TOWSON UNIVERSITY
OFFICE OF GRADUATE STUDIES

# THE EFFECT OF AMPLITUDE AND TIMING DIFFERENCES ON THE LISTENER ACCURACY OF LOCALIZATION FOR SMALL ARMS FIRE

by

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A thesis

presented to the faculty of

Towson University

in partial fulfillment

of the requirements for the degree

Doctor of Audiology

Department of Audiology, Speech Language Pathology, and Deaf Studies

Towson University

Towson, Maryland 21252

May 2015

**TOWSON UNIVERSITY**

**COLLEGE OF GRADUATE STUDIES AND RESEARCH**

**AUDIOLOGY DOCTORAL THESIS APPROVAL PAGE**

This is to certify that the Audiology Doctoral Thesis prepared by Tyler Raup entitled: The Effect of Amplitude and Timing on Listener Accuracy of Localization of Small Arms Fire has been approved by his or her committee as satisfactory completion of the Audiology Doctoral Thesis requirement for the degree of Doctor of Audiology (Au.D.).

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## Acknowledgements

I would like to thank the individuals who have assisted with this thesis project. I would like to thank my thesis chair, Stephanie Nagle, Ph.D., for her support and encouragement throughout this process. I would also like to thank my thesis committee, Jeremy Gaston, Ph.D. and Peggy Korzcak, Ph.D., both of whom contributed invaluable information and help throughout this process. Dr. Gaston and Tim Mermagen also provided additional materials that allowed this study to be possible.

**Abstract**

The Effect of Amplitude and Timing Differences on Listener Accuracy of Localization for Small Arms Fire

Tyler Raup

Sound localization allows listeners to create a spatial map of their surrounding environment, clueing them in on what obstacles there are in front and around them. Localization is dependent on several acoustical factors, including azimuth, phase differences, and amplitude differences between the sound source and listener. Soldiers, specifically, rely on these localization abilities and acoustic cues to enhance situational awareness and security. The purpose of this study was to observe whether acoustic manipulations to any of these factors either contributed to or hindered the localization abilities of those listening to the sounds of gunfire from an M4 carbine rifle. Results of this study showed significant differences between different azimuths located from +/- 60 degrees to the listener's immediate right and left. Specifically, the outermost azimuth (-/+60 degrees) was significantly different from the centermost position (0 degrees). Significant differences between the accuracy of muzzle blast and ballistic crack localization in isolation were also found. No significant effect of amplitude and timing differences between the ballistic crack and muzzle blast were found. The final experiment included real-world relationships of varying shooter positions (distance and azimuth). Results were significant for effects of azimuth, however no significant effects were found with relative distance (and therefore timing and amplitude) variation.

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# Chapter 1

## Introduction

As noted by Scharine, Letowski, and Sampson (2009), sound has the unique ability to give the listener access to a complete 360 degrees of acoustical information that can be used to build spatial awareness and acuity, even in the absence of light or other inhibitory environmental factors. Real world situations inundate listeners with a plethora of sound which can be broken down into smaller acoustical fragments and cues. Pieces of acoustic information are analyzed by the auditory system, allowing the listener to form a conceptual map of their surrounding environment, and localize the source of the sound.

The ability to localize sounds, specifically small arms fire, is advantageous for soldiers on the ground to increase their situational awareness, locate enemy fire, and become aware of surrounding geography (Fluitt, Gaston, Karna, & Letowski, 2010; Scharine et al., 2009). Localization is critical in determining the physical characteristics of the environment as well, for example, determining if the gunshot was shot in an open field or an enclosed alley. Soldiers can utilize the available acoustic information to locate not only the source of weapons fire, but enemy locales as well. The ability to accurately judge the location of a gunshot gives a soldier greater situational awareness that could directly benefit their safety and security (Scharine et al., 2009).

Today's military operations are more focused in urban settings as opposed to the open fields of previous conflicts, for example, in Korea. These situations can create problems for soldiers who are unable to see their enemies behind standing structures (Gaston & Letowski, 2012). It is with that in mind that the present study seeks to manipulate the acoustic properties and parameters of small arms fire to gauge any effects on localization abilities. Research in this area may be helpful on the battlefield by giving soldiers the tools to increase their own situational awareness as well as give them the capability to distract or confuse the enemy with manipulated acoustical properties of gunfire.

The focus of small arms fire related research has focused on detection, perception, and discrimination of small arms fire (Gaston & Letowski, 2010; Scharine et al., 2010). This specific study will focus on the manipulation of the acoustic properties, specifically the amplitude and timing phases between the muzzle blast and shockwave of a gunshot, and their effects, if any, on localization tasks.

# Chapter 2

# Review of Literature

Human sound localization allows listeners to create a spatial map of the environment which can be used to estimate the location of a sound source. The auditory system utilizes specific acoustic information in the time and spectral domains to create the acoustic map of the surrounding area. In the animal kingdom, sound localization has been shown to be a tool that allows mammals to respond to dangerous situations and give predators a chance to locate their prey (Oertel, 1999). Similarly, the ability to accurately localize sound is important for soldiers on the battlefield. In the event gunfire occurred at any point around the soldier, the listener could use intensity, timing, and spectral cue information to identify the sound source and its location. In addition, accurate sound localization can lead to increased situational awareness. Information from environmental reverberations and interactions could be used to determine if the gunshot occurred in an enclosed street versus an open field. The increased awareness can help create a mental map of the surrounding area which could protect the soldier from enemy fire or help to locate an escape route (Fluitt et al., 2010; Scharine, Letowski, & Sampson, 2009).

## Acoustic Properties of Localization

The ability to specifically locate a sound source relies on the ability to process information from varying degrees of azimuth, elevation, and distance (Smith, Lombard & Shaba, 2012). The listener is supplied with information from the horizontal and vertical planes, as well as information from competing signals and the surrounding environment. The sound signal can be transformed by environmental factors, effects from competing signals, and the effects of the human body. As changes occur to any of these three main attributes, differences in timing, intensity, and other acoustical information are processed to localize the sound. These transformed cues allow the listener to construct a virtual map of the surrounding environment that can allow for the localization of a specific sound source (Makous & Middlebrooks, 1989; Middlebrooks & Green, 1991).

**Azimuth.** The azimuth, or angle of the listener's head in relation to both the source of the sound and the median plane, gives the listener important information about the sound source and its location (Middlebrooks & Green, 1991). Research has shown that listeners are better able to localize sound when it is sourced in the frontal plane compared to the signal being within 90 degrees in either direction of the listener's midline (Good & Gilkey, 1996; Smith et al., 2012; Wightman & Kisler, 1992). The accuracy is attributed to intensity and phase (or timing) information related to the azimuth of the sound source.

***Interaural phase differences.*** Sound traveling from the source to the listener reaches the right and left ear at different times, depending on spatial orientation. Interaural phase differences (IPDs), also referred to as timing differences, are important localization cues. IPDs are measured when a sound source is located away from the midline (an imaginary line crossing from directly in front of to directly behind the subject of interest). For most orientations around a listener, the sound must travel different distances to each ear, so the sound reaches each individual ear at a slightly different time. This is related to the head shadow effect, where the head acts as a barrier for the sound, which then must take separate paths to each ear. IPDs allow the listener to estimate the azimuth of the sound location.

Timing differences are particularly useful for sounds with a wavelength less than 1500Hz. Wightman and Kisler (1992) showed that removal of low frequency sound from the signal of interest can create ambiguity and makes the listener rely more heavily on intensity differences. Similarly, Yost (1974) found that when the sound reaching one ear was out of phase with the other, the timing differences were no longer helpful to the listener. Research has suggested that the maximum timing difference of 660µs occurred when the azimuth was 90° from one ear. The same research also found that timing differences are negligible when the signal is equidistant (0° and 180°) from both ears (Feddersen, Sandel, Teas, & Jeffress, 1957).

