of 12 participants scoring less than five degrees difference between the two tests. This is an encouraging result and suggests that the test-retest reliability was good, despite the lack of statistical certainty due to the small sample size. The Bland Altman plot (figure 6.14) shows that regardless of individual error scores, the differences between the first and second test scores were stable across participants.

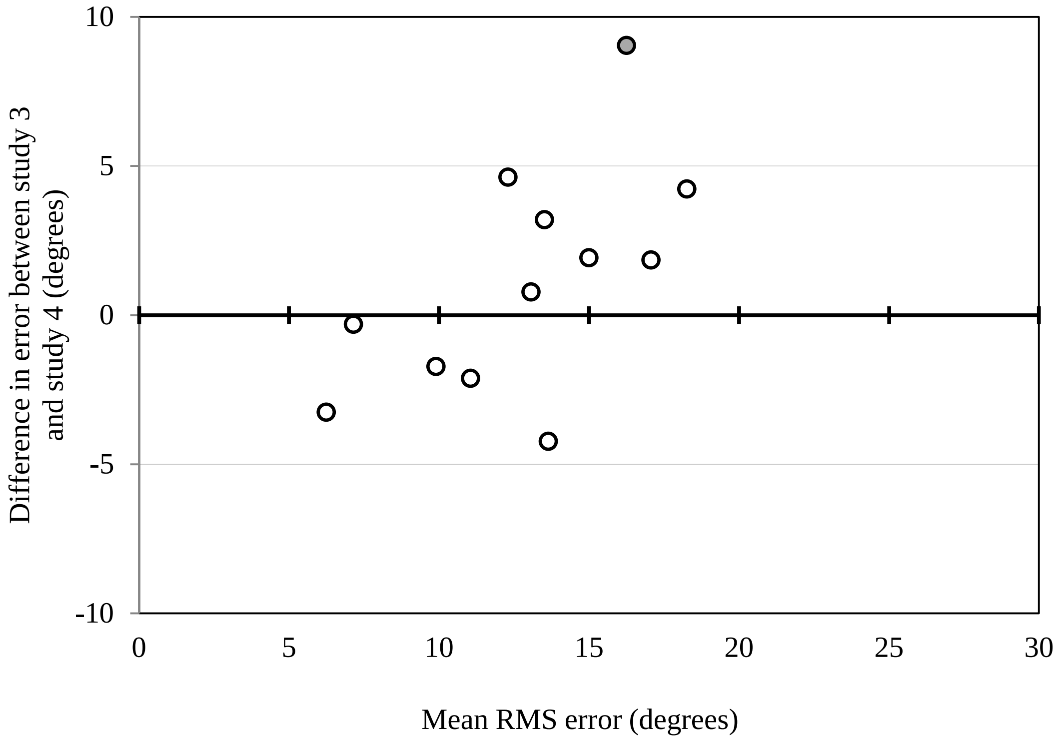


*Figure 6.14 Bland Altman plot to show difference in RMS error scores between study 3 and 4 for the broadband noise condition. Only one participant scored >5 degrees difference between study 3 and 4 (shaded in grey).*

### 6.4.4 Discussion

Study 4 aimed to measure the localisation accuracy of normal hearing civilian listeners as a starting point in the development of AFFD measures for infantry personnel. It was hypothesised that normal hearing civilian listeners would be able to localise the source of small arms fire at a level of accuracy above chance. Based upon the findings of Talcott et al. (2012) normal hearing listeners appeared to have some level of success localising a blank gunshot, but the accuracy of this judgement had not previously been measured under controlled conditions or using live ammunition.

The data collected from Study 4 has shown that normal hearing civilian listeners are able to locate the source of SA80 rifle fire to within 27.5º RMS error (SD = 7.6); this was more accurate than a source identification score associated with selecting a source at random without bias (56º± 4º at 0º azimuth). The measured level of accuracy was similar to that reported by Talcott et al. (2012); they found that in basic field study of gunshot localisation that the MAE was 22º (SD = 14), compared with 20.9º (SD = 5.1) for the current study. It is worth noting that with only eight source locations and a freefield method, the task used by Talcott et al. was likely to have been easier and the error analysis was calculated with front back errors removed (decreasing error rates). The current study was conducted in a controlled environment using consistent stimuli and can therefore be assumed to be a more accurate estimate of gunshot localisation accuracy with untrained listeners.

The systematic error shown at 15º and 30º azimuth during study 3 was not present in the gunshot recordings used in study 4. The localisation accuracy scores observed for the noise condition in study 4 were consistent with those measured in study 3 (17º and 16.3º RMS error, respectively). As discussed in section 6.3.4 the localisation accuracy for the noise condition was in agreement with previous literature; this was particularly evident when compared to Zotkin et al. (2003) who used a similar virtual localisation paradigm. Zotkin et al. reported an MAE of 16.1 (SD = 6.4) almost identical to the MAE of 16.2 (SD = 3.3) measured in the current study. There were some subtle differences between Zotkins' and the current study, predominantly the participant response method; Zotkin allowed listeners to choose any location in the fontal horizontal plane, whereas the current study had a fixed choice of 13 sources. The similarity in results may indicate that the response method may not have as much influence on localisation accuracy as suggested in the literature (Madjak et al. 2010, Hartmann et al. 1998). A further difference was the pinna size used to convolve the noise stimulus (small pinna used by Zotkin et al. and large pinna used in the current study). The effect of changing pinna size on interaural cues is discussed in appendix F (section 1).

Begault et al. (2001) used a virtual localisation paradigm, similar to the current study, but instead of a noise burst stimuli Begault et al. used a 3 s speech burst. A longer stimulus that varies in intensity and frequency content is known to be more accurately localised than a steady noise burst (Butler and Planert 1976). Despite this, Begault et al. reported 22.5º MAE for their baseline condition (no competing noise), compared with 16.1º (SD = 3.3) in the current study. This difference may have arisen due to the head movements of participants; as discussed in chapter 4 a head movement during a long stimulus presentation can result in an altered spatial image. When head tracking was used and the stimulus source location was altered to compensate for any head movement, Begault et al. found that the error rates reduced to 16.7 (SD = 7.7), very similar to the current study.

In an exploration of test-retest reliability comparing the broadband noise condition from study 3 and 4, localisation accuracy scores were highly correlated ($r = .88$, $n = 12$, $p <$

0.01, 95%). A Bland Altman analysis demonstrated that participants achieved scores with less than 5º deviation between study 3 and 4 (2.7º difference in scores, unsigned, on average). Whilst these measures of test-retest reliability show encouraging results (suggesting that the virtual localisation test produced consistent within-participant data) the small number of participants (n = 12) meant that the analyses had low statistical power. Further to this, it was only possible to predict the reliability of the broadband noise stimulus condition as the gunshot recordings were changed between study 3 and 4; therefore it was not possible to definitively state that the accuracy on the gunshot conditions would be consistent on multiple occasions. Ideally a larger number of individuals would be tested under identical conditions, using all stimulus types, on more than two occasions.

The similarity in findings between the current study and previous literature coupled with the encouraging test-retest reliability suggested that the virtual localisation paradigm was able to successfully and reliably assess performance on a frontal horizontal plane localisation task.

The secondary aim of study 4 was to determine the influence of the varying ITD and ILD cues available from the gunshot components on localisation accuracy. It was hypothesised that there would be a significant effect of stimulus condition on localisation accuracy and that this would relate to the level of ITD and ILD cues present in the gunshot components. It was predicted that participants would have greater success in localising the stimulus types in order of broadband noise > thump > gunshot > crack. It was thought that the broadband noise would be more easily localised due to the wide bandwidth and the resulting ITD and ILD cues. It was hypothesised that the thump condition would cause participants to respond with a lateral bias and increased overall RMS error. This was expected due to the narrower bandwidth and slightly higher than expected ITD cues compared with the noise.

The origin of the higher ITD cues is not known but may be due to factors in the environment or the angle of the bullet (adding additional head or torso shadow effects due to off axis shooting). It was assumed due to the frequency content of the thump stimulus (centred around 500 Hz) that ITD would be the dominant cue for localisation. The ITD of the thump at any given azimuth appeared to be broadly similar to the ITD of a broadband noise stimulus at a point 15º further from 0º. For example, at 30º azimuth the thump ITD was 240 µs, similar to the noise ITD at 45º (285 µs); likewise at -15º the ITD of the thump was 143 µs, close to the ITD of the noise at -30 (172 µs). It was expected that this would cause listeners to perceive the thump sound at a location further away from the centre, resulting in a higher lateral bias.

In agreement with the hypotheses, the thump condition did yield an increase in RMS error compared to the noise condition (noise RMS error = 17º (SD = 4.8), thump RMS error = 21.9º (SD = 5.0)). In further agreement, the thump stimulus caused listeners to exhibit an increase in lateral bias and random error, compared with the broadband noise stimulus (thump C = 17.3, broadband noise C = 12.8; thump RE = 13.7, broadband noise RE = 11.9). This concurs with the evidence that a stimulus with a greater bandwidth yields fewer localisation errors (Butler and Planert 1976, Brungart and Simpson 2009) as consistent ILD and ITD information are both readily available. Listeners would have been able to make use of high frequency ILD cues within the noise signal that were absent in the thump; it is known that high frequency content is critically important for the localisation of isolated signals (Brungart and Simpson 2009).

In addition to the smaller bandwidth, it was plausible that the short duration of the peak amplitude of the thump signal may have made it difficult for participants to gather as much spatial information. The noise signal remained reasonably constant in amplitude for the entire 50 ms burst but the thump signal had a very fast rise time and started to decline in amplitude after the first 10 ms. There is evidence to confirm that the shorter the signal, the higher the number of front-back localisation errors (Macpherson and Middlebrooks 2000). For the current study, using only sources in the frontal plane, these confusions may have resulted in greater end effects; confusion around the lateral sources may have caused participants to select the furthest lateral source if they were unsure. Participants reported that the crack and thump conditions were perceptually more difficult and appeared to guess the source location at 90º or -90º if they were sure of the general direction but unsure of the exact source.

It was hypothesised that the crack condition would yield greater central bias as well as an increase in overall RMS error. The crack is a high frequency signal containing very little ITD or ILD information regardless of the azimuth. It was assumed that the most useful cue for localisation of the crack would be the ILD due to the frequency content. Whilst the ITD cue appeared to be more useful, there is little energy within the crack signal below 1500 Hz limiting the use of ITD information. When the ILD was compared with the noise signal from Gardner and Martin (1995) the azimuth of the crack signal mirrors the ILD of the noise between 0º and 15º azimuth. With regards to judgements of source location for the crack, it was thought that participants would select only the central source locations resulting in a very high central bias.

In concurrence with the hypothesis the crack signal resulted in the highest RMS error rates of all the conditions. It also demonstrated the highest levels of RE (24º compared with 11.9º for the noise condition) and central bias (22.2º compared with 12.8º for the noise). Despite the high RMS error, the crack signal alone was still localised significantly better than if a participant was randomly guessing; somewhat surprisingly the listeners were able to make good use of the reduced spatial cues available. The crack is not, however, the most useful component of the gunshot and listeners are able to make significantly better localisation judgements using the thump signal alone.

It is important to note that the relative amplitude of the crack and thump conditions were not true to life. The gunshot recordings were already considerably below real-world levels (due to the recording set-up and the limits of the recording equipment). Therefore, for the localisation experiment, the crack was further attenuated to an ethical level (105 dB SPL peak amplitude at 90º azimuth) and the thump was amplified to a comfortable audible level. In reality the crack would have been in excess of 150 dB (C) and the thump in excess of 120 dB (C) ($L_{Cpeak}$).

Consequently the comparison of crack and thump conditions have limited applicability and are predominantly useful as a measure of the effect of varying ILD and ITD information. The localisation accuracy of the crack and thump independently does provide information about the usefulness of the gunshot components for localisation. The findings confirmed that the training provided to the infantry (as discussed during study 1, section 3.2.4) to 'listen for the thump and ignore the crack' may be helpful and there may be scope for providing further, more specific, training on localising gunshot sounds in open areas.

A limitation of the current study (and subsequent studies using the same stimulus) was the unknown absolute amplitude of the thump. The peak levels of the crack and gunshot stimulus were measured during the calibration process, the peak level of the thump was not. It is therefore not known whether the relative amplitude of crack and thump during the experiment was similar to the relative amplitude in the real world.

The most meaningful stimulus condition, when considering the development of AFFD measures, was the whole gunshot. The relative amplitude of the crack and thump was maintained and it demonstrated that normal hearing listeners (albeit not military personnel) were able to locate the source of small arms fire with 27.5º RMS error. As both components are audible within the gunshot stimulus it was hypothesised that some listeners would attempt to locate the source based on the spatial cues present in the crack and some would choose the origin of the thump.

The crack sound was louder than the thump and arrives first in the recording. There is evidence to suggest that the auditory system gives the first arriving signal priority when locating a source if multiple sounds are present, similar to the precedence effect (Scharine and Letowski 2005, Hartmann 1983). Unlike the precedence effect, both sounds are clearly separate in the recordings at 100 m downrange giving the listener the potential to use the spatial information provided by the thump if they were able to ignore the confusing crack component. For these reasons it was hypothesised the overall RMS error would be better than the crack signal alone - accounting for those individuals that used the spatial cues from the thump.

The RMS error measured for the gunshot condition was significantly better than the crack condition alone, as expected, and significantly worse than the thump. The range of participant responses was reflected by the larger SD (7.6º, compared with all other conditions <5º). In agreement with the hypothesis, the RE and bias measured for the gunshot stimulus was also in between those measured for the crack and thump. The results obtained from the current study demonstrate that normal hearing civilians are able to locate a recorded 'live' gunshot to a similar degree of accuracy as previously reported for gunshot-like sounds in the literature. Talcott et al. (2012) stated an MAE of 22º (SD = 14º) for a freefield measure of localisation accuracy using blank ammunition, compared with 22º (SD = 5.1º) for the recorded live gunshots used in the current study. The high SD reported by Talcott et al. suggests that the responses from the nine normal hearing participants were highly variable.

The current study has built on the findings of Talcott et al. by using recordings of live ammunition (that contain the sound of the supersonic bullet as well as the muzzle blast) and assumes that the human auditory system would be able to cope with levels as they are experienced in the real-world. In reality the amplitude of the crack may cause trauma to the organ of hearing resulting in temporary or permanent hearing damage. Speculatively, this would be noticeable and distressing to the listener and may happen fast enough to significantly reduce the perceived amplitude of the thump. In addition if the shot was fired very close to the listener the crack and thump could be perceived to be one acoustic event, stopping a listener from separating the components or making use of the binaural cues available within the thump. There would be no ethical way of testing these theories but it is a clear limitation of using an attenuated, recorded gunshot stimulus.

Talcott et al. used military personnel in their study; the major limitation of the current study was the restricted applicability of the findings for infantry personnel. It was thought that with specialist training and experience, infantry personnel would exhibit fewer localisation errors and localise the source of small arms gunfire with greater accuracy.

### 6.4.5 Conclusions, knowledge gap and justification for study 5

The primary aim of Study 4 was to measure the localisation accuracy of normal hearing civilian listeners using a gunshot stimulus. The civilian listeners were able to locate the source of a virtual small arms gunshot to a greater degree of accuracy than chance, in concurrence with the findings of Talcott et al. (2012).

The localisation test developed for the current study was shown to yield results similar to previous studies featuring virtual source identification tasks and comparable stimuli. Comparisons of the data collected from studies 3 and 4, together with data from previous literature, suggested that the test set up was able to reliably and accurately assess performance on a frontal horizontal localisation task.

A further aim of study 4 was to determine the effect of the varying binaural cues contained within the gunshot components on localisation accuracy. There were significant differences in RMS error, random error and lateral bias between the stimuli conditions. These differences were attributable to varying ITD and ILD cues within the stimuli and demonstrated that the thump is a more useful component of the gunshot than the crack, when attempting to locate the origin of gunfire. If military personnel perform in a similar way to civilian listeners, these findings would have significant implications for infantry localisation training exercises and the development of measures of AFFD.

**Knowledge gaps**

At the end of chapter 4 two gaps in knowledge were identified. It was not known whether normal hearing listeners were able to locate the source of small arms gunfire to a degree of accuracy greater than chance. Following the source identification experiment with civilian listeners (demonstrating levels of accuracy far greater than chance), a further knowledge gap needed to be addressed:

- **It is not known whether military personnel perform to the same degree of accuracy on a virtual source identification task as the civilian listeners in Study 4.**

**Justification for study 5**

From the findings of Study 4, it is highly likely that military personnel are able to localise a gunshot stimulus to a degree of accuracy greater than chance. However, due to their occupational background and operational experiences it is possible that their localisation accuracy would differ from the civilian population. It was therefore necessary to compare the data collected from civilian listeners in study 4 with data from a group of normal hearing military personnel. If all military personnel are able to accurately locate the source of small arms gunfire and performance is affected by hearing acuity, then it may be appropriate to incorporate a test of localisation into the AFFD test battery.

## 6.5 Study 5 – How accurately can normal hearing military personnel localise a small arms gunshot?

### 6.5.1 Introduction

Study 5 was designed to examine the differences between the civilian participants who took part in Study 4 and a cohort of normal hearing military participants using the virtual source identification task.

The participants tested during Study 4 were university staff and students, between the ages of 19 and 35 and the sample was split evenly between women and men. The participants had no experience of localising small arms gunfire in a real world scenario and had not received the specialist military training that could be expected to increase performance on the localisation MCAT. The UK military is a male dominated work force (70% male; Rutherford, 2014) from 17 to 60 years of age who have some level of experience, during training and operational tours, of localising military specific stimuli including small arms gunfire.

Training is known to improve performance on some psychoacoustic tasks; Fluitt et al. (2010) found that personnel were able to improve their scores by 16% on a weapon identification task with active-feedback training. The effect of training on localisation accuracy of small arms fire has not been investigated but it is known, and widely reported in the literature, that training improves localisation performance for other stimuli, both in virtual and freefield paradigms (Makous and Middlebrooks 1990, Goupell et al. 2010, Carlile et al. 1997, Middlebrooks 1999, Zahorik et al. 2006).

A further difference between military personnel and the civilians tested during Study 4 is their audiological history. Infantry personnel frequently use firearms and heavy machinery. It is known that few personnel wear their hearing protection regularly (Bevis et al. 2014, Okpala 2007) and due to this, military personnel are likely to have a history of noise exposure. Whilst a pure tone audiogram carried out before testing would highlight any effect of noise exposure on hearing thresholds, there is evidence to suggest that excessive noise affects the auditory system before a measurable decrease in thresholds is observed (Hopkins and Moore 2011, Kumar et al. 2012, Bratticoa et al. 2005). This is of particular importance when the sound to be localised is comprised of mainly low frequency energy (such as the muzzle blast from a weapon) as a human listener with degraded temporal resolution would struggle to utilise ITD cues.

Kumar et al. (2012) noted a decline in temporal processing skills in individuals who were exposed to occupational noise but had normal hearing thresholds. For all of the measures used by Kumar et al. (gap detection, modulation detection and duration pattern tests) a significant effect of noise exposure was found. Similar results were observed by Hopkins and Moore (2011) who measured TFS sensitivity of normal hearing older adults. The older group performed significantly worse on the task than the younger group; Hopkins and Moore suggest this decrease in temporal sensitivity is also likely to occur in noise exposed younger adults with normal HTLs.

From study 4 it was clear that the most important component of a gunshot sound when locating the firing point was the muzzle blast (thump). Even an individual with a significant NIHL may have normal low frequency hearing thresholds, so it was necessary to incorporate a further test to assess the temporal sensitivity of the auditory system at low frequencies. A test of TFS sensitivity was incorporated into study 5 to aid the interpretation of the results from the source identification task.

Both training/experience and noise exposure may affect localisation performance and it was therefore likely that data collected from civilians was not applicable to the military population. Further to this, if there were significant differences between the localisation accuracy scores of the groups then for future AFFD research it would be imperative that only military personnel were used for experiments to ensure that the results are representative of the population.

**Research questions:**

1) Is there a significant difference between the small arms localisation accuracy of normal hearing military personnel and normal hearing civilians?
2) Is there a significant difference between the ITD thresholds (as measured by a TFS sensitivity test) of normal hearing military personnel and normal hearing civilians?

**Hypotheses:**

1) It was thought that civilians and military personnel would perform the localisation task to a similar degree of accuracy providing other listener characteristics remained the same (for example age, handedness). An improvement in accuracy

due to experience would likely be counteracted by a deficit caused by a history of noise exposure.

2) It was hypothesised that, due to a history of noise exposure, military personnel would exhibit significantly higher ITD thresholds than civilian listeners.

### 6.5.2 Specific method and participants

The basic method used was outlined in section 6.2; recordings created 100 m downrange from the firer were used. All participants had normal hearing (thresholds in both ears below 20 dB HL at 0.25, 0.5, 1, 2, 4 and 8 kHz) as assessed by PTA and adhered to the exclusion criteria outlined in section 6.2.7.

Testing military personnel within the guidelines set out by the MoD Research Ethics Committee required many months of planning and a complicated recruitment pathway. Two sites were used for testing – a sound treated room at the Defence Audiology Service at the INM, Gosport and a quiet clinic room (with audiometry booth) at the medical centre of HMS Sultan, Fareham. The author was not able to have any contact with potential participants so an invitation to participate was included with daily orders at both sites. From this, personnel wishing to participate in the study could request more information (in the form of the participant information sheet, see appendix I) from the practice manager at HMS Sultan or the receptionist at the audiology service. The author’s details were issued to the potential participants and the onus was on them to make contact to arrange an appointment. This process would often take many weeks before a participant attended a testing session and meant that many personnel either did not attend their allocated session or cancelled; due to this, testing took five months from March to July 2015.

Despite the complications with the recruitment method, 20 normal hearing military personnel (15 Army and 5 Navy) attended a testing session. Before testing participants completed a consent form, a hearing health questionnaire and a military service questionnaire. Participant characteristics are outlined in table 6.8.

The participants recruited were not all infantry personnel. In order to carry out the testing in the correct conditions (low ambient noise levels, with access to an audiometer and sound proof booth) the testing locations were limited. The Defence Audiology Service and HMS Sultan were chosen as a good proportion of personnel seen in clinic there were serving infantry personnel, but as the author was unable to have access to their personal and occupational details prior to testing, all potential participants were recruited. This resulted in the recruitment of 5 Navy personnel. No obvious differences were found between the localisation accuracy scores of the Navy personnel and the Infantry personnel so the Navy participants were included within the sample. The sample size was chosen to match the group of civilian listeners recruited in Study 4.

In November 2015 (after completion of all experimental work) it was found that an incorrect version of the MATLAB experiment code had been used for studies 5 and 6. The code used was an earlier version of the MATLAB program that presented the gunshot stimuli conditions to participants. The only difference between the two versions of the code was the value used to adjust the stimulus levels. In the correct version of the code (used for studies 3 and 4) the level adjust was set at 0.977; multiplying the signal by this arbitrary value to avoid the digital wav file exceeding +/- 1 at either the left or right channels in the MATLAB code. In the incorrect version, the level adjust was set at 2 for the gunshot and crack stimuli and 8 for the thump stimulus (multiplying the digital signal twice or eight times).

With the digital signal altered in this way, the gunshot-based stimuli would have been severely clipped. It was assumed that this would have, at least, significantly altered the ILD cues present and would likely have affected localisation performance (particularly for the high frequency gunshot and crack conditions). Whilst subjective listening checks were carried out daily during testing, it is possible that (due to the transient nature of the stimulus) the distortion would not have been immediately obvious. As the incorrect code was only used for the gunshot conditions, the broadband noise condition was not affected by the incorrect level adjust and can be directly compared to the data collected from study 4.

*Table 6.8 Study 5: Military participant characteristics*

| **Participant** | **Age** (yrs) | **Gender** (M/F) | **Dominance** (R/L) | | **Time in MoD** (yrs) | **Operational tours abroad** | **Works with small arms** (Y=1/N=0) | **Time since live fire training exercise** (yrs) | **Blast exposure** (Y=1/N=0) |
|---|---|---|---|---|---|---|---|---|---|
| | | | **Hand** | **Eye** | | | | | |
| 1 | 21 | F | R | R | 0 | 0 | 0 | 0 | 0 |
| 2 | 27 | M | R | R | 6 | 1 | 0 | 5 | 0 |
| 3 | 35 | M | R | R | 19 | 6 | 1 | 1 | 0 |
| 4 | 30 | M | R | L | 1 | 0 | 0 | 1 | 0 |
| 5 | 35 | M | R | R | 17 | 3 | 0 | 5 | 0 |
| 6 | 38 | M | R | R | 9 | 3 | 1 | 2 | 1 |
| 7 | 31 | F | R | R | 1 | 0 | 1 | 1 | 0 |
| 8 | 45 | F | L | L | 24 | 4 | 1 | 4 | 0 |
| 9 | 30 | M | R | R | 2 | 0 | 0 | 2 | 0 |
| 10 | 54 | M | L | L | 37 | 1 | 0 | 4 | 0 |
| 11 | 34 | F | R | R | 16 | 4 | 1 | 1 | 1 |
| 12 | 18 | M | R | R | 1 | 0 | 0 | 0 | 0 |
| 13 | 18 | M | R | R | 1 | 0 | 0 | 0 | 0 |
| 14 | 21 | M | R | R | 4 | 0 | 1 | 4 | 0 |
| 15 | 27 | M | R | L | 6 | 0 | 0 | 5 | 0 |
| 16 | 30 | M | R | R | 9 | 3 | 1 | 1 | 0 |
| 17 | 27 | F | R | R | 5 | 2 | 1 | 2 | 0 |
| 18 | 25 | M | R | R | 6 | 1 | 1 | 2 | 0 |
| 19 | 35 | M | R | R | 10 | 0 | 1 | 1 | 0 |
| 20 | 24 | M | R | R | 1 | 0 | 0 | 1 | 0 |
| **Mean/Total** | 30.3 | M=15, F=5 | R=18, L=2 | R=16, L=4 | 8.75 | 1.5 | Y=10, N=10 | 2.1 | Y=2, N=18 |

**Binaural temporal fine structure sensitivity test**

Human sensitivity to ITD cues is commonly assessed by measuring the smallest discriminable difference in the time of arrival at the two ears, referred to as the threshold. The TFS test comprised of a four-interval three-alternative forced-choice discrimination task. This was delivered over insert earphones, using the same equipment set-up described for the source identification task (but without the visual frame of reference used for localisation). The task (developed by Rowan and Lutman (2006)) was similar in design to other adaptive low frequency TFS sensitivity measures used in psychoacoustic studies and have been shown to be reliable and sensitive (Hopkins and Moore 2010). Normal hearing listeners were found to have IPD thresholds in the region of tens of microseconds (Rowan and Lutman 2006).

Each trial contained four successive tones, the first of which was a reference tone (containing no ITD). One of the remaining tones, selected at random, contained an ITD introduced by a phase shift in the fine structure. No ITD was introduced to the temporal envelope of the signal. The listener was required to say which interval contained the phase shift (detecting the ‘odd one out’) (see figure 6.15 for tone presentation). The listener was aware that the ITD would not be in interval one, making the task slightly easier (a choice out of three, not four intervals). No feedback was given throughout, similar to the source identification task, to limit learning effects.

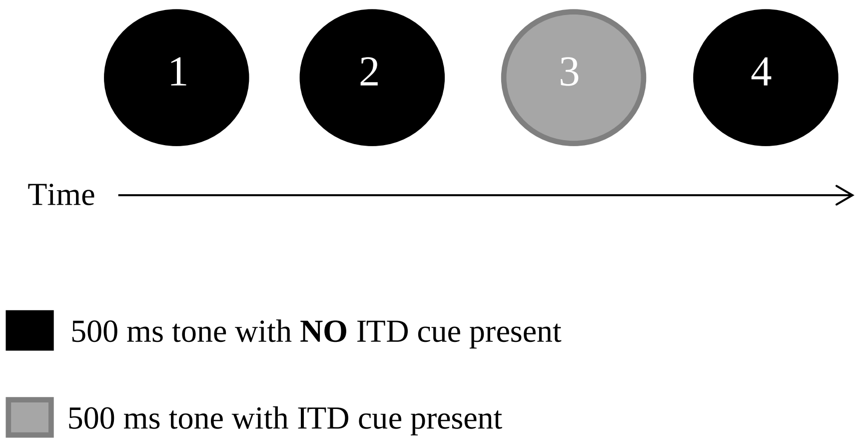


*Figure 6.15 Diagram to show presentation of pure tones in one trial of the TFS test. The first interval never contained the ITD.*

Stimuli were generated digitally using a custom MATLAB program (written by Daniel Rowan, appendix E) and presented through ER-2 insert earphones using a soundcard at a sampling rate of 44.1 kHz with 16 bit resolution. The stimuli used was a 500 Hz unmodulated pure tone, 400 ms long including 40 ms raised-cosine onset and offset ramps, presented to both ears simultaneously at approximately 50 dB SPL (the exact level could not be determined due to issues with the sound card as described in appendix F). There was a 400 ms gap between each tone. The starting ITD was 600 µs to ensure that the task was sufficiently easy for the listener to understand and an upper limit ITD of 1000 µs was applied. The ear receiving the signal with the phase delay was constant for each listener but varied across listeners.

The Levitt-type adaptive staircase procedure used a two-down one-up rule (Levitt 1971) and terminated after 60 trials or 8 reversals, whichever was reached first. An example of this is shown in figure 6.16. The step size decreased if the participant responded to two trials correctly, this aimed to reduce the testing time and reach the individual's threshold level more efficiently. If the listener did not score any reversals due to reaching the maximum ITD, a threshold of >1000 µs was given by the MATLAB program. The threshold responds to the ITD that the listener scored correctly on 71% of trials.

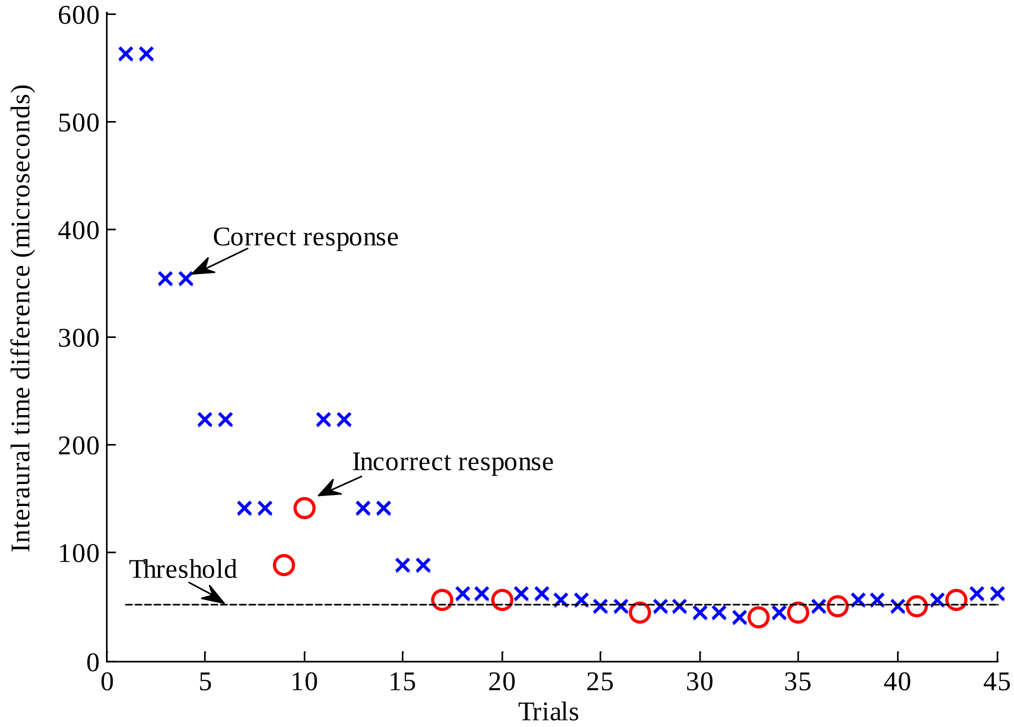


*Figure 6.16 Example adaptive procedure for the TFS sensitivity test. Crosses show a correct response and circles show an incorrect response. The example listeners ITD threshold was 52 µs.*

Participants were instructed on how to complete the test and reminded that if they were unsure of the answer, they should guess. Each participant carried out the test twice during their experiment session, once at the start (before the source identification task) and again at the end. The test lasted approximately five minutes. The leading ear for the TFS shift remained the same between the two tests, but was randomly selected for each participant (for example, participant one carried out the test twice with the ‘odd one out’ always sounding as though it shifted towards the left hand side). The mean of the two thresholds was calculated.

This test was also used to measure the ITD thresholds of the normal hearing civilians who participated in study 4; allowing a comparison to be made between the civilian and military population. Rowan and Lutman (2006) found high between-subject variability, particularly for participants that scored poorly, and therefore applied a logarithmic transformation to convert μs ITD thresholds into dB. The transformation below was applied to aid analysis of the data.

$$ITD\ threshold\ (dB) = 10 \times log_{10}(ITD\ threshold(\mu s))$$

All figures are plotted as ITD thresholds in dB relative to 1 μs. An ITD threshold of 10, 100 and 1000 μs became 10, 20 and 30 dB re 1 μs after the transformation.

### 6.5.3 Results

**Is there a significant difference in gunshot localisation accuracy between normal hearing military personnel and normal hearing civilians?**

All participants were able to localise all stimuli to a higher degree of accuracy than chance (56º± 4º at 0º azimuth calculated using a Monte Carlo estimation). MAE and RMS error scores are presented in table 6.9.

