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THE EFFECTS OF LATE REFLECTIONS ON AN INDIVIDUAL'S AUDITORY DISTANCE PERCEPTION.

by

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THESIS APPROVAL PAGE

This is to certify that the thesis prepared by Lisa A. Guerra, B.S., Au.D. Candidate, entitled The Effects of Late Reflections on an Individual's Auditory Distance Perception has been approved by the thesis committee as satisfactorily completing the thesis requirements for the degree Doctor of Audiology (Au.D.).

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ABSTRACT

The Effects of Late Reflections on an Individual's Auditory Distance Perception

Lisa A. Guerra

The effect of reflections on an individual's auditory distance perception has been widely studied in an enclosed space but has received less attention when conducted in an open air outdoor space. Auditory distance judgments were assessed for 14 normal hearing and normal visual depth perception participants aged 18 to 50 years. Participants were asked to judge the auditory distance of various sounds presented via a lap top computer and insert earphones. The task was completed using three different noise stimuli (pink noise, pulse train, speech), seven different microphone to loudspeaker distances (1 ft, 2 ft, 4 ft, 8 ft, 16 ft, 32 ft, and 64 ft) and seven different reflection delays (0 ms, 10 ms, 20 ms, 40 ms, 80 ms, 160 ms, and 320 ms). Results revealed that reflection delay did not significantly impact auditory distance perception in a simulated open air outdoor space, but that the combined effects of sound source distance, type of stimuli, and reflection delay interacting together did impact auditory distance judgments in a simulated open air outdoor space. This study further supports the findings of previous literature looking at the combination of various acoustic and non-acoustic effects on an individual's auditory distance perception.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

KEY TO ABBREVIATIONS

ANCOVA: Analysis of Covariance

APG: Aberdeen Proving Grounds

ARL: Army Research Laboratory

dB: Decibel

dB HL: Decibel Hearing Level

dB SPL: Decibel Sound Pressure Level

EAR: Environment of Auditory Research

ft: feet

HALL: Hearing and Listening Laboratory

Hz: Hertz

MD: Maryland

m: meters

ms: Milliseconds

Chapter 1: Introduction

The concept of spatial hearing is used when a person is trying to find the precise location of an auditory perception (Blauert, 1997). Spatial hearing is divided into two main areas: directional localization and distance perception (Blauert, 1997). Directional localization allows the subject to use both azimuth and elevation cues to help determine which direction the auditory perception is coming from around the subject's head (Middlebrooks & Green, 1991). Distance perception is used to help determine how far or near the auditory perception is to the subject (Zahorik et al., 2005).

Distance perception can be exocentric or egocentric (Strybel & Perrott, 1984). Exocentric distance perception is the distance of one sound source compared to another sound source. Egocentric distance perception is the distance between the sound source and the listener (Strybel & Perrott, 1984). In addition, auditory distance perception can be related to a single sound source or a sound source in motion (Ashmead et al., 1995).

There are many factors that play a role on the egocentric distance of a single, fixed sound source. Some of the factors are non-acoustic whereas others are acoustic (Zahorik et al., 2005). Non-acoustic cues include vision and the familiarity of a sound source and the acoustic cues include the intensity of a sound source, the frequency spectrum of the sound source, and the direct-to-reverberant energy ratio (Zahorik et al., 2005).

Regarding the non-acoustic cues, literature has shown mixed results regarding the effects of vision on auditory distance perception. Earlier studies by Gardner (1968) and Mershon et. al (1980) showed that auditory distance perception can be both under or overestimated with visual targets present. Whereas, later studies, such as Zahorik (2001) and Calcagno et al. (2012) found that auditory distance judgments became more accurate with the presence of visual information. Unlike the mixed results on visual cues, research looking at the familiarity of a sound source has unanimously found that the more familiar the subject is with the sound source, the more accurate their auditory distance judgment (Zahorik, 2002a).

Acoustic cues have also shown to play a major role on auditory distance perception. Many studies have looked at the frequency spectrum of a sound source as a possible contributor to auditory distance perception. Frequency spectrum has been shown to play a dual and relative role, rather than an absolute role (Coleman, 1968). In general, if the distance of a sound source already appears to be far away and there is a loss of high frequency energy, distance perception is increased whereas if the distance initially appears to be near the subject and high frequency energy is lost, a reduction in distance perception is perceived (Coleman, 1968; Little et al., 1992). Research has also shown that intensity plays a strong role in auditory distance perception, but similarly with frequency spectrum, not an absolute one (Mershon & King, 1975). In addition, it has been shown that as the distance between a sound source and the subject increases, the intensity of a sound source decreases (Begault, 1991). Reverberation, or the direct-to-reverberant energy ratio, on the other hand, has been shown to provide an absolute cue to auditory distance perception (Mershon & King, 1975). Previous studies have shown that as the reflections or reverberant energy is increased, therefore causing the direct-to-reverberant energy ratio to increase, auditory distance perceptions become more accurate (Mershon & King, 1975; Bronkhorst & Houtgast, 1999).

Since research has shown reverberation to be an absolute cue that has an effect on auditory distance perception, the present study seeks to explore this area further and see if there is a point where reflections no longer play a role in auditory distance judgments. Previous studies have been conducted in an enclosed space limiting the amount of space the direct energy and reverberant energy have to travel. Therefore, in order to accurately assess whether late reflections play a role in auditory distance perception, a study needs to be conducted in an open air space.

Chapter 2: Review of the Literature

Spatial Hearing

The precise moment that an auditory perception occurs is when the subject, or the person who is doing the perceiving, becomes cognizant and aware of the object, otherwise known as what is being perceived (Blauert, 1997). Auditory perceptions could not occur without both the subject and the object being present (Blauert, 1997). The relationship between the locations of these auditory perceptions and the physical location of a sound source is referred to as spatial hearing (Blauert, 1997). Spatial hearing is three-dimensional, with the listener analyzing information from the two dimensions of directional localization and the dimension of distance to determine the location of a sound source (Blauert, 1997; Middlebrooks & Green, 1991).

Directional Localization

Directional localization of a sound source is specified by two parameters; azimuth and elevation (Loomis, Klatzky, Philbeck, & Golledge, 1998; Middlebrooks & Green, 1991). Azimuth is defined as “the angle given by the sound source, the center of the listener’s head, and the median plane” (Middlebrooks & Green, 1991, p. 138). Elevation is also defined as the “angle given by the sound source, the center of the head,” but is in reference to the horizontal plane (Middlebrooks & Green, 1991, p. 138). There are many studies that go into great depth discussing the dimensions of both azimuth and elevation and how both dimensions help an individual determine where a sound is coming from, rather than how far or near the sound source is to the listener (Middlebrooks & Green, 1991). However, since directional localization is not the focus of the present study, those studies will not be discussed further.

Distance Perception

Distance perception, the other component to human localization, has received less attention in the literature when compared to directional localization (Butler, Levy, & Neff, 1980; Coleman, 1963; Zahorik et al., 2005). Distance can be classified as egocentric or exocentric (Strybel & Perrott, 1984). Exocentric distance perception is the judgment of how far, or close, one sound source is to another sound source (Strybel & Perrott, 1984). Egocentric distance perception is the distance judgment from the sound source to the listener (Strybel & Perrott, 1984). Distance perception can also be related to a single, fixed sound source or a sound source in motion (Ashmead, Davis, & Northington, 1995). The focus of this paper will be on egocentric auditory distance perception of a single, fixed sound source.