***Interaural level differences.*** Interaural level differences (ILDs), or intensity differences, functions under the same principle as IPDs, except the intensity reaching the ear closest to the sound source will be greater than that of the opposing ear because of distance and interactions with the pinna and head shadow (Fisher & Freedman, 1968). As the sound reaches the listener, wavelengths larger than the size of the head (about 57cm for males) are able to travel around to the opposite ear (Kuhn, 1977). Level differences are roughly negligible below 1400Hz because the wavelength is typically larger than the listener's head, allowing the sound to travel around the head nearly uninterrupted (Kuhn, 1977; Middlebrooks & Green, 1991). Studies have shown that humans have high sensitivities for timing and intensity differences between ears, where just noticeable differences (JND) are as small as 1 to 2dB for intensity and 10-20µs for timing (Domnitz & Colburn, 1977; Hafter, Dye, & Gilkey, 1979; Hershkowitz & Durlach, 1969).

***Duplex Theory.*** The IPDs and ILDs are the basis for what Lord Rayleigh first called the Duplex Theory, in which both the intensity and timing differences function simultaneously as a localization cue (Wang & Brown, 2005). The theory argues that IPDs are important to localizing the low frequency signals (those below 1400Hz) whereas intensity differences are vital for high frequency localization (frequencies above 1400Hz) (Macphereson & Middlebrooks, 2002). The exact cutoff where intensity and phase are most accurate is dependent upon the size of the listener's head (Kuhn, 1977). The area between 1500 and 3000Hz is an overlapping frequency region where differences in IPD and ILD may vary or become negligible (Middlebrooks & Green, 1991).

***Minimal audible angle.*** Research by Mills (1972) described the Minimal Audibility Angle (MAA), the smallest angle at which listeners can perceive a difference in location from separate sources. Results of these studies showed that listeners were better at perceiving changes in location with sounds below 1500Hz and above 3000Hz. Minimal audibility angles down to 2° are typical at the frontal midline, and became poorer at more lateral positions (Gelfand, 2010; Mills, 1972).

Perrott (1984) introduced the concept of Concurrent Minimum Audible Angle (CMAA), which focused on audibility angles in the presence of multiple or competing stimuli. Like the MAA, the best CMAA results occurred when the stimulus was located directly in front of the listener (0°). The presence of competing stimuli widened the audibility angles by 5-10° (Mills, 1972; Perrott, 1984). Makous and Middlebrooks (1989) also found that localization was most accurate when sounds are located directly in front of the listener on the frontal-horizontal plane. Accuracy errors as low as 2° were found at a 0° azimuth. Error rates increased, to a maximum of 20° at a 90° azimuth as the location became more peripheral to the listener (Makous & Middlebrooks, 1989).

**Elevation.** Localization on the vertical plane has been shown to be less accurate than the horizontal plane. Roffler and Butler (1967) found that binaural cueing played only a minimal role in vertical plane localization, indicating that only monaural cues may be necessary for vertical plane localization. For stimuli to be localized on the vertical plane, the signal had to be a complex sound with the majority of components greater than 7000 Hz. Also, when listeners covered or flattened their pinnae, they were unable to accurately localize, indicating the importance of the pinna and the effect it has on the sound wave as it enters the ear (Roffler & Butler, 1967).

Makous and Middlebrooks (1989) found that as the angle increased on the vertical axis, the errors increased (though never fell above 10%), agreeing with Wightman & Kistler (1997) that localization is better in the listener's frontal plane. Front to back errors were also found to be symmetrical. This may be explained by the effect of the shape of the pinna, effectively shadowing the sound from behind the listener. This difference may be based upon the anatomical layout of the ear, as the pinna is designed to maximize the sound energy reaching the concha, whereas the back of the pinna may actually deflect the sounds and therefore reduce the energy arriving to the ear (Middlebrooks, Makous & Green, 1989). Wightman and Kisler (1992) also surmised that localizing a sound source on the horizontal plane (left vs. right) was based upon the IPD and ILD whereas front to back localizations depended more on spectral cues.

Sounds that originate on the median plane and are equidistant to the ears may have identical phase and intensity. This area of ambiguity is often called the cone of confusion, and may be the cause of many front-to-back localization reversals (Middlebrooks & Green, 1991). Vertical localization is able to occur because the sound is transferred both directly and indirectly, and only needs to occur monaurally. The ambiguities can be overcome if the head is tilted in on direction or the other, aligning one ear at a slightly different angle. The spectral cues arrive at each ear with different timing and intensity cues, allowing the listener to overcome the cone of confusion and localize on the vertical plane while reducing front to back errors (Wightman & Kisler, 1999).

**Distance.** Distance between the listener and the signal source can impact the clarity and fidelity of the original signal as it travels through space. Changes in overall loudness and intensity allow the listener to make judgments on the distance of the sound. Strybel and Perrott (1984) found that as distance increased past 3 meters, even small changes in loudness perception were important to perceiving the distance change. At distances less than 3 meters, the just noticeable differences needed to be much higher to judge the actual distance (Middlebrooks & Green, 1991). As sound travels greater distances, higher frequencies are attenuated at greater rates than lower frequencies, muffling and distorting the sound as a result of atmospheric absorption and environmental interaction (Brungardt & Rabninowitz, 1999; Wiley & Richards, 1977).

As the distance increases, the sound must travel further to reach the listener, allowing for reverberations and an echo effect to possibly interfere with the initial signal of interest (Smith et al., 2012). The presence of reverberations and echoes are not completely inhibitory to the sound location mechanism, however. The listener utilizes acoustic cues from both direct and indirect sound sources. The interaction between the ratio of direct and indirect sounds, especially in a reverberant environment, has been shown to increase the listener's ability to accurately perceive the distance of a sound (Mershon & Bowers, 1979). Wallach, Newman, and Rosenzweig (1949) also described the law of the precedence effect, where the listener perceives the initial sound as the most important, as long as there is a time delay between the two competing sounds. When the difference between the original sound and the reverberation was greater than 40ms, they found that listeners perceived the competing sound as an echo. In contrast when the differences between the original sound and the reverberation were less than 40ms, they were perceived as the same sound (Wallach et al., 1949).

## Anatomy and Physiology of Localization

The brain is able to decipher specific acoustic cues within the sound wave, even in the presence of competing noise, to localize the signal of interest (Cherry, 1953). Sound energy traveling toward the listener is affected by the physical anatomy of the listener as well. Spectral cues are altered by the torso, head, neck, and other anatomy. The resulting alterations are used by the listener to better locate the signal of interest even when they are inundated with competing signals (Good & Gilkey, 1995). The signal is also analyzed within the central auditory system (Maeder et al., 2000).

**Head Related Transfer Function.** The size and shape of the human head, its smaller components like the pinna, and aspects of the torso, affect the sound waves as they diffract and reflect off of the body. These reflections and diffractions change the acoustic cues striking both of the ears. The phase and intensity changes to the stimulus from the Head Related Transfer Function (HRTF) “provide clues about the locus of a sound relative to the head” (Middlebrooks & Green, 1991, p. 136), thus allowing the listener to create a spatial map of the surrounding environment and generalize the location of the sound.

The HRTF varies between individuals, and depends on the diameter and shape of the head and proximal anatomy. When a signal reaches the head, the sound waves may enter the ear directly, or they may enter indirectly through a series of reflections and diffractions off of the head and pinna. These altered cues reach the ear at different times, and contain different acoustical energy compared to the original sound. HRTFs make it possible, as displayed by Wightman and Kisler (1989), to create a spatial map from the manipulation of acoustical aspects of sounds.

**Peripheral anatomy.** As that signal travels toward the listener, it contacts the physical anatomy of the listener. The head, neck, torso, and pinna all affect the acoustics of the sound before it enters the auditory system. Alterations of the outer ear anatomy may force some of the sound energy away from the ear canal, or delay portions of the signal (Brungardt & Rabinowitz, 1999; Merghardt & Mellert, 1977; Wightman & Kisler, 1989). Once the sound enters the outer ear, the energy strikes the tympanic membrane, activating the ossicles of the middle ear sending the sound energy through the oval window of the cochlea, and thus activating the basilar membrane. Once the inner ear is reached, the hair cells within the Organ of Corti are activated, sending a signal to the vestibulocochlear (VIII) nerve (Gelfand, 2010).

**Central anatomy.** Once sound energy has reached the VIII nerve, the auditory nerve sends the signal to the cochlear nucleus, and the first point of binaural interaction in the central auditory nervous system occurs at the superior olivary complex. The sound energy then travels through the auditory brainstem to the trapezoid body and lateral lemniscus. Further interaction within the inferior colliculus and medical geniculate body integrate phase and intensity information to eventually forward the transmission path toward the primary auditory cortex within the temporal lobe (Knudsen& Konishi, 1979; Maeder et al., 2000). Knudsen and Konishi (1979) have speculated that the lateral superior olive (LSO) is specifically sensitive to interaural intensity differences, while neurons within the medial superior olive are especially sensitive to interaural phase differences.