*Table 6.9 Average localisation scores for the 20 military participants (averaged across all azimuths). M = military participants from study 5, C = civilian participants from study 4. All values reported in degrees.*

| Stimulus condition | RMS Error | RMS error SD | MAE | MAE SD |
|---|---|---|---|---|
| M Gunshot | 33.7 | 7.4 | 24.9 | 6.1 |
| C Gunshot | 27.5 | 7.6 | 20.9 | 5.1 |
| | | | | |
| M Crack | 35.2 | 7.5 | 26.4 | 4.6 |
| C Crack | 31.5 | 4.9 | 25.2 | 4.1 |
| | | | | |
| M Thump | 29.1 | 7.2 | 22.1 | 6.0 |
| C Thump | 21.9 | 5.0 | 19.4 | 5.6 |
| | | | | |
| M Broadband noise | 27.4 | 6.2 | 20.5 | 5.4 |
| C Broadband noise | 17.0 | 4.8 | 16.2 | 3.3 |

Figure 6.17 shows the RMS error scores of military participants for each stimulus condition, compared with the civilian participants in study 4. Civilians appeared to localise with greater accuracy for all stimulus conditions compared with the military participants.

For all conditions there was a wide range of participant localisation scores; this was particularly apparent amongst the military listeners for the crack condition. The best performer on the localisation task was accurate to within 24° RMS error whereas the poorest performer was only accurate to within 54° (a participant selecting sources at random without bias would give an RMS error of 56º± 4º at 0º azimuth).

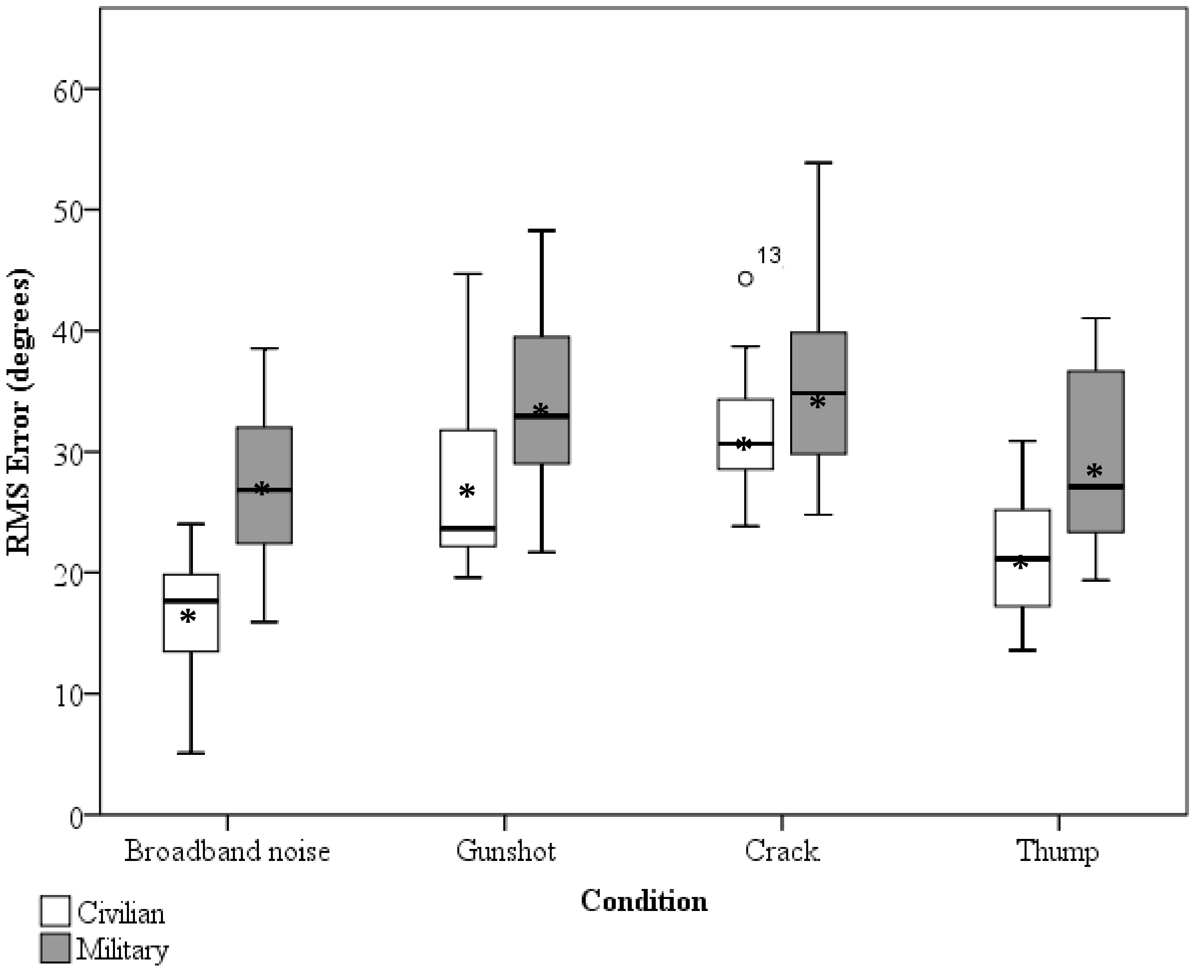


*Figure 6.17 Box plots to show to RMS error scores across stimulus conditions from study 4 and 5 (n=20 in both studies). Star symbol indicates the mean participant score. The RMS error score associated with selecting a source azimuth at random (without bias) is 56º± 4º at 0º azimuth.*

A mixed ANOVA was conducted with ‘stimulus condition’ (four levels) as the within subjects factor and ‘occupation’ (two levels) as the between subjects factor. There was a main effect of both stimulus condition ($F(3,114)=72.9$, $p<0.001$, partial $\eta 2 = 0.57$) and occupation ($F(1,38)=18.4$, $p<0.001$, partial $\eta 2 = 0.33$) on localisation accuracy. There was also a significant interaction between stimulus condition and occupation ($F(3,114)=3.89$, $p=0.011$, partial $\eta 2 = 0.09$).

Mixed ANOVA was appropriate in this instance as it allows both within-subject comparisons (effect of stimulus condition) and between-subject comparisons (effect of occupation). The data was largely normally distributed (measured using Shapiro-Wilks test) and the assumption of sphericity was not violated. Partial eta squared gives an indication of the percentage of variance attributed to the independent variable; for example, 57% of the variance in RMS error can be accounted for by the stimulus condition.

A further repeated measures ANOVA was conducted with the data from study 5 only to determine whether the military participants performed differently in the stimulus conditions. Mauchly's test indicated that the assumption of sphericity had been met. The results show that there was a significant effect of stimulus condition on localisation accuracy (in RMS error), $F(3,57) = 14.37$, $p < 0.001$, partial $\eta 2 = 0.43$. Post hoc tests (Bonferroni correction was applied; reducing the potential for type 1 error due to multiple comparisons) indicated that there were significant differences in localisation accuracy between most of the conditions except gunshot-crack and thump-broadband noise. Pairwise comparisons are shown in table 6.10.

*Table 6.10 Study 5: Pairwise comparisons of stimulus conditions (Bonferroni correction applied).*

| **Condition** | Crack | Thump | Broadband noise |
|---|---|---|---|
| Gunshot | x (*p*=1) | ✓ (*p*= .006) | ✓ (*p*= .003) |
| Crack | | ✓ (*p*= .007) | ✓ (*p*< .001) |
| Thump | | | x (*p*= 1) |

It was clear that there were large differences in the localisation accuracy of civilians and military personnel but it was not known why these differences arose. In order to explore this the error scores at each azimuth were considered. Figure 6.18 shows the RMS error for each source location for both military and civilian participants (just the whole gunshot and broadband conditions, for ease of comparison). The military participants were as accurate as the civilians at the farthest lateral sources, but much less accurate towards the central sources.

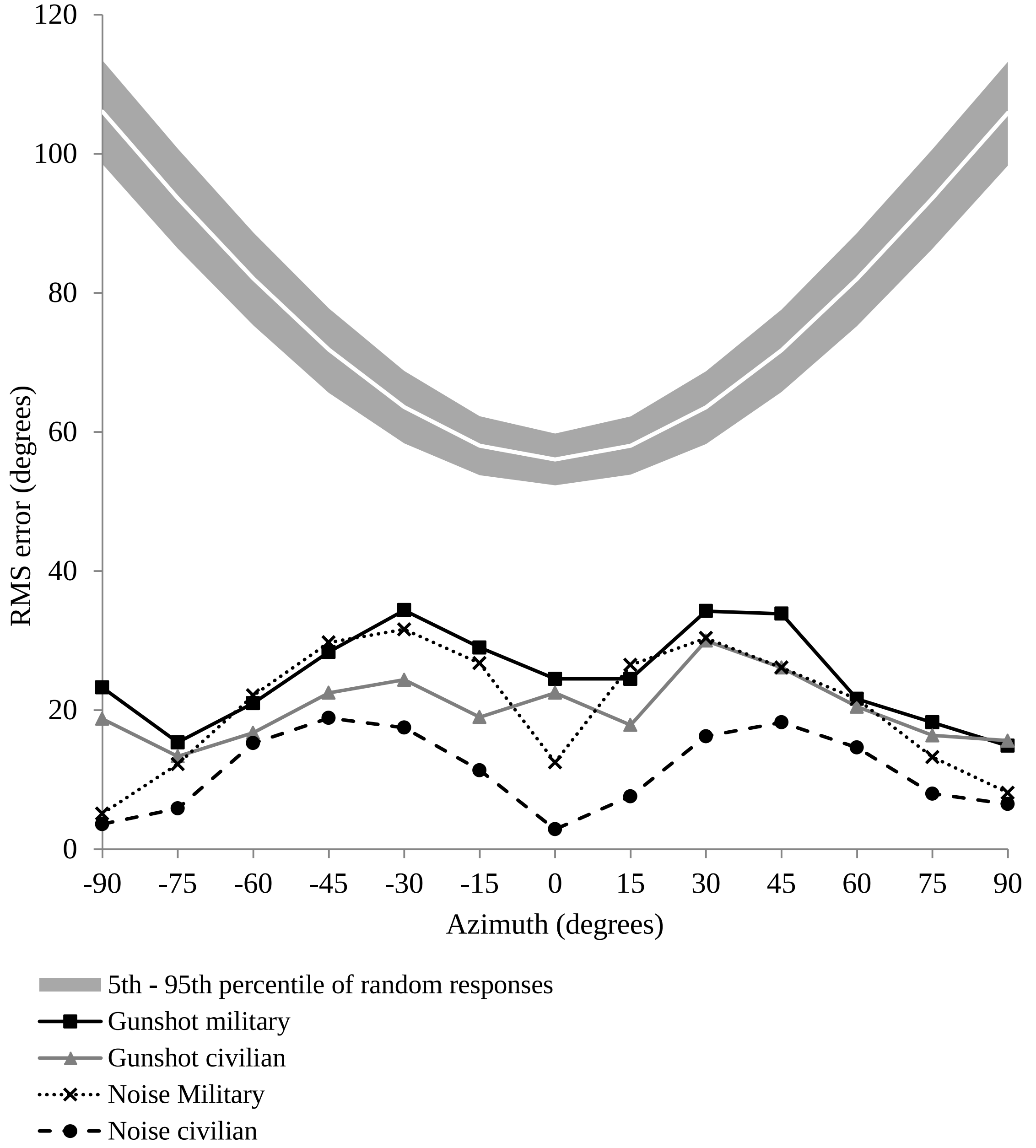


*Figure 6.18 Study 5: RMS error per azimuth for the four stimulus conditions. White line demonstrates mean RMS error of a participant selecting sources at random (shaded area shows 5th- 95th percentile) The RMS error associated with selecting a source azimuth at random without bias is 56°± 4° at 0° azimuth.*

Personnel appeared to perform with a similar error pattern regardless of the stimulus condition. Pearson’s r correlation co-efficient (scatter plot shown in figure 6.19) suggested that the military participants like civilians responded similarly regardless of the stimulus. In study 5, thump and broadband were moderately correlated (r = .61, n = 20, $p$ < .01, 95%) similar to the study 4 results (r = .55, n = 20, $p$ = .01, 95%). Broadband and gunshot conditions were also moderately correlated in study 5 (r = .50, n = 20, $p$ = .02).

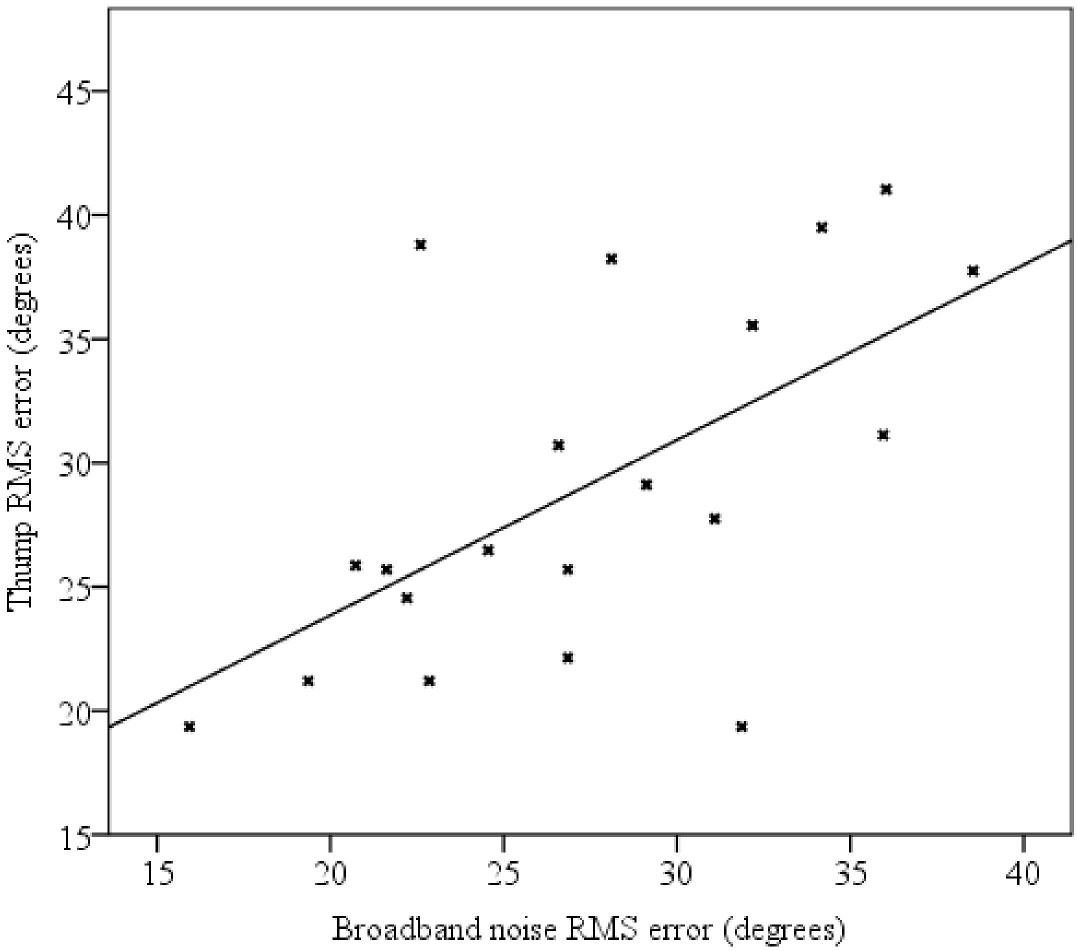


*Figure 6.19 Study 5: Scatter plot to show correlation between the broadband noise condition and gunshot condition. These stimulus conditions were moderately correlated. Linear regression line shown ($R^2$= 0.32).*

**What causes the difference in performance between civilian and military participants on the virtual localisation task?**

To explore the pattern of responses, bubble plots were constructed for the stimulus conditions. Figure 6.20 illustrates the military responses in study 5 and figure 6.21 shows the civilian responses from study 4 below for ease of comparison.

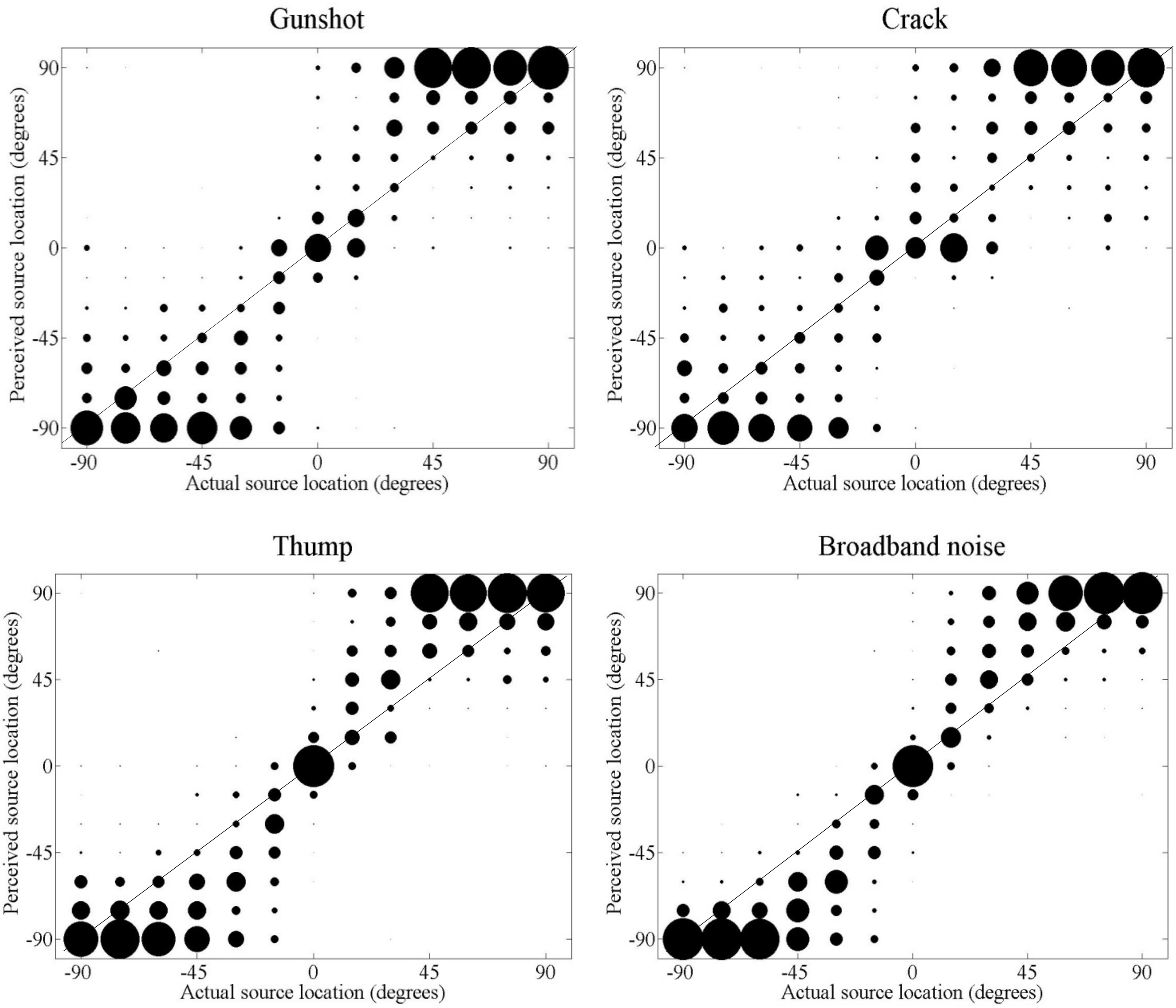


*Figure 6.20 Study 5: Bubble plots to show the distribution of responses from all military participants. The diagonal line represents a correct judgement of source location and bubble area represents the number of responses. The largest bubble represents 115 responses and the smallest (just visible) bubbles represent 2 responses.*

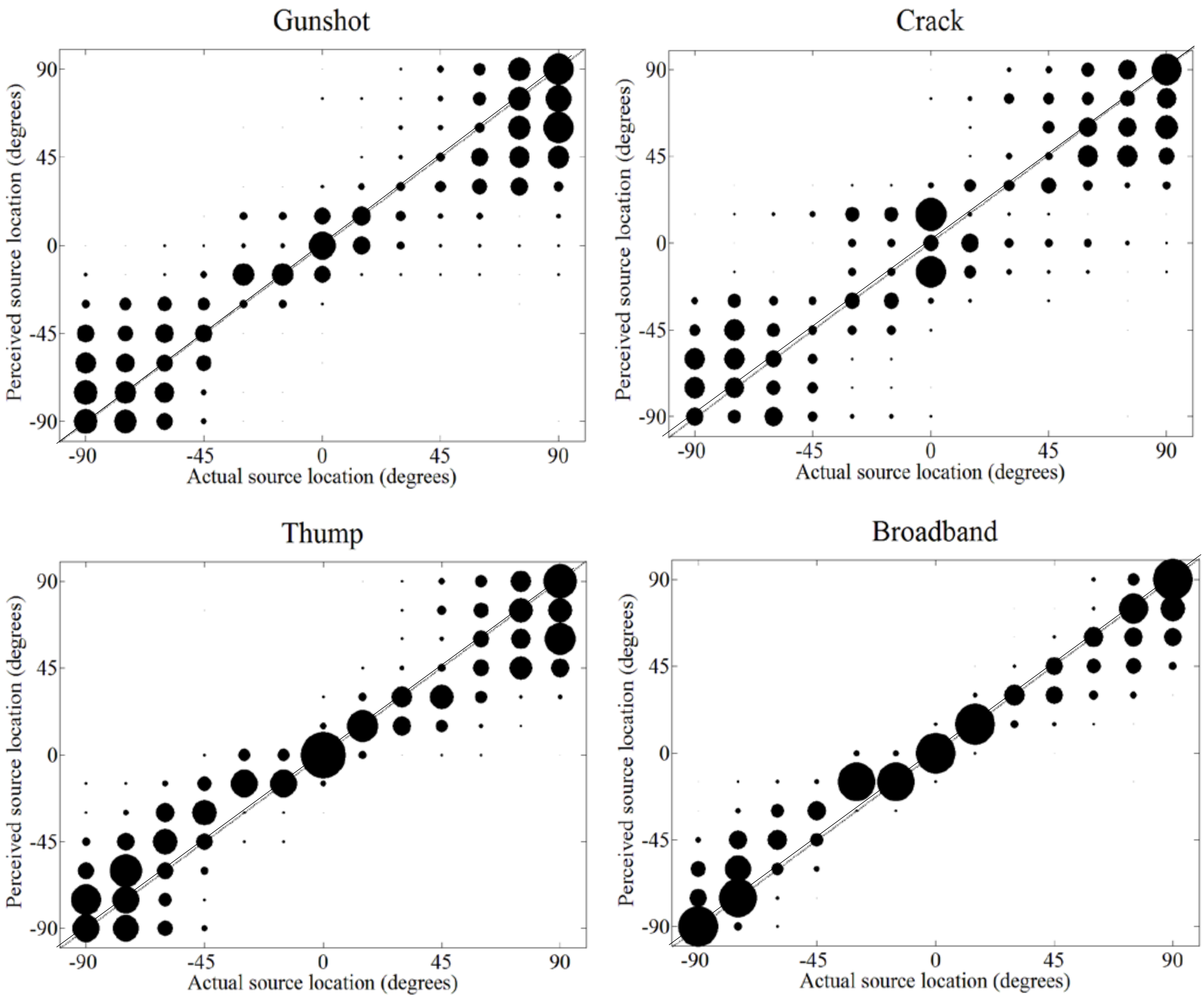


*Figure 6.21 Study 4: Bubble plots to show the distribution of localisation responses from civilian participants. The diagonal line represents a correct judgement of source location and bubble area denotes the number of participant responses. The largest bubble represents 109 responses and the smallest (just visible) bubbles represent 2 responses.*

From figure 6.20 there were clear differences in the way that the military personnel carried out the source identification task. They exhibited a strong preference for the lateral sources when a sound was presented from any source to that side of centre. In comparison to the civilian responses they also showed a greater variation in responses, appearing to select the source location with less precision. These interesting and unexpected trends (across all stimuli conditions) can also be seen in the level of bias and variation exhibited for each stimulus condition; data presented in table 6.11.

*Table 6.11 Measures of unsigned (C), signed (E) and random error (RE). Results from study 5 are prefixed Mil (military) and results from study 4 are prefixed Civ (civilian). All values are in degrees.*

| **Condition** | **RE (SD)** | **C (SD)** | **E (SD)** |
|---|---|---|---|
| Mil Gunshot | 23.2 (6.3) | 25.6 (7.1) | 2.1 (2.2) |
| Civ Gunshot | 19.4 (6.0) | 20.2 (7.9) | 2.4 (5.6) |
| | | | |
| Mil Crack | 25.1 (6.5) | 26.3 (6.7) | 4.4 (1.6) |
| Civ Crack | 24 (5) | 22.2 (4.7) | 3.2 (6.3) |
| | | | |
| Mil Thump | 17.3 (5.8) | 23.6 (8.0) | 1.0 (3.4) |
| Civ Thump | 13.7 (3.6) | 17.3 (5.1) | -0.2 (5.2) |
| | | | |
| Mil Broadband noise | 16.5 (4.3) | 22.3 (7.0) | -0.8 (4.1) |
| Civ Broadband noise | 11.9 (2.7) | 12.8 (4.9) | -0.6 (2.6) |

Military personnel show higher rates of bias (C) for all conditions. The smallest difference in bias is for the crack stimulus where rates of random error are much higher; the increase in bias for the military personnel may be masked by the general trend for them to make imprecise judgements. The decrease in precision and increase in lateral bias exhibited by the military participants in study 4 is likely to be responsible for the significant difference in overall localisation accuracy between civilian and military participants (as shown in figure 6.17).

It is possible from the data to ascertain whether the civilian and military participants were able to correctly judge that a sound source was to their left or their right hand side. This was calculated using an LPC score. This analysis was calculated using two methods; the first was a ‘true’ LPC score and the second was a more lenient measure to incorporate slight errors in judgement. For the first measure, if the source location was either A, B or C and the participant responded with A, B or C they scored correctly; likewise if the source was K, L or M and they responded K, L or M.

In previous studies utilising this type of lateral accuracy measure a further response source is sometimes incorporated to allow participants to choose a source either side of the correct one (Talcott et al. 2012, Takimoto et al. 2007, Madjak et al. 2011). This was of particular interest in the current study as military personnel are expected to localise using a simpler clock face system; allowing them to judge at 30º intervals as opposed to the 15º intervals used in the source identification task.

In this instance, the participant scored correctly if the source was A, B or C and they responded A, B, C or D (likewise for K, L and M, participants were also scored correctly for selecting J, as shown in figure 16.22). Presentations or responses for the central sources between D and J were not included in either analysis.

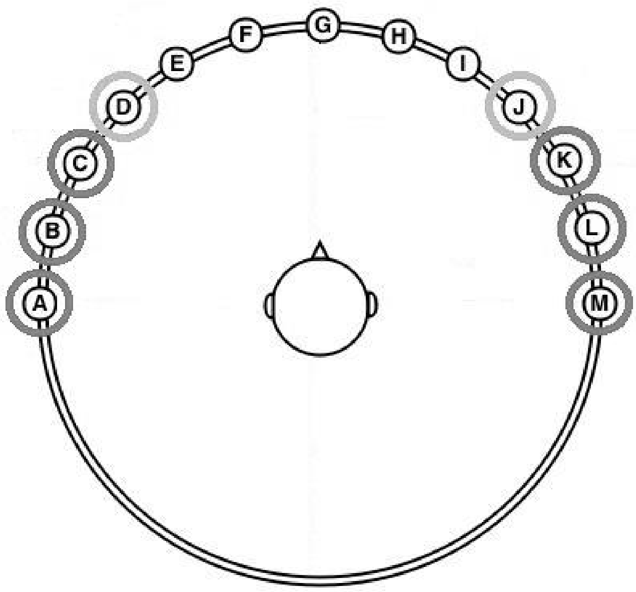


*Figure 6.22 Plan view of the experiment rig. Darker grey circles represent the 'correct' responses included in the first LPC analysis method, lighter grey circles represent (together with the dark grey) 'correct' responses in the second, more lenient, LPC analysis method.*

*Table 6.12 Lateral percent correct (LPC) scores using two methods, from study 4 and study 5. Results from study 5 are prefixed Mil (military) and results from study 4 are prefixed Civ (civilian).*

| **Condition** | **LPC: method 1 (SD)** | **LPC: method 2 (SD)** |
|---|---|---|
| Mil Gunshot | 65.4 (11.4) | 69.0 (10.8) |
| Civ Gunshot | 59.7 (9.8) | 61.1 (12.8) |
| | | |
| Mil Crack | 67.2 (11.1) | 70.3 (12.7) |
| Civ Crack | 57.0 (12.5) | 59.6 (10.1) |
| | | |
| Mil Thump | 72.1 (12.1) | 75.8 (10.0) |
| Civ Thump | 64.9 (9.7) | 67.5 (12.7) |
| | | |
| Mil Broadband noise | 79.4 (9.8) | 81.5 (11.3) |
| Civ Broadband noise | 69.1 (11.1) | 70.3 (11.2) |

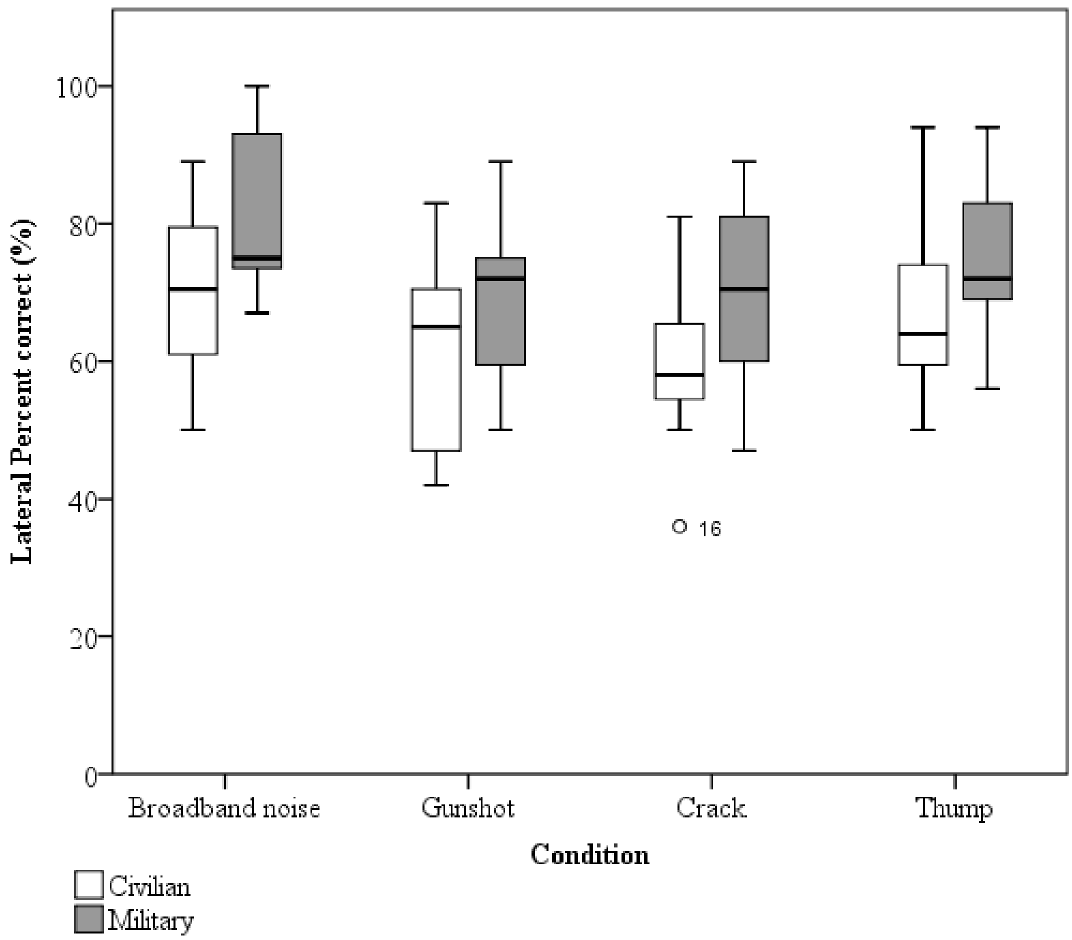


*Figure 6.23 Box plots to compare lateral percent correct scores (method 2) between study 4 (civilian participants – white bars) and study 5 (military participants – grey bars). n=20 in both studies.*

Lateral percent correct scores for the civilian and military listeners are shown in table 6.12 and figure 6.23. Ceiling effects were observed in the broadband noise condition; two military participants achieved LPC scores of 100%. Similar to the RMS error scores, participant LPC scores varied considerably between participants with over 30% between the best and worst performers in any stimulus condition.

Mixed ANOVA was used to determine the effect of occupation and stimulus condition on ability to correctly localise the furthest lateral sources in the array.

There was a significant effect of occupation on LPC scores, F (1, 38) = 12.77, $p$ = .001. This effect shows that, ignoring stimulus condition, military personnel lateralise sources more accurately than civilians, when assessed using the LPC score.

There was no significant occupation x stimulus condition interaction, F (3, 38) = 0.34, $p$ = 0.79. This demonstrates that the pattern of LPC scores for each stimulus condition did not significantly differ between military and civilian listeners.