Egocentric auditory distance perception is dependent on many parameters that are separated into two primary categories: Non-acoustic cues and acoustic cues (Zahorik et al., 2005). Non-acoustic cues include the role of vision and the familiarity of a sound (Zahorik et al., 2005). Acoustic cues include the intensity and loudness of a sound source, the spectral or frequency changes of a sound source, and the direct-to-reverberant energy ratio (Zahorik et al., 2005).

Non-acoustic Cue: Vision

Vision can greatly influence an individual's auditory localization and distance perception (Zahorik et al., 2005). Many studies have looked at the influence of vision on an individual's ability to localize sounds (Jack & Thurlow, 1973; Shelton & Searle, 1980; Thomas, 1941). However little is known about the influence vision has on an individual's ability to make auditory distance judgments (Calcagno, Abregu, Eguia & Vergara, 2012).

One study looked at the effects of vision on an individual's auditory distance perception (Gardner, 1968). In 1967, at Bell Telephone Laboratories, an experiment was performed where participants sat in an anechoic chamber, and faced a loudspeaker that was placed at eye level. Four speakers were placed directly behind the first speaker at eye level, all separated by an equal amount of distance, with the first speaker placed three feet from the listener and the last speaker placed 30 feet from the listener. Markers were placed on each speaker to indicate their distance since only the first speaker was visible to the participant. Recorded speech was played from the furthest loudspeaker at approximately 65 dBB and the participant was asked to state which loudspeaker the speech was coming from. The first participant and then all participants thereafter unanimously stated that the speech was coming from the nearest speaker. Gardner (1968) coined this phenomenon as the "proximity-image effect" meaning the nearest speaker is selected as the position of the sound source in the initial presentation of the sound when cues to distance, such as familiarity of the sound source, reverberation, and intensity, are not present.

Mershon, Desaulniers, Amerson, and Kiefer (1980) conducted a study similar to the Gardner (1968) experiment. Mershon et al. (1980) studied the proximity-image effect under semi-reverberant conditions as well as in an anechoic chamber while Gardner (1968) studied the effect in an anechoic chamber only. Five-hundred and thirty seven psychology students who reported normal hearing and vision volunteered to participate in the study. The stimulus used was a prerecorded broad band noise that was played through a tape recorder that was hooked up to a loudspeaker. The stimulus was presented for five seconds with the participant being assessed under one of two situations. The first situation involved the participant looking at a dummy speaker with the actual sound source speaker located behind the dummy speaker. The second situation involved the sound source speaker being placed directly in front of the participant with the dummy speaker located behind the sound source speaker. The participant could not see the sound source speaker and could only see the dummy speaker as a large cloth screen blocked any view of the sound source speaker. The participant heard the stimuli in one of three possible conditions. The differences among the three conditions were based on whether the experiment was conducted in an anechoic chamber vs. a semi-reverberant room, whether the sound source speaker was in front of (situation one) or behind the dummy speaker (situation two), and the distance between the dummy speaker and listener. Mershon et al. (1980) found that 90% of all test subjects reported the sound coming from the dummy speaker when in a semi-reverberant room, with 94% reporting the same conclusion in the anechoic chamber. Therefore, it was concluded that the proximity-image effect strongly exists for both anechoic spaces as well as semi-reverberant spaces. It was also found that distance estimates can be overestimated or underestimated due to the effects of a visual target, which in this case was a dummy speaker (Mershon et al., 1980). Gardner (1968) only reported an underestimation effect. Therefore, this study added to our knowledge of the proximity-image effect as well as the effects visual targets have on auditory distance judgments.

Another study looking at the role of vision in auditory distance perception was conducted by Zahorik (2001). The studies by Mershon et al. (1980) and Gardner (1968) concluded with some similarities and differences. Zahorik (2001) conducted a study combining the qualities of both studies to see if the different methodologies were in fact the reason for different findings between the studies. The study was conducted in a semi-reverberant room, similar to the Mershon et al. (1980) study, but used the methodology of Gardner (1968). Thirty-four undergraduate students all of whom had normal hearing and normal vision, after corrective lenses, participated in the study. As stated, the methodology was similar to Gardner (1968) in that five speakers were placed in a direct line, at eye level, in front of the participant. Speakers were spaced equally with the farthest distance from the listener equaling five meters. The stimulus used was a pre-recorded sentence, with a female voice, of high-fidelity. This stimulus was presented from one of the five speakers and each participant was asked to verbally judge the distance on a scale of feet or meters, depending on which measurement system each participant was familiar with (English or metric). The thirty-four participants were separated into two groups. One group was allowed to use their vision and see the loudspeaker array before and during the experiment and the other group was blindfolded and therefore could not use their vision to see the loudspeaker array both before and during the experiment. Zahorik (2001) found that in the condition where vision was used, the auditory distance judgments were relatively accurate. In addition, the accuracy of auditory distance judgments increased when the participant was allowed to visually see the loudspeaker array. The accuracy of the auditory distance judgments in the no vision condition was found to be significantly smaller. This finding differs from past studies in that the results do not provide strong evidence to support the proximity-image effect and rather produce results that are opposite of what the proximity-image effect predicts. Since the proximity-image effect was not observed in this experiment, that utilized a set-up and methodology from two different experiments where the effect was previously observed, Zahorik (2001) came to the conclusion that the proximity-image effect in distance is not as general as past studies have found it to be.

In a more recent study examining the influence of vision on auditory distance perception, Calcagno et al. (2012) conducted three different experiments all within a semi-reverberant room. The primary difference between Calcagno et al. (2012) and the previous studies of Gardner (1968) and Zahorik (2001) was that Calcagno et al. (2012) used a mobile loudspeaker rather than a setup of five speakers in a direct line. The use of a five speaker setup can lead to the potential problem of the signal becoming filtered which is caused by the acoustic shadow from the first speaker. Whereas with a mobile speaker, that can be moved around to various distances, the potential of the signal being filtered is not there. All experiments were conducted on eight to 32 participants, depending on the experiment, who had normal hearing and normal vision after corrective lenses were used. The first experiment was conducted to determine each participants visual distance perception, both without visual cues and with two or four visual cues, and act as a control and baseline. The second experiment was conducted to determine each participant's auditory distance perception, both with visual cues and in the absence of visual cues, and to see if auditory distance perception improved with vision. No prior knowledge of the test environment was known to any of the participants in the first two experiments. The third experiment was conducted to determine each participant's auditory distance perception with each participant having no visual cues, but a prior knowledge of the test room. Results of the first experiment showed nearly all visual estimated distances were significantly greater (more accurate) when either two or four visual cues were used in comparison to when visual cues were not used. This provided researchers with confidence that the visual cues would be efficient visual references for later experiments. Results of the second experiment showed significant increases in responses obtained between the absence of visual cues and the presence of two or four visual cues, with both groups responses providing support that vision effects auditory distance perception. Researchers found that when vision was absent, distance estimation increased linearly with the actual distance of the sound source, to distances of approximately three meters or less. This finding agrees with the findings of Zahorik (2001). When visual cues were present, auditory distance estimations were generally overestimated, more spread out, and the variability of the estimations increased. This finding in comparison to the finding of auditory distance estimations without vision would suggest that visual cues negatively impact auditory distance perception. However, results from experiment three suggest otherwise as very accurate auditory distance estimations were obtained when participants were given the time to visually review the room prior to the experiment. Calcagno et al. (2012) concluded that more experiments are needed in this area as the majority of past experiments have been conducted in unknown environments or in rooms that have been acoustically treated.