Research has been inconclusive as to which hemisphere dominates sound localization in the human brain (Maeder et al., 2000). Both right hemisphere dominance and bihemisphere co-dominance have been shown (Buchtel & Stewart, 1989; Clarke, Bellmann, deRibpierre, & Assal, 1996). A functional magnetic resonance imaging (fMRI) study by Maeder and colleagues (2000) showed the inclusion of the temporal lobe as a mechanism for localization. It is also important to note that the neural networks for recognition and localization are separate, yet interconnected matrices (Maeder et al., 2000). Functional imaging studies have shown activation in the following areas during localization tasks: inferior parietal lobe (primarily right), areas of the premotor cortex (bilateral), ventral portion of the prefrontal cortex, and the anterior cingulate of the right hemisphere (Maeder et al., 2000). Results of imaging studies have revealed a complex network within the brain that works jointly to discriminate background sounds from those of interest, and to locate sounds within the environment.

**Environmental Effects on Localization**

Sound energy that reaches the ear of the listener is affected by the pathway the signal took from the source to the listener; it may bounce off walls, trees, people, or anything between the two points of interest. Interactions of the sound energy with the surrounding environment acoustically change the signal by adding reverberations and time delays to the sound reaching the ear (Scharine et al., 2010). These acoustic changes can lead the listener to make false localization judgments. The changes are not always a hindrance to the listener, however. Scharine et al. (2010) found that reflected sounds can give the listener additional clues about the surrounding environment, specifically helping listeners to spatially learn their environment.

The ability to utilize echoes and reverberations is related to the previously discussed precedence effect. When the echo or reverberation occurs rapidly, the auditory system gives precedence to the main signal, and suppresses the effect of the following echoes. With later reflections and reverberation, as the reflection and reverberations create echoes, they can actually draw the listener’s attention toward the site of reflection. Mislocalization of the sound source may be a result of the presence of these late echoes and reverberations (Letowski, Mermagen & Henry, 2010; Wallach, Newman & Rosenzweig, 1949)

Most localization research studies are conducted in quiet. These research situations allow researchers to observe listener responses in ideal listening environments, which rarely occur in everyday life. Good and Gilkey (1995) tested subjects using variable signal-to-noise ratios (SNR) that may mimic real life, where signals of interest are not always the strongest or most intense signal reaching the listeners ear. This research found that as the signal-to-noise ratio (SNR) decreased (became poorer), the ability to localize sound decreased as well (Good & Gilkey, 1996).

## Localization of Small Arms Fire

The definition of small arms is fairly imprecise. The United Nations (UN) attempted to classify this group of weapons based on the overall portability of the gun. Specifically, the UN classified the following as small arms: revolvers and self-loading pistols, rifles and carbines, assault rifles, sub-machine guns and light machine guns (United Nations, 1997). The explosive release of gasses from these guns emits sound in all directions, but the majority of the energy is propelled forward in the direction of the pointed muzzle (Koenig, Hoffman, & Nakasone, 1998). The gunshot has two distinct acoustic properties that allow listeners to detect and locate the weapon: the muzzle blast and the ballistic shockwave (Maher, 2006).

**Acoustics of small arms fire.** The muzzle blast is generally associated with the "bang" that can be heard after a gun is fired. It consists of a high intensity sound wave that moves at the speed of sound (343m/s at 20 degrees Celsius). The blast is caused by an explosive charge that propels the bullet, and lasts only a few milliseconds (3-5ms), but carries more energy than that of a jet engine (Koenig et al., 1998). In isolation, the blast would be a short "pop," however the reality is that environmental and acoustical factors add reflections that can extend the signal perceived by humans over one second.

The explosion produced by the traveling bullet emits sounds in all directions, but the muzzle blast primarily propagates forward. The blast is also isotropic, as the bursts of gas expelled after the blast is sent in multiple directions. The area of greatest intensity and energy is related to the direction of the barrel and forward moving motion of the gas propulsion (Maher, 2006; Maher, 2007)

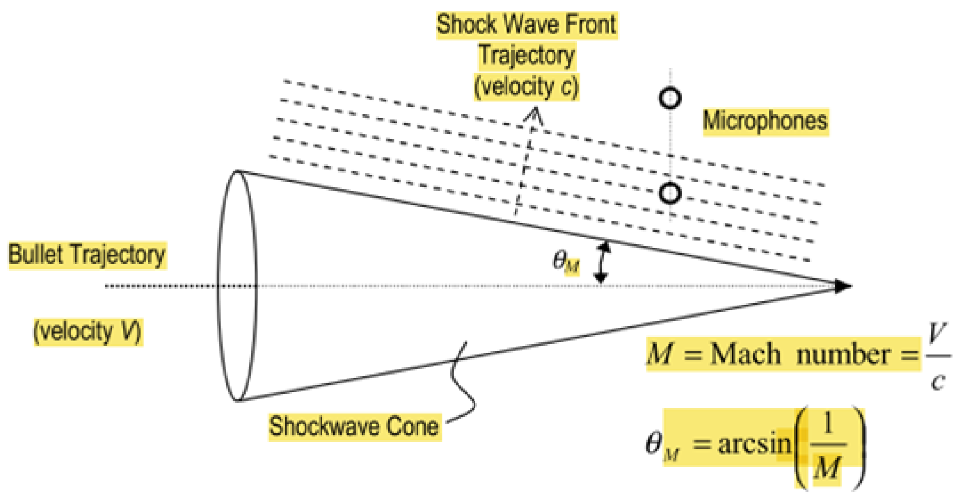


Figure 1. Supersonic shockwave description. Used with permission from "Summary of Gun Shot Acoustics" by R.C. Maher (2006). Montana State University.

The second aspect is the ballistic shockwave, also associated with the audible "crack." The shockwave typically lasts 200-300 microseconds and creates an acoustic N-shaped pattern (Naz Mary, Hengy, & Hamery, 2008). While the muzzle blast progresses at the speed of sound (>343m/s at 20 degrees Celsius), the shockwave moves at a slower speed, dissipating over time. If the bullet is moving at a subsonic speed, the shockwave will be nonexistent. This may also depend on temperature, as the speed of sound increases with temperature of the surrounding environment (Bilaniuk & Wong, 1993).

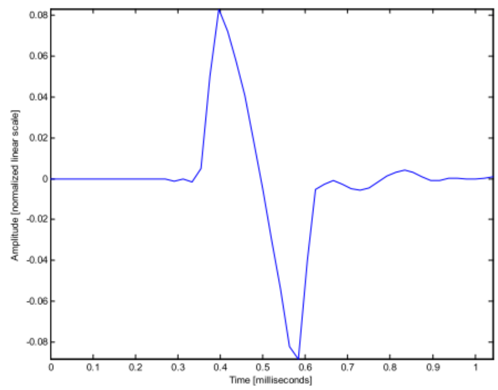


Figure 2. N-wave resulting from a shockwave recording. Used with permission from “Summary of Gun Shot Acoustics” by R.C. Maher (2006). Montana State University.

The “crack” is only heard at angles less than 90 degrees, with the magnitude of the shockwave depending on speed, size, mass, and weather factors (Harris, 1966; Maher, 2006). The wave propagates outward in a conical shape with the inner angle equal to the arcsin multiplied by (1/Mach), with the Mach equaling the velocity divided by the speed of sound. As the bullet speed changes, so does the angle and movement of the shockwave. A fast bullet would create a smaller inner angle with a perpendicular moving waveform. Conversely, the slow moving bullet elicits a large inner angle and a shockwave moving parallel (Maher, 2006; Maher, 2007).