**Is there a significant difference between the ITD thresholds (as measured by a TFS sensitivity test) of normal hearing military personnel and normal hearing civilians?**

The military personnel in study 5 exhibited very different patterns of localisation errors when compared to the civilian participants in study 4, shown by the level of bias, variation and LPC scores. The testing procedure remained constant between the two studies (except for the limitations found with the gunshot-based stimuli) but participant characteristics did vary between the groups; one characteristic of particular interest was history of noise exposure.

Hearing levels between the two groups were similar (mean pure tone thresholds of the better hearing ear were 6.6 dB HL for civilians and 7.4 dB HL for military personnel). The TFS test was carried out to detect any decrement in normal hearing participants' sensitivity to binaural temporal cues. Raised ITD thresholds (equivalent to a higher JND on the TFS test) may mean that an individual has limited access to ITD cues, particularly important when locating the source of low frequency stimuli such as the muzzle blast of a weapon.

Average ITD thresholds were similar between the first and second iteration of the TFS test, indicating acceptable test-retest reliability. There was a large variation in average participant responses; civilian thresholds ranged from 13.3 to 24 dB (27 to 209 µs) and military thresholds from 16 to 26.5 dB (35 to 416 µs).

Interaural time difference thresholds are presented in table 6.13. There was a significant difference in ITD thresholds (in dB) between civilian (M=17.6, SD=1.8) and military (M=20.1, SD=2.1); $t(50) = -4.4$, $p < .001$. Military personnel performed significantly worse on the test of low frequency TFS sensitivity when compared to civilian participants (although a considerable overlap in military and civilian ITD thresholds can be seen in figure 16.24).

Hopkins and Moore (2010) carried out a similar TFS test on ten normal hearing listeners (a two interval, two alternative forced choice task where one interval contained four tones of equal phase at the two ears and the other interval contained two equal phase tones and two phase-shifted tones). They obtained a similar average ITD threshold (converted to dB and recorded in table 6.13) for the 500 Hz pure tone stimulus as recorded in study 5 from the military participants.

In addition to Hopkins and Moore (2010) a low frequency TFS test using the same four-interval three-alternative forced choice method as study 5 was carried out by Rowan and Lutman (2007). Rowan and Lutman used a 125 Hz tone instead of 500 Hz and the ITD threshold of the 20 participants tested by them is presented in table 6.13.

*Table 6.13 Comparison of ITD thresholds measured using a low frequency TFS sensitivity test. ITD thresholds are in dB (re 1 μs). Hopkins and Moore (2010) used a 500 Hz pure tone and Rowan and Lutman (2007) used a 125 Hz pure tone.*

| | **Test 1 (SD)** | **Test 2 (SD)** | **Mean (SD)** |
|---|---|---|---|
| **Civilian (study 4)** | 17.5 (1.9) | 17.6 (2.1) | 17.6 (1.8) |
| **Military (study 5)** | 19.7 (2.3) | 20.5 (2.0) | 20.1 (2.1) |
| **Hopkins & Moore** | n/a | n/a | 21.2 (not reported) |
| **Rowan & Lutman** | n/a | n/a | 23.5 (not reported) |

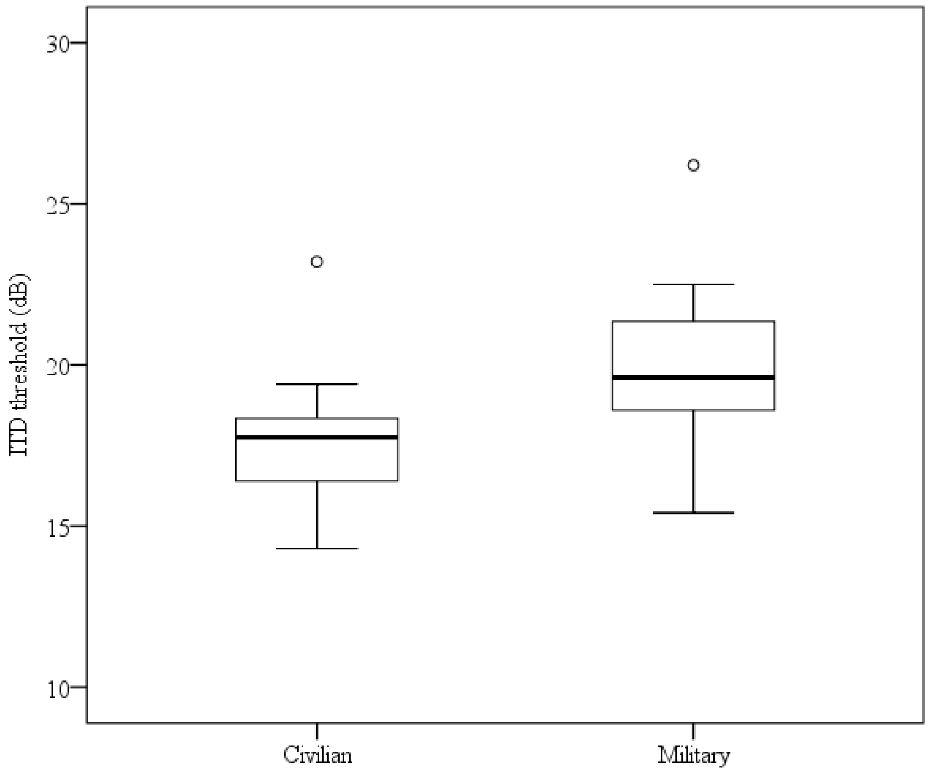


*Figure 6.24 Box plots to show distribution of ITD thresholds (dB re 1 µs) for military and civilian listeners (n=20 in both participant groups). Two outliers were present; both of these individuals performed close to chance level and therefore their results were removed from the t-test analysis in section 6.5.3.*

### 6.5.4 Discussion

The primary aim of study 5 was to determine if military personnel perform differently to civilians on a source identification task using a gunshot stimulus. Twenty normal hearing military personnel (15 Army, 5 Navy) recruited from the Defence Audiology Service and HMS Sultan completed a virtual localisation task and a test of sensitivity to low frequency TFS. Their results were compared to 20 normal hearing civilian listeners, recruited during Study 4.

It was hypothesised that civilians and military personnel would perform the localisation task to a similar degree of accuracy providing other listener characteristics remained the same (for example age, handedness). It was thought that an improvement in accuracy due to experience on the real-world MCAT could have been counteracted by a deficit caused by a history of noise exposure.

During November 2015, it was noted that the gunshot-based stimuli were presented to military listeners using an incorrect version of the MATLAB program, causing the digital signal to be clipped. Due to this, and the effect distortion would have had on the general sound quality and ILD cues of the stimuli, it was assumed that localisation performance on the gunshot-based conditions would be relatively poorer than the broadband condition. Even though hard clipping of the stimuli was not audible during the subjective listening checks, it was not possible to determine the exact effects of the distortion on binaural cues. For this reason, the discussion and conclusions of study 5 and 6 will be based predominantly on the broadband noise condition; the only distortion present in the broadband noise would have been due to the potentially overdriven sound card.

Military personnel were able to localise all stimuli more accurately than chance (as shown in figure 6.18) but a comparison of data from Study 4 and 5 revealed the opposite trend to that hypothesised. Military personnel performed significantly worse on the localisation task for the gunshot, thump and broadband noise conditions. This difference in scores appeared to arise from the way in which the participants in study 5 carried out the localisation task. Interestingly, military personnel had an increased tendency to select the farthest lateral sources (90º and -90º azimuth) as shown clearly in figure 6.20. This trend was apparent for all of the stimulus conditions. By responding to the majority of trials with the farthest lateral sources, the military personnel exhibited an increase in overall RMS error. Even though there was no significant difference between the RMS error of the crack conditions from study 4 and 5, the pattern of responses from the two groups was still markedly different. The high RMS error and random error observed in the study 4 crack condition may have caused the difference in lateral bias between the groups to be less apparent.

The reason for this difference was not immediately apparent. The two experiments were carried out under similar controlled conditions and ambient noise levels were kept to a minimum. On first inspection it seemed as though the differences between civilian and military could have arisen from the distorted stimuli used in study 5, however, very similar patterns of error were seen in the broadband noise condition which was less affected by distortion. It was possible that participants completing a gunshot-based condition first were less able to make confident localisation judgements using the distorted binaural cues and continued to apply a similar system of lateral guessing when presented with the broadband noise condition. The same patterns of responses were also present when the broadband noise condition was conducted first, ruling out the influence of an earlier ‘confusing’ set of stimuli. It therefore seemed likely that the changes in responses were due to differences in the participant groups.

The two groups did differ slightly on gender and age; there were more men in the military group, 15 compared with 9 in the civilian group, and the average age was 5 years lower in the civilian group. Regardless, these differences were unlikely to have had such a significant effect on participant responses. From previous literature (as discussed in Chapter 4) age and gender altered overall localisation accuracy by only a few degrees (due to an increase in random error and constant error respectively) and there is no evidence to suggest there would be an effect on lateral bias.

The most obvious difference between the groups was their occupational background and their resulting experience in localising gunfire. On average military participants had been on 1.5 operational tours abroad and 10 of the participants worked with small arms on a daily basis. It was assumed that all of the military personnel participating in Study 5 had experience of localising small arms during training (all military personnel undergo basic training) or enemy fire and only one participant was unaware of the terms crack and thump. In contrast only two of the civilian participants in Study 4 had any experience of fire arms and neither had ever attempted to locate the source of gunfire.

From the focus groups conducted in Study 1 and discussion with subject matter experts, it was suggested that infantry personnel are often unsure of a firer’s location. It was reported that they either opt to consult with colleagues, wait for a visual cue or simply turn to the left or right in order to place the source of gunfire close to 0º azimuth (a tactic also used by human listeners to improve their localisation accuracy (McAnally and Martin 2014, Iwaya et al. 2003, Brimijoin et al. 2013)). Considering this, it is conceivable that the military listeners were responding in a similar manner when they carried out the source identification task. If unsure of the exact source location, and regardless of the stimulus type, they may have turned to face either left or right (the general direction of the sound) and chosen the source that was directly in front of them. This may be related to the need for personnel to stay safe; during operational duties they may be expected to make a fast yet confident judgement of the source location, forcing them to select a general direction but not a specific azimuth.

Despite performing worse than civilian listeners for overall localisation accuracy, military listeners achieved significantly better LPC scores. This indicated that by selecting the farthest source locations, personnel were able to increase their ability to make a lateral judgement. If a left or right decision of the gunfire source is all that is needed to move to a safer location or return fire, military personnel show an advantage of up to 12% compared with civilian listeners. This improvement may indicate that experience or training is responsible for the increase in lateral bias.

Regardless of the cause, it would appear that during the task personnel were not responding to the question ‘where did the gunshot come from?’ but instead ‘in which direction would you face if you heard this sound?’ Beyond anecdotes, there was no evidence to confirm or deny that the increase in lateral bias is due to training or experience. Talcott et al. (2012) did not report levels of bias or random error for their gunfire localisation study so it was not possible to tell if similar errors of judgement were made by their military participants. The localisation task conducted by Talcott was considerably easier – it was a freefield study with only 8 sources – and this may have reduced the number of errors due to source uncertainty. Talcott’s study also had the advantage of using a 360º array of sources, eliminating the end effects that may have contributed to the pattern of errors exhibited by personnel in Study 5.

It is possible that the difference in response method between the groups was not due to experience or training but instead due to educational background or general intellect. Whilst neither of these parameters was measured directly, all of the civilian participants were degree level students or university staff, some with knowledge of psychoacoustics and experimental design. These civilians may have had a tendency to spread their ‘guessed’ responses more evenly amongst the source locations as they may have been aware of the random nature of presentations and the equal number of presentations from each source. In future, a group of totally naive civilians could be used to eliminate this concern.

The military personnel had mixed backgrounds. Six worked in engineering and specialist roles with a high level of education. The remainder had been in infantry roles since joining the military, having left school at 16. According to a parliamentary report (Defence Committee, 2003) almost 40% of new recruits to the Army have a reading age of 11 or lower. A low reading age alone is not an indicator of low cognitive function, but there is research (using cohorts of children, not adults) to suggest that low reading ability may associate with poor audio-visual integration (Birch and Belmont 1965) and poor understanding of complex tasks. It is plausible that this may have hindered performance on a task where an audio signal was matched with a visual target, as used in the current study.

If an audio-visual integration deficiency was the cause of the increased lateral bias then the temporal sensitivity test may not have been affected. There is no visual element to the test, simply requiring the listener to select the ‘odd one out’ using a number between two and four. It was found that military listeners performed significantly worse than civilians on the TFS test, indicating that civilian and military listeners respond differently regardless of the test used. Although, it is possible that low reading ability also caused other measurable deficiencies that affected the TFS sensitivity test scores such as ability to remember the number of the phase shifted tone.

The results of the TFS test were broadly similar to those reported in the literature. Rowan and Lutman (2007) reported ITD thresholds of 23.5 dB and Hopkins and Moore 21.2 dB, both higher than the thresholds of civilian and military listeners measured in the current research. This suggests that even though there was a significant difference between civilian and military ITD thresholds, they were both within the expected range for normal hearing listeners in the general population. The small but significant difference could have arisen from differences in average age (known to affect TFS processing, (Fullgrabe 2013)) or understanding of the test. These variables could be investigated in future by using a simpler test procedure, such as the two-alternative forced-choice task used by Hopkins and Moore (2012) and by age matching the participant groups.

It is possible that military personnel could perform worse than civilians in other psychoacoustical tasks, beyond measures of spatial perception, such as speech discrimination. Further research with military participants should incorporate a test of cognitive ability or, at the very least, thorough questioning of the participant to ensure they understood the test procedure sufficiently. When carrying out future psychoacoustical experiments with military personnel, it would be advisable to ask a few general questions about their decision making process and specific experience of the type of task to be carried out.

It is possible that participant motivation levels may have contributed to the differences between civilians and military personnel for the source identification task and the TFS test. The civilian listeners had an awareness of the importance of research studies from studying and working in a research environment. They were likely to have been highly motivated listeners, keen to carry out the task to the best of their ability in order to make a meaningful contribution to the research study. To an extent the military listeners were motivated. The onus was on them to sign up for the study, often doing so because they had an interest in their hearing levels or the future of hearing healthcare in the military. However, they would have had a limited understanding of the purpose of the research (all participants were deliberately not told about the study hypotheses in order to reduce bias) and they may not have had an understanding of the implications of the study's findings. It is plausible that during the study they performed in a suboptimum way, selecting one of the lateral sources to minimise the effort required for each trial. During the experiment military participants commented on the length of the testing time, the repetitive nature of the task and how tired they felt. During Studies 4 and 5 no payment was made to participants or reward offered for good performance. In future, this could be considered as a way to increase the motivation levels of military listeners.

The final factor that could have caused the differences observed in localisation and ITD discrimination was noise exposure. The military participants tested during Study 5 all presented with normal hearing thresholds but it was possible that undetectable damage to the auditory pathway had occurred due to excessive noise. It is known that military personnel have a higher exposure to occupational noise than civilians and with an average of 8.75 years spent in the armed forces, every military participant in Study 5 would have experienced high levels of noise during training and operational duties. Given the small numbers of military personnel wearing hearing protection regularly (Bevis et al. 2014, Okpala 2007); it is likely that the military participants had a higher incidence of noise exposure than the civilian participants. As discussed in Sections 2.2.2 and 6.5.2 early noise damage can cause changes to cochlear neurons and alter brainstem circuitry leading to decreased sensitivity to temporal cues. Whilst this mechanism could explain the TFS test findings it does not necessarily correlate with the localisation task findings.

If sensitivity to temporal cues was reduced then an inability to utilise ITDs would be expected but use of ILD cues should remain normal. This would present as a decrease in localisation accuracy for the thump stimulus (and gunshot stimulus, for those using the thump component to judge the source location) but the ILD-dominated crack stimulus would be unaffected. Military and civilians did not perform significantly differently for the crack stimulus; military participants did still exhibit the increase in lateral bias. For this reason auditory changes due to noise exposure that are not detectable using PTA are unlikely to be the sole cause of the performance difference between military personnel and civilians.

It was likely that more than one factor contributed to the unusual pattern of responses exhibited by military personnel during the tasks. The most plausible scenario was that a combination of factors, particularly military training, contributed to the increase in lateral bias when compared to civilian responses. As discussed above, it is unlikely that a ‘hidden’ noise induced auditory impairment or a lower education level had a detrimental effect on performance due to the variability of these factors between participants and the consistent nature of the errors.

The results from Study 5 may have serious implications for testing AFFD and future research using military personnel. The results obtained from the localisation task may accurately reflect performance on the real world MCAT, but the tests used may not measure true ‘localisation accuracy’ in a psychoacoustic sense. It is clear that the performance levels of military personnel cannot be predicted from civilian data.

The overarching aim of Study 4 and 5 was to determine the localisation accuracy of military personnel for a small arms gunshot stimulus as a first step in the development of localisation measures for AFFD. The studies have provided the first insight into the behaviour of military personnel when locating the source of live gunfire. From the data gathered, personnel were able to locate the source of a single recorded shot to a greater degree of accuracy than chance. The localisation task developed using recorded gunfire may not have assessed true ‘localisation accuracy’ but that does not disregard it as an appropriate measure of auditory fitness. Further work (discussed in more detail in chapter 7) would be needed to determine the suitability of the task as a measure of AFFD. The next stage of the process was to determine whether a decline in hearing thresholds would have a detrimental effect on performance levels - as expected for any auditory task. If performance on the task is highly correlated with hearing thresholds then PTA could be an appropriate measure of auditory fitness on the gunshot localisation MCAT.

### 6.5.5 Conclusions, knowledge gaps and justification for study 6

Study 5 aimed to determine the localisation accuracy of normal hearing military personnel using a small arms gunfire virtual source identification task. The results were compared with the findings of Study 4 where the localisation accuracy of 20 normal hearing civilians was measured.

Military personnel were found to be able to localise a gunshot stimulus within 33.7º RMS error. This was considerably more accurate than the RMS error associated with selecting sources at random without bias (56º± 4º at 0º azimuth). It was however significantly less accurate on average than the civilian population for the gunshot, thump and broadband stimuli. Military personnel exhibited higher lateral bias across all stimulus conditions. This was likely to be due to a combination of factors, including motivation levels and experience of gunfire localisation as a real-world task.

The lateral bias demonstrated by the military participants (whilst lowering overall accuracy) resulted in an increased ability to identify left and right sources, as measured by the LPC score. This indicated that in a real-world scenario military personnel may be better able to make a preliminary judgement of lateral direction; theoretically allowing them to utilise visual cues to better effect or more accurately localise a second auditory stimulus from the same source.

**Knowledge gaps**

- **It is not known why the military participants made localisation judgements with high lateral bias on the virtual source identification task.**
- **It is also not known whether the bias is only present during the simulated localisation task or whether this phenomenon is present when military personnel carry out the MCAT on operational duties (it would not be ethical to measure human localisation performance using live ammunition).**
- **It is not known whether localising small arms gunfire is sensitive to hearing impairment.**

**Justification for study 6**

From Study 5 it would appear that military personnel are able to carry out this localisation MCAT with a degree of accuracy greater than chance. To consider gunshot localisation as a measure of AFFD, hearing impairment would need to have a measurable impact on performance levels. Currently there are no studies reporting the effect of hearing impairment on localisation of gunshot-like stimuli. Study 6 was designed to begin investigating the relationship between increasing bilateral hearing thresholds and gunshot localisation accuracy.

## 6.6 Study 6 – Is localisation of a small arms gunshot sensitive to military hearing impairment?

### 6.6.1 Introduction

Military personnel are exposed to high levels of occupational noise and despite a comprehensive hearing protection programme large numbers of UK service personnel develop NIHL during their military service (Patil and Breeze 2011). NIHL manifests itself as a bilateral, generally symmetrical (depending on the origin of the noise) high frequency hearing loss, often with a audiometric notch around 4 kHz (Osei-Lah and Yeoh 2010, Coles et al. 2000, Rabinowitz et al. 2006). It is known that normal hearing military personnel are able to localise small arms fire to a degree of accuracy greater than chance (as assessed using recorded gunfire in a virtual source identification task during study 5). It is also known that localisation ability for generic stimuli is affected by degree of hearing impairment and that a measurable decrease in localisation accuracy has been observed when bilateral thresholds are >40 dB HL due to sensorineural loss of hearing (Proschel and Doring 1990 (as discussed in Noble 1994)).

Study 5 demonstrated that normal hearing military personnel did not carry out the localisation task in the way expected, with a higher incidence of lateral bias causing an overall increase in RMS error when compared with normal hearing civilians. As discussed in section 6.5.4 a combination of factors may have caused the increase in bias but as the trend was seen throughout the participant group it was likely to be linked in some way to the participant's military experience and training.

Despite the limitations discussed in section 6.5.4, the data collected in study 5 would seem to suggest that military personnel are able to perform the real world gunshot localisation MCAT to a degree of accuracy better than chance. Before considering gunshot localisation as a measure of auditory fitness, its sensitivity to military hearing loss needed to be investigated. If changes in pure tone thresholds have no impact on an individual's ability to perform the task, then completion of the task must be dependent on other sensory modalities beyond pure tone thresholds.

There are many possible configurations of hearing thresholds and reasons for hearing impairment amongst military personnel (for example symmetrical, asymmetrical, sensorineural, conductive, noise induced and blast injury). It was not possible to recruit sufficient military participants to investigate all types of hearing loss within the scope of this study. A preliminary investigation into bilateral symmetrical hearing loss was chosen as this was the most common type of hearing loss seen in patients at the Defence Audiology Service, Gosport.

**Aim:** To investigate the relationship between degree of symmetrical sensorineural hearing impairment and small arms fire localisation accuracy within a military population.

**Research question:** Is there a significant difference in RMS error for a gunshot stimulus between normal hearing personnel, personnel with a mild hearing impairment and personnel with a moderate impairment?

**Hypothesis:** From a review of the wider literature it was hypothesised that as bilateral hearing impairment increased localisation accuracy would decrease.

A detriment in localisation accuracy should be apparent when hearing thresholds reach 40 dB HL bilaterally (a moderate hearing impairment) in accordance with the findings from Rosenhall (1985). As discussed in Section 4.4.1, provided listeners are able to hear the stimulus and there is only mild damage to the outer hair cells in the cochlea, they are likely to be able to make near normal use of ITD and ILD cues.

For personnel with a moderate hearing impairment, the signal would still be audible but a decrease in localisation accuracy may be present due to hair cell damage causing distortion of the signal and decreased sensitivity to TFS (Hopkins and Moore 2011, Lorenzi et al. 1999).

### 6.6.2 Specific method and participants

The basic method used was outlined in section 6.2.; recordings created 100 m downrange from the firer were used. All participants had a symmetrical bilateral sensorineural hearing impairment assessed by PTA and fitted the exclusion criteria outlined in section 6.2.7.

Participants were recruited via the Defence Audiology Service at the INM, Gosport. The audiologist (Gerard Duffy) selected suitable candidates from their referral audiograms and sent the invitation to participate in the research (appendix J) together with their audiology appointment letter. It was made clear to them in the letter that the research study was not related to their audiology appointment and the results would not affect their service career in any way. Interested individuals then contacted the audiology department to book a research appointment. Personnel attended their audiology appointment (prior to their research appointment) and underwent PTA; the results were used to determine their eligibility for the study. Approximately 20 personnel were rejected at this stage due to asymmetric thresholds or other ear pathology (infections or conductive hearing losses). Asymmetry was defined as a difference of greater than 5dB between the ears at any frequency tested. This was a more stringent definition of asymmetry than generally used in audiology clinics, to avoid any effect of differing thresholds on interaural spatial cues.

Twelve participants were recruited between April and June 2015. The sample size was calculated based upon the null hypothesis of $r = 0$ (no correlation between hearing impairment and localisation accuracy). Assuming that there was a moderate correlation $r = 0.6$ (36% of the variance in localisation was attributable to hearing loss) a sample size of 17 was needed; with an equal mix of normal hearing, mild hearing loss and moderate hearing loss participants. As 20 normal hearing personnel were recruited in Study 5, six personnel with mild hearing losses and six with moderate losses were recruited to ensure that the sample size for study 6 (including 6 normal hearing participants) was sufficient.

Average hearing threshold was measured by taking an average of the pure tone thresholds at 0.5, 1, 2, 4 kHz in accordance with the BSA recommended procedures (2004). This particular descriptor was chosen as it was the most commonly used in the UK, utilised by NHS audiology clinics and often by UK-based research groups. The H-category descriptors (currently used by the UK military) were deliberately not used as, unlike the BSA descriptors, they were not designed to describe auditory disability in any way but instead were thought to have been developed as a framework for monetary compensation (Laroche et al. 2003, personal communication with Surgeon Commander Pearson 2012).

Mild hearing loss was classified as an average hearing threshold in the better ear ≥20 and ≤40 dB HL, moderate hearing loss was ≥41 and ≤70 dB HL. These groups were chosen to ensure a large enough difference between their audiometric configurations to highlight any effect of hearing loss on localisation ability. Average hearing thresholds of the different hearing ability groups are shown in figure 6.25. It was not possible to recruit any individual with hearing thresholds above 70 dB HL as the stimuli would not have been sufficiently audible, making the localisation task impossible. In the real-world a gunshot would be in the region of 150 dB (C) and therefore audible to even those with a profound hearing impairment. The stimuli used for the localisation study was kept at a constant, ethical level and this limited the recruitment to individuals with a moderate hearing loss.

There were two limitations of the method and participant sample. As discussed in section 6.5.2, the gunshot based stimulus conditions had an excessive level adjust applied due to the use of incorrect MATLAB code. This would have caused some distortion to the gunshot, thump and crack conditions; the extent or effect of the distortion was not directly measured. The broadband condition was unaffected by this digital clipping so the conclusions of study 6 were based predominantly on the data from this condition.

The second limitation was the age of the hearing impaired participants. The average of the hearing impaired participants was 43 years compared with 30 years for the normal hearing military participants. Increasing age has shown to be linked to a decrease in ability to use TFS cues (Fullgrabe 2013); this may have a detrimental impact on localisation accuracy and ITD thresholds. For future localisation tests the participants in each hearing ability group should be age matched to eliminate this confounding factor.

Before testing, participants completed a consent form, a hearing health questionnaire and a military service questionnaire. Participant characteristics are presented in table 6.14. Participants completed the TFS test first, followed by the localisation task (stimulus condition order determined by incomplete Latin square, as outlined in section 6.2.5), and finally the repeat of the TFS test.

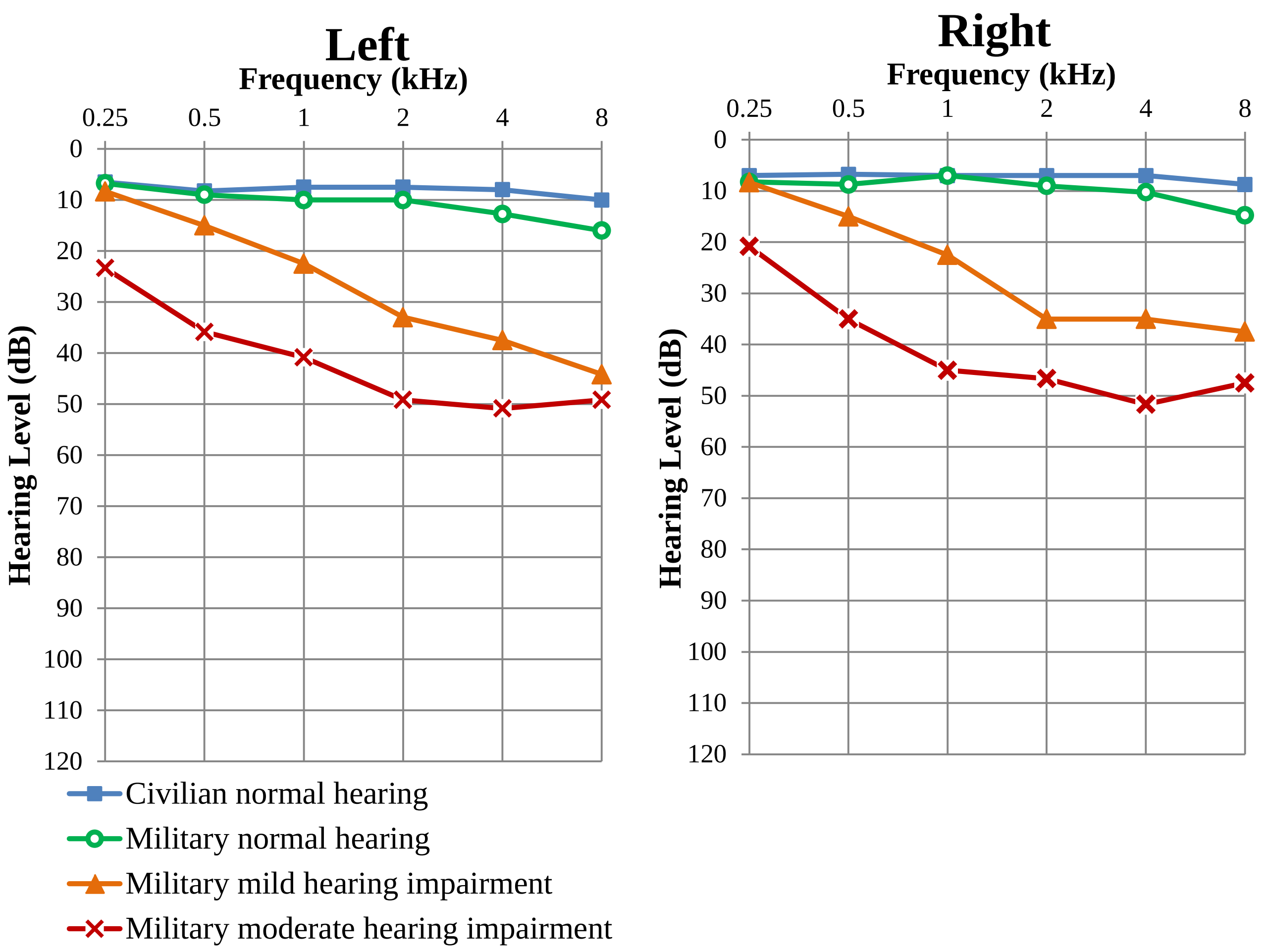


*Figure 6.25 Audiograms showing average hearing thresholds for participant groups from studies 4, 5 and 6.*

*Table 6.14 Study 6: participant characteristics*

| Participant | Average hearing threshold (better ear) | Age (yrs) | Gender (M/F) | Dominance (R/L) | | Time in MoD (yrs) | Operational tours abroad | Works with small arms (Y=1/N=0) | Time since live fire training exercise (yrs) | Blast exposure (Y=1/N=0) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Hand | Eye | | | | | |
| **Mild hearing impairment** | | | | | | | | | | |
| **1** | 22.5 | 52 | M | R | R | 28 | 2 | 0 | 3 | 1 |
| **2** | 23.8 | 61 | M | R | R | 33 | 5 | 1 | 3 | 0 |
| **3** | 25.0 | 41 | M | R | R | 20 | 7 | 1 | 2 | 0 |
| **4** | 31.3 | 41 | M | L | L | 23 | 7 | 1 | 1 | 1 |
| **5** | 22.5 | 39 | M | R | R | 22 | 10 | 0 | 1 | 0 |
| **6** | 27.5 | 28 | M | R | R | 7 | 4 | 0 | 3 | 0 |
| **MEAN** | 25.4 | 44 | | | | 22 | 6 | | 2 | |
| **Moderate hearing impairment** | | | | | | | | | | |
| **7** | 43.8 | 48 | M | R | R | 24 | 5 | 1 | 1 | 0 |
| **8** | 53.8 | 34 | F | R | R | 15 | 6 | 1 | 1 | 0 |
| **9** | 41.3 | 53 | M | R | L | 37 | 15 | 1 | 2 | 1 |
| **10** | 42.3 | 27 | M | R | R | 30 | 7 | 1 | 0 | 1 |
| **11** | 43.8 | 43 | M | R | R | 19 | 2 | 1 | 0 | 0 |
| **12** | 40.4 | 53 | M | R | R | 31 | 8 | 0 | 3 | 0 |
| **MEAN** | 44.0 | 43 | | | | 26 | 7 | | 1 | |

### 6.6.3 Results

**Is there a significant difference in RMS error for a gunshot stimulus between normal hearing personnel, personnel with a mild hearing impairment and personnel with a moderate impairment?**

All participants were able to localise the gunshot stimulus and the broadband noise stimulus to a level of accuracy greater than chance. The highest measured RMS error for the gunshot and noise conditions were 48º and 42º respectively, compared with the mean 'chance' RMS error of 56º ± 4º, estimated for at 0º azimuth. RMS error and MAE are presented in table 6.15. Statistical analyses were performed to compare the hearing ability groups. Whilst the size of these samples was unbalanced, sampling a smaller group from the normal hearing participants would have been statistically harmful and may have created a biased group due to random sampling error. Due to this, MAE and RMS error of the whole participant groups were used as they allowed comparison with previous studies, both within the thesis and in the wider literature.