Non-acoustic Cue: Familiarity of a sound source

Familiarity of a sound source is another non-acoustic cue that has been shown to have an effect on an individual's auditory distance judgments (Zahorik, 2002a). Research has shown that auditory distance judgments are less accurate when the sound is unfamiliar to the listener and that the auditory distance estimates become more accurate as the unfamiliar sound becomes more familiar (Zahorik, 2002a).

Gardner (1969) investigated subjects' ability to estimate the distance of both single and multiple speech sources in an anechoic chamber. The speech sources used were both recorded and live voice with recorded materials played at randomly selected intensity levels that ranged from 65 dBB to 10 dBB. Sounds appeared to originate at or near distances ranging from 3 to 30 feet directly in front of the subject at ear level. However, each subject did not know that when recorded speech was used, only one speaker was connected to the amplifier, which was always speaker one, located at 10 feet, or speaker five, located at 30 feet. In the experiment where live voice was used, each participant was blindfolded and speakers were placed at distances of 3, 10, 20, or 30 feet away from the subject. Speakers spoke in one of four manners: a whispered voice, a confidential, low voice, a conversational voice, or a shouted voice. Results showed that when recorded speech was used, whether it be a single source or multiple sources, distance estimations "were independent of the actual distance involved" (Gardner, 1969, p. 47). When live voice was used, however, the ability of each subject to make auditory distance estimations greatly depended on the manner of voice that was used. For example, when the speaker used a voice that was shouting, distance estimations were overestimated and when the speaker used a voice that was whispering, distance estimations were reported to be closer than what they actually were (Gardner, 1969). This finding suggests that listeners use their familiarity of different manners of speech, in that when a speaker whispers they are usually close to the listener and when a speaker shouts they are usually far away from the listener, to help in processing the acoustic cues of a sound source to estimate auditory distance perception (Gardner, 1969).

Coleman (1962) conducted a study focusing on the familiarity of a sound source in aiding one's ability to estimate the auditory distance of a sound source. Rather than initially focusing on familiar sound sources, he focused his study on unfamiliar sound sources. He hypothesized that accurate distance estimations could not be made from the initial exposure to an unfamiliar sound. He formed this hypothesis based on previous literature that showed both intensity and frequency spectrum play a role in the distance of a sound source, yet when distance changes occur due to changes in either of these two cues, people cannot pick up on the changes. Therefore, Coleman (1962) conducted an experiment involving 14 speakers placed in front of the subject in the median plane, all separated by a distance of two feet, with the nearest speaker located five feet from the subject. The experiment was conducted outside on a frozen lake. Stimuli was measured to be 65 dB at one foot in front of each speaker and consisted of wide-band random noise, played for one-second. Twenty males, with normal hearing, participated in the study. Each subject was given one hundred trials and was asked to identify which speaker they thought was the sound source for each trial. Only the 10 middle loudspeakers were sound sources, a fact not known to the participants. Participants were divided into four groups of five. Group one had the loudspeaker located nine feet from them on the first, eleventh, and hundredth trial. Group two, three, and four had the sound source located at 15 feet, 21 feet, and 27 feet from the participant for the same trials. All sound sources were presented in a random order and an equal number of times. Results showed that distance estimation errors increased as the distance between the sound source and the participant increased and that as the trials increased, from one to 11 to 100, errors in distance estimation decreased. Additionally, the participants auditory distance judgments were more accurate with the more trials they were exposed to suggesting that as participants became more knowledgeable and familiar with the intensity and frequency spectrum of the sound source, they were able to make more accurate distance judgments (Coleman, 1962).

McGregor, Horn, and Todd (1985) expanded on the results of Coleman (1962). Instead of using white noise to see if distance perception improved with familiarity, researchers used speech stimuli. Two speech stimuli were used: A familiar one and an unfamiliar one. The familiar speech stimulus was the following sentence: “How far away do you think I am?” The unfamiliar speech stimulus was the same sentence, but to make it unfamiliar, researchers played it backwards. Both stimuli were recorded twice: at a near distance of two meters and at a far distance of 30 meters. Twenty-two people, divided into six groups, visiting a biological field station were the participants for this study. Each participant heard the familiar and unfamiliar recordings in stimulus pairs five times and was asked to indicate whether the second sound of the two was farther, nearer, or equal to the first sound. Results showed that 13 of the 20 subjects were able to accurately estimate the distances of the familiar sounds, but only six participants were able to do the same for the unfamiliar sounds. This study supports the results of Coleman (1962) in that the familiarity of a sound source, in this case speech, acts as a cue in auditory distance estimation (McGregor et al., 1985).

Brungart and Scott (2001) further explored the subject of familiarity of a sound source influencing a subject’s auditory distance perception. Researchers wanted to focus on an area that has thus far received no attention. How people use production level (different manners of voice) and presentation level (different intensities) to make an auditory distance estimate and how different speakers and sentences affect or change people's auditory distance estimates. Brungart and Scott (2001) conducted three different experiments over headphones, all involving pre-recorded speech on eight participants with normal hearing. In experiment one, both production levels and presentation levels were adjusted so that the speech stimuli would appear to be coming from distances ranging from 0.25 meters to 64 meters. The first experiment resulted in distance estimations that were overshadowed by the adjusted distance of the speaker. Therefore, researchers conducted a second experiment to take a more detailed look at how both presentation and production level together affect the auditory distance perception of speech. Brungart and Scott (2001) conducted this by producing a speech signal over a 60 dB SPL range of various speech levels (quiet voice to a loud voice) and by presenting the signal at different intensities, specifically a 34 dB SPL range. Results of experiment two as well as one showed that participants use the changes in both production level and presentation level to help aid in making distance estimations, however, did not provide information to indicate what acoustic properties of the signal are essential to make these distance judgments. Therefore, researchers conducted another experiment to see if understandable speech or a speech signal that was temporally and spectrally similar to the understandable, normal speech signal would help a participant to make auditory distance estimations. The last experiment involved participants judging the auditory distance of time-reversed speech. Results of the last experiment indicated that the time-reversed speech does not contain the essential acoustic cues needed for a participant to estimate the auditory distance of a voice that is shouting but does for a low-level conversational voice. Overall, this study provided insight into how the familiarity of different speech signals plays a key role in auditory distance perception (Brungart & Scott, 2001).

Philbeck and Mershon (2002) conducted another study that focused on familiarity of a sound source acting as a cue to auditory distance perception. These researchers wanted to expand on the studies of Gardner (1969) and Brungart and Scott (2001) in that neither of those studies determined whether the familiarity effects were caused from long-term exposure or the repeated trails. If the familiarity effects occurred as a result of repeated trials, researchers suspected that familiarity of the sound had nothing to do with auditory distance estimations, and rather differences in intensity, reverberation, etc. between the trials helped the listener estimate distance perception. Therefore, researchers explored this concept and prevented comparison between the trials by analyzing the data from each and every stimulus presentation right after it had occurred. Researchers noted that if long-term knowledge played a role in auditory distance perception, then changes in intensity should result in different auditory distance estimates from trial one. To conduct their experiment, researchers blindfolded one-hundred and ninety-two participants, all with normal hearing, and asked each participant to estimate the apparent sound source distance to three different recordings. The three different recordings were a whispered voice, a voice at normal conversation level, and a shouted voice saying, “How far away from you does my voice seem?” Both male and female voices were used for the recordings and each participant was not given any previous knowledge of the recordings. Results showed that shouted voices were perceived to be farther away and whispered voices were perceived to be nearer, even on the first presentation. Therefore, it can be concluded that prior knowledge due to past experiences does play a role in auditory distance perception without comparisons between trails needed (Philbeck & Mershon, 2002).