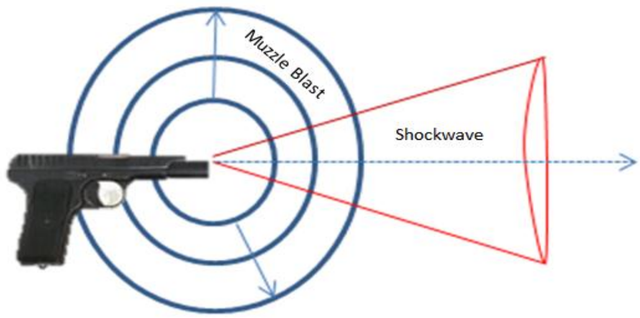


Figure 3. Shockwave and muzzle blast propagation in relation to the shooter. Adapted from "Summary of Gun Shot Acoustics" by R.C. Maher (2006). Montana State University.

**Recording weapons fire.** When recording the acoustic components of a gunshot, microphone placement is an important factor for capturing the complexity of the recording. If the gun is fired in the opposite direction of the microphone, the shockwave will not be recorded and the muzzle blast will be perceived with decreased intensity. Likewise, as the distance traveled by the bullet increases, the shockwave will be so diffuse the microphone may not be able to differentiate it from environmental sounds (Maher, 2006). As the distance increases, the kinetic energy dissipates due to friction, decreasing the Mach value. As the Mach value decreases, the angle increases until the bullet is moving at a close to sub sonic speed, where the shockwave nearly disappears. In this case, the characteristic N-shaped wave becomes a less robust S-shape (Stoughton, 1997).

**Problems in Localization Research**

Sound localization has been shown to be dependent on several factors including azimuth, elevation, and distance. Environmental factors, and the concept that every listener has a 360 degree auditory image of their surroundings, also influence a listener's localization abilities. Spatial limitations make replications of natural environments almost impossible (e.g. presenting a stimulus at every possible azimuth). The natural auditory environment also includes several competing sounds. It is important to see how those specific cues initiate localization cues when found in a natural environment where multiple cues are occurring simultaneously. Recreating stimuli that will be heard through speakers or headphones in a study need to be as realistic as possible to get the most accurate localization information (Middlebrooks & Green, 1991).

Localization research has tended to focus on the detection and perception of either complex or non-complex sounds including tonal stimuli, music and speech. Perception of impulse sounds, a category that includes gunfire, has also been researched using balls of varying size and mass falling on ceramic tiles (Grassi, 2005). Localization research specifically addressing the perception of small arms fire has focused on the recognition of weapon type (Fluitt et. al, 2011; Gaston & Letowski, 2012), discrimination of forward-fire and off axis firing events (Sherwin & Gaston, 2013) and the localization of fired blanks (Casali et. al. 2012; Scharine et al., 2010). Localization research, however, has tended to focus on simple signals such as tonal stimuli, narrowband or broadband noise (Good & Gilkey, 1995; Middlebrooks & Green, 1991; Wightman & Kisler, 1997).

Generally, this previous research has focused on stimuli that are not related to small arms weapons fire.

**Statement of Purpose**

The ability for soldiers to be consciously aware of their surrounding environment is imperative for their safety and security. Scharine et al. (2009) discussed the possibility that soldiers may encounter situations where the visual field is inhibited due to darkness or smoke, and the only available cue to situational awareness is sound. Gaston and Letwoski (2012) discussed the importance of perception and discrimination of different types of gunfire for the same reasons. Knowing the location of the sound source can help to locate enemies and also give clues about the physical environment (e.g. behind trees or rocks). Today's military operations are more focused in urban settings as opposed to the open fields of previous conflicts. These situations can create problems for soldiers who are unable to see their enemies behind standing structures.

Localization techniques can help soldiers focus on a specific area on both the horizontal and vertical plane. This could be especially useful if enemy fire were coming from an alley way versus an open courtyard. In these situations, the effects of reverberations and reflections could give the soldier some idea of the surrounding environment, as hearing gives a 360 degree acoustic view of the environment, (Fluitt et al., 2010; Scharine et al., 2010). By manipulating specific acoustic parameters and properties such as overall amplitude of small arms fire, the ability to accurately localize the sound source may be altered. Research in this area may be helpful on the battlefield by giving soldiers the tools needed to increase their own situational awareness as well as give them the capability to distract or confuse the enemy with manipulated acoustical properties of gunfire.

The purpose of this study is to understand the importance of acoustic variables (i.e. phase and intensity) and what effects, if any, alterations of those variables may have on the listener's ability to localize small arms fire. Specifically, this study will focus on the amplitude and timing differences of a muzzle blast and ballistic crack, and the relationship between the shooter and the listener's location. Results from this study may ultimately help to understand how soldiers localize gunfire, as well as lead to research that could confuse enemies by manipulating acoustical components of their own small arms.

# Chapter 3

# Research Methodology

## Participants

30 adults were recruited to participate in this study (12 male, 18 female). Ages ranged from 18 to 52 years, with a mean age of 26.4 years. Participants were recruited from Towson University's Department of Audiology, Speech Language Pathology, and Deaf Studies and from both the campus and the surrounding community. Participants received a hearing screening, which they were required to pass (thresholds <25dB), before beginning the study. Participants must have had normal hearing, dexterity to use a computer mouse or keyboard, and no reported cognitive deficits that could impact their ability to understand and/or complete the task. Participants with a previous history of active duty military service in a combat zone and those with experience shooting military assault weapons were excluded due to related experience localizing to weapons fire.

## Procedures

**Questionnaire.** Prior to the hearing screening, the participant was given a questionnaire to provide information regarding previous medical history and experience with small arms fire. The participant was asked to clarify if he/she has been diagnosed with any neurologic disorders, traumatic brain injuries, cerebrovascular accidents, and/or concussions. The participant was also be asked to explain any previous military history, including any time spent serving in active military combat zones where localization to gunfire would be routine and necessary.

**Hearing Screening.** A hearing screening occurred in a sound treated audiologic booth at Towson University. Pure tone stimuli were delivered through TDH 49 insert headphones by a GSI 61 audiometer. Air conduction testing occurred at 250, 500, 1000, 2000, 4000, and 8000Hz. Bone conduction testing occurred at 500, 1000, 2000, and 4000Hz. Audiometric testing utilized the modified Hughson Westlake method (Carhart & Jerger, 1959). Those who had air conduction thresholds greater than 25 dB HL at any frequency, or presented with air bone gaps greater than 5dB were ineligible for participation in the study due to effects of hearing loss on localization abilities (Goodman, 1965; Noble, Byrne, & Lepage, 1994).

**Testing and Computer Paradigm.** The participant was seated in front of a laptop computer and instructed to listen for a sound file of small arms fire. Once the file began to play, the participant was asked to locate the point on a response arc that best corresponded to the location of the gunshot (stimuli will be described below). The response arc and related custom software was developed at the Applied Research Laboratory (ARL) in Aberdeen, Maryland by engineer Tim Mermagen using Visual Basic+. The computerized software included a clickable arc representing possible sound locations from $-60^{o}$ to $+60^{o}$ in $1^{o}$ degree increments. Once the participant clicked on a location within the response arc, the next stimuli file began to play. If the participant did not make a selection, a new stimulus was played after 7 seconds. After giving verbal instructions, the researcher placed AKG K701 circumaural headphones on the participant. There were be 5 separate experiments in this study, with experiments 1-5 occurring in a random order that was given to the participant prior to beginning the test. Each participant was given the chance to perform five practice trials before each experiment began, and the option to continue practicing if any confusion was noted.

***Experiments 1 and 2.*** The listener was played a gunshot recording from the set of seven randomized stimuli. After each recording, the listener used the computer mouse to point and click on the area of the response arc that best corresponded to where he/she believed the gunshot originated. Experiment 1 was solely looking at muzzle blast stimuli, and Experiment 2 was focused solely on ballistic crack stimuli.

***Experiment 3.*** The listener was played a gunshot recording from a set of 48 randomized stimuli. After each recording, the listener used the computer mouse to point and click on the area of the response arc that best corresponded to where he/she believed the gunshot originated. Each stimulus was played five times at random, for a total of 240 trials.

***Experiments 4.*** The listener was played a gunshot recording from a set of 48 randomized stimuli. After each recording, the listener used the computer mouse to point and click on the area of the response arc that best corresponded to where he/she believed the gunshot originated. Each stimulus was played five times at random, for a total of 240 trials.

***Experiment 5.*** The listener was played a gunshot recording from the set of 42 randomized stimuli. After each recording, the listener used the computer mouse to point and click on the area of the response arc that best corresponded to where he/she believed the gunshot originated. Each stimulus was played five times at random, for a total of 210 trials.