*Table 6.15 Localisation accuracy for the hearing ability groups (mild hearing loss n = 6, moderate hearing loss n = 6, normal hearing n = 20). All values are given in degrees.*

| Hearing ability group | Stimulus condition | RMS error | RMS error SD | MAE | MAE SD |
|---|---|---|---|---|---|
| **Normal hearing** | Gunshot | 33.7 | 7.4 | 24.9 | 6.1 |
| | Broadband noise | 27.4 | 6.2 | 20.5 | 5.4 |
| **Mild loss** | Gunshot | 40.0 | 5.6 | 26.3 | 2.8 |
| | Broadband noise | 31.2 | 3.4 | 24.1 | 3.1 |
| **Moderate loss** | Gunshot | 37.4 | 1.8 | 27.5 | 1.7 |
| | Broadband noise | 26.6 | 2.7 | 19.8 | 2.2 |

As shown in figure 6.26 there was a greater range of accuracy scores (in RMS error) for the normal hearing participants. This was likely to be because there were a greater number of participants in that group. The gunshot condition yielded higher RMS error scores than the broadband noise condition for all of the hearing ability groups. The outliers shown in the moderate hearing loss group demonstrate that four out of six participants performed similarly to each other (and were therefore clustered close to the mean) but the remaining two participants performed considerably better or worse than the mean. If a greater number of participants had been tested, these 'extreme' scores may not have been outliers due to a more even distribution of scores as seen in the normal hearing group.

A mixed ANOVA was conducted with stimulus condition (two levels) as the within subjects factor and hearing ability (three levels) as the between subjects factor. There was no significant main effect of hearing group, $F(1,29) = 0.62$, $p = 0.54$, partial $\eta 2 = 0.04$. This suggests that localisation accuracy did not vary significantly between participants with normal hearing, mild hearing loss or moderate hearing loss. In concurrence with the findings of study 4 and 5, there was a significant main effect of stimulus condition $F(1, 29) = 17.83$, $p < 0.01$, partial $\eta 2 = 0.38$, indicating a consistent difference in localisation accuracy between gunshot and broadband noise conditions regardless of hearing ability.

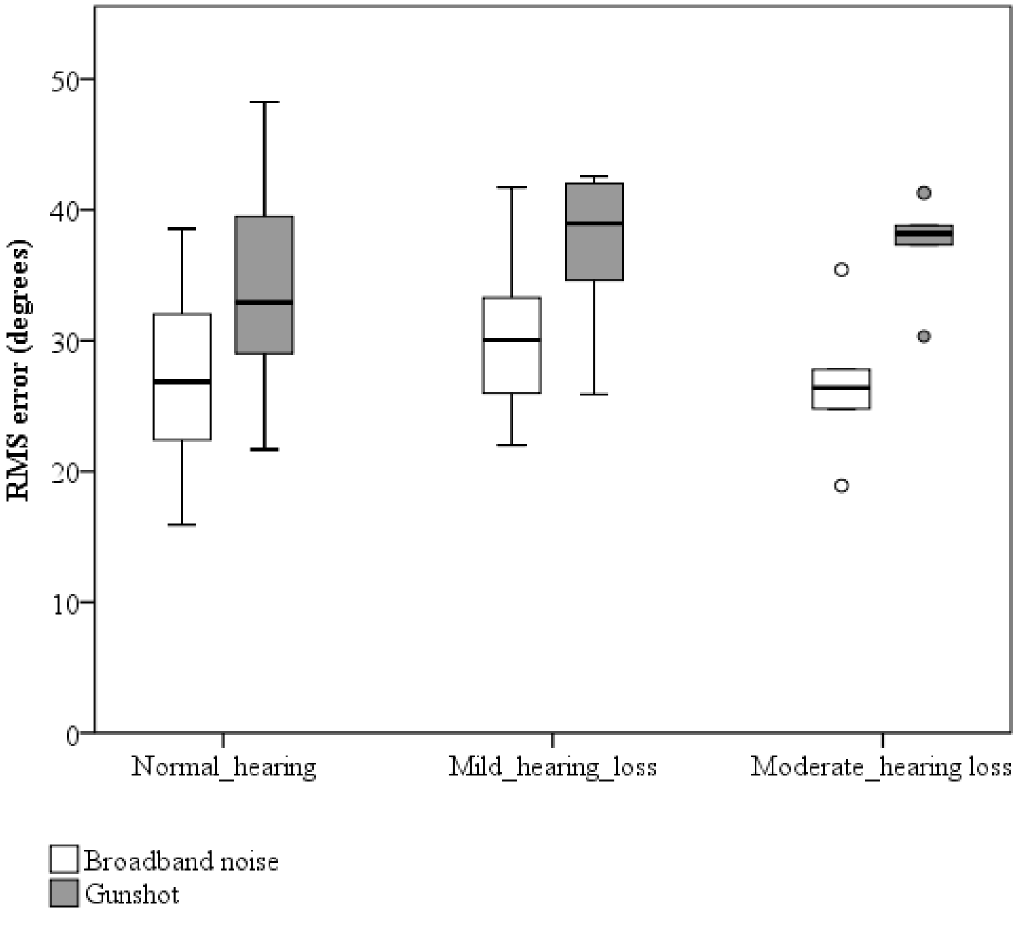


*Figure 6.26 Box plots to show localisation accuracy of hearing ability groups for the broadband noise and gunshot conditions. Circles represent outliers in the moderate hearing loss group. The RMS score associated with selecting random sources without bias is 56º± 4º at 0º azimuth. n=20 normal hearing, 6 mild hearing loss and 6 moderate loss participants.*

Despite there being no significant effect of hearing ability group on localisation performance, it was still worthwhile performing correlational analyses to detect any, more subtle, associations between hearing thresholds and RMS error.

It was plausible that any effect of hearing loss on localisation was not shown in a statistical comparison of means. Due to the small sample size it is possible that a small number of abnormal results could have a large impact on the mean of the group. Correlational analysis is better able to highlight an association between two variables; in this instance, hearing thresholds and localisation accuracy.

There was no correlation between hearing level and gunshot localisation accuracy $r = .25$, $n=32$, $p=.164$. Interestingly, the poorest accuracy scores were recorded from normal hearing listeners (47 and 48.2° RMS error). Further to this, from the scatter plot shown in figure 16.27, it is clear that there was considerable variation in RMS error for individuals with a similar average hearing threshold. Two individuals with average hearing thresholds of 41 and 42 dB HL had localisation accuracy scores of 31° and 42° RMS error respectively. A similar trend was observed for the broadband noise stimulus (figure 16.28), indicating that degree of bilateral symmetrical hearing impairment did not have an effect on localisation accuracy, regardless of the stimuli used (or whether the stimuli were distorted).

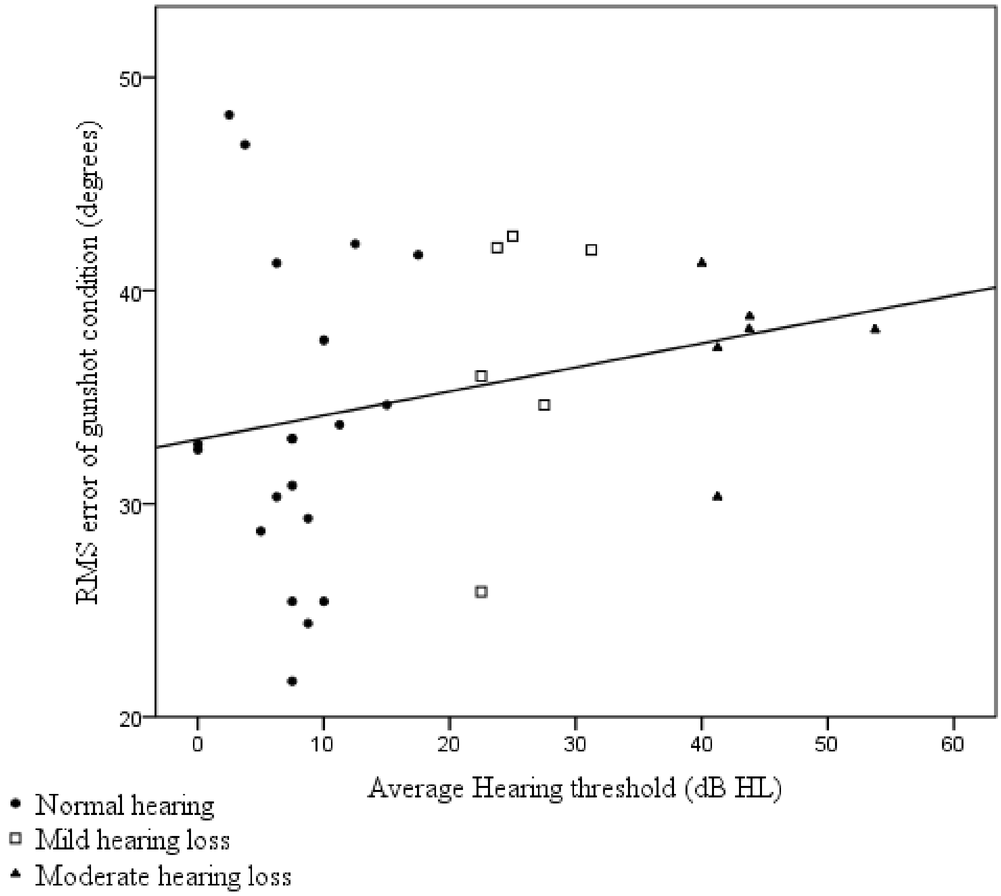


*Figure 6.27 Scatter plots to show the relationship between average hearing threshold and localisation accuracy for the gunshot stimulus. Linear regression line $R^2$ = 0.064 when all three groups are considered, $R^2$ = 0.032 when only mild and moderate hearing impairment are included.*

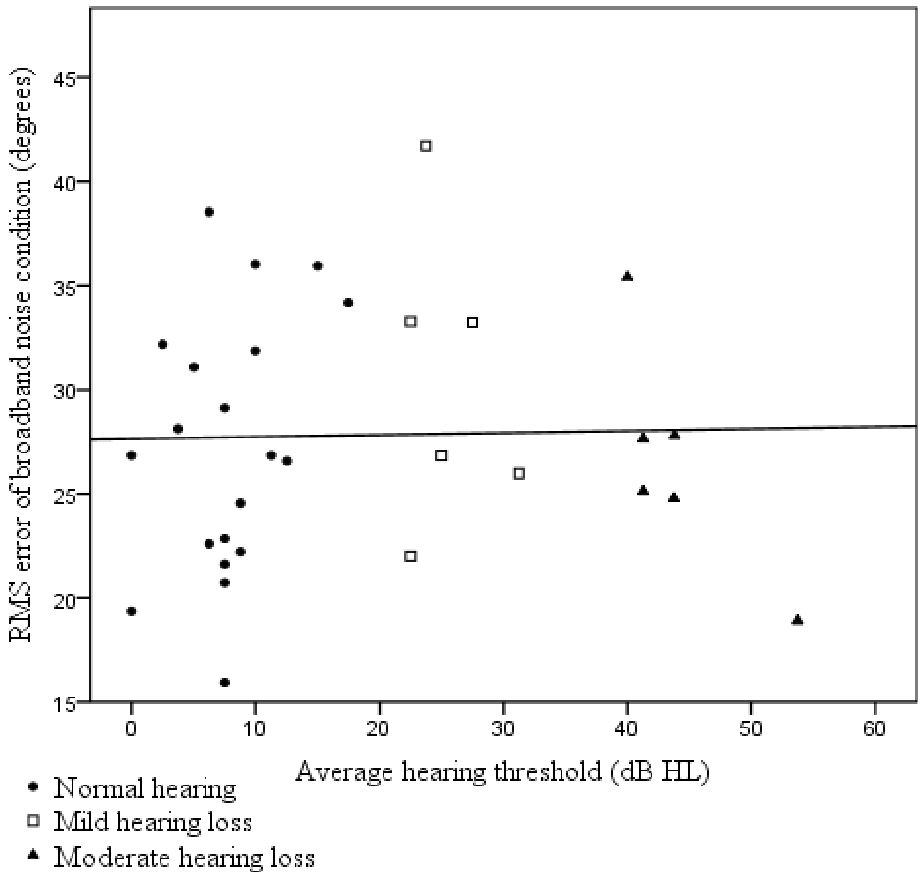


*Figure 6.28 Scatter plot to show the relationship between average hearing threshold and localisation accuracy for the broadband stimulus. Linear regression line shows no association, $R^2$ = 5.2 x10-4.*

In order to examine whether degree of hearing loss had any effect on pattern of localisation errors (that may not have been highlighted by RMS alone) bubble plots were created to show the spread of responses (figure 6.29). Rates of RE and bias were also calculated (table 6.16).

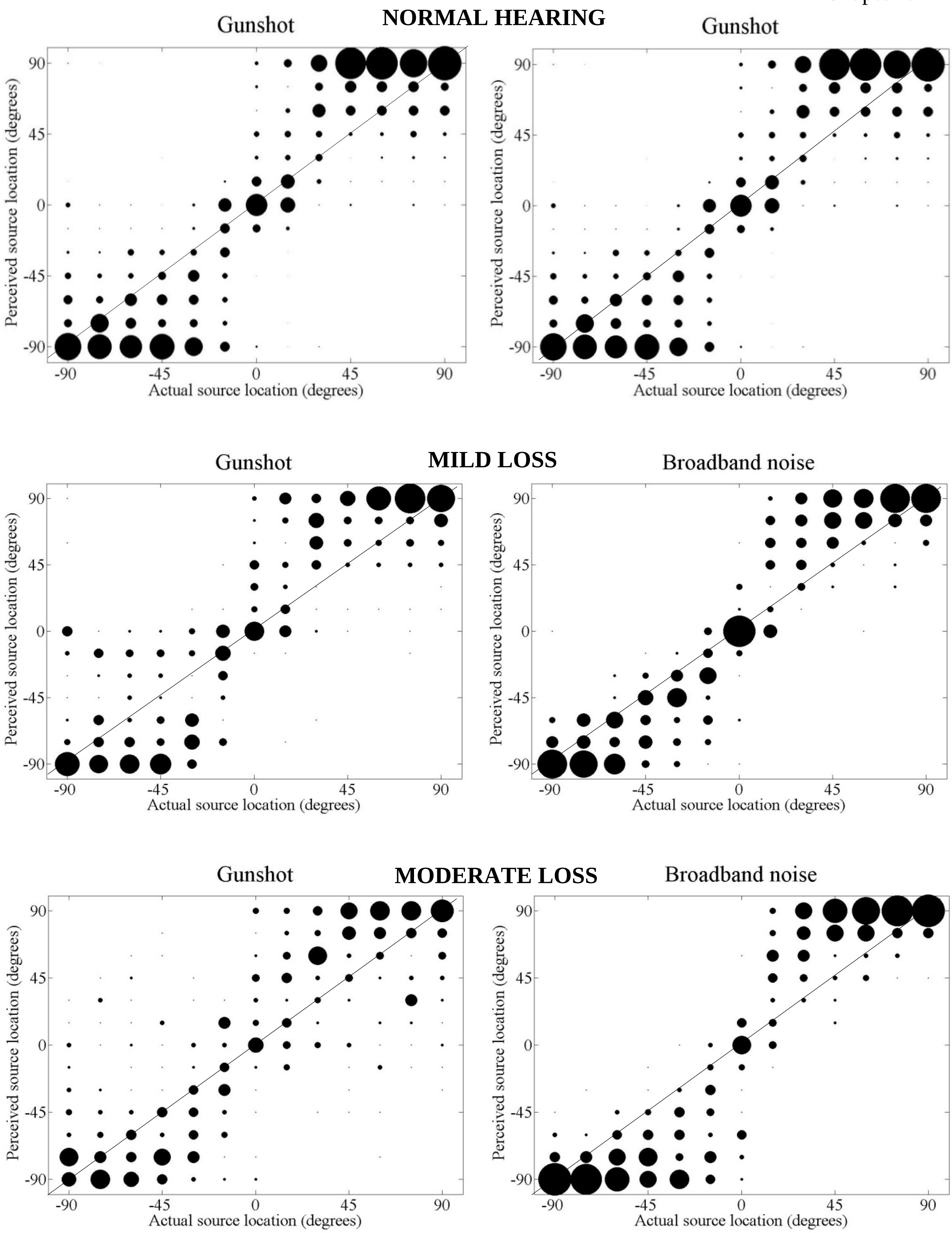


*Figure 6.29 Study 6: Bubble plots showing the pattern of responses from the hearing ability groups. Bubble area represents the number of responses and the line at 45º runs through the correct responses. The largest bubble represents 115 responses and the smallest (just visible) bubbles represent 2 responses.*

*Table 6.16 Study 6: Measures of unsigned bias (C), signed (E) and random error (RE). All data are in degrees (°). RE was higher for the moderate hearing ability group compared with mild and normal hearing, but only during the gunshot condition (shaded in grey).*

| Condition | Hearing ability | Random error (SD) | Unsigned error (SD) | Signed error (SD) |
|---|---|---|---|---|
| **Gunshot** | Normal | 23.2(6.3) | 25.6(7.1) | 2.1(5.7) |
| | Mild loss | 22.1(3.2) | 28.4(2.4) | 4.3(6.4) |
| | Moderate loss | 28.6(3.1) | 26.4(5.2) | 3.4(3.4) |
| **Broadband noise** | | | | |
| | Normal | 16.5(4.3) | 22.3(7.0) | -0.8(4.1) |
| | Mild Loss | 16.4(2.7) | 26.5(4.6) | -1.5(2.7) |
| | Moderate loss | 16.9(1.3) | 21.3(3.2) | -2.8(2.3) |

It was hypothesised that hearing impairment would have an effect on ITD thresholds. No significant correlation was found between ITD threshold and hearing level at 500 Hz $r = .14$, $n=32$, $p=.436$. This is shown in table 6.17 and figure 6.29. The lack of association between ITD thresholds and degree of hearing loss was unexpected. From figure 6.29 it is apparent that in each group there was a large range of performance levels achieved; responses ranged from a threshold of 15.4 dB to 26.2 dB (35 µs to 416 µs) in the normal hearing group alone.

*Table 6.17 Comparison between military hearing impaired TFS sensitivity test scores and previous literature. ITD thresholds are in dB (re 1 µs). Hopkins and Moore (2010) used a 500 Hz pure tone and Rowan and Lutman (2007) used a 125 Hz pure tone.*

| | Test 1 (SD) | Test 2 (SD) | Mean (SD) |
|---|---|---|---|
| **Normal hearing** | 19.6 (2.7) | 20.15 (2.1) | 19.9 (2.3) |
| **Mild hearing loss** | 19.6 (1.5) | 20.3 (2.2) | 20.0 (1.6) |
| **Moderate hearing loss** | 20.3 (1.8) | 21.7 (1.8) | 21.1 (1.6) |
| **Hopkins & Moore** | n/a | n/a | 21.2 (not reported) |
| **Rowan & Lutman** | n/a | n/a | 23.5 (not reported) |

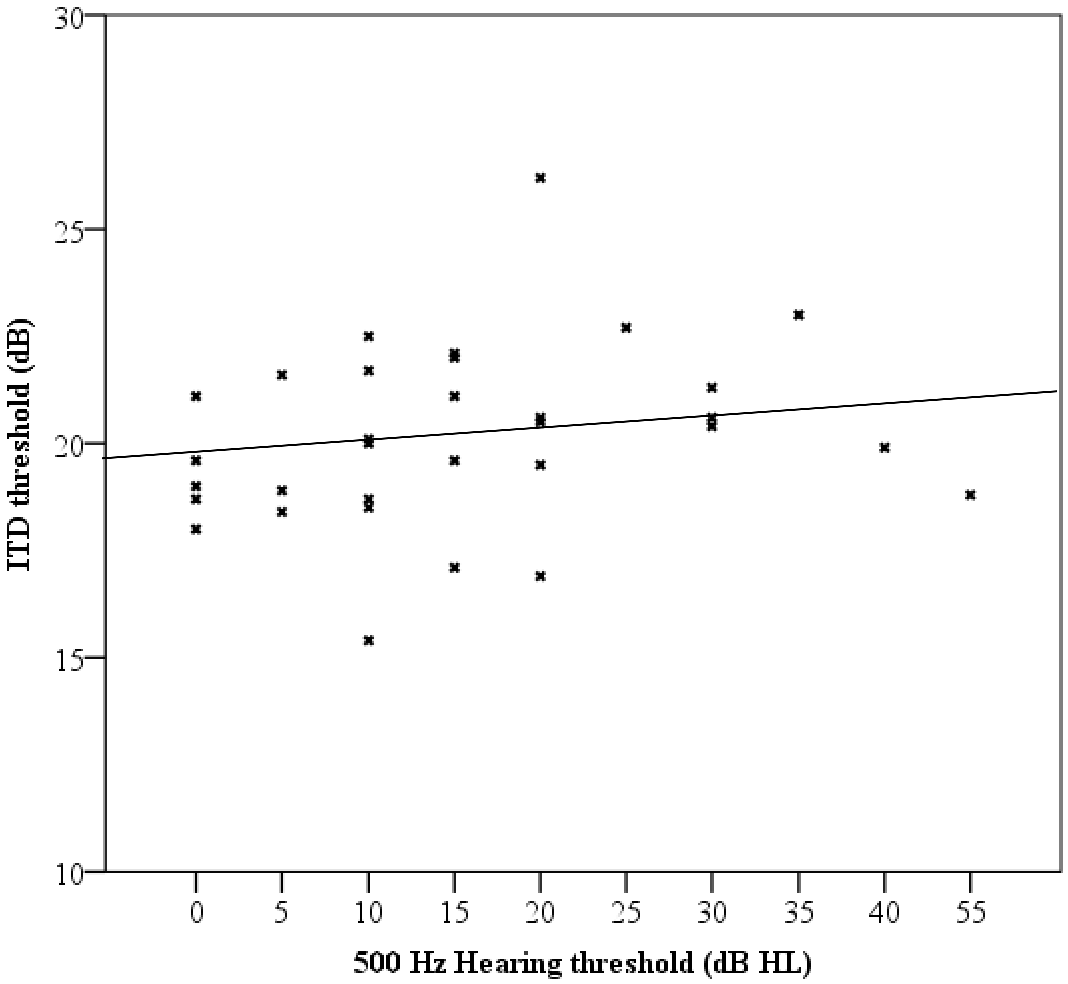


*Figure 6.30 Scatter plot to show relationship between hearing threshold measured at 500 Hz (average between two ears) and ITD threshold (re 1 µs). Regression line $R^2$ = 0.084.*

### 6.6.4 Discussion

Noise induced hearing loss affects large numbers of serving infantry personnel working for the British military. For these personnel to be deemed ‘fit for duty’ they must possess the ability to carry out MCATs, including localising small arms fire. At the time of print, there was no evidence to indicate whether a decrease in hearing thresholds affects an individual’s ability to localise gunfire and therefore whether it would be appropriate to incorporate a test of localisation in an AFFD test battery. The aim of study 6 was to start exploring the relationship between symmetrical sensorineural hearing impairment and small arms fire localisation accuracy within a military population.

All personnel, regardless of their degree of hearing loss, were able to locate the source of small arms fire to a degree of accuracy greater than that associated with selecting a virtual source at random without bias (calculation for this is described on page 133). This demonstrates that, when in an ideal listening environment, personnel with (up to and including) a symmetrical moderate hearing loss are likely to be able to locate the source of a single gunshot to within 37º RMS error. Whilst the personnel tested throughout study 5 and 6 performed significantly worse on average than the civilian listeners in study 4, the results suggest that they are able to perform the task with a level of success which may ultimately maintain their safety and effectiveness during this MCAT on operational duties.

It was hypothesised that as hearing thresholds increased, localisation accuracy for both the gunshot and broadband noise stimulus would decrease. Previous literature suggested that moderate hearing impairment (average hearing thresholds of >40 dB HL in the better hearing ear) causes localisation accuracy to deteriorate due to audibility and decreased sensitivity to TFS (Hopkins and Moore 2010, Lorenzi et al. 1999). However, study 6 found no significant effect of hearing loss on localisation accuracy. There was large variability in participant RMS error scores irrespective of their HTLs but no association between degree of loss and localisation accuracy.

There were several potential reasons for these findings. The first possible explanation was sampling error. It was possible that the groups of hearing impaired personnel were not representative of the wider hearing impaired military population and instead consisted by chance of ‘better than average localisers’. This was unlikely as there was a similar, wide variation of results within the normal hearing population. This reduces the chance of all 12 hearing impaired listeners falling into this category. It was also possible that the hearing impaired participants were better than expected due to a sampling bias; participants could have chosen to take part because they felt they were skilled at similar tasks in everyday life or in their military duties. This was also unlikely. Relatively little information about the nature of the task was given to participants during the recruitment process and it would have been difficult for individuals to rate their level of success (particularly in comparison with others) on localisation tasks in everyday life.

A second possible reason why the current study’s findings did not agree with those found in previous literature was the configuration of participant hearing losses. Proschel and Doring (1990, from Noble et al. 1994 as unable to access the original article in English) found significant differences in frontal horizontal localisation ability exhibited by three groups of listeners. Similar to the current study, the three groups had differing levels of bilateral symmetrical hearing impairment (group 1: >20 dB HL, group 2: >20<40 dB HL and group 3: >40 dB HL), but the configuration of the losses were not described in Noble et al. (1994). It is conceivable that the decrease in localisation accuracy observed by Proschel and Doring arose from poor low frequency thresholds, reducing the usefulness of interaural time cues. In the current study, the nature of participants' hearing loss (high frequency sloping) meant that low frequency hearing thresholds were good enough to consistently allow them access to time cues; known to be the predominant cue for frontal horizontal localisation. This was noted by Noble et al. (1994) during a comparison of localisation accuracy for individuals with conductive and sensorineural losses. Performance on the localisation task remained accurate when good hearing was preserved at low and mid frequencies as listeners were able to capture both low frequency ILD cues and mid frequency ITDs. Noble et al. noted that large unexplained variance in localisation performance during their study may have been due to characteristics of hearing impairment beyond attenuation. The existence of 'distortions' (a collective term for impaired psychoacoustical ability) is widely reported (e.g. Plomp 1978) and may explain some of the variations in performance in the current study. As the mechanism of these distortions is largely unknown and extremely difficult to measure, it is possible that the normal hearing military population are similarly affected due to noise exposure or blast injury. As discussed in section 6.5.4 this may go some length towards explaining the differences between civilian and military listeners.

It is plausible that an association between hearing thresholds and localisation ability exists for military personnel, but that this association was masked in the current study by other characteristics of the participant responses. As discussed in section 6.5.4 military personnel performed the localisation task in a different way to civilian listeners, resulting in higher lateral bias and overall RMS error for all stimulus conditions. From figure 6.28 (bubble plots to show the pattern of responses) it is clear that the hearing impaired personnel responded to the task in a similar way to the normal hearing personnel in study 5. It is possible that the overall increase and variability in RMS error masked any effect of hearing loss on localisation accuracy. In order to determine if this was the case, a study of hearing impaired civilian listeners matching the method of study 6 could be carried out; this would highlight whether increasing hearing thresholds alters localisation performance in the general population. If an association exists but has not been detected using the current study it would indicate that the current localisation test method was not appropriate to measure auditory fitness for localisation tasks. The addition of clipping to the gunshot stimuli may also have caused the military personnel to perform poorly during the localisation task, masking any additional difficulty caused by hearing loss. However, as the personnel performed similarly on the broadband noise condition, this was unlikely to be the sole cause of the poor performance and for both the normal hearing and hearing impaired personnel.

A larger sample size of hearing impaired personnel may have highlighted a general trend in the current study even if the variability in individual participant scores was high. Whilst increasing the sample size may identify a significant difference between the hearing ability groups, the magnitude of that difference would likely still be small, conclusively demonstrating little to no association between thresholds and localisation accuracy.

It is also possible that high frequency hearing impairment actually improved localisation accuracy for the gunshot stimulus. As discussed above, high frequency loss would attenuate and distort ILD cues (present in the crack portion of the stimulus), causing the predominant cue to come from the ITD-rich thump component. This may have encouraged impaired listeners, both during the current study (and potentially during operational duties) to use the thump signal for localisation. As proven during Study 4, localising using the thump has the potential to improve localisation accuracy by 11º RMS error on average compared with the crack stimulus. Although, due to the increased tendency for personnel to choose the lateral sources, this potential advantage may not translate to an improvement in overall accuracy.

Whilst no association between overall RMS error and hearing thresholds was observed, there was a difference in the level of RE for the gunshot stimulus. Military personnel with a moderate hearing impairment demonstrated a higher rate of RE compared with the normal hearing and mildly impaired listeners (moderate impairment RE = 28.6°, mild impairment RE = 22.1°, normal hearing RE = 23.2°). This trend was also highlighted in the bubble plots in figure 6.28; the spread of responses was similar between the mild impairment and normal hearing groups but the moderate group showed an increase in random variability. This was likely to have been due to audibility; whilst the peak amplitude of the gunshot would have been clearly audible, some of the quieter sections of the signal (the ground reflection for example) may have been inaudible to those with thresholds above 40 dB HL. The mild hearing group had low frequency thresholds within or very close to normal (< 20 dB HL) whereas the moderate group had some deterioration of low frequency hearing which may have impacted their ability to use ITD cues. Perceptually this would have made the localisation task more difficult, decreasing participant's confidence or forcing them to make a random judgement of source location.

It was hypothesised that there would be a positive correlation between ITD thresholds and pure tone thresholds. Correlational analysis instead showed no significant association between these two variables (r = .14, n=32, *p*=.436). The range of scores present from all hearing ability groups was wide; the third best performer had a mild hearing loss and the worst performer had normal hearing. Predicting ITD threshold from pure tone thresholds would be impossible according to the findings of study 6. Research suggests that people with cochlear hearing impairment are less sensitive to TFS than normal hearing listeners (Moore et al. 2006, Hopkins and Moore 2007, Fullgrabe 2013) but previous studies have also discovered that ability to use TFS information varies among individuals with similar hearing configurations (Hopkins and Moore 2010). Hopkins and Moore (2010) examined ITD thresholds from 10 normal hearing listeners and noted a large variation in responses (thresholds from 10 - 100 µs) using a 500 Hz tone, similar to the current study (average individual thresholds from 42 – 183 µs). They noted that when audiometric configuration is similar between participants, little effect of hearing impairment is seen and this may account for the similarities between hearing ability groups.

Fullgrabe (2013) found a significant increase in ITD thresholds as a function of increasing age (even when comparing 20-30 year olds with 40-49 year olds). As there was a difference in average age between the normal hearing and hearing impaired participants in study 6 it was thought that a difference in ITD thresholds would be apparent due to age if not hearing impairment. It is possible that the sample size was too small in study 6; Fullgrabe only found small (but significant) difference in TFS sensitivity using 102 normal hearing adults.

Finally, it is possible that some of the personnel were unable or not motivated to carry out the TFS sensitivity task to an acceptable standard regardless of their hearing acuity. This was discussed in section 6.5.4 and may have resulted in an overall increase in guessed responses and higher overall ITD thresholds. It was unlikely that the task was too difficult; participants were given clear instructions and carried out a simple practice trial which all participants were able to complete correctly. The personnel participating would be expected to be able to carry out reasonably complicated tasks requiring some level of working memory as part of their occupation and therefore should be able to carry out the listening task. Their motivation levels may not have been so reliable. Motivation was not monitored in any formal way during testing but this potential variable could be minimised in future experiments by adding a competitive element to the test (for example asking personnel to try and 'beat' colleagues to the lowest ITD threshold) or by providing a monetary incentive.

### 6.6.5 Conclusions and knowledge gaps

Study 6 aimed to investigate the relationship between degree of symmetrical sensorineural hearing impairment and small arms gunfire localisation accuracy within a military population. The localisation accuracy and ITD thresholds of 12 hearing impaired military personnel and 20 normal hearing personnel were measured and analysed using a virtual source identification task and test of TFS sensitivity.

No association was found between localisation accuracy and hearing thresholds for the gunshot or broadband noise stimulus. This indicated personnel with up to (and including) moderately impaired hearing were able to locate stimuli sources with a level of success greater than if they were randomly selecting a source. Personnel with hearing impairment performed with similar levels of lateral bias than normal hearing personnel demonstrating that hearing impaired personnel are similarly inclined to make lateral judgements as discussed in study 5. However, average RE did increase for the moderately impaired personnel suggesting that as the stimulus audibility decreased the rate of random guessing increased. In concurrence with the literature this was likely to be particularly apparent at low frequencies; ITD cues created by low frequency signals are the predominant cue for frontal horizontal localisation.

Sensitivity to ITD cues was not found to be associated with hearing thresholds levels. Hearing impaired personnel performed the TFS sensitivity test with highly variable results, similar to the normal hearing personnel. This suggested that some personnel either lacked motivation to complete the test correctly or that sensitivity to ITD cues was variable among personnel due to noise exposure, age of participants or cognitive ability.

**Knowledge gaps**

- Whilst mild and moderate bilateral symmetrical sensorineural hearing loss does not appear to significantly impact military personnel's ability to localise the source of small arms fire, other configurations of hearing impairment may have an impact. **In order to definitively state whether hearing impairment has an effect on**

**localisation of small arms, personnel with conductive or asymmetrical hearing impairments would need to be assessed.** Assessing the localisation accuracy of personnel with severe to profound hearing impairment may not be necessary as those individuals would likely struggle to carry out simple speech communication and sound detection tasks regardless of their localisation ability; equally important when considering auditory fitness.

- **It is still not fully understood why personnel, whether hearing impaired or not, perform the localisation task and TFS sensitivity test differently to civilians.** As discussed, it was likely due to a combination of factors including motivation, cognitive ability, military training and previous exposure to noise. In order to develop accurate and robust measures of AFFD these differences must be investigated further to ensure that they do not mask any impact of hearing impairment on psychoacoustical measurements.