In a more recent study, Wisniewski, Mercado, Gramann, and Makeig (2012) studied the effect of sound familiarity on auditory distance perception while also recording electroencephalographic tests. Researchers noticed an area within the subject of sound familiarity that was lacking information and wanted to explore it further. Therefore, Wisniewski et al. (2012) studied the neural generators, by the use of electroencephalographic tests that are involved or activated when familiarity of a sound source effects a subject's auditory distance perception. Researchers examined each subject's ability to accurately estimate the auditory distance of three different sounds that varied in familiarity, but were similar in their acoustics. The familiar sound used was English speech, which was both lexically and phonetically familiar. Another sound used was Bengali speech which was only phonetically familiar. The unfamiliar sound source was the English speech and Bengali speech played backwards, which was lexically and phonetically unfamiliar to all participants. Results of the study showed that speech stimuli that were phonetically familiar, both the English speech and the Bengali speech, yielded more accurate auditory distance judgments (Wisniewski et al., 2012).

Acoustic Cues

While it is apparent that both the non-acoustic cues, vision and familiarity of a sound source, play a role in an individual's ability to make auditory distance judgments, it is important to note that auditory distance judgments can still be made when neither non-acoustic cue is available. Zahorik et al. (2005) provide two classic examples of when the distance information obtained relies solely on the auditory domain. One example where vision can no longer provide a cue to auditory distance perception is in a dark environment. An example of this would be reaching for your alarm clock when it is still dark outside. Another example is when the sound source is not in an individual's field of vision. Such an example of this scenario is a car approaching an individual from behind. Since the car is approaching from behind the individual, where the visual cue cannot help, the distance information obtained from the auditory domain is the primary factor that will cue the individual to move out of the car's way (Zahorik et al., 2005). The acoustic cues that help aid in distance estimations when vision is not present and/or a sound is not familiar are intensity, the frequency spectrum of the sound source, and the direct to reverberant energy ratio (Zahorik et al., 2005).

Intensity

Intensity has long been known to be a cue in an individual's ability to make auditory distance judgments (Coleman, 1963; Zahorik et al., 2005). Starch and Crawford (1909) are some of the earliest researchers to first examine the acoustic cues that play a role in auditory distance perception. In their experiment two participants, one an associate psychology professor and the other the writer of the experiment, sat on a stool in the center of an un-ceiled steeple room with their eyes closed. The participants heard the stimulus, a catch-spring pivot action involving a hammer hitting a chamois covered wooden block, at a standard distance of one meter from their head. Once approximately two seconds had passed the stimulus was played again at a pre-determined distance that was nearer or father than the standard distance. After each trial, the participant was asked to compare the two stimuli and state whether they thought the second stimuli was nearer or father than the first stimuli. A total of 100 judgments were made in 13 different directions for a total of 2,600 judgments. Researchers found that intensity was the primary factor aiding the two participants auditory distance judgments, with sounds being judged as father away when the intensity was not as strong and closer when intensity was greater. Specifically, the first participant said that 95% and the second participant said that 92% of their auditory distance judgments were based solely on intensity. When a group of inexperienced participants did the same experiment, consistent responses were seen as they also reported intensity to be the main factor when estimating auditory distance perception (Starch & Crawford, 1909).

Edwards (1955) was another researcher who took interest in auditory depth perception. He conducted two experiments each involving university students. The first experiment had 31 participants and the second experiment had 50 participants. Each participant was seated with the stimulus directly behind them at head level. For both experiments the participant was asked to state when they felt the sound source was in a standard position (either 300, 500, or 700 centimeters). From there, the researcher would move the sound source toward or farther away from the participant. The participant was then asked to state if the sound source appeared nearer or farther from them. This set-up was conducted numerous times in both directions, for both experiments, a fact that all participants were aware of. The only difference between the two experiments was the stimulus used. In the first experiment, where there were only 31 participants, the sound source was a metronome and wire that was capable of moving nearer and farther from the participant by being attached to a pulley system. The second experiment had a clock’s tick act as the sound source. The tick of the clock was made quieter by surrounding the clock with a cloth and placing it in a box. The sound source was moved nearer and farther from the participant by having one of the researchers walk on mattresses to ensure that the sound of walking did not aid in each participant's auditory distance judgments. Edwards (1955) averaged the responses for each standard distance and found that there was higher accuracy in auditory distance judgments when the sound source was closer to the participant. This finding is not surprising as the distance estimations became greater as the intensity of the sound source became less, following the rule of the inverse square law (Edwards, 1955).

Mershon & King (1975) explored the cues of both intensity and reverberation on auditory distance judgments to see if both cues are absolute cues or relative cues to auditory distance perception. For example, if intensity proved to be an absolute cue to auditory distance perception, then two different intensities should result in two different auditory distance judgments without having to be compared. To test this, researchers conducted two different experiments that had methodologies to examine both the intensity factor and reverberation factor in auditory distance perception. For the both experiments, 80 psychology students, with normal hearing, acted as the participants. The stimulus for both experiments was a pre-recorded five second presentation of white noise that was played out of a speaker that was either 2.74 meters away from the participant or 5.49 meters away from the participant. A switching circuit was also attached to both speakers so that the experimenter could play two of the same stimuli at different intensities out of the same speaker. The speakers were located at ear level and at the participant's midline. In experiment one, the participant was blindfolded at the door and led into a tunnel comprised of acoustically reflective panels with opaque curtains at both ends of the tunnel. The tunnel was not lit and the participant sat in a chair that was placed just inside one of the tunnel ends. In experiment two, the participant was blindfolded and led to a chair located within an anechoic chamber. The other primary difference between the two experiments was experiment one played the stimulus at a sound intensity of 60 or 50 dBA from either speaker whereas in experiment two, the sound intensity was played at a level of 65 or 55 dBA from the nearer speaker and at a level of 55 or 45 dBA from the farther speaker. In both experiments, participants were asked to write down their distance estimation of the sound source in feet or inches after each presentation of the sound. Results of experiment one showed no significant differences in auditory distance estimations between the higher and lower intensities from either speaker. Similarly, there were no significant differences in auditory distance estimations in experiment two even though the intensity range was as large as 20 dB for some trials. These results provide support that intensity does not serve as an absolute cue to auditory distance perception but rather serves as a “strong” cue in auditory distance estimations under similar conditions as were presented in this experiment (Mershon & King, 1975).

Begault (1991) was another researcher who conducted an experiment focusing on intensity or loudness as a cue to auditory distance perception. In past research, there have been inconsistent findings as to whether the inverse square law, which states “sound in free space decreases as the square of the distance from the sound source, i.e., 6 dB SPL with each doubling of distance from a given reference point,” is always accurate in all situations (Begault, 1991, p. 1020). Therefore, Begault (1991) designed an experiment to find out how loud a sound source needs to be increased for the original sound source to appear as though it is twice as close to the participant. The study included two experiments, both of which had no reverberation and presented the stimuli to the participants via headphones. Six participants took part in experiment one and nine participants took part in experiment two, all having normal hearing sensitivity. The first experiment was looking at whether the preferred increase of intensity needed to half the distance was due to the inverse square law or the inverse cube scheme. The reference stimulus was a piano tone played at 65 dB with two probe stimuli also being the piano tone, but played at 71 dB (a 6 dB increase to represent inverse square law) and 74 dB (a 9 dB increase to represent the inverse cube scheme). The presentation of the stimulus, such as reference-probe or probe-reference and 6 dB or 9 dB increases was randomized and presented an equal number of times, with each participant listening to six blocks of 18 trials. The participants were asked to write down a one for yes and a zero for no to answer whether or not the probe stimulus appeared to be half the distance of the reference stimulus. Results of 216 judgments for experiment one indicated a significant 2:1 ratio between the 9 dB increase and the 6 dB increase. With regards to which method is better at perceiving distance as being half of what the distance really is, this finding does not support the inverse square law, but rather the inverse cube law, as being the preferred method. The second experiment was set up similar to the first experiment. The main differences were instead of two different dB increases being tested (6 and 9), four were tested (3, 6, 9, and 12) and trials consisted of two sets of three stimuli that were compared with each other. Results of experiment two were similar to experiment one in that the higher increases (9 and 12 dB) were preferred over the smaller increases (3 and 6 dB). Both experiments together provide evidence that the inverse square law is not the preferred choice in having a participant perceive the distance of the sound source to be twice as close to them Begault, 1991).