## Stimuli

Stimuli used in this study consisted of muzzle blast and ballistic crack recordings from a single-shot M4 carbine. The recordings were made at a small arms firing range at Aberdeen Proving Ground in Aberdeen, Maryland.

**Stimuli development.** The ballistic crack and muzzle blast portions of the stimuli were extracted from a recorded M4 carbine measured 16 meters in front of the muzzle, which was directly along the shooter's target line with $0^o$ incidence. For each recording a 1000 ms segment of the reverberation tail was excised at a point 200 ms following the peak of the muzzle blast. For each stimulus condition, the muzzle blast and ballistic crack stimulus components were combined with the appropriate time offsets and differences in peak amplitudes. The reverberation tail was added for context and to make the stimuli sound more realistic. The sets were edited in Adobe Audition 3.0

Initially, the original muzzle blast and ballistic crack recordings were prepared by normalizing the peak amplitudes to the same -3 dB(P). The stimuli were then convolved with head related transfer functions (HRTF's) recorded on the Knowels Electronic Mannequin for Acoustic Research (KEMAR) using B&K microphones placed in the concha. These measurements were made every 10 degrees from $-60^o$ to $+60^o$ for a total of 14 positions resulting in 14 muzzle blast and ballistic crack stimuli respectively from which to construct the experimental stimuli for each experiment. The stimulus relationships correspond to modeled observer/shooter positions as a function of absolute distance and observer incidence angle of the shooters target line. As such, the stimulus names corresponded to these modeled relationships to convey and maintain the relative stimulus differences, even though the stimuli were not played back to listeners at the absolute modeled levels. For the purposes of this study, the -3dB level of the base stimuli prior to convolution was referenced to the 156 dB level for modeled relationships since this is the highest modeled peak level for any of the stimulus components. For all stimuli, following editing, the onset time to ballistic crack peak was set at 200 ms and the offset time following the final peak to stimulus end was set at 1200 ms. The total duration of the ballistic crack and muzzle blast stimuli were 1400 ms plus the time delay between ballistic crack and muzzle blast peaks. The muzzle blast portion of the combined stimuli was 200 ms long and the final 1000 ms was a generic reverberation tail taken from the original gunshot stimulus inserted to make the stimuli sound more realistic

**Experiment 1**. The muzzle blast stimuli were modeled to reference a peak level of 150 dB (P). The stimuli range from +60 to -60 degrees in steps of 20 degrees. In Experiment 2, ballistic crack stimuli were modeled to reference 150 dB(P). The stimuli range from +60 to -60 degrees in steps of 20 degrees. Each stimulus was played five times at random, for a total of 35 trials.

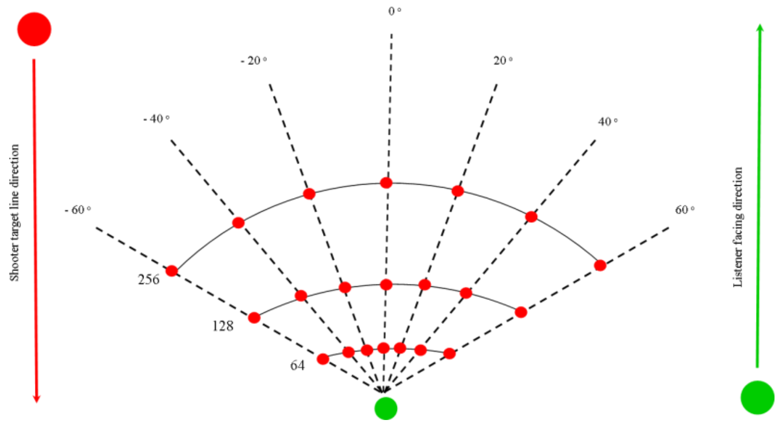


Figure 4. Representation of shooter positions by distance and azimuth with the red circles representing listener position.

**Experiment 2.** In Experiment 2, ballistic crack stimuli were modeled to reference 150 dB(P). The stimuli ranged from +60 to -60 degrees in steps of 20 degrees. Each stimulus was played five times at random, for a total of 35 trials.

**Experiment 3.** The muzzle blast portions of the stimuli ranged from +60 to -60 degrees in steps of 20 degrees. The ballistic crack angle was either + 60 (for rightward stimuli) or – 60 (for leftward stimuli). These were the only two values used for all ballistic crack and muzzle blast stimuli because, across all of the modeled relationships, as the arrival angle of the muzzle blast changed so did the ballistic crack angle, such that the two added to approximately 60 degrees. For example, at a muzzle blast angle of 0 degrees, the difference in angle was 60 degrees, at 20 degrees the difference in angle was 40 degrees, and at 60 degrees the difference was 0 degrees. For these stimuli, the muzzle blast was always referenced to 138 dB(P) and the time delay between ballistic crack and muzzle blast peaks was always 160 ms. The reference was the ballistic crack, which varied from levels of 120 dB(P) to 156 dB(P) in 6 dB steps. This range covered the relative amplitude differences between ballistic crack and muzzle blast peaks across the range of modeled shooter-observer relationships. The goal of this experiment was to show how the difference in amplitude across ballistic crack and muzzle blast peaks affects localization. Timing was not a factor because for all stimuli the timing offset was fixed (160 ms).

**Experiment 4.** For these stimuli, the muzzle blast was referenced to 138 dB(P) and the ballistic crack amplitude was also fixed at 138 dB(P), creating a 0 dB difference. The timing offsets between ballistic crack and muzzle blast were varied by 5, 10, 20, 40, 80, 160, and 320 ms. The goal of this experiment was to test how the difference in timing between ballistic crack and muzzle blast peaks affects localization. Amplitude was not a factor because for all stimuli the amplitude offset was fixed (0dB).

**Experiment 5.** The timing and amplitude relationships were modeled for each specific observer/shooter position. There were thus 39 unique stimuli (seen in Table 1) corresponding to the 13 modeled angles (+60 to -60 degrees in 10 degree increments) at the 3 distances (64, 128, 256 m) the exact range of parameters (timing and amplitude) for the stimuli are referenced in the file names of the stimuli.

Table 1

*Experiment 5 parameters*

| Azimuth | Timing Delays | Amplitude Differences |
| --- | --- | --- |
| -60 | 0ms, 10ms, 20ms | 12dB,14dB, 16dB |
| -50 | 10am, 20ms, 40ms | 12dB, 12dB, 14dB |
| -40 | 20ms, 40ms, 80ms | 12dB, 12db, 14dB |
| -30 | 40ms, 70ms, 140ms | 10dB, 10db, 12dB |
| -20 | 60ms, 110ms, 210ms | 6dB, 6dB, 8dB |
| -10 | 80ms, 160ms, 280ms | 2dB, 4dB, 6dB |
| 0 | 110ms, 210ms, 350ms | 4dB, 12dB, 18dB |
| 10 | 80ms, 160ms, 280ms | 2db, 4dB, 6dB |
| 20 | 60ms, 110ms, 210ms | 8,dB, 8dB, 8dB |
| 30 | 40ms, 70ms, 140ms | 10dB, 10dB, 10dB |
| 40 | 20ms, 40ms, 80ms | 10dB, 12dB, 14dB |
| 50 | 10ms, 20ms, 40ms | 12dB, 12dB, 14dB |
| 60 | 0ms, 10ms, 20 | 12dB, 12dB, 14dB, |

*Note.* Timing and amplitude differences as an effect of changing shooter position utilizing KEMAR.

**Statistics**

Measurements of listener accuracy were recorded for this study-specifically, the difference between the actual angle of the sound or shooter location and the perceived angle or location as reported by the listener. Absolute values were used to assess accuracy. As such, an error to the left was judged equally as an error to the right, with no negative value assigned. IBM SPSS Statistics software was used to complete statistical analysis. Descriptive statistics were used to observe information about the accuracy of listener localization. An alpha level of $p \leq .05$ was used to judge statistical significant for each individual experiment. As post hoc testing became necessary, the family wise error rate was controlled using a Bonferroni correction.

**Experiments 1 and 2.** A two-way repeated measures Analysis of Variance (ANOVA) was run to measure the effect of stimulus type (muzzle blast and ballistic crack) on listener localization accuracy, as well as the azimuth. When significant effects existed, post hoc testing was done to further evaluate effects of specific azimuth on listener accuracy.