# Chapter 7: Discussion, future work and conclusions

## 7.1 Discussion

Infantry personnel must be able to communicate effectively, identify and locate sounds in their environment and maintain situational awareness to ensure their safety during operational duties. They are also at high risk of noise induced hearing impairment, which is likely to hinder their performance on occupational auditory tasks. Use of the current auditory fitness protocol may lead to the redeployment of personnel that are not capable of performing their role to an acceptable level or the medical downgrading of personnel that are still able to perform the tasks required of them.

The aims of this thesis were addressed by a combination of qualitative research involving focus groups and questionnaires and quantitative research using a virtual source identification task to measure localisation of small arms gunfire. This chapter integrates the findings of studies 1 to 6 and considers the implications of this work on the field of infantry AFFD. Recommendations for continuing this research are made in section 7.2 and the overall conclusions are outlined in section 7.3.

This thesis intended to answer the following research questions:

1. What are the mission critical auditory requirements of UK infantry personnel?
2. What localisation cues are available within a small arms gunshot?
3. How accurately are normal hearing military personnel able to localise a small arms gunshot?
4. Is small arms localisation ability sensitive to military specific hearing loss?

### 7.1.1 What are the mission critical auditory requirements of UK infantry personnel?

It is known that current AFFD measures for the UK infantry may not appropriately assess functional hearing abilities, such as those required to complete MCATs. The first stage in improving auditory fitness measures required a detailed understanding of the auditory tasks performed during infantry training and operational duties.

Studies 1 and 2 aimed to identify these auditory tasks and gather information about the acoustic environments experienced by infantry personnel. Over 180 personnel took part in this stage of the research and the data collected provided a novel and thought-provoking insight into the hearing requirements of personnel. Study 1 comprised of 16 focus groups with infantry personnel, allowing them to describe and discuss situations where their hearing was required during operational duties. Content analysis was used to narrow over eight hours of dialogue into themes and subthemes relating to hearing and hearing impairment. The analysis highlighted 17 auditory tasks carried out by personnel during training and frontline fighting.

These tasks became the basis of a questionnaire (developed and implemented by Semeraro (2015)) asking a further 80 personnel to rank the consequences to poor performance on the task, how frequently it was performed and by whom. Nine tasks were deemed to be ‘high priority’ MCATs; performed by all infantry personnel with severe to critical consequences if performed below the necessary standard. It is paramount that the auditory skills required to carry out these tasks are appropriately assessed by AFFD measures.

The findings of studies 1 and 2 were in keeping with the current knowledge of AFFD presented in the literature. In agreement with Tufts et al. (2009) auditory tasks fell into three general themes; speech communication, sound localisation and sound identification. As described by Vaillancourt et al. (2011) there were many factors that affected an individual’s ability to carry out occupational auditory tasks. For the Canadian Coast Guard and DFO, hearing impairment and background noise were described as a hindrance to successful completion of the tasks during Vaillancourt’s job analysis.

The current research correspondingly identified these factors but added to those reported in the literature. Infantry personnel felt that they were unable to hear, and therefore complete, critical auditory tasks due to stress (mentioned 31 times during the focus groups) and the need to carry out multiple tasks simultaneously (mentioned 43 times). These previously unconsidered factors emphasise the importance of adequate functional hearing for infantry personnel; it is vital that personnel are able to utilise all of their senses in complex and potentially life threatening situations.

In keeping with the aims, these studies identified auditory skills that should be assessed as part of an AFFD test battery. Further to this, the findings stress the importance of measuring AFFD beyond the audiogram; the tasks performed by personnel almost never involved detecting single sounds in quiet environments.

The results of the job analysis have wide ranging implications. The reasons for personnel disliking their hearing protection should be considered by developers of new protection devices to increase compliance with hearing preservation guidance. Personnel felt that the current hearing test used was not representative of the real-world auditory environments they experience during operational duties. It is therefore recommended that new AFFD measures have higher face validity, to ensure that personnel are motivated to complete the testing correctly. The hours of dialogue recorded during this research also serves as a permanent record of the experiences, attitudes and behaviours of serving infantry personnel during training exercises and on tours of duty. No other record of this kind, relating to hearing and hearing health, currently exists for UK infantry personnel.

As the participants were solely recruited from infantry battle groups, the conclusions and recommendations resulting from studies 1 and 2 are not applicable to other cohorts of military personnel. The auditory tasks performed by personnel would differ greatly depending on an individual's military occupation and as such their auditory fitness requirements would also differ from the infantry.

As with all focus groups studies, the data from study 1 was anecdotal and the conversation was guided by a facilitator. This method introduced a risk of facilitator bias and the chance that some MCATs were forgotten by personnel; allowing them to be missed off the list of 17 tasks compiled after content analysis. Great care was taken to reduce these potential sources of error by selecting and asking open ended questions and by collecting data until a saturation point was reached.

Due to the qualitative nature of the data collected, the consequences of performing the auditory tasks incorrectly could not be determined. Personnel, on occasion, alluded to the failure of a task resulting in serious injury or fatality and stated that colleagues would be 'useless' or 'redundant' without certain hearing abilities. Further investigation is required to measure the performance levels of normal hearing and hearing impaired personnel on all of the prioritised MCATs.

Localisation of small arms fire was discussed by personnel throughout the qualitative stage of the research. There were conflicting opinions about the accuracy of localisation judgements; some personnel claimed to be highly skilled at the task, others admitting no apparent skill at all. The task was reported as vital to the safety and efficiency of missions and an auditory requirement of all infantry personnel by respondents to the questionnaire in study 2. As there appeared to be a range of self-reported abilities for this task, it called into question whether all infantry personnel are able to localise small arms gunfire.

### 7.1.2 What localisation cues are available within a live small arms gunshot?

A comprehensive literature search revealed a paucity of studies investigating human localisation of small arms fire. Research conducted by Talcott et al. (2012) and Sherwin and Gaston (2013), whilst not directly measuring localisation of live gunfire, indicated that military personnel may be able to locate a firer to a degree of accuracy greater than chance.

A localisation task using recordings of gunfire was designed with the aim of measuring localisation accuracy. The recordings were created by placing binaural and omnidirectional microphones 30 cm from the bullet trajectory at 50, 100, 200 and 300 m downrange. Single live SA80 small arms gunshots were recorded. The binaural microphones (placed at the ears of a KEMAR dummy head) were rotated in 15º intervals on a turntable through 360º.

The gunshot recordings were analysed to determine which component (crack or thump) provided the most useful information for human localisation. It was found that the crack contained little useful ILD information, despite this being the dominant localisation cue for a high frequency signal. The thump produced ITD and ILD cues similar to (and marginally higher than) those created by a broadband signal recorded by KEMAR under similar conditions (Gardner and Martin 2005). A human listener is likely to make greater use of the ITD information within the thump due to the low frequency nature of the signal. Analysis of the gunshot recordings allowed specific hypotheses about the accuracy and bias of localisation judgements to be formed based upon the binaural cues available to listeners.

The recordings were used to create a virtual source identification task, requiring participants to identify the source of single gunshots and also broadband noise bursts convolved with KEMAR HRTFs from the CIPIC database. Additionally, the gunshots were split into crack and thump to assess the localisation accuracy of the components separately. A study of 20 normal hearing civilians demonstrated that the virtual source identification method provided reliable results that were in agreement with previous literature. The broadband noise condition yielded accuracy scores very similar to those presented by Zotkin et al. (2003) and Begault et al. (2001) both using similar virtual source identification tasks (MAE: 16.1º and 22.5º respectively, compared with 16.2º for study 4). In concurrence with Talcott et al. (2012) civilian participants were able to localise the gunshot stimuli with greater accuracy than selecting source azimuths at random. The participants in study 4 were, on average, less accurate than those assessed in Talcott's experiment (RMS error: 22º compared with 27.5º for study 4). As discussed, this was likely to be due to differences in the experimental design (Talcott's experiment was a free-field task with fewer sources).

Study 4 revealed clear differences in localisation judgements between the stimulus conditions. As expected, participants demonstrated greater accuracy when localising the broadband noise and thump stimuli compared with the gunshot. The crack yielded the poorest accuracy scores when averaged across all participants. These overall RMS error results were not unexpected and were in agreement with well-established theories about human localisation as discussed in section 6.4.4. It was thought that the crack and gunshot would yield higher central bias due to the smaller ITD and ILD cues available to the listener at any given azimuth. In contrast participants exhibited higher lateral bias (this was particularly apparent for the crack condition). Similar to a study by Macpherson and Middlebrooks (2000) (who found an increase in localisation errors for short duration signals) it was felt that participants selected the end sources more often if they were unsure.

These findings are of interest for two reasons: 1) they show the need to preserve the audibility of the thump component of small arms fire; a particularly important consideration when developing hearing protection devices, 2) they highlighted the potential for training personnel to 'ignore' the crack component and instead focus on the perceived origin of the thump. Infantry training exercises, as discussed during the focus groups, already incorporate this message to a degree but there may be scope for greater emphasis on this as a localisation tactic. It may only increase localisation accuracy in the frontal horizontal plane by a few degrees but the increase in confidence of personnel may be beneficial regardless.

The main limitation of study 4 was related to the participant sample (further limitations of the methodology are discussed later in this chapter). The data collected from university staff and students was not representative of the infantry population. Civilian listeners would not have had specialist military training or experience of the real-world MCAT that the source identification task was designed to simulate.

### 7.1.3 How accurately are normal hearing military personnel able to localise a small arms gunshot?

Twenty normal hearing military personnel were recruited from the INM and HMS Sultan to carry out the virtual source identification task. The study method was identical to that used with the civilian participants and the results of the two studies were compared. This experiment sought to determine whether there were differences in localisation accuracy and patterns of localisation errors between civilian and military populations. Before localisation AFFD measures could be considered, evidence was needed to confirm whether personnel are able to perform the localisation MCAT.

Military personnel were found to be able to localise all stimulus types to a degree of accuracy greater than chance. Despite this, personnel exhibited significantly higher RMS error scores than the civilian group for the broadband noise, gunshot and thump stimulus conditions. Interestingly whilst their overall RMS error rates were higher, military personnel actually performed significantly better when localisation accuracy was analysed using an LPC score. This indicated that they were able to perceive whether sources were to the left or right with greater accuracy than civilian listeners.

The literature investigating human small arms localisation did not report the types of localisation errors made by participants. It was therefore not possible to measure the concurrent validity of these unexpected findings. The overall RMS error of the gunshot stimulus was 11° greater for the current research than that measured by Talcott et al. (2012). As discussed previously, the source identification task used by Talcott had fewer sources and was conducted using blank gunfire in the open air. As the current study used non-individualised HRTFs and a virtual experiment design, the localisation accuracy of participants was expected to be poorer. Additionally, the blank ammunition used in Talcott's experiment would not have contained the crack component allowing participants to localise using the thump only, possibly increasing the accuracy of judgements.

There was no stand-alone reason for the difference in performance between military and civilian listeners. As discussed in section 6.5.4 it was likely due to a combination of factors. KEMAR-based HRTFs may not have matched the military personnels' HRTFs as well as the civilians (the participant groups differed in both average age and gender), potentially causing the sources to be perceived incorrectly. A mismatch in HRTFs is known to increase localisation errors, particularly front back confusions (Begault et al. 2001, Wightman and Kistler 2005), which may have resulted in greater end effects.

It was possible that the military participants were completing a different task to the one requested of them. Instead of choosing the perceived direction of the gunshot, military participants may have been ‘looking’ in the general direction of the stimulus. This tactic is logical in a real world scenario where a single shot is likely to be followed by a second (or a visual cue), confirming the position of the firer. It is well-documented that humans can improve their localisation ability for long duration stimuli or multiple stimuli by moving their head to place the source close to their midline (Brimijoin et al. 2013, Iwaya et al. 2003).

The localisation task used was only able to assess performance in the frontal horizontal plane. The task was deliberately designed as a simplified simulation of the MCAT. As a result of this, the source identification task is likely to yield fewer localisation errors than the real MCAT. In training or operational environments there would be additional difficulties of off-axis firing from 360º around the individual, additional background noise, multiple types of weaponry, and possibly other tasks to be completed simultaneously.

During the focus group study personnel noted that being in a potentially life threatening situation heightened their senses and gave them more acute situational awareness. Whilst it is possible that factors introduced during the operational MCAT could cause localisation accuracy to decrease, it is equally possible that the source identification task underestimated localisation accuracy in a stressful battlefield environment.

A further conceivable limitation of study 5 was the varying roles of the military participants. The original aim of the study was to assess infantry localisation accuracy but due to the small numbers of infantry personnel referred to the Defence Audiology Service, recruitment was widened to include any military personnel with (at least) training experience of small arms gunfire. Eleven out of 20 worked with small arms on a daily basis but the others may not have had such recent or relevant experience of small arms gunfire and may never have encountered an MCAT involving localisation of gunfire. The patterns of localisation errors however were very similar for all military participants suggesting that there was no significant advantage of regular small arms use.

Despite the limitations personnel were still able to complete the source identification task to a degree of accuracy more acute than chance. It is likely that even under challenging conditions normal hearing personnel would be successful at locating the source of small arms gunfire from a single shot fired in the frontal horizontal plane. This finding suggests that the focus group participants were correct to question their ability to perform this task;

identifying the source of small arms fire was not as easy as localising a simple broadband noise and personnel were shown to have variable success on the task.

The final aim of this thesis was to investigate the relationship between military specific hearing impairment and localisation accuracy. If performance on the localisation task was not affected in any way by hearing impairment (of any origin), then there would be no merit in assessing localisation of small arms as a component of AFFD. If accuracy remained the same regardless of hearing impairment then the task must rely on other sensory or cognitive processes beyond hearing.

### 7.1.4 Is small arms localisation ability sensitive to military specific hearing loss?

Study 6 was developed to assess the impact of bilateral symmetrical sensorineural hearing loss (consistent with NIHL) on localisation accuracy. Twelve hearing impaired military personnel were recruited from the INM Gosport; this number consisted of six personnel with a mild impairment and six with a moderate impairment. The source identification task was completed by all participants and these data were compared to the responses of the normal hearing military personnel from study 5.

As found in study 5, all personnel were able to localise all stimuli to a degree of accuracy greater than that associated withselecting sources at random, regardless of their hearing thresholds. This finding was contradictory to the hypothesis and some of the previous literature. Proschel and Doring (1990) found deterioration in localisation accuracy for individuals with a moderate hearing impairment. Similarly, Talcott et al. (2012) found a significant difference between normal hearing and impaired listeners during their gunfire localisation experiment. Whilst mild and moderate bilateral symmetrical sensorineural hearing loss did not appear to significantly impact military personnel’s ability to localise the source of small arms fire, other configurations of hearing impairment may have an impact. As discussed in section 6.6.4 the discordance in results may be due to the configuration of pure tone thresholds; the participants in Proschel and Doring’s study may have had poorer low frequency hearing and some (if not all) of Talcott’s participants had asymmetrical thresholds.

The source identification task relied on hearing ability alone; it would not be possible to complete the task if the stimuli were not audible. In a real world scenario similar to the simulated task (a shot fired towards the listener from 100 m downrange) the crack and thump would both be audible (and potentially damaging) even for personnel with severe to profound hearing loss. For shots fired at greater distances than 100 m, the crack remains at high intensity but the thump intensity reduces rapidly as distance increases (as discussed in section 5.4.2). As the thump was the dominant cue for localisation, a low frequency hearing loss is likely to have a greater impact on localisation accuracy in real world scenarios. Further work in this area is vital to determine the effect of different configurations of hearing loss, particularly asymmetric thresholds that are known to affect localisation ability (Noble et al. 1994, Lorenzi et al. 1999).

Assessing localisation accuracy for personnel with severe to profound hearing impairment may not be necessary as these individuals would be unable to carry out other MCATs including speech discrimination or identification of sounds in quiet or noisy environments. Consideration of an individual's auditory fitness must incorporate all of the high priority MCATs; infantry personnel must have all of the required auditory skills to be considered safe and effective on operational duties.

Study 6 made a preliminary contribution to knowledge surrounding hearing loss and small arms localisation. Personnel with mild to moderate bilateral sensorineural hearing loss appear able to complete the source identification task to the same degree of accuracy as normal hearing personnel. However the relationship between hearing impairment and small arms localisation requires further investigation.

Localisation of small arms fire was identified as an auditory task carried out by all infantry personnel on operational duties during training and in the battlefield. The research presented in this thesis aimed to determine whether personnel had the necessary auditory skills to carry out this complex task and whether their ability should be assessed as part of an auditory fitness test battery. Further work is required to investigate how small arms gunfire is localised during real-life operational MCATs. This should incorporate the hindering factors discussed by personnel during the focus groups; the impact of stress, background noise and completing multiple tasks simultaneously.

## 7.2 Future work

In summary, it is recommended that further work is carried out to address two specific aims:

1) **To create a simulation of the small arms localisation MCAT that more closely mirrors the real life situation faced by infantry personnel on operational duties.**

So far, the source identification task has only assessed localisation accuracy for single SA80 gunshots in the frontal horizontal plane. As described by personnel during the focus groups, multiple gunshots could originate from any direction and personnel would be required to locate the sound source in high pressure situations and in background noise. Personnel should also be wearing appropriate hearing protection.

In order to determine the true performance levels of infantry personnel on operational duties, a simulation of the MCAT could be developed incorporating some of the additional factors described by personnel. Sources could be placed 360º around the listener (gunshot recordings are already available for this set-up) and stimuli could be filtered or attenuated to mimic hearing protection devices. Assessing localisation accuracy using a task simulation that is closer to the MCAT would provide a better prediction of performance in operational scenarios. However, it would not be possible (or ethical) to create a simulation that is identical to real-life due to the emotional and physical reactions experienced by personnel in dangerous or life threatening situations.

2) **To assess the localisation accuracy of military personnel with a range of hearing threshold configurations**

From the literature it is apparent that configurations of pure tone thresholds beyond bilateral mild to moderate sensorineural hearing loss may have an effect on localisation accuracy. In order to thoroughly investigate whether small arms gunfire localisation is sensitive to hearing impairment (and whether it should be assessed as a component of AFFD), military personnel with other types of hearing deficit must be tested. It is hypothesised that asymmetry between the left and right hearing thresholds will have the greatest impact on localisation ability; this has been highlighted as an important consideration when developing AFFD protocols by Tufts et al. (2009). Investigations into the effect of type of loss (conductive or sensorineural) may also be beneficial to quickly identify infantry personnel who are greater risk of falling below auditory fitness standards.

## 7.3 Conclusions

The main conclusions of this thesis are:

1. Pure tone audiometry may not be an accurate predictor of functional performance on infantry MCATs.

2. Infantry AFFD measures should assess performance on the nine priority MCATs identified by infantry personnel. Localising small arms gunfire is a priority MCAT carried out by all infantry personnel during operational duties, the consequences of poor performance on this task were described as life-threatening by some infantry personnel.

3. Normal hearing military personnel were able to localise the source of small arms gunshots in the frontal horizontal plane, measured using a virtual source identification task and recordings of live SA80 rifle fire.

4. Military personnel with a mild to moderate bilateral sensorineural hearing loss were able to localise gunfire to the same degree of accuracy as normal hearing personnel. Further work is recommended to investigate the relationship between other hearing loss configurations and small arms localisation accuracy.

5. Future work to improve the simulation of the MCAT should be considered to assess localisation accuracy in scenarios that more closely mirror frontline operational environments.

# Appendix A – Presentations and military exercises

**Presentations:**

- Presentation of focus group findings to Institute of Naval Medicine Research Group 01/2013
- Presentation: The institute of Acoustics at the Southern branch 40th anniversary conference 09/2014
- Radio interview: The Naked Scientists, BBC. Aired: 09/2014
- 3 Minute thesis competition: Faculty of Engineering and the Environment finalist
- Poster presented at: Biomedical, Engineering, Science and Technology, BEST research in human health 04/2014
- 'Identifying the hearing requirements of Army personnel on OP HERRICK 16' presented at Human Sciences Group poster presentation day 03/2013
- ‘Fit for the frontline? A focus group exploration of auditory tasks carried out by infantry and combat support personnel’ poster presented at BSA 09/2013
- ‘What does gunfire sound like when you are the target? Investigating the acoustic characteristics of small arms fire’ poster presented at BSA 09/2014
- Poster: ‘Localising small arms fire: investigating the acoustic characteristics of a gunshot.’ Presented at the Defence Medical Research council meeting 09/2014
- Poster presented at: ‘Moving sounds, moving listeners’ Glasgow 11/2014
- Featured in: Acoustics Bulletin magazine, March/April 2015
- Proposal: Ministry of Defence Research Ethics Committee review, Whitehall, 03/15
- Workshops discussing research topic with 16-18 yr olds for open days and FE2HE events

**Participation in military training exercises:**

- Small arms handling field lecture, Royal Military Academy, Sandhurst 06/2012
- Artillery and armoured vehicle demonstration exercise, Larkhill Garrison 06/2012
- Royal Marine Commando section attack training exercise, Braunton Burrows, Devon 02/2013
- Overnight (2 day) armoured vehicle (Warrior) exercise, Salisbury plain, 06/2013

# Appendix B – Audiometric descriptors

An individual's hearing acuity (as measured by PTA) is often described in general terms rather than the measured thresholds at different frequencies. The British Society of Audiology recommend the following descriptors based upon the average hearing thresholds at 250, 500, 1000, 2000 and 4000 Hz. Averages do not represent any particular configuration of hearing loss and often other terms are added to describe the 'shape' of the audiogram (for example, 'high frequency sloping') (BSA 2004).

| Descriptor | Average HTLs (dB HL) |
|---|---|
| Mild hearing loss | 20-40 |
| Moderate hearing loss | 41-70 |
| Severe hearing loss | 71-95 |
| Profound hearing loss | > 95 |

Average HTLs of less than 20 dB HL do not necessarily represent normal hearing. The audiometric descriptors above do not imply any other classification of function, educational attainment or potential. The BSA state that they should not be taken directly as a measure of disability.

# Appendix C – Job analysis methods

'Job, task and role (JTR) analysis is any systematic procedure for obtaining detailed and objective information about a job, task or role that will be performed or is currently being performed' (Pearn and Kandola 1998). The information collected by an in depth job analysis can be used for a number of applications; changing working practice, solving problems in the workplace and human resource development. Job analysis forms an important part of the test development process. It is impossible to create a set of occupational standards without information about the tasks that personnel are required to perform. To gather data appropriately, a number of areas need to be considered (Pearn and Kandola 1998):

**Orientation:** Job analysis can usually be divided into worker-based or task-based orientations. To create job-based legislation and outline the physical demands of an occupation, analysis of the job must be primarily task-based.

**Quantification:** Some job-analysis techniques involve collecting quantitative or numerical data whereas other focus on purely subjective or qualitative information.

**Structure:** An open-ended interview is the most common method of collecting data for job analysis. The level of detail recorded and the topics focussed on are largely determined by the interviewer rather than structured by the method of data collection. At the other extreme, a job specific checklist could be used to determine the specific responsibilities of an individual within an organisation. This approach would not be appropriate if the nature of the job was unknown.

**Applicability:** If a job analysis interview was carried out with one member of personnel then the level of applicability to other jobs within the organisation would be limited.

Other important points to consider are the sensitivity of a job analysis (whether less visible/obvious tasks have been identified) and the sophistication of the technique used (and whether the individuals carrying out the analysis require training).

The job analysis method chosen can vary depending on the information needed from the analysis. If the analysis is being undertaken to increase worker efficiency within the company then the method of analysis will differ when compared to designing new employment standards. Pearn and Kandola (1998) outline the 10 most useful (and most used) job, task and role analysis techniques. Not all of the techniques would have been appropriate for identifying military tasks, so only three were considered. The remaining seven (including checklists, job component inventories and position analysis questionnaires) could not be adapted and therefore would not collect the necessary information about the hearing requirements of a military task.

**Observation**

Of all the job analysis methods, observation of the task is the most straightforward and least sophisticated technique. It relies on an observer with knowledge of the tasks observed and doesn't give any indication of the task importance, difficulty or skill level required for the completion. The data generated depends on the type of observations carried out but often 'time sampling' or 'unit sampling' will be used to make a note of the time taken to complete a task or the number of times the task is completed in a given length of time (Kandola and Pearn 1998).

Although this is a readily available tool, it presents some problems in a working environment. Firstly, the act of observation will have an effect on the way the task is performed and the process is inherently subjective and therefore any conclusions drawn will depend on the level of behavioural analysis training an observer has had. There were also a number of problems in applying this to military tasks. Observing infantry personnel on frontline duties would not be possible for safety and confidentiality reasons, but observing training sessions would not gather all the information required about an individual's normal working environment and the tasks they are required to perform. For these reasons, observation of military tasks would not have been an appropriate job analysis technique.

**Self-description/Diaries/Logs**

This method uses recorded and written descriptions of tasks supplied by the jobholders themselves and can include 'day-in-the-life' narratives, logs and diaries of day-to-day activities. This technique does not require the constant input of the analyst but can often prove time consuming due to the large sample needed to form a representative and accurate list of all tasks performed within a given occupation. This type of analysis relies on a certain level of comprehension and literacy on the employee's part. Chang and Kleiner (2002) discussed the pitfalls of self-description job analysis, describing it as 'tedious and the method most open to abuse or false results'.

To gather information about military environments, a written description of the occupation would be useful as personnel would be able to document tasks as they arise. This is particularly important when an individual may be abroad for months at a time and other job analysis techniques could only be employed once they had returned to the United Kingdom. However, the information needed about acoustic environments and military stimuli may not be collected effectively unless personnel were prompted to reveal certain pieces of information. In a self-report analysis of the task many important details would be missed unless the analyst was present or the job holder had specific training.

**Interview**

Interviews with the job holder are the most flexible and productive approach to job analysis (Chang and Kleiner 2002). When properly structured, an interview can gather information about any aspect of an occupation. This approach can be followed up by a structured questionnaire to larger numbers of personnel to clarify the responses of the interviewees (Chang and Kleiner 2002). Pearn and Kandola (1998) discuss the types of interview used by job analysts and how they differ in approach and outcomes. A completely unstructured framework allows the job holder to describe the occupation they perform and relies on the skill of the interviewer to gently guide the conversation to important topics.

A structured interview can also be completed. The interviewer prepares a set format for the interview and asks more directed questions to quickly gather all the necessary information. This style of interview requires less training for the analyst and is often quicker to perform. It can be described as an intermediary step between an unstructured interview and a questionnaire (Pearn and Kandola 1998). The third method of interview involves ‘co-counselling’, where two job holders effectively interview each other about the task that they perform. However, by removing the analyst from the equation, this method often has variable outcomes; necessary information may not be collected or the interviewees may not maintain a good enough rapport with each other (Pearn and Kandola 1998).

Interviews with job holders is the most widely used method of job analysis and has a high sensitivity (Campion et al. 1988) but many authors state that it should not be used as the sole method of job analysis due to the limited sample size and the potential bias introduced by the interviewer (Campion et al. 1988; Pearn and Kandola 1998; Innes and Straker 1998; Rayson 2000).

# Appendix D – Ethical approval documents

**Approval for study 1**

Ministry of Defence
Research Ethics Committee

---

Miss Zoe Bevis
Hearing and Balance Centre
Institute of Sound and Vibration Research
Building 13
University of Southampton
Southampton
SO17 1BJ

Ref: 359/GEN/12

---

Dear Miss Bevis,

**Re: Identification of key listening situations for military personnel** – version 4

Thank you for submitting this interesting protocol for ethical review and making minor amendments.

I am happy to give ethical approval for this research on behalf of the MOD Research Ethics Committee (General) and should be grateful if you would send me a copy of your final report on completion of the study. Please would you also send me a brief interim report in one year's time if the study is still ongoing.

This approval is conditional upon adherence to the protocol – please let me know if any amendment becomes necessary.

Yours sincerely,

Dr Robert Linton
Chairman MOD Research Ethics Committee (General)

telephone: 020 8877 9329

e-mail: robert@foxlinton.org
mobile: 07764616756

## Approval for studies 3 & 4

***Your Ethics Submission (Ethics ID:9043) has been reviewed and approved***

Submission Number: 9043
Submission Name: Localisation accuracy of small arms stimuli
This is email is to let you know your submission was approved by the Ethics Committee.

You can begin your research unless you are still awaiting specific Health and Safety approval (e.g. for a Genetic or Biological Materials Risk Assessment)

Comments
None
Click here to view your submission

------------------
ERGO : Ethics and Research Governance Online
http://www.ergo.soton.ac.uk
------------------

**Approval for study 5 &6**

# Ministry of Defence Research Ethics Committee

*From the Alternate Vice Chairman*

**Professor David Baldwin**

**Professor of Psychiatry and Head of Mental Health Group**

**University of Southampton Faculty of Medicine**

**University Department of Psychiatry**

**Academic Centre, College Keep, 4-12 Terminus Terrace,**

**Southampton SO14 3DT**

---

Miss Zoë Bevis
Institute of Sound and Vibration Research
Hearing and Balance Centre
ISVR
Building 13
University of Southampton
SO17 1BJ

Our Reference:
636/MODREC/15

Date: 23 March 2015

---

Dear Zoe

Thank you for submitting your revised Protocol 636/MODREC/15 with tracked changes, and the covering letter with detailed responses to the MODREC letter. I can confirm that the revised protocol has been approved by the Officers of MODREC ex-Committee. I wish you and your colleagues a successful study.

In due course please send the Secretariat a final report containing a summary of the results so that these can be filed in accordance with the arrangements under which MODREC operates**.** Please would you also send a brief interim report in one year if the study is still continuing.

This approval is valid for three years and is conditional upon adherence to the protocol – please let me know if any amendment becomes necessary.