Intensity plays an important role in auditory distance perception (Zahorik, 2002a). The general concept is that as the distance between the listener and the sound source becomes greater, the intensity decreases. In an ideal situation, the relationship between distance and intensity follows the inverse square law; however, due to factors such as reverberation, this is not always the case. Intensity changes also depend on the frequency of the stimulus as well as environmental factors such as reverberation (Zahorik, 2002).

Frequency

Frequency spectrum is another acoustic cue that aids an individual's ability to make auditory distance judgments (Coleman, 1963; Zahorik et al., 2005). As previously mentioned, Starch and Crawford (1909) were some of the earliest researchers to first examine the acoustic cues that play a role in auditory distance perception. In their experiment it was found that the vast majority of participants auditory distance judgments were made due to the contributing factor of intensity. The frequency or pitch of the sound source was found to be the other contributing factor for the outstanding judgments. Researchers noted, however, that there was some inconsistency among these remaining judgments as the sound coming from a further distance was at times described as being higher in pitch, yet at other times, the closer sound was described as being higher in pitch (Starch & Crawford, 1909). Due to this inconsistency, a reasonable conclusion can be made that more research is needed in this area.

Coleman (1968) was another researcher who examined the effects of frequency spectrum on auditory distance perception. Coleman (1968) compared the results of

Bekesy (1938) to a study by Ingard (1953) which discussed the influences that different atmospheric effects have on sound propagation. Bekesy (1938) found that for a distance of 25 centimeters, an increase in the low frequency energy of a stimulus makes the sound source appear nearer to the participant whereas a decrease of low frequency energy in the stimulus causes the sound source to appear farther away from the participant. These results were obtained in a spherical soundfield (Bekesy, 1938). Coleman (1968) noted however that once the distance between the sound source and the participant becomes greater than a few feet, Bekesy's (1938) conclusions are no longer valid for the wavefront is no longer a spherical shape but rather a plain one. Yet, Ingard (1953) reported high frequencies are attenuated more (lose more energy) than other frequencies, such as low and mid frequencies, when passing through air. Ingard (1953) found that along with the gustiness of wind and ground attenuation, that both humidity and temperature play a large role in determining the magnitude of the absorption coefficient. When the relative humidity is 50% and the temperature is 20 degrees Celsius, Ingard (1953) indicated detectable changes in frequency spectrum can be noticed at distance changes of 20 to 30 feet, providing a cue to auditory distance judgments. Coleman (1963) also noted this point in his literature review on different cues to auditory depth perception and found this point to be especially true when the stimulus was composed of primarily high frequencies. Therefore Coleman (1968) proposed the following hypothesis for his study, "as distance from the observer increases the influence of frequency composition of the stimulus should shift from that shown by von Bekesy for near distances to that in which differential attenuation of high frequencies signifies a more distance stimulus" (Coleman, 1968, p. 631). To test his hypothesis, Coleman (1968) had six young male participants, all with normal hearing, sit in an acoustically treated room with 14 PDR-10 transducers placed in the midsaggital plane in front of them. Each numbered loudspeaker was separated by a distance of two feet with the nearest loudspeaker being four feet from the participant and the farthest loudspeaker being 32 feet from the participant. The stimuli, a 0.1 millisecond square pulse through an Allison 2ABR filter with a randomly selected cutoff frequency of 7,680 and 10,560 Hz, was played through one of the randomly selected loudspeakers. Each participant was asked to state which loudspeaker they thought the two stimuli were coming from. Coleman (1968) found that the higher frequency stimulus was nearly always identified as coming from a nearer loudspeaker whereas the lower frequency sound was said to be farther away. The results of Coleman's (1968) and Bekesy's (1938) studies together provide evidence that there is a dual role of frequency spectrum when making auditory distance judgments.

Little, Mershon, and Cox (1992) also conducted a study looking at the role of frequency spectrum in making auditory distance judgments. These researchers not only wanted to demonstrate that frequency spectrum does in fact play a role in auditory distance perception, but also wanted to investigate an area that has not yet been explored. Therefore, Little et al. (1992) also conducted an experiment to determine if the frequency spectrum cue was an absolute cue, meaning the participant can distinguish a difference in distance with only one presentation, or a relative cue, in which the participant needs multiple presentations so that they can compare the different sounds. There were 96 participants, all with normal hearing, that took part in the experiment. The stimuli, consisting of a low (5.0 kHz cutoff), medium (6.0 kHz cutoff), and a high (6.7 kHz cutoff) stimulus, was played to each participant at zero, two, four, and eight above or below the 65 dBA starting level. If played above, the low frequency stimulus was presented and if played below, the high frequency stimulus was played. The total number of participants was divided into two groups: One that heard the high frequency stimulus and the other that heard the low frequency stimulus. Results of the experiment showed the higher frequency stimuli were perceived as being closer than the lower frequency stimuli and vice a versa. Also, while frequency spectrum does play a role in auditory distance perception, it does not play an absolute role, but rather a relative one with regards to auditory distance perception (Little et al., 1992). However, it was also concluded that frequency spectrum is an independent cue to auditory distance perception in that it does not rely on other cues such as intensity and reverberation to notice a difference (Little et al., 1992).

Reverberation

Mershon and King (1975) were a team of researchers who studied the reverberation cue to auditory distance perception. In their study, they wanted to determine if both intensity and reverberation acted as an absolute cue or relative cue to auditory distance judgments. The methodology was described in detail and can be found in the intensity section of this paper. While they did not find intensity to serve as an absolute cue to auditory distance judgments, they did find reverberation to serve as an absolute cue to auditory distance perception. The participant groups from experiment one unanimously had larger auditory distance judgments when compared to all groups of participant's auditory distance judgments in experiment two, a finding that is statistically significant across all subgroups of both experiments. Distance estimations made in the anechoic chamber, where no reflections were aiding auditory distance judgments, were very small. However, when more reverberation was added, with a reflective tunnel, distance estimations of the sound source were perceived to be father away. These findings provide support that reverberation not only serves as a cue to auditory distance perception, but serves as an absolute cue to auditory distance perception (Mershon & King, 1975).