**Experiment 3.** A two-way repeated measures ANOVA was run to measure the effect of both timing and azimuth on listener localization accuracy as well as interactions between timing and angle. When significant effects were found, post hoc testing was done to further investigate the effect of specific timing differences and angles on listener accuracy.

**Experiment 4.** A two-way repeated measures ANOVA was run to measure the effect of peak intensity differences and azimuth on listener localization accuracy as well as interactions between peak intensity differences and azimuth. When significant effects were found, post hoc testing was done to further investigate the effect of specific intensity differences and angles.

**Experiment 5.** A two-way repeated measures ANOVA was run to measure the effect of shooter location (distance and angle) on listener localization accuracy. When significant effects were found, post hoc testing was done to further investigate the effect of specific shooter location and angles.

## Chapter 4

## Results

This study was comprised of five different experiments that focused on several different acoustic aspects of gunshot localization. Accuracy errors to the right of the actual azimuth were recorded as a positive error, while leftward errors were recorded as a negative error. The data was analyzed using the absolute values of all errors.

A series of two-way repeated-measures ANOVAs were conducted to observe what effects, if any, occurred as a result of azimuth, stimulus type, timing and amplitude differences, and shooter position/azimuth. When significant effects were found, subsequent *post hoc* testing was conducted using a Bonferroni correction to determine the significance of specific levels of stimuli, timing, amplitude, or shooter position. Alpha levels were set at $p < .05$ for all non-*post hoc* testing for each experiment. All experiments utilized azimuth as a variable (-60 degrees to + 60 degrees in 20 degree increments for experiments 1-4, and 10 degree increments in experiment 5). Table 1 (below) describes the variables analyzed in each repeated measures ANOVA. Rather than presenting the results separately for each experiment, the results will be reported as a function of the variables of interest.

Accuracy errors to the right of the actual azimuth were recorded as a positive error, while leftward errors were recorded as a negative error. The data was analyzed using the absolute values of all errors.

Table 2

*Comparisons of variables between experiments*

| Experiment | Two-way ANOVA variables | Variable levels |
|---|---|---|
| All experiments | azimuth** | -60°, -40°, -20°, 0°, 20°, 40°, 60° |
| 1 and 2 (collapsed) | stimulus type | muzzle blast, ballistic crack |
| 3 | timing differences | 10, 20, 40, 80, 16, 320 ms |
| 4 | amplitude differences | 120, 126, 132, 138, 144, 150dB |
| 5 | shooter position | 64, 128, and 256 meters |

*Note.* A one-way ANOVA was run to analyze experiment 1 and 2 separately. Data was subsequently collapsed together to obtain information on the effect of stimulus type. **Azimuth was a common factor between all experiments, ranging in 20° increments from -60° to +60° in experiments 1-4, and 10° increments in experiment 5.

**Azimuth.** Results of two-way ANOVAs across all experiments revealed a significant main effect of azimuth on the accuracy of gunshot localization across all conditions (Experiments 1 and 2: $F(6, 1043) = 24.88$, $p < .001$; Experiment 3: $F(7, 143) = 52.209$, $p < .001$; Experiment 4: $F(7, 143) = 73.982$, $p < .001$; Experiment 5: $F(13, 137) = 115.718$, $p < .001$). Figure 7 (below) displays mean accuracy as a function of azimuth averaged across experiments (-60 degrees to + 60 degrees in 20 degree increments). As Figure 7 shows, there was a systematic decrease in mean localization error as the sound location goes from directly in front (0˚) to the extreme sides (60˚). Subsequent *post hoc* testing (see results in Table 2 below) utilizing a Bonferroni corrected alpha level of $p < .001$ (correction factors: experiments 1and 2: .05/42; experiments 3 and 4: .05/56; experiment 5: .05/182), confirms the significance of this pattern, with stimuli presented at

0 degrees significantly different from the most leftward ($p < .001$) and rightward angles ($p < .001$) in all experiments.

Table 3

*Comparison of average azimuth errors between 0°, -60°, and +60°*

| | 0 degrees | | -60 degrees | | +60 degrees | |
|---|---|---|---|---|---|---|
| Experiment | Mean | SD | Mean | SD | Mean | SD |
| 1 | 28.47 | 25.03 | 15.85 | 12.85 | 17.56 | 14.64 |
| 2 | 32.11 | 27.66 | 20.92 | 17.78 | 21.53 | 18.22 |
| 3 | 28.75 | 25.63 | 15.85 | 12.85 | 17.21 | 14.63 |
| 4 | 48.61 | 1.02 | 18.68 | 0.79 | 19.5 | 0.93 |
| 5 | 51.26 | 1.19 | 19.05 | 0.98 | 18.17 | 0.94 |

*Note*. Means and standard deviations were obtained at 0, -60, and +60 degrees for each experiment.

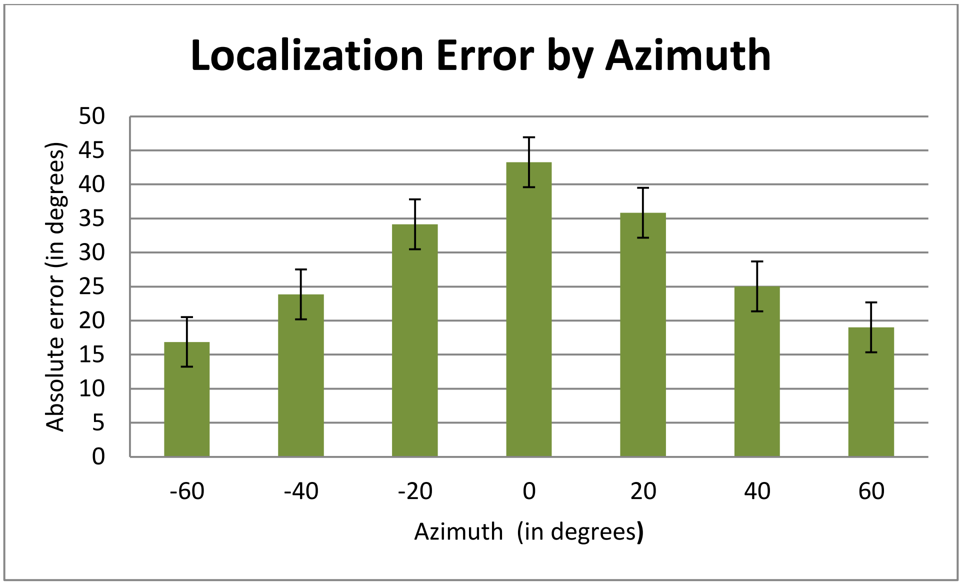


Figure 7. Graphical representation of localization errors from the given shooter angle and the listener's chosen angle at common azimuth positions (20 degree increments from -60 degrees to +60 degrees) across all experiments with error bars representing the standard error.

**Stimulus type.** Data from experiments 1 and 2 were collapsed and analyzed using a two-way repeated-measures ANOVA to observe effects of stimulus type (muzzle blast and ballistic crack) and azimuth on localization accuracy. Results showed a significant effect of stimulus type on listener localization $F(1, 149) = 14.686$, $p = .000$. Mean error was always observed to be better for muzzle blast stimuli compared to ballistic crack stimuli (as seen in Figure 8).