Yours sincerely

Professor David Baldwin MB BS DM FHEA FRCPsych

Cc Professor Allister Vale, Professor David Jones, Ethics Secretariat

# Appendix E – MATLAB programs

## E.1 Code that generates broadband noise stimuli for source identification task (written by Daniel Rowan)

```
function localise_xtalk(file_name, inifile)

% Defaults
if nargin == 0
    file_name = 'participantx';
    inifile = 'Zoe_test_ini';
else
    % Prints error message and quits program if file_name already exists
    if length(file_name) < 3
        error('Use longer file_name')
    end
    exs = exist(num2str(file_name), 'file');
    if exs == 2
        error('file_name already in use')
    end
    exs = exist(num2str(inifile), 'file');
    if ~exs
        error('cannot find inifile')
    end
end
clear exs
if exist('loc_xtalk_temp.mat', 'file')
    delete loc_xtalk_temp.mat
end

% Grab user-defined variables
eval(inifile)

% Initialise
fs = 44100;
run_test = 1;
trial = 0;

debuggin = 0;
loc_on = 1;
xtalk_on = 0;
calib_on = 1;
play_on = 1;
resp_on = 1;
save_on = 1;
analyse_on = 1;

save loc_xtalk_temp

% % User inputs (if not required, comment this out)
% disp('Note: the following selection of TA and TD overwrites the ini file')
% disp(' ')
% TA = input('TA (dB) = ');
% if isempty(TA)
%     TA = 100;
%     disp('Use default value for TA (i.e. 100 dB)')
% end
% switch TA
%     case 0
%     case 5
%     case 20
%     case 50
%     case 100
%     otherwise
%         error('Incorrect choice of TA')
% end
% TA_R = TA;
% TA_L = TA_R;
%
% TD = input('TD (s) = ');
% if isempty(TA)
%     TD = 0;
%     disp('Use default value for TD (i.e. 0 s)')
```

```
% end
% switch TD
%     case 0
%     case 200e-6
%     case 700e-6
%     otherwise
%         error('Incorrect choice of TD')
% end
% TD_R = TD;
% TD_L = TD;
% save loc_xtalk_temp TA_R TA_L TD_R TD_L -APPEND

% Function to check user defined variable are sensible
check_variables

% Inialise other variables
clear all
load loc_xtalk_temp

ISI_use = zeros([1, ISI_pts_used]);
az_poss = 0:5:355;
save_data = ones([length(angles_used), reps])*-1;
angles_used2 = [];
for count = 1:reps
    angles_used2 = [angles_used2, angles_used];
end
if training
    angle_order = 1:length(angles_used2);
else
    angle_order = randperm(length(angles_used2));
end
save loc_xtalk_temp ISI_use az_poss save_data angles_used2 angle_order -APPEND

questdlg('Start experiment?','start','start','start');

% Trial by trial
while run_test
    clear all
    load loc_xtalk_temp
    trial = trial + 1;
    angle = angles_used2(angle_order(trial));  % actual angle
    save_angle(trial) = angle; % log actual angle

    disp(' ')
    disp(['TRIAL NUMBER ', num2str(trial)])
    disp(['Speaker angle ', num2str(angle), ' degrees'])

    if num && ~debuggin
        pause(PSI_ip)
        for count_num = 1:num
            % Step 1. Synthesise stimulus
            stim = cos2ramp_v2(noiseband_v2(lfreq, hfreq, stim_pts_used, fs),
ramp_pts_used);
            stereo_stim = [stim; stim]';
            % Step 2. Convolve with impulse response, given angle
            if loc_on
                stereo_stim = conv_hrir(stereo_stim, angle);
            else
                disp('Convolution with impulse responses switched off')
            end
            % Step 3. Model BC
            if xtalk_on
                stereo_stim = xtalk(stereo_stim);
            else
                disp('Model of cross-talk switched off')
            end
            % Step 4. Calibrate stimulus
            if calib_on
                stereo_stim = calib(stereo_stim);
            else
                disp('Calibration of stimuli switched off')
            end
            stereo_stim_num(:, count_num*2 - 1) = stereo_stim(:, 1);
            stereo_stim_num(:, count_num*2) = stereo_stim(:, 2);
%             rms_l = std(stereo_stim_num(:, 1));
%             rms_r = std(stereo_stim_num(:, 2));
%             disp(['Left rms ', num2str(rms_l)])
%             disp(['Right rms ', num2str(rms_r)])
        end
        % Step 5. Construct and play trial
```

```
        if play_on
            play_trial(stereo_stim_num);
        else
            disp('Presentation of stimuli switched off')
        end
    else
        disp('Debugging mode')
    end
    % Collect response
    if ~training && resp_on
        collectresp = 1;
        while collectresp
            collectresp2 = 1;
            while collectresp2
                speaker_name = input('Which speaker did subject choose? ','s');
                if ~isempty(speaker_name)
                    collectresp2 = 0;
                end
            end
            if ~isempty(find(poss_speaker_name == speaker_name, 1))
                collectresp = 0;
            end
        end
        speaker_index = find(poss_speaker_name == speaker_name);
        ang_ind = find(angles_used == angle);
        for count = 1:reps
            minusone = save_data(ang_ind, count);
            if minusone == -1
                save_data(ang_ind,count) = angles_used2(speaker_index);
                break
            end
        end
        disp(['Response angle ', num2str(angles_used2(speaker_index)), ' degrees'])
        save loc_xtalk_temp save_data -APPEND
    else
        disp('Collection of response switched off')
    end
    % Save and check if test complete
    save loc_xtalk_temp trial save_angle -APPEND
    if trial >= length(angles_used2)
        run_test = 0;
    end
    if run_test && num && ~debuggin
        pause(ITI)
    end
end
% Analyse
if ~training && analyse_on
    MAE = analyselocalise('loc_xtalk_temp');
    disp(' ')
    disp(['MAE = ', num2str(MAE), ' degress'])
    save loc_xtalk_temp MAE -APPEND
end
% Save final data for access with Excel
if ~training && save_on
    save_for_excel(:,1) = angles_used';
    save_for_excel(:,2:reps+1) = save_data;
    save(file_name)
    save(file_name, 'save_for_excel', '-ASCII')
end
% Finish
clear
delete loc_xtalk_temp.mat


function check_variables

load loc_xtalk_temp

% Check that variables are sensible
if ~exist('reps','var')
    reps = 1;
else
    if reps < 0
        error('reps must be > 0')
    elseif ~isintegerDR(reps)
        error('reps must be an integer')
    end
end
if ramp*2 >= dur
```

```
    error('Ramp duration times two must be shorter than signal duration')
end
if lfreq >= hfreq
    error('Low-frequency edge of noise must be lower than high-frequency edge')
end
if ~num % i.e. no stimulus per trial
    disp('Debugging mode')
end
if fdbk ~= 0 && fdbk ~= 1
    disp('Feedback assumed to be on')
end
if PSI_ip < 0 || PSI_ip > 5
    error('Potentially silly choice for PSI')
end
if ISI_ip < 0 || ISI_ip > 5
    error('Potentially silly choice for ISI')
end
if ITI < 0 || ITI > 5
    error('Potentially silly choice for ITI')
end
if fb_pause < 0 || fb_pause > 5
    error('Potentially silly choice for fb_pause')
end
if TD_L ~= TD_R
    disp('Transcranial delay is asymmetrical: you really want this?')
end
if TA_L ~= TA_R
    disp('Transcranial attenuation is asymmetrical: you really want this?')
end
if TD_L > 0.002 || TD_L < 0
    error('Potentially silly choice for TD_L')
end
if TD_R > 0.002 || TD_R < 0
    error('Potentially silly choice for TD_R')
end

% Check durations are whole number of sample points
%   Stimulus
stim_pts = dur * fs;
stim_pts_used = round(stim_pts);
dur_used = stim_pts_used/fs;
if dur_used ~= dur
    disp(['Using signal duration of ', num2str(dur_used), ' seconds']);
end
save loc_xtalk_temp stim_pts_used -APPEND
%   Ramp
if ramp
    ramp_pts = ramp * fs;
    ramp_pts_used = round(ramp_pts);
    ramp_used = ramp_pts_used/fs;
    if ramp_used ~= ramp
        disp(['Using ramp duration of ', num2str(ramp_used), ' seconds']);
    end
else
    ramp_pts_used = 0;
end
save loc_xtalk_temp ramp_pts_used -APPEND
%   Inter-stimulus interval
if ISI_ip
    ISI_pts = ISI_ip*fs;
    ISI_pts_used = round(ISI_pts);
    ISI_use = ISI_pts_used/fs;
    if ISI_use ~= ISI_ip
        disp(['Using ISI duration of ', num2str(ISI_use), ' seconds']);
    end
else
    ISI_pts_used = 0;
end
save loc_xtalk_temp ISI_pts_used -APPEND
%   Transcranial delay to right cochlea
if TD_R
    TD_R_pts = TD_R*fs;
    TD_R_pts_used = round(TD_R_pts);
    TD_R_use = TD_R_pts_used/fs;
    if TD_R_use ~= TD_R
        disp(['Using TD_R duration of ', num2str(TD_R_use), ' seconds']);
    end
else
    TD_R_pts_used = 0;
end
```

```
save loc_xtalk_temp TD_R_pts_used -APPEND
%   Transcranial delay to left cochlea
if TD_L
    TD_L_pts = TD_L*fs;
    TD_L_pts_used = round(TD_L_pts);
    TD_L_use = TD_L_pts_used/fs;
    if TD_L_use ~= TD_L
        disp(['Using ISI duration of ', num2str(ISI_use), ' seconds']);
    end
else
    TD_L_pts_used = 0;
end
save loc_xtalk_temp TD_L_pts_used -APPEND


function stereo_stim_conv = conv_hrir(stereo_stim, angle)

load loc_xtalk_temp

bitatthestart = cd;
bitinthemiddle = '/CIPIC_hrtf_database/special_kemar_hrir/kemar_horizontal';
bitontheend = 'large_pinna_final.mat';
hrir_set_ext = [bitatthestart, bitinthemiddle];
cd(hrir_set_ext)
load(bitontheend)
cd(bitatthestart)

az_ind = find(az_poss == angle);
ir_l = left(:, az_ind);
ir_r = right(:, az_ind);

stereo_stim_conv(:, 1) = conv(stereo_stim(:, 1), ir_l);
stereo_stim_conv(:, 2) = conv(stereo_stim(:, 2), ir_r);


function stereo_stim_xtalk = xtalk(stereo_stim)

load loc_xtalk_temp

silentgap_R = zeros([1, TD_R_pts_used]);
silentgap_L = zeros([1, TD_L_pts_used]);

left_stim = stereo_stim(:, 1)';
right_stim = stereo_stim(:, 2)';

left_cochlea = [left_stim, silentgap_L] + [silentgap_L, 10^(-TA_L)*right_stim];
right_cochlea = [right_stim, silentgap_R] + [silentgap_R, 10^(-TA_R)*left_stim];

stereo_stim_xtalk = [left_cochlea; right_cochlea]';


function stereo_stim_calib = calib(stereo_stim)

load loc_xtalk_temp

stereo_stim_calib(:, 1) = 10^(A_stim/20) * 10^(A_stim_L/20) * stereo_stim(:, 1);
stereo_stim_calib(:, 2) = 10^(A_stim/20) * 10^(A_stim_R/20) * stereo_stim(:, 2);


function play_trial(stereo_stim_num)

load loc_xtalk_temp

if max(abs(stereo_stim_num)) > 1
    error('Sound file exceeded clipping threshold - reduce amplitude')
end

if num == 1
    level_rove_dB = 10^(rand*(level_rove - level_rove/2)/20);
    stereo_stim_play_l = level_rove_dB*stereo_stim_num(:, 1);
    stereo_stim_play_r = level_rove_dB*stereo_stim_num(:, 2);
    sound([stereo_stim_play_l, stereo_stim_play_r], fs)
    pause(length(stereo_stim_play_l)/fs)

    wavwrite(stereo_stim_play_l, fs, 'simuli_l')

else
    level_rove_dB = 10^(rand*(level_rove - level_rove/2)/20);
    stereo_stim_play_l = level_rove_dB*stereo_stim_num(:, 1);
    stereo_stim_play_r = level_rove_dB*stereo_stim_num(:, 2);
```

```
    for count_num = 2:num
        level_rove_dB = 10^(rand*(level_rove - level_rove/2)/20);
        stereo_stim_play_l = [stereo_stim_play_l', ISI_use,
level_rove_dB*stereo_stim_num(:, count_num*2 - 1)']';
        stereo_stim_play_r = [stereo_stim_play_r', ISI_use,
level_rove_dB*stereo_stim_num(:, count_num*2)']';
    end
    sound([stereo_stim_play_l, stereo_stim_play_r], fs)
    pause(length(stereo_stim_play_l)/fs)

    wavwrite(stereo_stim_play_l, fs, 'simuli_l')
end
```

## E.2 Parameters for broadband noise condition of source identification task (written by Daniel Rowan)

```
% Stimulus parameters
lfreq = 100;     % Low edge-frequency of band of noise (Hz)
hfreq = 10e3;  % High edge-frequency of band of noise (Hz)
dur = 0.05;       % Duration of one burst of noise (seconds)
ramp = 0.005;     % Duration of onset/offset ramps of noise burst (0 for no ramps) (seconds)
num = 1;         % Number of burst of stimulus per trial

% Trials parameters
reps = 6;
PSI_ip = 0;       % Pre-stimulus silent interval (seconds)
ISI_ip = 0.08;       % Time interval between each burst in train (seconds)
fdbk = 0;        % Give feedback? 0 is off, 1 is on
fb_pause = 0; % Feedback duration (seconds)
ITI = 0;       % Inter-trial silent interval (seconds)
level_rove = 10; % Range of level roving (+/- half this)

% Localisation parameters
% angles_used = [270, 315, 0, 45, 90];
% poss_speaker_name = ['a','b','c','d','e']; % 0 is straight ahead and increases to right -
i.e. left_90 is 270.
angles_used = [270:15:345,0:15:90];
poss_speaker_name = ['a','b','c','d','e','f','g','h','i','j','k','l','m']; % 0 is straight
ahead and increases to right - i.e. left_90 is 270.
training = 1;   % If training = 1 angles run from -90 to 90 in order
                %   otherwise if training = 0 angles in random order

% Cross-talk model parameters (dB or seconds)
TA_R = 100;
TA_L = 100;
TD_R = 0;
TD_L = 0;

% Calibration parameters (dB)
A_stim =   -10.8;
A_stim_R = 0;
A_stim_L = 0;
```

## E.3 Code that presents gunshot stimuli during source identification task (written by Carla Perkins, Hannah Semeraro and Zoe Bevis)

```
function varargout = gunshot_exp(varargin)
% UNTITLED MATLAB code for untitled.fig
%      UNTITLED, by itself, creates a new UNTITLED or raises the existing
%      singleton*.
%
%      H = UNTITLED returns the handle to a new UNTITLED or the handle to
%      the existing singleton*.
%
%      UNTITLED('CALLBACK',hObject,eventData,handles,...) calls the local
```

```
%       function named CALLBACK in UNTITLED.M with the given input arguments.
%
%       UNTITLED('Property','Value',...) creates a new UNTITLED or raises the
%       existing singleton*.  Starting from the left, property value pairs are
%       applied to the GUI before untitled_OpeningFcn gets called.  An
%       unrecognized property name or invalid value makes property application
%       stop.  All inputs are passed to untitled_OpeningFcn via varargin.
%
%       *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%       instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help untitled

% Last Modified by GUIDE v2.5 21-May-2014 17:00:45

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
    'gui_Singleton',  gui_Singleton, ...
    'gui_OpeningFcn', @untitled_OpeningFcn, ...
    'gui_OutputFcn',  @untitled_OutputFcn, ...
    'gui_LayoutFcn',  [] , ...
    'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before untitled is made visible.
function untitled_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to untitled (see VARARGIN)

% Choose default command line output for untitled
handles.output = hObject;

% make sure no buttons selected at start (calling function)
[handles] = reset_btns(handles);

%load audio data and random order (new for each test, calling function)
[handles] = read_in_GCTB(handles);

%set first trial number to 0
handles.trialnum = 0;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes untitled wait for user response (see UIRESUME)
% uiwait(handles.figure1);

% --- Outputs from this function are returned to the command line.
function varargout = untitled_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

% --- Executes on button press in Clickheretostarttest.
function Clickheretostarttest_Callback(hObject, eventdata, handles)
% hObject    handle to Clickheretostarttest (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

%store the presentation and answers
```

```
handles.trialnum = handles.trialnum+1;
trialnum = handles.trialnum;
set(handles.Clickheretostarttest,'string', 'Next')   %change start test button to 'Next'
after first trial

if trialnum ~= 1 %only try and store an answer after the first trial

    handles.results{handles.trialnum-1, 2} = handles.tempans; %stores answers in second
column of results
    handles.results{handles.trialnum-1, 1} = handles.question{trialnum-1}; %stores question
in first column of results

end

handles = reset_btns(handles); % calls function (below) to make sure buttons are no longer
selected

testcondition = handles.testcondition;
fs = 44100;

if testcondition == 'G'             %if test condition is G and trial num is less than 27
then sounds the nth element of trialnum, if trialnum is 27 then...
    if trialnum == 26+1               % ...save the results and close the GUI (same for all
others below)
        Results = handles.results;
        filename = [date,'-',handles.subjnum,'-',handles.sessnum,'-
',handles.testcondition];
        save(filename,'Results');
        close gunshot_exp
        return
    end

    stimulusG = handles.Gun{trialnum};

    %assuming calib is -10.8 dB, max abs noise = 0.9777;
    %so scale gunshot to this value
    %max_gun = max abs of the gunshot stimuli

    level_adjust = 2;

    stimulusGun = stimulusG*level_adjust;

    sound(stimulusGun, fs);

    %sound(handles.Gun{trialnum}, fs);

elseif testcondition == 'C'
    if trialnum == 26+1
        Results = handles.results;
        filename = [date,'-',handles.subjnum,'-',handles.sessnum,'-
',handles.testcondition];
        save(filename,'Results');
        close gunshot_exp
        return
    end

    stimulusC = handles.Crack{trialnum};
    level_adjust = 2;

    stimulusCrack = stimulusC*level_adjust;

    sound(stimulusCrack, fs);

    %sound(handles.Crack{trialnum}, fs);

elseif testcondition == 'T'
    if trialnum == 26+1
        Results = handles.results;
        filename = [date,'-',handles.subjnum,'-',handles.sessnum,'-
',handles.testcondition];
        save(filename,'Results');
        close gunshot_exp
        return
    end

    stimulusT = handles.Thump{trialnum};
    level_adjust = 8;

    stimulusThump = stimulusT*level_adjust;
```

```
    sound(stimulusThump, fs);

    %sound(handles.Thump{trialnum}, fs);

elseif testcondition == 'B'

    if trialnum == 13+1
        Results = handles.results;
        filename = [date,'-',handles.subjnum,'-',handles.sessnum,'-
',handles.testcondition];
        save(filename,'Results');
        close gunshot_exp
        return
    end
    sound(handles.Broad{trialnum}, fs);

set(handles.trialnumdisp,'string', trialnum)
set(handles.totalnumoftrials,'string', size(questions))

end
guidata(hObject, handles);


% --- Executes when selected object is changed in answergroup.
function answergroup_SelectionChangeFcn(hObject, eventdata, handles)
% hObject    handle to the selected object in answergroup
% eventdata  structure with the following fields (see UIBUTTONGROUP)
%   EventName: string 'SelectionChanged' (read only)
%   OldValue: handle of the previously selected object or empty if none was selected
%   NewValue: handle of the currently selected object
% handles    structure with handles and user data (see GUIDATA)

handles.tempans = get(eventdata.NewValue,'tag');  %store the callsign which has been
selected

guidata(hObject, handles); %update handles structure


%Resets buttons functions (called above)
function [handles] = reset_btns(handles)

answergroup_values = get(handles.answergroup, 'Children');

for i = 1:length(answergroup_values)
    set(answergroup_values(i), 'Value', 0)
end

% Reset the stored values in the handles

handles.tempans = ' ';

function [handles] = read_in_GCTB(handles)

% Error = 1;
% while Error == 1

testcondition = input('Please select test condition (G,C,T,B): ','s');
handles.testcondition = testcondition;

handles.subjnum = input('Please enter subject number (e.g. sub1): ','s');

handles.sessnum = input('Please enter session number: ','s');

% reads in the wav files and randomises the order, new for each test. only
% carries this out for selected test condition

if strcmp(testcondition, 'G') == 1

    counter = 0;
    for m = 'A':'M'
        for n = 1:2
            counter = counter+1;
            Gun{counter} = wavread([m,'G',num2str(n)]);
            questions{counter} = [m, num2str(n)];
        end
    end
    randomiseG = randperm(size(Gun,2));
    Gun = Gun(randomiseG);
    questions = questions(randomiseG);
```

```
    handles.Gun = Gun;

elseif strcmp (testcondition, 'C') == 1
    counter = 0;
    for m = 'A':'M'
        for n = 1:2
            counter = counter+1;
            Crack{counter} = wavread([m,'C',num2str(n)]);
            questions{counter} = [m, num2str(n)];
        end
    end
    randomiseC = randperm(size(Crack,2));
    Crack = Crack(randomiseC);
    questions = questions(randomiseC);
    handles.Crack = Crack;

elseif strcmp (testcondition, 'T') == 1
    counter = 0;
    for m = 'A':'M'
        for n = 1:2
            counter = counter+1;
            Thump{counter} = wavread([m,'T',num2str(n)]);
            questions{counter} = [m, num2str(n)];
        end
    end
    randomiseT = randperm(size(Thump,2));
    Thump = Thump(randomiseT);
    questions = questions(randomiseT);
    handles.Thump = Thump;

elseif strcmp (testcondition, 'B') == 1
    %Read in broadband
    counter = 0;
    for m = 'A':'M'
        for counter = counter+1;
            Broad{counter} = wavread([m,'B']);
            questions{counter} = [m];
        end
    end
    randomiseB = randperm(size(Broad,2));
    Broad = Broad(randomiseB);
    questions = questions(randomiseB);
    handles.Broad = Broad;

end
handles.question = questions;
% end

% --- Executes on button press in A.
function A_Callback(hObject, eventdata, handles)
% hObject    handle to A (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of A

% --- Executes on button press in B.
function B_Callback(hObject, eventdata, handles)
% hObject    handle to B (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of B

% --- Executes on button press in H.
function H_Callback(hObject, eventdata, handles)
% hObject    handle to H (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of H

% --- Executes on button press in C.
function C_Callback(hObject, eventdata, handles)
% hObject    handle to C (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of C
```

```
% --- Executes on button press in D.
function D_Callback(hObject, eventdata, handles)
% hObject    handle to D (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of D

% --- Executes on button press in E.
function E_Callback(hObject, eventdata, handles)
% hObject    handle to E (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of E

% --- Executes on button press in F.
function F_Callback(hObject, eventdata, handles)
% hObject    handle to F (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of F

% --- Executes on button press in G.
function G_Callback(hObject, eventdata, handles)
% hObject    handle to G (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of G

% --- Executes on button press in I.
function I_Callback(hObject, eventdata, handles)
% hObject    handle to I (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of I

% --- Executes on button press in J.
function J_Callback(hObject, eventdata, handles)
% hObject    handle to J (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of J

% --- Executes on button press in K.
function K_Callback(hObject, eventdata, handles)
% hObject    handle to K (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of K

% --- Executes on button press in L.
function L_Callback(hObject, eventdata, handles)
% hObject    handle to L (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of L

% --- Executes on button press in M.
function M_Callback(hObject, eventdata, handles)
% hObject    handle to M (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of M



function Progress_Callback(hObject, eventdata, handles)
% hObject    handle to Progress (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of Progress as text
```

```
%        str2double(get(hObject,'String')) returns contents of Progress as a double


% --- Executes during object creation, after setting all properties.
function Progress_CreateFcn(hObject, eventdata, handles)
% hObject    handle to Progress (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function trialnumdisp_Callback(hObject, eventdata, handles)
% hObject    handle to trialnumdisp (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of trialnumdisp as text
%        str2double(get(hObject,'String')) returns contents of trialnumdisp as a double


% --- Executes during object creation, after setting all properties.
function trialnumdisp_CreateFcn(hObject, eventdata, handles)
% hObject    handle to trialnumdisp (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function slash_Callback(hObject, eventdata, handles)
% hObject    handle to slash (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of slash as text
%        str2double(get(hObject,'String')) returns contents of slash as a double


% --- Executes during object creation, after setting all properties.
function slash_CreateFcn(hObject, eventdata, handles)
% hObject    handle to slash (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function totalnumoftrials_Callback(hObject, eventdata, handles)
% hObject    handle to totalnumoftrials (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of totalnumoftrials as text
%        str2double(get(hObject,'String')) returns contents of totalnumoftrials as a double


% --- Executes during object creation, after setting all properties.
function totalnumoftrials_CreateFcn(hObject, eventdata, handles)
% hObject    handle to totalnumoftrials (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
```

## E.4 Code to determine RMS error, signed constant error, bias error and lateral percent correct scores from participant responses (written by Daniel Rowan)

```
function locerr = calclocerr2(stim_resp, stim_spkraz, stim_resp_unit)
% stim_resp_unit can be 'azi' for azimuth or 'num' for number

% dbstop in calclocerr2 at 13

if ~nargin
    load('messin')
    stim_spkraz = (-90:18:90)';
    stim_resp_unit = 'azi';
end

A = stim_spkraz(2) - stim_spkraz(1);
% Loose any columns with missing data
if sum(sum(isnan(stim_resp)))
    disp(num2str(stim_resp))
%     M = stim_resp';
%     M = M(0== sum(isnan(M), 2), :);
%     stim_resp = M';
%     disp(num2str(stim_resp))
end
[N, M] = size(stim_resp); % N total number of speakers, M is number of trials
stim_spkrnum = (1:N)';

% Convert to speaker number from speaker azimuth ifnecessary
switch stim_resp_unit
    case 'azi'
        for k = 1:N % k is current speaker number
            for Mi = 1:M
                if isnan(stim_resp(k, Mi))
                    stim_respnum(k, Mi) = NaN;
                else
%                     stim_spkraz
%                     stim_resp(k, Mi)
                    stim_respnum(k, Mi) = find(stim_spkraz == stim_resp(k, Mi));
                end
            end
        end
    case 'num'
        stim_respnum = stim_resp;
    otherwise
        error('Inappropriate value for stim_resp_unit. Choose ''azi'' or ''num''')
end

% Lat correct
numcorrect = 0;
numtotal = 0;
analyse_spkrnum = [1,2,3;9,10,11]; % Analyse stimuli from these speakers
correctif_spkrnum = [1,2,3,4;8,9,10,11]; % Mark correct if response if to these speakers
[numside, numspkr] = size(analyse_spkrnum);
[~, correctifnumspkr] = size(correctif_spkrnum);
for countside = 1:numside
    for countspkr = 1:numspkr
        analysedata = stim_respnum(analyse_spkrnum(countside,countspkr),:);
        analysedata = stripoutnans(analysedata);
        numtotal = numtotal + length(analysedata);
        for countcorrectif = 1:correctifnumspkr
            aa = find(analysedata == correctif_spkrnum(countside,countcorrectif));
            numcorrect = numcorrect + length(aa);
        end
    end
end
latpcorrect = numcorrect/numtotal;

% MAE. <-- need to deal with NaN from here
for Mi = 1:M % Mi is current trial number
    abserr(:, Mi) = abs(stim_respnum(:, Mi) - stim_spkrnum);
end
MAE = A*mean(nanmean(abserr));

% Signed constant error, E.
```

```
meanrespnum = nanmean(stim_respnum,2);
meanresp = meanrespnum*A - 90 - A;
biasspkrnum =  meanrespnum - stim_spkrnum;
Ebar = A*mean(biasspkrnum);

% RMS stuff: D, s and C.
% See Hartmann et al (1998) JASA 104(6), 3546.
for k = 1:N % k is current speaker number
    for Mi = 1:M
        sqderrnum(k, Mi) = (stim_respnum(k, Mi) - k)^2;
    end
    sqddevnum(k, :) = (stim_respnum(k, :) - nanmean(stim_respnum(k, :))).^2;
    biasnum(k, :) = (nanmean(stim_respnum(k, :)) - k).^2;
end

% Overall RMS error, D.
% "bar" here and beloew denotes average across all speakers.
Dsq = A^2*nanmean(sqderrnum,2);
D = sqrt(Dsq);
Dbar = sqrt(mean(Dsq));

% Random error (variability), s.
ssq = A^2*nanmean(sqddevnum,2)*(M/(M-1));
s = sqrt(ssq);
sbar = sqrt(mean(ssq));

% Unsigned constant/bias error, C.
Csq = A^2*biasnum;
C = sqrt(Csq);
Cbar = sqrt(mean(Csq));

% Check to make sure s and C tie in with D, to dps decimal points.
dps = 2;
Dbar_check = round((Dbar - sqrt(sbar^2 + Cbar^2))*10^dps)/10^dps;

% Adjusted unsigned constant error, adjCbar.
%   See Grantham et al (2007) Horz Plane Loc Bilat CIs. Ear Hear.
Cbar_adj = sqrt(Cbar^2 - Ebar^2);

locerr =  [latpcorrect Ebar Dbar sbar Cbar]';


function a = stripoutnans(analysedata)
a = [];
for count = 1:length(analysedata)
    if ~isnan(analysedata(count))
        a = [a, analysedata(count)];
    end
end
```

## E.5 Code to determine RMS error of random responses (written by Ben Lineton)

```
% simulation of uniform distribution for confusion matrices.

NMonteCarlo=10000; % size of ensemble for the Monte Carlo simulation
K=13; % number of source locations
DeltaTheta=180/(K-1); % 15 deg here.
RmsErr=zeros(NMonteCarlo,1);

Ntrial=6;         % number of presentations at a given locations for a given subject
Nsub=20;          % number of subjects
NAvg=Ntrial*Nsub; % total number of averages per presentation angle
Theta_true=[0:K-1]*DeltaTheta-90;  % true presentation angle
% Values for calculating distribution of RMSerror
Mbin=100;          % number of bins in histogram of RmsErr
Nbin=zeros(K,Mbin);
XbinLo=2*DeltaTheta;                          % histogram lowest bin centre
XbinHi=8*DeltaTheta;                          % histogram highest bin centre
XbinWdth=[XbinHi-XbinLo]/(Mbin-1); % histogram bin width
Xbin=[XbinLo:XbinWdth:XbinHi];     % histogram bin centres (i.e. x-axis of histogram)
for k=1:K %loop over speakers
    for iens=1:NMonteCarlo;  % loop over replications in Monte Carlo ensemble
        Theta_Resp=floor(rand(1,NAvg)*K)*DeltaTheta-90; % reported presentation angle
(=wild guess), repeated NAvg times (as in experiment)
```

```
        Err=Theta_Resp-Theta_true(k);
        RmsErr(iens)=sqrt(mean(Err.^2));
    end
    % get distibution of RmsErr
    Nbin_1=hist(RmsErr,Xbin);
    Nbin(k,:)=Nbin_1(:).';                    % number of occurrences in each bin (i.e. y-
axis of histogram)
    MeanRMSerr(k)=mean(RmsErr);               % mean RMS err
    MedianRMSerr(k)=quantile(RmsErr,0.5);     % median RMS err
    Q95RMSerr(k)=quantile(RmsErr,0.95);       % 95th-percentile of RMS err (error angle
below which 95% of trial fall)
    Q05RMSerr(k)=quantile(RmsErr,0.05);       % 5th-percentile of RMS err  (error angle
below which 5% of trial fall)
end

figure,
H1=plot(Theta_true,MeanRMSerr,'r-','linewidth',2);hold on
H2=plot(Theta_true,Q95RMSerr,'r^:','linewidth',2);
H3=plot(Theta_true,Q05RMSerr,'rv:','linewidth',2);
xlabel('True shooter angle (deg)')
ylabel('RMS error statistic (deg)')
title(['Guessed responses averaged over ',num2str(Nsub),' subjects x ',num2str(Ntrial),'
trials']);
legend([H1;H2;H3],{'mean';'95%-tile';'5%-tile'})

figure
for k=1:(K+1)/2;
    subplot(3,3,k)
    plot(Xbin,Nbin(k,:)*100/NMonteCarlo);
    xlabel('rms error (deg)')
    ylabel('% occurrence in bin')
    text(0.5,0.9,['True Angle=',num2str((k-1)*DeltaTheta-90),' deg'],'units','normalized')
    if k==2;
        title(' Distribution of RMSerr values assuming random guessing');
    end
    xlim([XbinLo,XbinHi]);
    ylim([0,max(Nbin(:)*100/NMonteCarlo)+5]);
end
```