Mershon and Bowers (1979) further studied the reverberation cue in regards to the absolute and relative information it provides about auditory distance perception. To do this, they constructed three different experiments. The first experiment had 200 psychology students as participants, all with normal hearing. The first experiment was very similar to the experiments conducted in Mershon and King (1975) in that participants walked into a dark room, blindfolded, and heard a 5 second broadband noise stimulus at a constant intensity of 60 dBA from one of five speaker distances, 55, 100, 200, 400 or 800 centimeters. Participants were then asked to write down the perceived distance in feet or inches. The main differences were that the current study was held in a semi-reverberant room, participants were also asked to note the perceived loudness of the sound, and the entire experiment was tested again with half the observers turning 90 degrees to the left and the other half turning 90 degrees to the right. Results of experiment one showed that distance estimations were significantly different depending on the actual sound source distance. Overestimations occurred for distances that were closer to the participant and underestimations occurred as the distance became great between the listener and speaker. Experiments two and three had researchers examining what amount of prior auditory knowledge regarding the experiment setting was needed. Results of experiment two also showed that distance estimations were significantly different depending on the actual sound source distance no matter how much or how little prior knowledge the participant had (Mershon & Bowers, 1979).

Bronkhorst and Houtgast (1999) were another group of researchers who studied the reverberation cue on auditory distance perception. They recognized that many previous studies have had difficulty “quantifying the actual stimulus presented to the listener’s ears” and therefore designed two experiments that utilized virtual sound technology to avoid the past problems of previous studies (Bronkhurst & Houtgast, 1999, p. 518). Researchers conducted two different experiments each involving six participants. One experiment was conducted in a damped room, with a reverberation time of 0.1 seconds, and the other experiment was conducted in a reverberant room, with a reverberation time of 0.5 seconds. In both experiments each participant listened through headphones to a pink noise mixed with a binaural impulse response. There was a loudspeaker placed in each room. The binaural impulse component was added to the stimulus so that each participant would perceive the sound coming from the loudspeaker rather than the headphones. There were various anchor points, represented by the loudspeaker (experiment one) and the loudspeaker and two poles (experiment two). Each participant was instructed to estimate the perceived distance of the virtual sound source. Results of the study showed that as the number of reflections were increased, causing the direct-to-reverberant ratio to increase, auditory distance judgments were increased as well (Bronkhorst & Houtgast, 1999). Specifically, researchers found that when more than 27 reflections were used, distances of two meters or greater resulted in slow increases of perceived distance whereas smaller distances resulted in perceived distances that were nearly the same as what the actual sound source distance was. This effect found is known as the horizon effect. Researchers noted however that while reflections play a role in a person's ability to make auditory distance judgments, the individual's ability to adapt to the different environments and sounds sources is a key factor as well (Bronkhorst & Houtgast, 1999).

Zahorik (2002b) was another researcher who looked at the past research conducted on the direct to reverberant energy ratio and expanded on it. Zahorik (2002b) provided a brief description of what is known about the direct to reverberant energy ratio thus far. One, that the ratio usually results due to a sound signal bouncing off a very reflective environment such that the enclosed space will contain the original signal plus any reflections of the signal (early or late). Furthermore, as distance becomes greater, the reverberant energy does not change, but a 6 dB decrease occurs to the direct energy every time the distance doubles, causing the direct to reverberant energy ratio to decrease. Nonetheless the amount of change the direct to reverberant energy ratio increases or decreases is based upon how much reverberant energy is present. The reverberant energy is determined based on the environment it lies in, such as the size, distance, and reflections involved. Since the direct to reverberant energy ratio is such an important cue to auditory distance perception, Zahorik wanted to study it further by exploring an area with little previous research. He wanted to examine the sensitivity humans have to changes in the direct to reverberant energy ratio. Therefore, he conducted a study utilizing virtual acoustics to better control the stimulus. He played four different sounds through headphones to six participants that appeared to be coming from a loudspeaker located 1.22 meters away from the listener. All sound sources were designed to appear as though they were recorded in a semi-reverberant auditorium. The four sound sources played were an impulse, a speech syllable, a shot duration noise burst with a quick onset and offset, and a long duration noise burst with a more gradual onset and offset. Direct to reverberant energy ratios ranged from 0 to 20 dB by "digitally scaling the reverberant energy in measured binaural room impulse-responses" (Zahorik, 2002, p. 2111). A 3-down, 1-up method was used to obtain each participant's discrimination threshold for all stimuli. Results of the study showed no differences among the different stimuli as each stimuli resulted in a nearly constant five to six dB range of thresholds. While previous studies have found the direct to reverberant energy ratio to be an absolute cue, Zahorik (2002) found the opposite. Zahorik (2002) concluded that his results support the direct to reverberant energy ratio being more of a relative cue since participants were only able to identify changes in distance that were greater than a factor of two.

The goal of the present study is to expand on what the previous literature has found, specifically in the acoustic area of reflections. Previous research has shown that while intensity, spectrum, and familiarity of a sound source all provide cues to auditory distance perception, the direct to reverberant energy ratio is the only cue that provides an absolute cue to auditory distance perception. However, the question still remains as to whether the human brain has a precise point in separation between the direct energy and reverberant energy to where the reflections may no longer play a role in their auditory distance perception. Later reflections for example, usually occurring after 150 milliseconds, have generally been shown to not contribute to auditory distance perception since the reflections collide together and one can no longer discern each different reflection. However, studies resulting in this conclusion have been conducted in an enclosed room, limiting the distance for the sound to travel. The present study seeks to explore if late reflections do in fact play a role in auditory distance perception when they occur in a large open air space. In particular, three primary areas will be examined to look for this effect: the distance between the microphone and the speaker, the time of the delay, and the type of stimuli noise. By investigating these three factors, the researchers hope to gain more of an understanding on how much or little late reflections contribute to a person's auditory distance perception. The following hypotheses have been formulated:

1. Both early and late reflections will affect the accuracy of a person's auditory distance perception since the present study is being conducted in an open air space versus an enclosed space.
2. Accuracy of auditory distance perception will be highest with pink noise, then speech, and lowest with pulse train stimuli due to the spectral and temporal qualities of each stimulus.

Chapter 3: Methodology

Participants

Fourteen participants were recruited to participate in this study, all on a voluntary basis. All participants were between the ages of 18 and 50 (M = 24.57, SD = 1.83) with an equal number of the participants being males and females. The primary recruitment method was word of mouth. Test sessions took place at a time period that was convenient to both the tester and the participant. All participants signed an informed consent to acknowledge their understanding in the study as well as their participation before any testing began. Institutional Review Board (IRB) approval was obtained before any testing was conducted.

Pre-screening

All participants in this study were required to have hearing within normal limits (less than or equal to 20 dB HL) in both ears. Therefore, a hearing screening at 20 dB HL across all octave frequencies from 125 to 8000 Hz was administered to all participants before any testing began. In addition, subjects were asked to complete a short assessment to screen for normal visual depth perception. Each participant stared at a bright green dot on the opposite side of the room from them (approximately 15 ft) and extended their arm so that their pointer finger was at eye level in between the center of the bright circle and the center of their vision (Kain, n.d). Each participant was given four separate instructions by the tester and was asked to answer one question per instruction. The four instructions with questions were (a) with your finger held between you and the bright circle, and your eyes focused on the circle, how many finger(s) do you see?; (b) with your finger held between you and the bright circle, and your eyes focused on your finger, how many circle(s) do you see?; (c) with your finger held between you and the bright circle, and your left eye closed, is your finger to the right or left of the bright circle?; (d) with your finger held between you and the bright circle and your right eye closed, is your finger to the right or left of the bright circle? The desired answers were two, two, left, and right respectively (Kain, n.d.). Both pre-screening measures were given to ensure all participants had normal hearing and normal visual depth perception; thus enabling them to take part in the study.