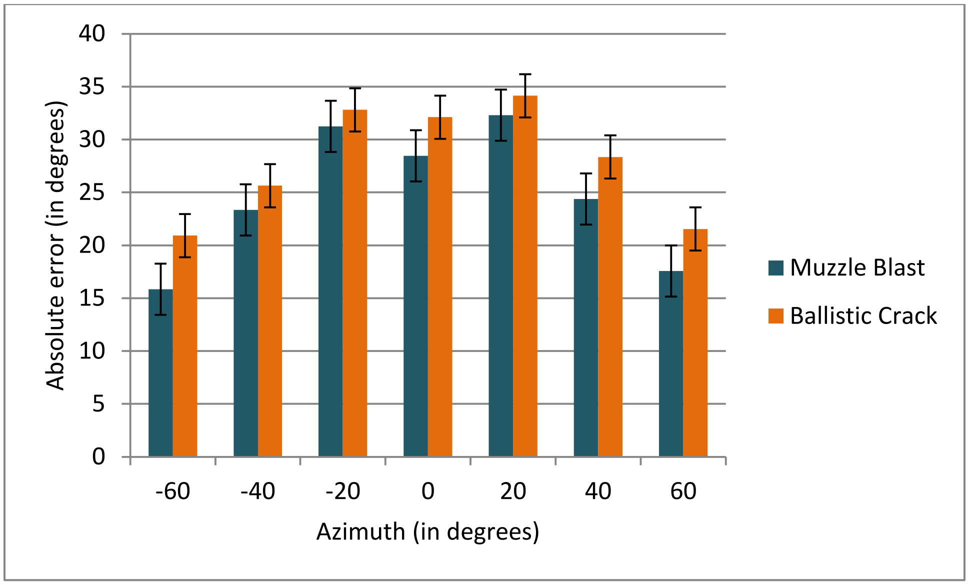


Figure 8. Graphical representation of data from experiments 1 and 2 comparing listener accuracy when presented with either a muzzle blast or ballistic crack alone from -60 to +60 degrees, in 20 degree increments. Error bars represent the standard error.

**Shooter position.** Experiment 5 specifically looked at the effect of azimuth and distance on listener accuracy. As noted previously, there was a significant main effect of azimuth $F(13, 137)=115.718$, $p < .001$, with localization of extreme azimuth positions significantly different from centralized positions. Stimuli at -/+60 degrees were significantly different than all angles from -30 degrees to +30 degrees ($p < .001$). Accuracy at 0 degrees was significantly different from all other azimuths ($p < .001$ for all azimuths). No main effect of distance was found. $F(2, 148)= 2.008$, $p= .138$. As shown in Figure 9, the patterns of accuracy were very similar across distances.

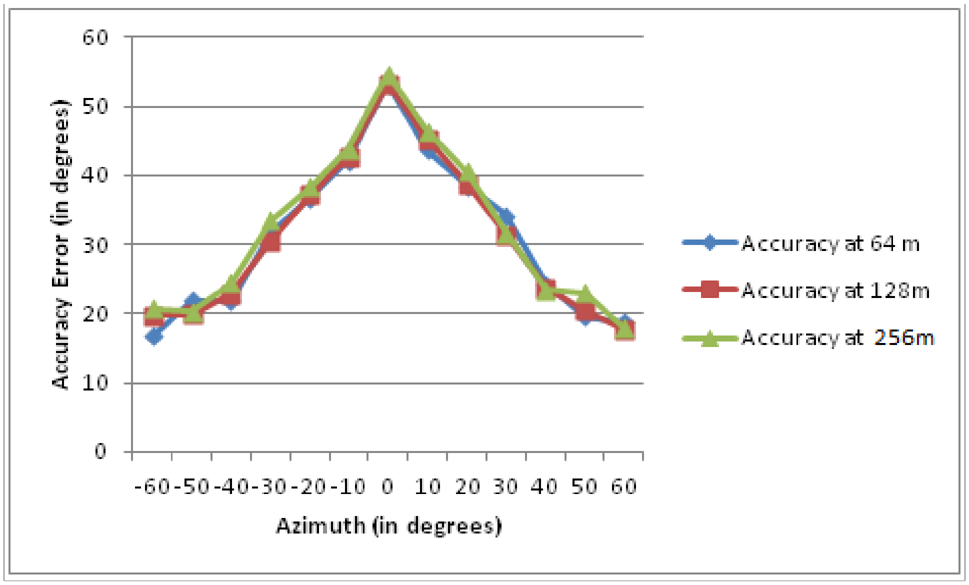


Figure 9. Graphical display of listener accuracy across azimuth positions of -60$^{o}$ to +60$^{o}$ in 10$^{o}$ increments at three different distances, 64, 128, and 256 meters.

**Timing and amplitude.** Overall, no significant effect was found for amplitude ($F$(5, 145)= 3.102, $p$= .011) or timing variations ($F$(5, 145)= 1.043, $p$= .395) between the ballistic crack and muzzle blast (Figures 10 and 11 below) on localization error. Finally, distance was not shown to have a significant effect ($F$(2, 148)= 2.008, $p$= .138) on localization error.

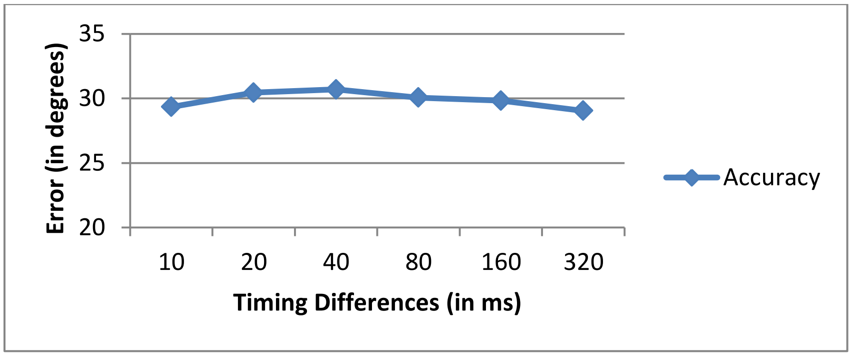


Figure 10. Mean accuracy differences as timing between the ballistic crack and muzzle blast onset change from 10, 20, 40, 80, 160, and 320 ms.

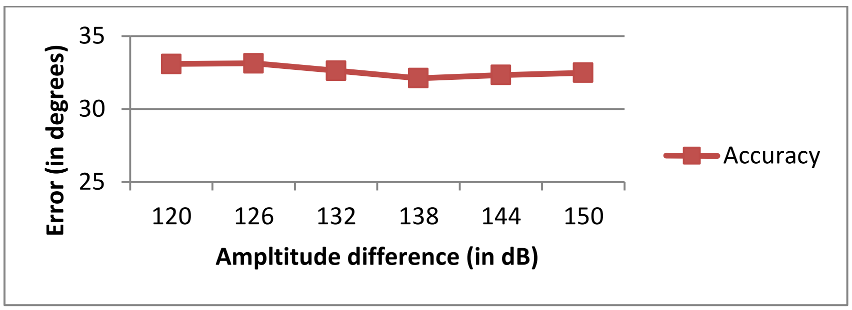


Figure 11. Mean accuracy is represented as the amplitude differences between the ballistic crack and muzzle blast change from 120 to 150dB in 6 degree increments.

# Chapter 5

## Discussion

Sound localization is an innate ability that allows listeners to create a spatial map of their surroundings, resulting in increased situational awareness (Fluitt et al., 2010; Scharine et al., 2009). The ability to localize sound can be especially helpful to soldiers on the battlefield, who utilize acoustic signals to gain a greater awareness of their immediate surrounding environment and locale. Soldiers, specifically, need to localize gunfire in a variety of combat situations in order to provide a better understanding of their location in relation to the shooter, leading to the ability to better protect themselves and each other from further enemy fire (Fluitt et al., 2010).

The main purpose of this study was to examine listeners' sound localization abilities for systematic manipulations of the sounds of M4 carbine military rifle fire. Participants listened to gunshot recordings that had acoustic modifications including the spatial separation of the muzzle blast and ballistic crack components, as well as varying onset times and amplitudes between the two acoustic components. The final aspect of the study examined localization accuracy with naturally varying acoustic relationships as a result of distance and azimuth changes (causing timing and amplitude differences) between the listener and "shooter".

**Azimuth.** Research has shown that listeners are more accurate in their ability to locate sound sources in front of them compared to sounds behind them (Makous & Middlebrooks, 1989). Accuracy in the frontal plane has also been shown to increase as the signal is presented more directly in front of the listener as opposed to more lateral presentations, which were shown to exhibit greater variability (Makous & Middlebrooks, 1989; Perrot, 1984; Smith et al., 2012). Studies by Mills (1972) and Perrot (1984) found that audible differences between stimuli were smaller (around $2^{o}$) at midline and tend to increase as the signal moved laterally, meaning the listener could differentiate between the location of two sounds more accurately an azimuth near 0 degrees compared to 90 degrees.