## E.6 Code for temporal fine structure sensitivity test (written by Daniel Rowan)

```
function itd_jnd_ZB14(file_name, lead_ear)
% itd_jnd(file_name, lead_ear)
%
% 41-3AFC (Rowan and Lutman, 2004)
% Modified Levitt (Trahiotis et al, 1990) and feedback for training
% Log-ITD stepping rule (Saberi, 1995)
% Whole waveform shift in ITD, imposed in frequency domain (Bernstein and Trahiotis, 2001)
%
% Stimuli are generated prior to test (with calibration factors) but ITD imposed during
test
% Prof Les Bernstein kindly provided MFILES to impose ITD in frequency domain
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%
% USER__DEFINED__VARIABLES
% Stimulus parameters
fs = 22050;
bits = 16;
Fm = 500;
bwoct = 1; % bw of noise in octaves
l_freq = Fm/2^(bwoct/2);
h_freq = Fm*2^(bwoct/2);
FcR = 4000;
FcL = FcR;
nrpts = 4;  % Number of periods of modulator corresponding to period of stimulus
            %  (Note that period of modulator ~necessarily= period of AM stimulus, because
            %   carrier period is different from modulator)
Pm = rand*360;
Pc = rand*360;
dur = 0.4;
ramp = 0.04;

% Trials parameters
```

```
PSI = 0.4;
ISI1 = 0.1;
ISI2 = 0.8;
fb_pause = 0.4;
ITI = 0.5;
alt = 2;

% Block parameters (adaptive Levitt-type rules)
down_rule = 2;
up_rule = 1;
step_size1 = 10^0.2;
step_size2 = 10^0.2;
step_size3 = 10^0.05;
ss1_lasts = 1;       % Number of reversals in smallest step size
ss2_lasts = 2;       % Number of reversals in intermediate step size
res_limit = 1;       % Resolution of step sizes
lbound = 0;          % Lower bound of staircase
ubound = 2000;       % Upper bound of staircase
reversals = 8;       % Stopping rule for testing
max_trials = 60;     %   i.e. don't go on forever!
trials = 60;         % Stopping rule for training
discard = 1;         % Number of reversals in smallest step size discarded in analysis
jitter = 0;          % Jitter imposed on initial value
%%%%%%%%%%%%%%%%%%%%%%%%%%

% Defaults
if nargin == 0
    file_name = 'fred';
    lead_ear = 'r';
end

% Prints error message and quits if file_name already exists
if file_name(length(file_name)-3:length(file_name)) ~= '.mat'
    file_name = [file_name '.mat']; end
exs = exist(num2str(file_name),'file');
if exs == 2; errordlg('file_name already in use',''); return; end

% Define test and stimulus types and starting value of test
test_type = 1;%input('Test type. Test (1), training (2), first training block (3): ');
stimulus_type = input('Stimulus type. Tone (1), noise (2): ');
switch test_type
case 1
    vari_val = 700;
case 2
    vari_val = input('Previous JND: ') * step_size1;
case 3
    vari_val = 700;
    test_type = 2;
end

% Initialise variables
if ~isevenDR(reversals); ERRORDLG('Reversals must be even number',''); return; end
switch lead_ear; case 'r'; lead_ear = 1; case 'l'; lead_ear = -1; end
step_size=step_size1;run_test = 1;trial_number=0;reversal_number=0;correct=0;threshold =
[];
incorrect=0;null_trial=0;vari_values=0;change =
0;response=0;response_values=0;reversal_at=0;
direction = 0;log_direction = 0;target = 0;target_int = [0 0 0];response_int = [0 0 0];

% Calculate initial ITD
vari_val = vari_val - jitter/2 + rand*jitter;

% Generate PSI and ISI
PSI = linspace(0,0,PSI*fs);
ISI1 = linspace(0,0,ISI1*fs);
ISI2 = linspace(0,0,ISI2*fs);

% Open user interface
close all
fig = openfig('interface','reuse'); set(fig,'Position',[0.3 -0.7 159.2 46.6])
text = findobj(fig,'Tag','text'); set(text,'String','Press any button to start'); drawnow

% Wait for button press before starting.
pause
set(text,'String',''); drawnow

% Start procedure after a short pause
pause(1)
```

```
%
    %
while run_test
  %______________________TRIAL________________________%
  %                                                   %
    figure(fig);drawnow
    trial_number = trial_number + 1;

    % Ensure vari_val is of an appropriate value...
    vari_val = round(vari_val/res_limit)*res_limit; % Within resolution of system,
    if vari_val < lbound                            %  does not cross lower bound
        vari_val = lbound;
    elseif vari_val > ubound                        %  and does not exceed upper bound
        vari_val = ubound;
    end
    vari_values(trial_number) = vari_val;

    % Stimuli
    switch stimulus_type
    case 1  % Tone
        Pm = rand*360;
        S1 = cos2ramp(tone(Fm, Pm, dur, fs), ramp, fs);
        Pm = rand*360;
        S2 = cos2ramp(tone(Fm, Pm, dur, fs), ramp, fs);
        Pm = rand*360;
        S3 = cos2ramp(tone(Fm, Pm, dur, fs), ramp, fs);
        Pm = rand*360;
        S4 = cos2ramp(tone(Fm, Pm, dur, fs), ramp, fs);
        Pm = rand*360;
        S5 = cos2ramp(tone(Fm, Pm, dur, fs), ramp, fs);
        Pm = rand*360;
        T  = cos2ramp(tone(Fm, Pm, dur, fs), ramp, fs);
    case 2  % NBN
        S1 = cos2ramp(noiseband(l_freq, h_freq, dur, fs), ramp, fs);
        S2 = cos2ramp(noiseband(l_freq, h_freq, dur, fs), ramp, fs);
        S3 = cos2ramp(noiseband(l_freq, h_freq, dur, fs), ramp, fs);
        S4 = cos2ramp(noiseband(l_freq, h_freq, dur, fs), ramp, fs);
        S5 = cos2ramp(noiseband(l_freq, h_freq, dur, fs), ramp, fs);
        T  = cos2ramp(noiseband(l_freq, h_freq, dur, fs), ramp, fs);
    end
    S1_R = 10^(0/20)*S1;
    S1_L = 10^(0/20)*S1;
    S2_R = 10^(0/20)*S2;
    S2_L = 10^(0/20)*S2;
    S3_R = 10^(0/20)*S3;
    S3_L = 10^(0/20)*S3;
    S4_R = 10^(0/20)*S4;
    S4_L = 10^(0/20)*S4;
    S5_R = 10^(0/20)*S5;
    S5_L = 10^(0/20)*S5;
    T_R = 10^(0/20)*T;
    T_L = 10^(0/20)*itd_bernstein(T,fs,lead_ear*vari_val,0);

    % Generate vector representing trial
    stim_order = randperm(alt);
    switch find(stim_order == 1)
    case 1
        R = [PSI, S4_R, ISI1, T_R, ISI1, S5_R, ISI2, S1_R, ISI1, S2_R, ISI1, S3_R];
        L = [PSI, S4_L, ISI1, T_L, ISI1, S5_L, ISI2, S1_L, ISI1, S2_L, ISI1, S3_L];
        target = 1;
    case 2
        R = [PSI, S1_R, ISI1, S2_R, ISI1, S3_R, ISI2, S4_R, ISI1, T_R, ISI1, S5_R];
        L = [PSI, S1_L, ISI1, S2_L, ISI1, S3_L, ISI2, S4_L, ISI1, T_L, ISI1, S5_L];
        target = 2;
    end
    target_int(target) = target_int(target) + 1; % Count number of times target in first or
second interval

    % Emergency stop - if for some reason stimuli scaled too high
    if max(abs(R)) > 0.99 || max(abs(L)) > 0.99
        ERRORDLG('Stimulus reached clipping threshold',''); close(fig); return
    end

    % Play trial
    set(text,'BackgroundColor','green'); drawnow
    sound([L;R]',fs,bits);
    pause(length(R)/fs-0.1); figure(fig); drawnow

    % Collect response
    set(text,'BackgroundColor','blue'); drawnow
```

```
    figure(fig);drawnow
    keyresp = 1;
    while keyresp
        response = num2str(input('Response: ', 's'));
        switch response
            case '1'
                response = 1;
                keyresp = 0;
            case '2'
                response = 2;
                keyresp = 0;
            otherwise
        end
    end
    set(text,'BackgroundColor','black'); drawnow
    response_int(response) = response_int(response) + 1; % Count number of times response
to first or second 2AFC obs interval

    % Give feedback if training
    switch test_type
    case 1 % Test
    case 2 % Training
        figure(fig); drawnow
        set(findobj(fig, 'Tag', num2str(target)),'BackgroundColor', 'blue'); drawnow
        pause(fb_pause)
        set(findobj(fig, 'Tag', num2str(target)),'BackgroundColor','black'); drawnow
    end

  %___________________________________________________%
  %                (end of trial)                      %

    % Score and apply decision rule
    if null_trial                                  % If null_trial = TRUE, don't count -
used in training procedure
        null_trial = 0;                            %  reset null_trial
    else
        % Score response and apply adaptive rule
        if response == target                      % IF RESPONSE 'CORRECT'...
            response_values(trial_number) = 1;     %   log response type i.e. correct
(1) or incorrect (0)...
            correct = correct + 1;
            incorrect = 0;
            if correct == down_rule                %   If number of correct responses is
equal to down_rule...
                change = 1;                        %     plan to make next trial harder
(0 = same, 1 = harder, 2 = easier)
                correct = 0;                       %     initialise consec_correct,
                direction = 0;                     %     log direction (harder = 0,
easier = 1).
            else
                change = 0;                        %   Otherwise don't change direction
of track
            end
        else                                       % IF RESPONSE 'INCORRECT'...
            if trial_number == 1                   % Ignore incorrect response on first
trial...
            else
                response_values(trial_number) = 0;
                incorrect = incorrect + 1;
                correct = 0;
                if incorrect == up_rule
                    change = 2;                    % make next scored trial easier...
                    incorrect = 0;
                    direction = 1;
                    switch test_type
                    case 1  % Test
                        null_trial = 0;
                    case 2 % Training
                        null_trial = 1;            % but, if training, discard next
trial
                    end
                else
                    change = 0;
                end
            end
        end
    end
    if null_trial
    else
        % Identify if reversal has occurred
```

```
        log_direction = [log_direction
direction];                                             % Log direction of staircase
        if trial_number >
1                                                                    % If there has been
sufficient trials
            if log_direction(length(log_direction)) ~= ...
                    log_direction(length(log_direction) -
1)                                  %   reversal occured if direction has changed over past 2
trials,
                reversal_number = reversal_number +
1;                                        %   count number of reversals,
                reversal_at(reversal_number) =
trial_number;                                  %   log trial number of reversal.
            end
        end
        % Select step size
        if reversal_number == ss1_lasts
            step_size = step_size2;
        elseif reversal_number >= ss1_lasts + ss2_lasts
            step_size = step_size3;
        end
        % Change by step size
        switch change
        case 1
            vari_val = vari_val / step_size;
        case 2
            vari_val = vari_val * step_size;
        end
    end

    % End test?
    switch test_type
    case 1  % Test
        null_trial = 0;
        if reversal_number - (ss1_lasts + ss2_lasts + discard) == reversals...
         || trial_number == max_trials
            run_test = 0;
        end
    case 2  % Training
        if trial_number == trials
            run_test = 0;
        end
    end
    % Save current data in temporay file
    save('temp_data.mat', 'reversal_at', 'vari_values', 'response_values')
    pause(ITI)
end

 (end of block)                                              %

% Instruct listener test complete visually and...
set(text,'String','Test complete.  Thank you.'); set(text,'BackgroundColor','black');
drawnow
%   present a low level pure tone to indicate completion
end_tone = 10^(-30/20) * cos2ramp(tone(1000,0,2,22050),0.04,22050);
end_tone = [end_tone; end_tone]';
sound(end_tone,22050,16);

%%%%%%%%%%%%%%%%%%%%
% ANALYSE
% Determine scored reversals
rev_small = reversal_number - ss1_lasts - ss2_lasts;% Only count those in smallest step
size
rev_use = rev_small - discard;                        % Don't count inital trial(s) in
smallest step size
if ~isevenDR(rev_use)                                   % Discard additional initial reversal
if odd number of reversals collected
    rev_use = rev_use - 1;
end
reversal_vari = vari_values(reversal_at);

% If no scored reversals, score as -1
if rev_use <= 0
    scored_vari = [];
    threshold = -1;
else
    scored_vari = reversal_vari(length(reversal_vari) - rev_use + 1:length(reversal_vari));
end

% Throw away any reversal pair where clipping by lbound has been required...
```

```
for i = 1:2:length(scored_vari - 1)
    if scored_vari(i) == lbound || scored_vari(i+1) == lbound
        scored_vari(i:i+1) = [0 0];
    end
end
if ~isempty(scored_vari)
    scored_vari = scored_vari(find(scored_vari~=0));
end
% ...and if none left score as lbound
if isempty(scored_vari) && isempty(threshold)
    threshold = lbound;
end

% Throw away any reversal pair where clipping by upper bound has been required...
for i = 1:2:length(scored_vari - 1)
    if scored_vari(i) == ubound || scored_vari(i+1) == ubound
    scored_vari(i:i+1) = [0 0];
    end
end
if ~isempty(scored_vari)
    scored_vari = scored_vari(find(scored_vari~=0));
end
% ...and if none left score as ubound
if isempty(scored_vari) && isempty(threshold)
    threshold = ubound;
end

% Calculate threshold based on mean of reversals
if isempty(threshold)
    threshold = round(geomean(scored_vari)/res_limit)*res_limit;
end
MRE_data = threshold;
if scored_vari % If some scored reverals
    scored_trials = reversal_at(length(reversal_at)-length(scored_vari)+1);
    pCorrectScored =
round(sum(response_values(scored_trials:length(response_values)))/length(response_values(sc
ored_trials:length(response_values)))*100);
else
    scored_trials = 0;
end
%%%%%%%%%%%%%%%%%%%%

% Calculate or log additional data of interest
pCorrectTotal = round(sum(response_values)/length(response_values)*100);
p_target_int = target_int/trial_number;
p_response_int = response_int/trial_number;
block_data = [0, trial_number, length(scored_vari), pCorrectTotal, pCorrectScored];
reversal_data = [reversal_at; reversal_vari]';
p_target_int = target_int/trial_number;
p_response_int = response_int/trial_number;
DateTime = clock;
stim_variable = 'Interaural time difference (microseconds)';

% Save data
save(file_name, 'DateTime', 'lead_ear', 'block_data', 'MRE_data', 'reversal_data',
'response_values', 'vari_values', 'p_response_int', 'p_target_int', 'stim_variable') %save
as .MAT file for use in MATLAB

% Wait for button press...
pause
%  before closing interface...
close(fig)
%  plotting staircase...
plot_staircase(file_name)
% and displaying data
display_data(file_name)

function output = tone(freq, phaz, dur, fs)
% output = tone(freq, phaz, dur, ear, fs, level)
npts = dur*fs;
t = linspace(0, dur, npts);
phaz = pi*phaz/180;
output = sin(2*pi*freq*t + phaz);
output = 0.98 * output/max(abs(output)
```

# Appendix F – Exploration of stimuli limitations

## F.1 Effect of pinna size

There was a mismatch in HRTFs used across the stimuli conditions. The gunshot conditions were recorded using a KEMAR with small pinnae whereas the broadband noise stimuli were convolved with KEMAR large pinnae HRTFs. To investigate the impact of varying the pinna size between stimuli conditions, a 50ms broadband noise was convolved with the KEMAR CIPIC HRTFs for both small and large pinnae. As described in section 5.3.4, theoretical ITDs and ILDs were calculated using a custom-made MATLAB programme comparing the signals from the left and right ears. Level differences are measured using the RMS power differences between left and right ears over the whole duration of the signal (Brungart and Simpson 2002). Time differences were calculated by first using Hilbert transformation to realise the envelopes of the signals, followed by determining the maximum peak delay in the Hilbert transformations from both ears (as utilised by Aaronson and Hartmann 2010).

This analysis was carried out for a signal presented from 90º to the left and 90º to the right of the KEMAR to allow a comparison between the pinna sizes to be made (shown in table G1).

*Interaural time and level differences for stimuli recorded with KEMARs small and large pinnae. Stimulus was a 50 ms broadband noise burst convolved with HRTFs from the CIPIC database.*

| **Cue** | **ITD (µs)** | | **ILD (dB)** | |
|---|---|---|---|---|
| **Azimuth** | **-90º** | **90º** | **-90º** | **90º** |
| **Small pinnae** | 794 | 748 | 29 | 24 |
| **Large pinnae** | 831 | 771 | 31 | 28 |

It appears that changing the pinna size from small to large for this particular signal, increases the ITD cue by a maximum of 20-40 µs and the ILD cue by a maximum of 2-4 dB. While these are not negligible amounts (study 5 demonstrated that normal hearing civilian listeners were able to detect an ITD of ≥27 µs), the stimuli were never directly compared by the listeners. A participant would have completed a condition containing only large pinnae HRTFs (the broadband noise condition) followed by a stimulus condition using only small pinnae HRTFs (for example the gunshot condition). As all of the HRTFs used in the virtual localisation task were non-individualised it is likely that performance was not enhanced or reduced by a change in HRTFs between the stimuli conditions. In addition, no feedback was given throughout the experiment, reducing a participant's ability to 'adapt' to using a particular set of HRTFs that were not their own. Human listeners are known to be able to learn to use new pinna cues as demonstrated by Hofman et al. (1998) if given sufficient time and feedback from other sensory systems.

## F.2 Distortion introduced by RME Babyface soundcard

Care was taken during the calibration of the stimuli at the start of the experimental to set the amplitude of the broadband noise to a level that was appropriate and within safe noise exposure guidelines. During calibration of a BSc student project it was noted that, using an identical equipment set-up, that the sound card was unable to output a pure tone at 96 dB (A) without distortion. This raised concerns over the level of the stimuli used for studies 3-6 of this thesis.

The RME babyface sound card used has indicator lights that change from green to red if the stimuli outputted are causing the sound card to be overdriven. It was found after the experimental work carried out in this thesis that on the setting used, the lights did not always correctly correspond to the outputted stimuli. This meant that there was a possibility that the sound card was overdriven but the lights would have remained green (the sound card was monitoring the wrong output channel – 'line out' instead of 'headphone out').

In order to determine whether distortion was introduced by the soundcard, the stimuli were re-calibrated using an identical equipment set-up in February 2016. It was found that the sound card was able to output the broadband noise stimulus at the levels calibrated in section 6.2.4 without audible distortion. However, when a 1000 Hz pure tone was played through the system and measured using an oscilloscope at 96 dB the waveform was clipped.

Due to the nature of the noise, it would not be easy to determine the extent of any distortion introduced by the soundcard. It is worth noting that the maximum output of 105 dB SPL peak was measured for a signal presented from 90º or 270º and a signal presented from a more central source may have been lower in peak amplitude at each channel (reducing the potential for distortion introduced by the sound card).

If clipping was present, it was unlikely to have had as significant an impact on the broadband signal as a pure tone stimulus as a much smaller proportion of the signal reaches the peak output. This is also true for the gunshot stimuli; the signal only reaches the maximum output for a fraction of a second. However, any distortion may have had an impact on the ILD cues, as the signal to one ear may have been clipped but the contralateral ear would not have been.

A study was conducted using lower intensity stimuli (but a virtually identical experimental design) by BSc student Miriam Dalley. Twenty normal hearing civilians were tested using a similar broadband noise stimulus and the whole gunshot on an identical virtual source identification task. There were three repeats of each stimulus at each of the 13 source locations, as opposed to 6 repeats used in studies 3, 4, 5 and 6. As the peak output used for the BSc student project was considerably lower (94 dB SPL), there was very little chance of distortion introduced by the sound card. The results from the study are shown in the table below.

*Comparison of MAE data from study 4 and a BSc student project carried out by Miriam Dalley. All data reported in degrees.*

| | **Gunshot MAE (SD)** | **Broadband noise MAE (SD)** |
|---|---|---|
| **Study 4** | 20.9 (5.1) | 16.2 (3.3) |
| **BSc study** | 21.2 (4.4) | 16.7 (6.1) |

These results suggest that any distortion present in the stimuli used during study 4 (and subsequent studies) had a minimal or no effect on the localisation accuracy of civilian listeners.

# Appendix G – Incomplete Latin square used for stimulus condition order, Chapter 6

Stimulus conditions:

1: Broadband noise

2: Gunshot

3: Crack

4: Thump

| Participant number | Order of conditions | | | |
|---|---|---|---|---|
| 1 | 1 | 2 | 3 | 4 |
| 2 | 1 | 2 | 4 | 3 |
| 3 | 1 | 3 | 2 | 4 |
| 4 | 1 | 3 | 4 | 2 |
| 5 | 1 | 4 | 2 | 3 |
| 6 | 2 | 4 | 1 | 3 |
| 7 | 2 | 1 | 3 | 4 |
| 8 | 2 | 1 | 4 | 3 |
| 9 | 2 | 3 | 4 | 1 |
| 10 | 2 | 4 | 3 | 1 |
| 11 | 3 | 4 | 2 | 1 |
| 12 | 3 | 1 | 2 | 4 |
| 13 | 3 | 1 | 4 | 2 |
| 14 | 3 | 2 | 1 | 4 |
| 15 | 3 | 2 | 4 | 1 |
| 16 | 4 | 3 | 2 | 1 |
| 17 | 4 | 2 | 1 | 3 |
| 18 | 4 | 1 | 2 | 3 |
| 19 | 4 | 2 | 3 | 1 |
| 20 | 4 | 3 | 1 | 2 |

# Appendix H – Study 3: Additional details

Participant characteristics were as follows:

*Study 3: Participant characteristics*

**two participants had participated in recreational rifle shooting for <1 year*

| Characteristic | Number of participants |
|---|---|
| **Gender M(F)** | 10 (10) |
| **Age Mean(range)** | 26 (21-45) |
| **Handedness R(L)** | 18 (2) |
| **Eye dominance R(L)** | N/A |
| **Experience with Firearms Y(N)** | 2* (18) |

Further analysis was conducted to determine the relationship between participant localisation accuracy and stimulus condition.

Repeated measures ANOVA was used to examine whether there was a significant effect of stimulus condition on RMS error. The levels of the independent variable were the four stimulus conditions 1) gunshot; 2) crack; 3) thump, 4) broadband noise. The dependent variable was the RMS score averaged across azimuths. See table 6.5 (section 6.3.3) for the mean and SD data from study 3.

The Shapiro-Wilks test for normality, examining standardized skewness, indicated that three out of four conditions were normally distributed ($F>0.05$) and the fourth (crack) was almost normally distributed ($F=0.048$). As ANOVA tolerates violations of normality well (Schmider et al. 2010) with only small effects on type I error rates, it was considered a suitable statistical measure in this instance.

Mauchly's test indicated that assumptions of sphericity were violated ($p< 0.05$) and therefore Greenhouse-Geisser correction was used. The results show a statistically significant effect of stimulus condition, $F(2,32) = 35.99$, $p < 0.05$, $r= 0.65$. Pairwise comparisons show significant differences between all of the stimulus conditions except gunshot and thump; this can be seen in the table below.

*Study 3: ANOVA pairwise comparisons of the stimulus conditions*

| **Condition** | Crack | Thump | Broadband noise |
|---|---|---|---|
| Gunshot | ✓(p< 0.01) | Not significant | ✓ (p<0.01) |
| Crack | | ✓ (p<0.01) | ✓ (p<0.01) |
| Thump | | | ✓ (p<0.01) |

A systematic error was found at 15º and 30º azimuth. This was shown in figure 6.6 in section 6.3.3. The table below gives the RMS error values (an average of all participant responses and 6 repeats of each source) for each azimuth. The values shown at 15º and 30º for the gunshot-derived conditions (between 28º and 37.4º RMS error) are considerably higher than the RMS error scores recorded at the other source locations.

*Study 3: RMS error scores at each source azimuth for the 4 stimulus conditions.*

| | **-90** | **-75** | **-60** | **-45** | **-30** | **-15** | **0** | **15** | **30** | **45** | **60** | **75** | **90** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gunshot** | 20.4 | 17.0 | 17.5 | 16.4 | 14.6 | 14.6 | 12.8 | 37.4 | 30.9 | 21.6 | 16.4 | 13.9 | 16.6 |
| **Crack** | 29.0 | 27.6 | 24.2 | 17.1 | 19.6 | 13.4 | 18.1 | 37.1 | 34.7 | 26.4 | 24.2 | 18.9 | 27.3 |
| **Thump** | 16.9 | 12.9 | 13.1 | 13.0 | 12.1 | 12.9 | 10.3 | 36.0 | 28.0 | 20.8 | 17.0 | 12.9 | 15.4 |
| **Broadband noise** | 7.3 | 10.5 | 15.9 | 18.1 | 18.3 | 14.5 | 5.3 | 16.3 | 19.0 | 17.5 | 15.5 | 10.0 | 11.5 |

# Appendix I – Information for participants

**Study title**

Investigating the localisation accuracy of small arms fire

**Invitation to take part**

You are invited to participate in this research because you have been referred to the Defence Audiology Service at the Institute of Naval Medicine, Gosport, or because your normal place of work is HMS Sultan

By taking part in this research you are contributing to a body of knowledge regarding military specific hearing requirements.

**What is the purpose of the research?**

This research is part of a PhD study investigating hearing in the Military. I (Zoë Bevis) am a PhD student at the University of Southampton, sponsored by the MoD. The study is investigating how well personnel can detect where a gunshot sound is coming from.

**Who is doing this research?**

University of Southampton PhD Researcher, Zoë Bevis

**Why have I been invited to take part?**

You have been invited to take part because you are a member of the armed forces

**Do I have to take part?**

No. Participation is on a voluntary basis.

**What will I be asked to do?**

There are 2 tests. For the first test you will be requested to listen to some gunshot sounds over headphones, whilst seated in a chair surrounded by a ring of letters. You will be asked to say a letter that describes the direction you believe the sound came from. Sometimes it will be easy to tell where the sounds come from and sometimes it will be difficult, you need to respond every time even if you are not sure.

The gunshots have been reduced in volume so that they present no risk to your hearing health.

For test 2 you will be asked to listen to series of 4 noises in a row. You will be asked which of these noises appears to come from a different place than the others. Again, some of these will be more difficult than others and you will be asked to guess which sound is different.

You may also be asked to carry out a pure tone audiometry hearing test.

You will be offered regular breaks and can take a break whenever you need to. Water and refreshments will be available. You are requested to attend one testing session, lasting a maximum of 90 minutes which will take place after your appointment at The Defence Audiology Service.

You will be asked to complete a short questionnaire about your hearing and general ear health.

**What is the device or procedure that is being tested?**

A sound source identification task is used to measure localisation accuracy. A ‘moving noise’ detection task is used to test your ability to hear small time differences in sounds.

**What are the benefits of taking part?**

There will be no direct benefit to you as an individual, however by taking part you will contribute to a body of knowledge regarding military specific hearing requirements.

**What are the possible disadvantages and risks of taking part?**

There are no disadvantages or risks involved in this study. The levels of noise that you will be exposed to will be no different to that expected in everyday life.

**Can I withdraw from the research and what will happen if I don't want to carry on?**

You have the right to withdraw from this study at any time without giving reason. Your legal rights will not be affected. There is no impact on your service career if you do not wish to carry on.

**Are there any expenses and payments which I will get?**

No.

**Will my taking part or not taking part affect my Service career?**

No. The results will have no influence on your Service career. If you choose to not take part, this will not be recorded and will have no effect on your military career.

**Whom do I contact if I have any questions or a complaint?**

For further information please contact Zoë Bevis (zb1g08@soton.ac.uk) or Surg Cdr Chris Pearson, Institute of Naval Medicine, Gosport, PO12 2DL (NAVYINM-UMDCONSENT@mod.uk).

**What happens if I suffer any harm?**

Contact Dr Adrian Allsopp (details above) who will put you in touch with the medico-legal department at the Institute of Naval Medicine. In the event of any injury, illness or death as a direct result of participating as a volunteer in Ministry of Defence research, you or your dependants may enter a claim with the Ministry of Defence for compensation under the provisions of the no-fault compensation scheme.

**What will happen to any samples I give?**

Any data you provide will be anonymised and kept confidentially by the primary researcher in a password protected file.

**Will my records be kept confidential?**

Yes. This study complies with the Data Protection Act. All data collected will remain confidential. Reported data will be kept anonymous. During the study only the Chief Investigator (Zoe Bevis) will have access to your personal data.

**Who is organising and funding the research?**

This research is funded by the MoD and organised by Dr Adrian Allsopp at the Institute of Naval Medicine, Gosport.

**Who has reviewed the study?**

The study has received University of Southampton risk assessment approval and has also been approved by the University of Southampton Ethical Research Governance Committee and MoD

Research Ethics Committee.

**Further information and contact details.**

For further information please contact the Defence Audiology Service on 02392 768072

**Compliance with the Declaration of Helsinki.**

This study complies , and at all times will comply, with the Declaration of Helsinki [1] as adopted at the 64th WMA General Assemble at Fortaleza, Brazil in October 2013

# Appendix J – Invitation to participate (Study 5 and 6)

Institute of Sound and Vibration Research

UNIVERSITY OF Southampton

*Recipients address.*

Miss Zoë Bevis (PhD Researcher, University of Southampton)
Email: zb1g08@soton.ac.uk
Institute of Sound and Vibration Research
University of Southampton
SO17 1BJ
Telephone (Defence Audiology Service): 02392 768072

*Date*

Dear *recipient's name*

I am writing to inform you about a study being carried out the Institute of Naval Medicine (INM), in collaboration with the University of Southampton. The study aims to investigate how accurately personnel can locate the sound of gunfire. The test will involve personnel listening to recorded gunshots and identifying where the sound came from. This study is being carried out at INM.

I would be very grateful if you would be happy to participate in the study on the same day you will attend the Audiology Clinic for your appointment. The session lasts for no more than 90 minutes, including regular breaks.

Attached to this letter is a participant information sheet and consent form which contain further information about the study; please take the time to read this. If you are willing to participate in the study please phone the audiology department at the INM. You do not need to sign the consent form until you attend the audiology clinic and only if you are willing to participate in the study.

Yours sincerely

Zoë Bevis
PhD Researcher, University of Southampton

# List of References

AARONSON, N. L. & Hartmann, W. M. (2010) Interaural coherence for noise bands: waveforms and envelopes. *Journal of the Acoustical Society of America*. 127 (3). 1367–1372.

ABDEL-MOTY, E., Compton, R., Steele-Rosomoff, R., Rosomoff, H. & Khalil, T. M. (1996) Process analysis of functional capacity assessment. *Journal of Back & Musculoskeletal Rehabilitation.* (6). 223–236.

ABEL, S. M., & Hay, V. (1996) Sound Localization: The Interaction of Aging, Hearing Loss and Hearing Protection. *Scandinavian Audiology Supplement*. (25). 3–12.

ABEL, S. M., DuCharme, M. & van der Werf, D. (2010) Hearing and Sound Source Identification With Protective Headwear. *Military Medicine*. 175 (11). 865–870.

ABEL, S. M. (2005) Hearing Loss in Military Aviation and Other Trades: Investigation of Prevalence and Risk Factors. *Aviation, Space and Environmental Medicine*. 76 (12). 1128–1135.

ADOBE AUDITION (2007) Adobe systems (Version 3). [Computer program].

AKEROYD, M., Chambers, J., Bullock, D., Palmer. A., Summerfield, A. et al. (2007) The binaural performance of a cross-talk cancellation system with matched or mismatched setup and playback acoustics. *Journal of the Acoustical Society of America*. 121 (2). 1056-1069.

ANDERSON, S., White-Schwoch, T., Parbery-Clark, A., & Kraus, N. (2013) Reversal of age-related neural timing delays with training. *Proceedings of the National Academy of Sciences*. 110 (11). 4357–4362.

APOUX, F., Yoho, S. E., Youngdahl, C. L., & Healy, E. W. (2013) Role and relative contribution of temporal envelope and fine structure cues in sentence recognition by normal-hearing listeners. Journal of the Acoustical Society of America. 134 (3). 2205–2212.

ARMY TECHNOLOGY (n.d.) SA80 A2 L85 Assault Rifle, United Kingdom. [Online] Available from: from http://www.army-technology.com/projects/sa80-a2-l85-assault-rifle/. [Accessed: 2nd February 2015]

AXELSSON, A. & Prasher, D. (2000) Tinnitus induced by occupational and leisure noise. *Noise and Health.* 2 (8). 47-54.

AXELSSON, A. & Sandh, A. (1985) Tinnitus in noise-induced hearing loss. *British Journal of Audiology*. 19 (4). 271-276.

AXELSSON, A., Borchgrevink, H., Hamernik, R., Hellstrom, P., Henderson, D. et al. (1996) *Scientific Basis of Noise-Induced Hearing Loss*. 1st edition. New York, Thieme.

BECK, S. D., Nakasone, H. & Marr, K. W. (2011) Variations in recorded acoustic gunshot waveforms generated by small firearms. *Journal of the Acoustical Society of America*. 129 (4). 1748–1759.

BECK, S. D., Nakasone, H., & Marr, K. W. (2011) Variations in recorded acoustic gunshot waveforms generated by small firearms. *Journal of the Acoustical Society of America*. 129 (4). 1748–1759.

BEGAULT, D. R., Wenzel, E. M., & Anderson, M. R. (2001) Direct comparison of the impact of head tracking, reverberation, and individualized head-related transfer functions on the spatial perception of a virtual speech source. *Journal of the Audio Engineering Society*. 49 (10). 904–916.

BERGER, E. H. (2013) “Calibrating” the insertion depth of roll-down foam earplugs. Proceedings of Meetings on Acoustics. *Journal of the Acoustical Society of America*. 19. 1-9.

BERGMAN, M. (1957) Binaural Hearing. *Archives Otolaryngology*. (66). 572–578.

BEVIS, Z. L., Semeraro, H.D., van Besouw, R.M., Rowan, D., Lineton, B. et al. (2014) Fit for the frontline? A focus group exploration of auditory tasks carried out by infantry and combat support personnel. *Noise and health*. 16 (69). 127–135.

BIGGS, T. & Everest, A. (2011) British military hearing conservation programme. *Clinical Otolaryngology*. 36 (3), 299–301.

BILZON, J. L. J., Scarpello, E. G., Bilzon, E. & Allsopp, A. J. (2002) Generic task-related occupational requirements for royal naval personnel. *Occupational Medicine*. 52 (8). 503-510.

BIRCH, H. G. & Belmont, L. (1965) Audio-visual integration, intelligence and reading ability in school children. *Perceptual and Motor Skills*. (20). 295–305.

BLAUERT, J. (1997). *Spatial Hearing: The psychophysics of human sound localization*. First edition. Cambridge, USA. MIT Press.

BOHNE, B. & Rabbitt, K. (2000) Degeneration in the cochlea after noise damage: primary versus secondary events. *Hearing Research*. 21 (4), 505–509.

BORG, E., Nilsson, R. & Liden, G. (1982) Fatigability of the Stapedius Reflec in Inductrial Noise. *Acta Otolaryngology*. (94). 385–393.

BOWERS, D. & Heilman, K. M. (1980) Pseudoneglect: effects of hemispace on a tactile line bisection task. *Neuropsychologia*. 18 (4-5). 491–498.

BRADLEY, J. V. (1958) Complete Counterbalancing of Immediate Sequential Effects in a Latin Square Design. *Journal of the American Statistical Association*. 53 (282). 525–528.

BRATTICOA, E., Kujalaa, T., Alkud, P. & Ambrosie, L. (2005) Long-term exposure to occupational noise alters the cortical organization of sound processing. *Clinical Neurophysiology*. 116 (1). 190–203.

BRIMIJOIN, W. O., Boyd, A. W. & Akeroyd, M. A. (2013) The contribution of head movement to the externalization and internalization of sounds. *PLOS One*. 8 (12). [Online] Available from: http://journals.plos.org/plosone/article?id=10.1371 [Accessed: 2nd February 2014]

BRITISH BROADCASTING CORPORATION (2010) News article: Statistics reveal Britain's 'Mr and Mrs Average'. [Online] Available from: http://www.bbc.co.uk/news/uk-11534042. [Accessed: 5th January 2014].

BRITISH SOCIETY OF AUDIOLOGY (2004) Pure tone air and bone conduction threshold audiometry with and without masking and determination of uncomfortable loudness levels. *Recommended procedures*. [Online] Available from: http://www.thebsa.org.uk/resources. [Accessed: 15th September 2012].

BRONKHORST, A. (1995) Localization of real and virtual sound sources. *Journal of the Acoustical Society of America*. 98 (5). 2542–2553.

BRUNGART, D. S. & Simpson, B. D. (2002) The effects of spatial separation in distance on the informational and energetic masking of a nearby speech signal. *Journal of the Acoustical Society of America*. 112 (2). 664-676.

BRUNGART, D. S. & Simpson, B. D. (2008) Effects of temporal fine structure on the localization of broadband sounds: Potential implications for the design of spatial audio displays. *Proceedings of the 14th International conference on auditory display*. Paris, France. [Online] Available from: https://smartech.gatech.edu/handle/1853/49904. [Accessed on: 17th April 2013].

BRUNGART, D. S. & Simpson, B. D. (2009) Effects of bandwidth on auditory localization with a noise masker. *Journal of the Acoustical Society of America*. 126 (6). 3199–3208.

BUTLER, R. (1970) The effect of hearing impairment on locating sound in the vertical plane. *International Journal of Audiology*. (1). 117–126.

BUTLER, R. & Planert, N. (1976) The influence of stimulus bandwidth on localization of sound in space. *Perception and Psychophysics*. 19 (1). 103–108.

BUTLER, R., & Humanski, R. (1992) Localization of sound in the vertical plane with and without high-frequency spectral cues. *Perceptual Psychophysics*. (51). 182–186.

BYRNE, D. & Noble, W. (1992) Effects of Long-Term Bilateral and Unilateral Fitting of Different Hearing Aid Types on the Ability to Locate Sounds. *Journal of the American Academy of Audiology*. (3). 369–382.