Equipment and Procedures

All testing was performed at the Hearing and Listening Lab (HALL) at Towson University located in Towson, MD. The audiological screening was administered in a sound-treated, single-walled sound booth. The audiometric pure-tone screening was administered using a calibrated Grason-Sadler GSI-61 audiometer and ER-3A insert earphones. The practice session and test stimuli were administered in HALL. All stimuli utilized in the study were presented from a Dell Latitude D520 laptop computer through ER-3A insert earphones. Participants heard all 147 recordings in a random order and were required to estimate the distance, in feet, that the sound was perceived (which was the distance from the recording location to the microphone). For stimulus presentation, the computer sound output was set to two-thirds of the maximum computer volume and the output levels of the stimuli were measured to abide by the exposure limits recommended by the Occupational Noise and Safety Administration (OSHA) (OSHA, 2012). The output levels of the stimuli were measured using an Extech Instruments (model #: 407730) digital sound level meter (SLM) attached to the tube of the HA-2 coupler. The nub of the insert earphone was attached to the tube of the HA-2 coupler and the levels for the pink noise, pulse train, and speech stimuli were measured for the most intense set of stimuli; a loudspeaker to microphone distance of 1 ft at all reflection delay conditions. The pink noise, pulse train, and speech stimuli were also measured for the least intense set of stimuli, a loudspeaker to microphone distance of 64 feet at a reflection delay of 320 ms, to make sure each of the three stimuli were still audible in that condition. The average noise level for the pink noise stimuli at a loudspeaker to microphone distance of 1 ft across the seven reflection delays was 65 dB A using the fast mode setting on the SLM. The average noise level for the pulse train stimuli at a loudspeaker to microphone distance of 1 ft across the seven reflection delays was 67 dB A using the fast mode setting on the SLM. The average noise level for the speech stimuli at a loudspeaker to microphone distance of 1 ft across the seven reflection delays was 67 dB A using the fast mode setting on the SLM. The noise level measured using the fast mode setting on the SLM at a loudspeaker to microphone distance of 64 ft for a 320 ms reflection delay for the pink noise, pulse train, and speech stimuli was 46 dB A, 46 dB A, and 49 dB A respectively.

Stimuli

All stimuli were recorded at the Environment for Auditory Research (EAR) facility located at Aberdeen Proving Grounds (APG) in Aberdeen, MD. The EAR facility has both enclosed indoor spaces, which range from anechoic environments to several simulated environments, and an outdoor space (OpenEAR), which represents a real-field environment. All the environments are routinely used to conduct research on spatial hearing and speech communication. For the purposes of this study, the OpenEAR facility was the only space that was utilized when making the recordings and measurements. The OpenEAR space is a grassy field that is enclosed by three storage buildings made up of cinder block walls, steel doors, and tin roofs. To make the recordings, a Cesva dodecahedral speaker omnidirectional sounds source, model # FP-120, was mounted on a 4 ft tall tripod stand. A G.R.A.S. ½ inch diameter, free-field microphone (model # 46AF) was also mounted on a 4 ft tall microphone stand. The microphone was calibrated prior to recording. Seven distances between the microphone and speaker were recorded which include: 1 ft, 2 ft, 4 ft, 8 ft, 16 ft, 32 ft, and 64 ft. Reflection distances were artificially simulated using Adobe Audition software version 3.0. The reflection distances were: 10 ms, 20 ms, 40 ms, 80 ms, 160 ms, and 320 ms. The following formula was used to calculate the amount of dB that was attenuated from each direct path to properly estimate each reflection delay: 20 • log10 (direct path + reflection/direct path). The amount of attenuation used for each direct path per reflection delay is shown in Table 1 below.

Table 1

Attenuation Amounts According to Direct Path Delay and per Reflection Delay

Direct Path Delay	Reflection Delay					
	10 ms	20 ms	40 ms	80 ms	160 ms	320 ms
1 ft	20.8	26.44	32.3	38.2	44.1	50.2
2 ft	15.6	20.8	26.44	32.3	38.2	44.1
4 ft	10.9	15.6	20.8	26.44	32.3	38.2
8 ft	7.04	10.9	15.6	20.8	26.44	32.3
16 ft	4.21	7.04	10.9	15.6	20.8	26.44
32 ft	2.36	4.21	7.04	10.9	15.6	20.8
64 ft	1.26	2.36	4.21	7.04	10.9	15.6

Note. Amount of attenuation (in dB) needed to simulate spherical spreading from the source via the reflected path to the listener.

Once the amount of attenuation was calculated, the individual sound clips were made by subtracting the appropriate amount of dB from the direct path and by copying and mix pasting a specified number of reflections to the direct path. A 320 ms reflection delay added six reflections to the direct path (a 10 ms, 20 ms, 40 ms, 80 ms, 160 ms, and 320 ms), a 160 ms reflection delay added five reflections to the direct path (a 10 ms, 20 ms, 40 ms, 80 ms, and 160 ms), an 80 ms reflection delay added four reflections to the direct path (a 10 ms, 20 ms, 40 ms, and 80 ms), a 40 ms reflection delay added three reflections to the direct path (a 10 ms, 20 ms, and 40 ms), a 20 ms reflection delay added two reflections to the direct path (a 10 ms and 20 ms), and a 10 ms reflection delay added one reflection to the direct path (10 ms). The loudspeaker was hooked up to a XLR cable that was connected to an Intel 2 Duo CPU E6750 desktop computer in the common control room. Three different pre-recorded stimuli, a pulse-train stimulus, pink noise stimulus, and a speech stimulus, were presented through the loudspeaker using Window Media Player program on the computer. The speech stimulus was a female voice recorded at a low vocal effort at approximately 1 m from the microphone saying “over here”. Adobe Audition version 3.0 software was used to record and edit each stimulus, distance, and reflection distance condition. The utilization of three different stimuli, at seven different microphone to loudspeaker distances, as well as seven different reflection distances resulted in 147 different stimuli, distance, and reflection conditions.

Statistical Analysis

After all participant data had been collected, statistical analysis was performed to evaluate the data. Descriptive statistics and statistical analysis were performed using the

SPSS Statistics and Microsoft Excel. An ANCOVA test was performed to determine the relative strength of each independent variable, the stimulus, the distance between the loudspeaker and the microphone, and the reflection distance, as well as to determine if there are any interactions and co-variant effects. Additionally, an ANCOVA was performed to determine if any of the independent variables have a statistically significant effect on the dependent variable, the auditory distance judgments of each participant.

Chapter 4: Results

All 14 participants passed the hearing and visual depth perception screening; therefore their data were included in the analyses. A 3 x 7 x 7 within subject analysis of covariance (ANCOVA) was performed on the estimated distance data to examine the effects of independent variables of distance, reflection delay, and stimulus type. This analysis was performed using SPSS version 21. The statistical analysis revealed there was a significant three-way interaction between distance, reflection delay, and stimulus type, $F(72, 936) = 1.495$, $p < .05$. There was also a significant two-way interaction between delay and stimulus type, $F(12, 49.363) = 2.750$, $p < .05$, and a significant two-way interaction between distance and stimulus type, $F(12, 162.818) = 5.072$, $p < .001$. Figure 1 shows the two-way interaction of distance and stimulus type and Table 2 shows the amount of variability in each subject's responses (error bars) across the seven distances.