Participants in the present study were more accurate when localizing to signals at the outward most azimuth (+/- 60 degrees). For the 0 degree position, the localization error was much greater than at the lateral (60 degree) positions. This was unexpected, given the findings of previous research. One reason for the differences found in the present study compared to previous research may be in how the localization response was measured, and thus determined to be “correct”. Makous and Middlebrooks (1989), for example, counted responses within +/- 5 degrees of the given stimulus to be “correct,” whereas responses in this study were judged by the absolute value of the listener’s response in relation to the actual given stimulus. The studies by Makous and Middlebrooks (1989) and Smith et al. (2012), also asked the listener to turn his/her head to “face” the sound source and used tracking devices such as a laser attached to the head to gauge accuracy. Makous and Middlebrooks (1989) specifically used a “closed-loop” system where the stimulus did not stop presenting until the listener made a final decision, giving the listener an extended time period to listen and analyze the sound. The present study, in contrast, used a clickable arc with a computer mouse to localize the sound with a precision of 1 degree increments only after the stimuli had been played.

Another real possibility is that the differences in results could have been a function of the limited azimuth range given to the listener to choose from. For the purposes of this study, -/+90 degrees was the most lateral azimuth that could be selected by the listener, as opposed to the entire 360 degrees sphere utilized by Mills (1972) and Perrot (1984). This may also have led to a quasi "ceiling effect" wherein any sound that sounded like it came from the greater left or right may be perceived as -/+ 60 degrees because it did not share the same "binaural" characteristics of the 0 degrees azimuth gunshot.

**Stimulus Type.** The muzzle blast and ballistic crack components of a gunshot can be heard differently by the listener depending on the listener's location in relation to the trajectory of the bullet (Maher, 2006). The ballistic crack progresses forward in a conical shape, while the muzzle blast propagates outward in all directions. Theoretically, if the listener were behind the shooter, the muzzle blast might be the only component heard (Maher, 2006). Participants were more accurate when they localized to the muzzle blast in isolation compared to the ballistic crack. The muzzle blast propagates in all directions, and therefore would reach the listener in an essentially straight line (Maher, 2006). If the listener were localizing the shooter based solely on the ballistic crack, the timing cue would not only include the time it took for the bullet to propagate to the necessary point in its firing line, but also the time to propagate from the firing line toward the listener (Letowski et al., 2012). In essence, the muzzle blast localizes toward the shooter, while the ballistic crack would provide information about where the target was located (Letowski et al., 2012; Maher, 2006). The muzzle blast contains more energy and is longer in duration compared to the ballistic crack, giving greater emphasis on the muzzle blast component of the gunfire to the listener (Letowski et al., 2012). Therefore, the results of this study showing greater accuracy with muzzle blast localization was to be expected, as the increased energy and duration should make localizing toward the muzzle blast easier than the ballistic crack.

**Shooter position.** In general, when distance increases, the overall intensity of the sound reaching the listener decreases. This change also increases the time it takes to reach the listener (Smith et al., 2012; Strybel & Perrott, 1984). Scharine et al. (2012) noted that distance, as a rule, is harder to estimate acoustically because most people have an inadequate reference even with a visual field. Findings from the present study indicate that sounds presented to the listeners' extreme left and right are most accurately localized. Listeners were unaffected by changes in the relative distance of the shooter, which was expected, as all presented stimuli were beyond the 3 meter threshold where, regardless of the change in intensity, the distances provide the listener no advantage in localizing the sound (Middlebrooks & Green, 1991).

**Limitations and Future Research.** Overall results of this study show that accuracy is affected by the azimuth of the shooter. Further research may be necessary, however, to focus on a greater number of azimuth positions. Observing localization capabilities with a full 360 degree azimuth window may dilute the effects of the "quasi-ceiling" effect that was surmised earlier by expanding the azimuth range on either side of the listener. Increasing the azimuth window to include the full 360 degrees surrounding the listener could also prove beneficial in representing gunshot locations in frontward and rearward locations, with the expectation that accuracy would be poorer in the rearward locations (Makous & Middlebrooks, 1989).

Gunfire is rarely heard in isolation, and the importance of accurately localizing gunfire increases for soldiers in combat, with any and all inherent noise (other gunfire, military vehicles, people, etc.) and equipment (helmets, body armor, etc.) that could interfere in the localization task. Research focusing on localization of gunfire in the presence of background noise and competing sounds would provide important information in relation to previous research findings that minimum audible angles are increased by 5-10$^{o}$ in the presence of competing noise (e.g., Perrot, 1984). Further research into the effect of competing noises on localization ability would be beneficial to the military population, who must make quick judgments based upon their ability to localize surrounding gunfire (Scharine et al., 2009).

This study was also limited in the use of only one type of weapon (M4 carbine) and the lack of real environmental obstacles that could affect the acoustics of gunfire, such as reverberations from surrounding buildings, trees, etc. (Brungardt & Rabninowitz, 1999). These obstacles would introduce reflections and reverberations that would alter the acoustic cues reaching the listener and in some cases could help with distance perception (Mershon & Bowers, 1979) but significantly hinder azimuth localization (Letowski et al., 2010; Wallach et al., 1949). Further research should incorporate real-world environmental situations to better assess listener accuracy in battlefield-like conditions.

**Conclusions.** The ability of soldiers to localize gunfire positions on the battlefield is an integral aspect of their situational awareness and safety. Locating the source of gunfire can provide invaluable information about the direction in which the gunfire was initiated, how close the gunfire originated from the listener's present position, and any obstacles between the shooter and listener in the surrounding terrain. As shown in this study, localization accuracy was better for sounds at -/+ 60$^{o}$ in relation to the front-facing listener. Gunfire originating at 60$^{o}$ angles to the left and right of the listener were more accurately localized than others, including directly ahead of the listener at 0 degrees. Distance, as well as timing and amplitude differences, did not affect the overall accuracy of the listener's ability to localize the gunfire, putting even more importance on the listener's ability to utilize interaural timing and intensity differences to determine at which azimuth the shooter was located.

Importantly, listeners were able to accurately localize the gunshots with isolated acoustic components (muzzle blast or ballistic crack alone), and in the presence of a second sound (ballistic crack and muzzle blast together). Listeners with at least some knowledge of the acoustics of gunfire should be able to localize the shooters position by listening to the muzzle blast, even when the ballistic crack may appear to be originating from a different location. The accuracy, according to results from this study, would be greater if the gunshot occurred to the right or left of the listener instead of occurring at a point straight ahead of the listener.

# Appendix

TOWSON UNIVERSITY

## APPROVAL NUMBER: 14-A042

To: Tyler Raup
8000 York Road
Towson MD 21252

From: Institutional Review Board for the Proctection of Human Subjects Stacy Spaulding, Member

Date: Wednesday, November 13, 2013

RE: Application for Approval of Research Involving the Use of Human Participants

Office of Sponsored Programs
& Research

Towson University
8000 York Road
Towson, MD 21252-0001

t. 410 704-2236
f. 410 704-4494

Thank you for submitting an Application for Approval of Research Involving the Use of Human Participants to the Institutional Review Board for the Protection of Human Participants (IRB) at Towson University. The IRB hereby approves your proposal titled:

*Listener Accuracy in the Localization of Small Arms Fire: The Effect of Changes in Amplitude and Timing Differences*

If you should encounter any new risks, reactions, or injuries while conducting your research, please notify the IRB. Should your research extend beyond one year in duration, or should there be substantive changes in your research protocol, you will need to submit another application for approval at that time.
We wish you every success in your research project. If you have any questions, please call me at (410) 704-2236.

CC: S. Nagle
File

TOWSON UNIVERSITY

Date: Wednesday, November 13, 2013

**NOTICE OF APPROVAL**

**TO:** Tyler Raup **DEPT:** ASLD

**PROJECT TITLE:** *Listener Accuracy in the Localization of Small Arms Fire: The Effect of Changes in Amplitude and Timing Differences*

**SPONSORING AGENCY:**

**APPROVAL NUMBER:** 14-A042

The Institutional Review Board for the Protection of Human Participants has approved the project described above. Approval was based on the descriptive material and procedures you submitted for review. Should any changes be made in your procedures, or if you should encounter any new risks, reactions, injuries, or deaths of persons as participants, you must notify the Board.

A consent form: [✓] is [ ] is not required of each participant

Assent: [ ] is [✓] is not required of each participant

This protocol was first approved on: 2013-11-13

This research will be reviewed every year from the date of first approval.

, MPA (SOR)

Stacy Spaulding, Member

Towson University Institutional Review Board

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