CAIAZZO, A. & Tonndorf, J. (1977) Ear Canal resonance and Temporary Threshold Shift. *Acoustical Society of America Spring Supplement*. 61 (1). 78.

CAIN, P. A. (1998) Update - Noise Induced Hearing Loss and the Military Environment. *Journal of the Royal Army Medical Corps*. (144), 97–101.

CAMPION, M. A., Pursell, E. D. & Brown, B. K. (1988) Structured interviewing: raising the psychometric properties of the employment interview. *Personnel Psychology*. 41 (1). 25-42.

CARLILE, S., Philip, L. & Hyams, S. (1997) The nature and distribution of errors in sound localization by human listeners. *Hearing Research*. (114). 179–196.

CASCIO, W. F. & Aguinis, H. (2005) Test development and use: New twists on old questions. *Human Resource Management*. 44 (3). 219–235.

CHENG, C. I. & Wakefield, G. H. (2001) Introduction to head related transfer functions (HRTF's): representations of HRTF's in time, frequency, and space. *Journal of the Audio Engineering Society*. 49 (4). 231–249.

CHUNG, D. Y., Gannon, R. & Mason, K. (1984) Factors Affecting the Prevalence of Tinnitus. *Audiology*. (23). 441–452.

COLEMAN, P. D. (1962) Failure to localize the source distance of an unfamiliar sound. *Journal of the Acoustical Society of America.* 34 (3). 345–346.

COLES, R. R. A., Lutman, M. E. & Buffin, J. T. (2000) Guidelines on the diagnosis of noise-induced hearing loss for medicolegal purposes. *Clinical Otolaryngology*. (25). 264–273.

COLLEE, A., Legrand, C., Govaerts, B., Van Der Veken, P., De Boodt, F. et al. (2011) Occupational exposure to noise and the prevalence of hearing loss in a Belgian military population : A cross-sectional study. *Noise and Health*. 13 (50), 64–70.

COLLETTI, V. & Sittoni, W. (1985) Noise History, audiometric profile and acoustic reflex responsivity. In Salvi, R., Henderson, D., Hamernik, R,. & Colletti, V. (eds.). *Basic and Applied Aspects of Noise-Induced Hearing Loss.* New York, Plenum Press. 269–347.

COOK, L. & Hickey, M. (2003) Physical hazards and noise in law enforcement. *Clinical Occupational Environmental Medicine*. (3). 419–442.

CORBALLIS, M. C. (2003) From mouth to hand: gesture, speech, and the evolution of right-handedness. *The Behavioral and Brain Sciences*. 26 (2). 199–208.

COX, H. & Ford, G. (1995) Hearing loss associated with weapons noise exposure: when to investigate an asymmetrical loss. *The Journal of Laryngology and Otology*. 109 (4). 291–295.

DAMASKE, P. (1971) Head-Related Two-Channel Stereophony with Loudspeaker Reproduction. *Journal of the Acoustical Society of America*. 50 (4). 1109–1115.

DEFENCE COMMITTEE (2003) *Defence - Third Report*. Chapter 3: Recruitment, Section 79: Education. [Online] Available from: http://www.publications.parliament.uk/pa/cm200405/. [Accessed: 27th February 2014].

DIETZ, M., Wendt, T., Ewert, S. D., Laback, B. & Hohmann, V. (2013) Comparing the effect of pause duration on threshold interaural time differences between exponential and squared-sine envelopes. *The Journal of Acoustical Society of America*. 133 (1). 1-4.

DOBREVA, M. S., O'Neill, W. E. & Paige, G. D. (2011) Influence of aging on human sound localization. *Journal of Neurophysiology*. 105 (5). 2471-2486.

DONZIER, A. & Cadavid, S. (2005) Small arm fire acoustic detection and localization systems: gunfire detection system. Proceedings of SPIE (Society of Photo-optical Instrumentation Engineers) defense conference. (5778). 245–253.

DOWNE-WAMBOLDT, B. (1992) Content analysis: Method, applications, and issues. *Health Care for Women International*. 13 (3). 313–321.

DUFOUR, A., Touzalin, P. & Candas, V. (2007) Rightward shift of the auditory subjective straight ahead in right- and left-handed subjects. *Neuropsychologia*. 45 (2). 447–453.

DURLACH, N., Thompson, C. & Colburn, H. S. (1981) Binaural Interaction in Impaired Listeners. *International Journal of Audiology*. 20 (3). 181–211.

ENDSLEY, M. R. (1995) Toward a theory of situational awareness in dynamic systems. *Human Factors.* 37 (1). 32-64.

FLUITT, K., Gaston, J., Karna, V. & Letowski, T. (2010) Feasibility of Audio Training for Identification of Auditory Signatures of Small Arms Fire. *Army Research Laboratory*. (December). 1–50.

FRASER, T. M. (1992) *Fitness for work: The Role of Physical Demands Analysis and Physical Capacity Assessment*. London, UK. CRC Press.

FUJIKI, N., Riederer, K., Jousmäki, V., Mäkelä, J. P. & Hari, R. (2002) Human cortical representation of virtual auditory space: Differences between sound azimuth and elevation. *European Journal of Neuroscience*. 16 (11). 2207–2213.

FULGRABE, C. (2013) Age-dependent changes in temporal-fine-structure processing in the absence of peripheral hearing loss. *American Journal of Audiology*. (22). 313-315.

GARDNER, B., & Martin, K. (1995). HRTF Measurements of a KEMAR Dummy-Head Microphone. Open source database. [Online] Available from: http://sound.media.mit.edu/resources/KEMAR.html. [Accessed: 5th May 2014].

GELFAND, S. A. (2004) *Hearing: An introduction to psychological and Physiological Acoustics*. Fourth Edition. London, UK. Taylor and Francis.

GHASEMI, M., Saedi, B., Mojtahed, M., Rezaee Najafabadi, M., Afshari, M. et al. (2012) Hearing threshold shift measured by pure tone audiometry after gun shot exposure in military personnel not using hearing protectors. *Journal of Military Medicine*. 13 (4). 201–206.

GIGUÈRE, C., Laroche, C., Soli, S.D. & Vaillancourt, V. (2008) Functionally-based screening criteria for hearing-critical jobs based on the Hearing in Noise Test. *International Journal of Audiology*. 47 (6). 319–328.

GOUPELL, M. J., Majdak, P. & Laback, B. (2010) Median-plane sound localization as a function of the number of spectral channels using a channel vocoder. *Journal of the Acoustical Society of America*. 127 (2). 990-1001.

GRAVES, J. R. (2010) *Audio Gunshot Detection and Localisation systems: history, basic design and future possibilities*. Northern Michigan University, USA. MA thesis.

GREENE, T. (1929) The ability to localize sound. *Archives of Surgery*. (6). 1825-1841.

GRIFFIN, M., Lawton, B. & Lutman, M. (1996) *Guide to experimentation involving human subjects. ISVR Technical memorandum, no.808*. University of Southampton, UK. 1-46.

GROSE, J. H. & Mamo, S. K. (2010) Processing of temporal fine structure as a function of age. *Ear and Hearing*. 31 (6). 755-760.

GROTHE, B., Pecka, M. & McAlpine, D. (2010) Mechanisms of sound localization in mammals. *Physiological Reviews*. 90 (3). 983-1012.

HARTMANN, W. (1983) Localization of Sound in Rooms. *Journal of Acoustical Society of America*. 74 (5). 1380–1391.

HARTMANN, W. M., Rakerd, B. & Gaalaas, J. B. (1998) On the source-identification method. *Journal of the Acoustical Society of America*. 104 (6). 3546–3557.

HAWKINS, D. B. & Wightman, F. (1980) Interaural Time Discrimination Ability of Listeners with Sensorineural Hearing Loss. *Audiology*. (19). 495–507.

HAWLEY, M. L. Litovsky, R. Y. & Colburn, H. S. (1999) Speech intelligibility and localization in a multi-source environment. *Journal of the Acoustical Society of America*. 105 (6). 3436–3448.

HEALTH & SAFETY EXECUTIVE (2004) Statistics: Noise-Induced Deafness. [Online] http://www.hse.gov.uk/noise/statistics.htm. [Accessed: 24th May 2014].

HELFER, K. S. & Vargo, M. (2009) Speech recognition and temporal processing in middle-aged women. *Journal of the American Academy of Audiology*. 20 (4). 264–271.

HELLSTRÖM, P. (1996) Individual Differences in Peripheral Sound Transfer Function: Relationship to NIHL. In: Axelsson, A., Borchgrevink, H., Hamernik, R., Hellström, P. A. et al. (eds.). *Scientific Basis of Noise-Induced Hearing Loss*. New York, Thieme. 110–116.

HENDERSON, D. & Hamernik, R. (1995) Biologic basis of noise-induced hearing loss. In: Morata, T. C. & Dunn, D. E. (eds.). *Occupational Hearing Loss: state of the art reviews*. Vol 10. Philadelphia, Hanley & Belfus Inc. 513–534.

HOFMAN, P. M., Van Riswick, J. G. & Van Opstal, A. J. (1998) Relearning sound localization with new ears. *Nature Neuroscience*. 1 (5). 417–421.

HONG, O. (2005) Hearing loss among operating engineers in American construction industry. *International archives of occupational and environmental health*. [Online] 78 (7), 565–574. Available from: http://www.ncbi.nlm.nih.gov/pubmed.

HOPKINS, K. & Moore, B. C. J. (2007) Moderate cochlear hearing loss leads to a reduced ability to use temporal fine structure information. *Journal of the Acoustical Society of America*. (122). 1055-1068.

HOPKINS, K. & Moore, B. C. J. (2010) Development of a fast method for measuring sensitivity to temporal fine structure information at low frequencies. *International Journal of Audiology*. 49 (12). 940–946.

HOPKINS, K. & Moore, B. C. J. (2011) The effects of age and cochlear hearing loss on temporal fine structure sensitivity, frequency selectivity, and speech reception in noise. *Journal of the Acoustical Society of America*. 130 (1). 334–349.

HUANG, J., Ohnishi, N. & Sugie, N. (1998) Spatial Localization of Sound Sources: Azimuth and Elevation Estimation. *IEEE Instrumentation and Measurement*. [Online] Available from: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=679796. [Accessed: 6th June 2015].

HUMES, L. E., Joellenbeck, L. M. & Durch, J. S. (eds.) (2005) *Noise and Military Service: Implications for Hearing Loss and Tinnitus.* Washington, USA. The National Academies Press.

INNES. E. & Straker, L. (1998) A clinician's guide to work-related assessments: 3-Administration and interpretation problems. *Work.* 11 (2). 207–219.

INNES, E. (1997) Work assessment options and the selection of suitable duties: An Australian perspective. *New Zealand Journal of Occupational Therapy*. 48 (1). 14–20.

IRVINE, D. R., Brown, M. & Rajan, R. (2001) Injury- and Use-Related Plasticity in Adult Auditory Cortex. *Audiology & Neuro-Otology*. (6). 192–195.

IWAYA, Y., Suzuki, Y. & Kimura, D. (2003) Effects of head movement on front-back error in sound localization. *Acoustical Science and Technology*. 24 (5). 322–324.

JIE, W. (2010). A robust algorithm for binaural audio reproduction using loudspeakers. *IEEE Measuring technology and Mechatronics Automation.* [Online] Available from: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5460188&tag=1 [Accessed: 6th June 2015].

KILLION, M. C., Monroe, T. & Drambarean, V. (2011) Better protection from blasts without sacrificing situational awareness. *International Journal of Audiology*. (50). 38–45.

KITZINGER, J. (1995) Introducing focus groups. *British Medical Journal.* (311). 299–302.

KRIPPENDORFF, K. (2003) *Content Analysis: An Introduction to Its Methodology*. Second Edition. Beverly Hills, USA. Sage.

KUHN, G. F. (1977) Model for the interaural time differences in the azimuthal plane. *Journal of Acoustical Society of America.* (62). 157–167.

KUJAWA, S. & Liberman, M. (2009) Adding insult to injury: cochlear nerve degeneration after 'temporary' noise-induced hearing loss. *The Journal of Neuroscience*. 29 (45), 14077–14085.

KULKARNI, A. & Colburn, H. S. (1998) Role of spectral detail in sound-source localization. *Nature*. 396 (December). 747–749.

KULKARNI, A. & Colburn, H. S. (2005) Models of sound localization. In Popper A. & Fay R. (eds.). *Sound Localization*. New York, USA. Springer.

KUMAR, U. A., Ameenudin, S. & Sangamanatha. A. V. (2012) Temporal and speech processing skills in normal hearing individuals exposed to occupational noise. *Noise and Health*. 14 (58). 100–105.

LANGFORD, T. (1994) Individual differences in sensitivity to interaural disparities of time and level. *Journal of the Acoustical Society of America*. 5 (96). 3256–3257.

LAROCHE, C., Giguère, C., Soli, S. D. & Vaillancourt, V. (2008) Establishment of fitness standards for hearing-critical jobs. *9th International Congress on Noise as a Public Health Problem*. Los Angeles, USA.

LAROCHE, C., Soli, S., Giguère, C., Lagacé, J., Vaillancourt, V. et al. (2003) An approach to the development of hearing standards for hearing-critical jobs. *Noise and Health*. 6 (21). 17–37.

LECHNER, D., Roth, D. & Straaton, K. (1991) Functional capacity evaluation in work disability. *Work*. 1 (3). 37–47.

LE PRELL, C. & Henderson, D. (2012) Perspectives on Noise-Induced Hearing Loss. In: Le Prell, C., Henderson, D., Fay, R. R. & Popper, A. N. (eds.). *Noise-Induced Hearing Loss: Scientific Advances*. New York, USA. Springer.

LETOWSKI, T. & Letowski, S. (2011) Localization Error : Accuracy and Precision of Auditory Localization. In Strumillo, P. (ed.), *Advances in Sound Localization*. Rijeka, Croatia: InTech Europe.

LITTLE, A. D., Mershon, D. H. & Cox, P. H. (1991) Spectral content as a cue to perceived auditory distance. *Perception*. 21 (3). 405–416.

LORENZI, C., Gatehouse, S. & Lever, C. (1999) Sound localization in noise in hearing-impaired listeners. *Journal of the Acoustical Society of America*. 105 (6). 3454–3463.

LOWER, M. C., Paddan, G. S. (under review) Factors affecting sound exposure from firing an SA80 high-velocity rifle. *Submitted to Applied Acoustics.*

MACPHERSON, E. A. & Middlebrooks, J. C. (2000) Localization of brief sounds: effects of level and background noise. *Journal of the Acoustical Society of America*. 108 (4). 1834–1849.

MAHER, R. C. & Shaw, S. R. (2008) Deciphering gunshot recordings. *Acoustical Engineering Society 33rd international conference proceedings.* Denver, USA. 1-8.

MAHER, R. C. (2006) Modeling and Signal Processing of Acoustic Gunshot Recordings. *IEEE proceedings on Applications of Signal Processing to Audio and Acoustics*. 257–261.

MAJDAK, P., Goupell, M. J. & Laback, B. (2010) 3-D localization of virtual sound sources : Effects of visual environment , pointing method , and training. *Attention, Perception and Psychophysics*. 72 (2). 454–469.

MAJDAK, P., Goupell, M. J. & Laback, B. (2011) Two-dimensional localization of virtual sound sources in cochlear-implant listeners. *Ear and Hearing*. 32 (2). 198–208.

MAKOUS, J. C. & Middlebrooks, J. C. (1990) Two-dimensional sound localization by human listeners. *Journal of the Acoustical Society of America*. 87 (5). 2188–2200.

MALLOCK, A. (1908) A note on the sensibility of the ear to the direction of explosive sounds. 110-112. *Proceedings of the Royal Society of London* [Online] Available from: http://rspa.royalsocietypublishing.org/content/royprsa/80/536/110. [Accessed: 13th May 2015]

MATRIX LABORATORY (2012) The Mathworks (Version 7.14) [Computer program].

MAZEROLLE, L., Watkins, C., Rogan, D. & Frank, J. (1999) Random Gunfire Problems and Gunshot Detection Systems. *United States Department of Justice report*. [Online] Available from: https://www.ncjrs.gov/txtfiles1/nij/179274.txt. [Accessed: 2nd November 2014]

McANALLY, K. I.,& Martin, R. L. (2014) Sound localization with head movement : implications for 3-d audio displays. *Frontiers in Neuroscience*. 8 (August). 1–6.

McFADDEN, D. (1998) Sex differences in the auditory system. *Developmental Neuropsychology*. 14 (2-3). 261–298.

MERSHON, D. H. & King, L. E. (1975) Intensity and reverberation as factors in the auditory perception of egocentric distance. *Perception and Pschophysics*. 18 (6). 409–415.

MIDDLEBROOKS, J. C. & Green, D. M. (1991) Sound localization by human listeners. *Annual Revue Psychology*. (42). 135–159.

MIDDLEBROOKS, J. C. (1999) Virtual localization improved by scaling nonindividualized external-ear transfer functions in frequency. *Journal of the Acoustical Society of America*. 106 (3). 1493–1510.

MINISTRY OF DEFENCE (2013) *Joint Service Publication 950: Assessment of hearing acuity*. Annex D, Leaflet 6-7-3. [Online] Available from:

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/436071/20150. [Accessed 5th June 2015].

MØLLER, H., Sørensen, M. F., Jensen, C. B. & Hamershoi, D. (1996) Binaural technique: Do we need individual recordings? *Journal of the Audio Engineering Society*. (44). 451-469.

MOON, I. J. & Hong, S. H. (2014) What is temporal fine structure and why is it important? *Korean Journal of Audiology*. 18 (1). 1–7.

MOORE, B. C. J. (1989) *An introduction to the psychology of hearing*. Fourth edition. San Diego, CA: Academic Press.

MOORE, B. C. J. (2007). *Cochlear Hearing Loss: Physiological, Psychological and Technical Issues*. Second edition. New Jersey, USA: Wiley.

MOORE, B. C. J., Glasberg, B. R. & Hopkins, K. (2006) Frequency discrimination of complex tones by hearing-impaired subjects: Evidence for loss of ability to use temporal fine structure. *Hearing Research*. (222). 16-27.

MOREST, D. (1982) Degeneration in the brain following exposure to noise. In: Hamernik, R., Henderson, D. & Salvi, R. (eds.). *New Perspectives in Noise-induced Hearing Loss*. New York, USA. Raven Press.

MORETTI, F., van Vliet, L., Bensing, J., Deledda, G., Mazzi, M., Rimondi, M. et al. (2011) A standardized approach to qualitative content analysis of focus group discussions from different countries. *Patient Education and Counselling*. 82 (3). 420-428.

MUHR, P. & Rosenhall, U. (2011) The influence of military service on auditory health and the efficacy of a Hearing Conservation Program. *Noise and Health*. 13 (53). 320–327.

MUHR, P. (2010) *Hearing in young men- The influence of military noise and epidemiological aspects*. Karolinska Institute, Sweden. Ph.D thesis.

NOBLE, W., Byrne, D. & Lepage, B. (1994) Effects on sound localization of configuration and type of hearing impairment. *Journal of the Acoustical Society of America*. 95 (2). 992–1005.

NORDLUND, B. (1964) Directional Audiometry. *Acta Oto-Laryngologica*. (57). 1–18.

NVIVO (2012) QSR International Pty Ltd (Version 10) [Computer program].

OCKLENBURG, S., Hirnstein, M., Hausmann, M. & Lewald, J. (2010) Auditory space perception in left- and right-handers. *Brain and Cognition*. 72 (2). 210–217.

OKPALA, N. C. (2007) Knowledge and attitude of infantry soldiers to hearing conservation. *Military Medicine*. 172 (5). 520–522.

OSEI-LAH, V. & Yeoh, L. (2010) High frequency audiometric notch: an outpatient clinic survey. *International Journal of Audiology*. 49 (2). 95–98.

PALMER, K., Coggon, D., Syddall, H., Pannett, B. & Griffin, M. (2001) *Occupational exposure to noise and hearing difficulties in Great Britain.* Contract Research Report 361. Norwich, UK. Health and Safety Executive Books.

PARLIAMENT (1987) *Crown Proceedings (Armed Forces) Act 1987*. Chapter 25. [Online] Available from: http://www.legislation.gov.uk/ukpga/1987/25/section/1/enacted. [Accessed 15th January 2014]

PASHLER, H. (1994) Dual-task interference in simple tasks: data and theory. *Psychological Bulletin*. 116 (2). 220–244.

PASSCHIER-VERMEER, W. & Passchier, W. (2000) Noise exposure and public health. *Environmental Health Perspectives*. 108 (1). 123–131.

PATIL, M. L. & Breeze, J. (2011) Use of hearing protection on military operations. *Journal of the Royal Army Medical Corps*. 157 (4). 381–384.

PATUZZI, R. (1998) A four-state kinetic model of the temporary threshold shift after loud sound based on inactivation of hair cell transduction channels. *Hearing Research*. 125 (1-2). 39–70.

PAYNE, W. & Harvey, J. (2010) A framework for the design and development of physical employment tests and standards. *Ergonomic*s. 53 (7). 858–871.

PEARN, M. & Kandola, R. (1988) *Job Analysis: A Practical Guide for Managers*. First edition. New York, USA. Hyperion Books.

PETERS, L. & Garinther, G. (1990) *The effects of speech intelligibility on crew performance in an M1A1 tank simulator.* [Online] Available from: http://www.researchgate.net/publication/235211677. [Accessed: 4th June 2013]

PICHORA-FULLER, M. K., Schneider, B. A., MacDonald, E., Pass, H. E. & Brown, S. (2007) Temporal jitter disrupts speech intelligibility: A simulation of auditory aging. *Hearing Research*. 223 (1-2). 114–121.

PIRILA, T. (1991) Left-right Asymmetry in the Human Response to Experimental Noise Exposure. *Acta Otolaryngology*. (111). 677–683.

PLOMP, R. (1978) Auditory handicap of hearing impairment and the limited benefit of hearing aids. *Journal of the Acoustical Society of America*. (63). 533–549.

PLOURDE, G. (2006) Auditory evoked potentials: Best practice & research. *Clinical Anaesthesiology*. 20 (1). 129–139.

POWELL, R. & Forrest, M. (1988) *Noise in the Military Environment (Land Warfare).* Pennsylvania, Brassey's Defence Publisher. 10-24.

PROSCHEL, U. L. & Doring, W. H. (1990) Richtungshoren in der Horizontalebene bei Storungen der auditiven Selecktionsfahigkeit und bei seitengleicher

Innenohrschwerhhorihkeit. Unable to access paper in english, information discussed was presented in Noble et al. 1994.

RABINOWITZ, P., Galusha, D., Slade, M., Dixon-Ernst, C., Sircar, K. et al. (2006) Audiogram notches in noise-exposed workers. *Ear and Hearing*. 27 (6). 742–750.
RACKHAM, N. & Morgan, T. (1977) *Behaviour analysis in training*. London, UK. McGraw-Hill.

RAMAZZANI, B. (2001) Translation of the 1713 'De Morbis Artificum Diatriba [Diseases of Workers'. *American Journal of Public Health*. 91 (9). 1380-1382. [Online] Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1446785. [Accessed: 15th September 2012].

RASMUSSEN, P., Flamme, G., Stewart, M., Meinke, D. & Lankford, J. (2009) Measuring Recreational Firearm Noise. *Sound and Vibration*. (August). 14-18.

RAYLEIGH, Lord (1907) On our perception of sound direction. *Philosophical Magazine*. (13). 214–232.

RAYSON, M. P. (2000) Fitness for work: the need for conducting a job analysis. *Occupational medicine.* 50 (6). 434-436.

RECANZONE, G. H., Makhamra, S. & Guard, D. C. (1998) Comparison of absolute and relative sound localization ability in humans. *Journal of the Acoustical Society of America*. (103). 1085-1097.

ROBERTO, M. & Zito, F. (1988) Scar formation following impulse noise-induced mechanical damage to the organ of Corti. *Journal of Laryngology and Otology*. 102 (1). 2–9.

ROGINSKA, A., Wakefield, G. H. & Santaro, T. S. (2011) User Selected HRTFs: reduced complexity and improved Perception. *Proceedings of the Undersea Human System Integration Symposium*. 1–14. [Online] Available from: https://admin.navalengineers.org/SiteCollectionDocuments. [Accessed: 22nd February 2015]

ROSENHALL, U. (1985) The influence of Hearing loss on Directional Hearing. *Scandinavian Audiology*. 14 (4). 187–189.

ROSER, D. (1966) Directional hearing in persons with hearing disorders. *Journal of Laryngology and Otology*. (45). 423–440.

ROSOWSKI, J. (1991) The effects of external- and middle-ear filtering on auditory threshold and noise-induced hearing loss revised. *Journal of Acoustical Society of America*. 90 (1). 124–135.

ROTH, G. L., Kochhar, R. K. & Hind, J. E. (1980) Interaural time differences: Implications regarding neurophysiology of sound localization. *Journal of the Acoustical Society of America*. 68 (6). 1643–1651.

ROURKE, L., Anderson, T., Garrison, D. & Archer, W. (2000) Methodological Issues in the Content Analysis of Computer Conference Transcripts. *International Journal of Artificial Intelligence in Education*. (12). 8–22.

ROWAN, D. & Lutman, M. E. (2006) Learning to discriminate interaural time differences: an exploratory study with amplitude-modulated stimuli. *International Journal of Audiology*. 45 (9). 513–520.

ROWAN, D. & Lutman, M. E. (2007) Learning to discriminate interaural time differences at low and high frequencies. *International Journal of Audiology*. 46 (10). 585–594.

ROYAL BRITISH LEGION (2014) *Lost Voices: A Royal British Legion report on hearing problems among Service personnel and veterans.* 1-40. [Online] Available from: http://www.britishlegion.org.uk/media/2282/lostvoiceshearinglossreport. [Accessed: 1st December 2014].

RUTHERFORD, T. (2014) *Defence personnel statistics*. House of Commons report: SN/SG/02183. 1-14.

SABIN, A., Macpherson, E. & Middlebrooks, J. C. (2005) Human sound localization at near-threshold levels. *Hearing Research*. (199). 124–134.

SAUNDERS, G. H. & Griest, S. (2009) Hearing loss in veterans and the need for hearing loss prevention programs. *Noise and Health*. 11 (42). 14–21.

SAUNDERS, J. C. & Flock, A. (1986) Recovery of threshold shift in hair-cell stereocilia following exposure to intense stimulation. *Hearing Research*. 23 (3). 233–243.

SAUNDERS, J. C., Cohen, Y. & Szymko, Y. (1991) The structural and functional consequences of acoustic injury in the cochlea and peripheral auditory system: a five year update. *Journal of the Acoustical Society of America*. 90 (1). 136–146.

SCHARINE, A. & Letowski, T. (2005) Factors Affecting Auditory Localization and Situational Awareness in the Urban Battlefield. *Army Research Laboratory*. [Online] Available from: http://permanent.access.gpo.gov/gpo5602/ARL-TR-3474. [Accessed: 9th November 2012]. 1–61.

SCHARINE, A., Binseel, M. S., Mermagen, T. & Letowski, T. R. (2014) Sound localisation ability of soldiers wearing infantry ACH and PASGT helmets. *Ergonomics*. 57 (8). 1222–1243.

SCHARINE, A., Letowski, T. & Sampson, J. (2009) Auditory Situation Awareness in Urban Operations. *Journal of Military and Strategic Studies*. 11 (4). 1–24.

SEMERARO, H. D. (2016) *Developing a measure of auditory fitness for duty for military personnel*. University of Southampton, Southampton. Ph.D. Thesis.

SEMERARO, H. D., Bevis, Z. L., Rowan, D., van Besouw, R. M. & Allsopp, A. J. (2015) Fit for the frontline? Identification of mission-critical auditory tasks (MCATs) carried out by infantry and combat-support personnel. *Noise and Health*. 17 (75). 98-107

SHERWIN, J. & Gaston, J. (2013) Soldiers and marksmen under fire: monitoring performance with neural correlates of small arms fire localization. *Frontiers in Human Neuroscience*. 7 (March). 67.

SHI, X. & Nuttall, A. (2003) Upregulated iNOS and oxidative damage to the cochlear stria vascularis due to noise stress. *Brain Research*. 967 (1-2). 1–10.

SIMPSON, B., Bolia, R., McKinley, R. & Brungart, D. (2005) The Impact of Hearing Protection on Sound Localization and Orienting Behavior. *Human Factors*. 47 (1). 188–198.

SNOW, W. (1967) Survey of Acoustic Characteristics of Bullet Shock Waves. *IEEE proceedings on Transactions on Audio and Electroacoustics*. (3). 161–176.

SPOENDLIN, H. (1971) Primary structures changes in the Organ of Corti after acoustic overstimulation. *Acta Otolaryngology*. (71). 166–176.

STEVENS, S. & Newman, E. (1936) The localization of actual sources of sound. *American Journal of Psychology*. 48 (2). 297–306.

STROUSE, A. L. (1998) Temporal Processing in the Aging Auditory System. *Journal of the Acoustical Society of America*. 57 (8). 2385–2399.

TAKEUCHI, T. (2001) *Systems for virtual acoustic imaging using the binaural principle*. University of Southampton, UK. Ph.D. thesis.

TAKIMOTO, M., Nishino, T., Itou, K. & Takeda, K. (2007) Sound localization under conditions of covered ears on the horizontal plane. *Acoustical Science and Technology*. 28 (5). 335–342.

TALCOTT, K. A., Casali, J. G., Keady, J. P. & Killion, M. C. (2012) Azimuthal auditory localization of gunshots in a realistic field environment: Effects of open-ear versus hearing protection-enhancement devices (HPEDs), military vehicle noise and hearing impairment. *International Journal of Audiology*. (51). 20–30.

THORNE, P. (2007) Best practice in noise-induced hearing loss management and prevention: A review of literature, practices and policies for the New Zealand context. *New Zealand Medical Journal*. 121 (1280). 33-44.

TOLLIN, D. J. (2003) The lateral superior olive: a functional role in sound source localization. *The Neuroscientist*. 9 (2). 127–143.

TONNING, F. (1975) Auditory Localization and its Clinical Applications. *International Journal of Audiology*. (14). 368–380.

TUFTS, J. B., Vasil, K.A. & Briggs, S. (2009) Auditory Fitness for Duty: A Review. *Journal of the American Academy of Audiology*. 20 (9). 539–557.

VAILLANCOURT, V., Laroche, C., Giguère, C., Beaulieu, M. A. & Legault, J. P. (2011) Evaluation of Auditory Functions for Royal Canadian Mounted Police officers. *Journal of the American Academy of Audiology*. 22 (6). 313–331.

VAN DEN BOGAERT, T., Klasen, T. J., Moonen, M., Van Deun, L. & Wouters, J. (2006) Horizontal localization with bilateral hearing aids: Without is better than with. *Journal of the Acoustical Society of America*. 119 (1). 515.

VERSCHUUR, C. A., Lutman, M. E., Ramsden, R., Greenham, P. & O'Driscoll, M. (2005) Auditory localization abilities in bilateral cochlear implant recipients. *Otology and Neurotology*. 26 (5). 965–971.

VIEHWEG, R. & Campbell, R. (1960) Localization difficulty in monaurally impaired listeners. *Annals of Otology, Rhinology and Laryngology*. (69). 622–634.

WANG, Y., Hirose, K. & Liberman, M. C. (2002) Dynamics of noise-induced cellular injury and repair in the mouse cochlea. *Journal of the Association for Research in Otolaryngology*. 3 (3). 248–268.

WENZEL, E. M., Arruda, M., Kistler, D. J. & Wightman, F. (1993) Localisation using non-individualized head-related transfer functions. *Journal of Acoustical Society of America*. 94 (1). 111–123.

WIGHTMAN, F. & Kistler, D. J. (1989) Headphone simulation of free-field listening. II: Psychophysical validation. *Journal of the Acoustical Society of America*. 85 (2). 868–878.

WIGHTMAN, F. & Kistler, D. J. (1992) The dominant role of low-frequency interaural time differences in sound localization. *Journal of the Acoustical Society of America*. 91 (3). 1648–1661.

WIGHTMAN, F. & Kistler, D. J. (2005) Measurement and Validation of Human HRTFs for Use in Hearing Research. *Acta Acustica*. 91 (3). 2–5.

YANKASKAS, K. (2013) Prelude: Noise-induced tinnitus and hearing loss in the military. *Hearing Research*. 295 (1-2). 3–8.

YLIKOSKI, M. & Ylikoski, J. (1994) Hearing loss and handicap of professional soldiers exposed to gunfire noise. *Scandinavian Journal of Work, Environment and Health*. 20 (2). 93–100.

ZAHORIK, P., Brungart, D. & Bronkhorst, A. (2005) Auditory Distance Perception in Humans : A Summary of Past and Present Research. *Acta Acustica*. (91). 409–420.

ZAKRISSON, J., Borg, E., Liden, G. & Nilsson, R. (1980) Stapedius reflex in industrial impact noise: fatigability and role for temporary threshold shift (TTS). *Scandinavian Audiology Supplement*. 12 (August). 326–334.

ZOTKIN, D. N., Hwaiig, J., Duraiswami, R. & Davis, L. S. (2003) HRTF personalization using anthropometric measurements. *IEEE Workshop on application of signal processing to audio and acoustics*. (October). 17–20.

ZWISLOCKI, J. & Feldman, R. S. (1956) Just noticeable differences in dichotic phase. *Journal of the Acoustical Society of America*. 28 (5). 860–864.