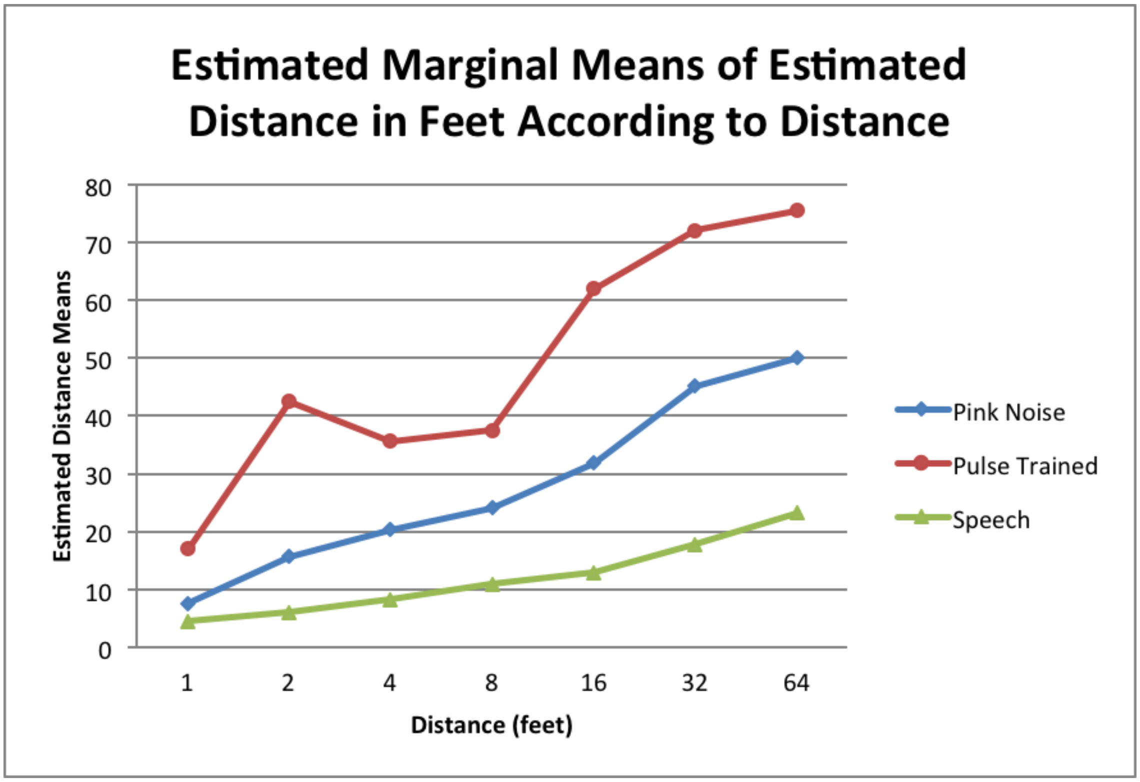

Figure 1. Estimated distance means are shown across the seven sounds source distances for the three stimulus conditions.

Table 2

Standard Error of Estimated Distance in Feet According to Distance

Stimulus	Actual Distance						
	1 ft	2 ft	4 ft	8 ft	16 ft	32 ft	64 ft
Pink Noise	9	18	17	24	26	40	39
Pulse Train	15	44	34	29	66	72	66
Speech	6	6	8	8	10	21	31

Note. Variability among participant estimated distance responses across the seven actual sound source distances and across the three stimuli used.

As mentioned above, the statistical analysis revealed a significant two-way interaction between delay and stimulus type. Figure 2 shows the two-way interaction of reflection delay and stimulus type and Table 3 shows the amount of variability in the subject's estimated distance responses across the seven different reflection delays.

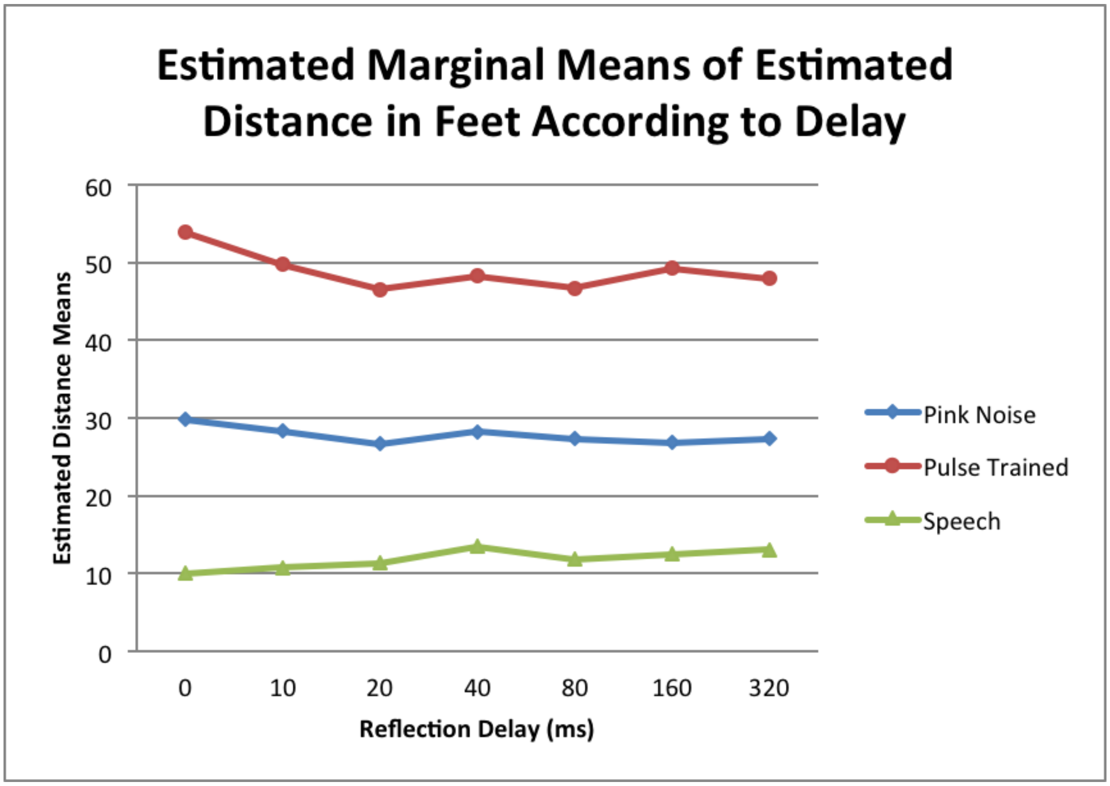

Figure 2. Estimated distance means are shown across the seven reflection delays for the three stimulus conditions.

Table 3

Standard Error of Estimated Distance in Feet According to Reflection Delay

Stimulus	Reflection Delay						
	0 ms	10 ms	20 ms	40 ms	80 ms	160 ms	320 ms
Pink Noise	32	28	27	34	31	29	30
Pulse Train	61	50	52	54	51	54	52
Speech	10	11	14	24	18	17	18

Note. Variability among participant estimated distance responses across the seven reflection delays and across the three stimuli used.

Chapter 5: Discussion

There are many factors that influence an individual's ability to make accurate judgments of a sound source distance (Zahorik et al., 2005). These factors both include non-acoustic and acoustic cues (Zahorik et al., 2005). The non-acoustic cues that have the potential to influence an individual's auditory distance perception include the use of visual cues and how familiar the listener is with the sound source (Zahorik et al., 2005). Acoustic cues that can impact an individual's auditory distance perception include the intensity of a sound source, the frequency spectrum of the sound source, and the direct to reverberant energy ratio (Zahorik et al., 2005).

In the current study, it was of particular interest to examine the role of the direct to reverberant energy ratio. Research has shown reverberation to be the only absolute cue to auditory distance perception, with the other acoustic cues of intensity and frequency spectrum being relative cues to auditory distance perception (Mershon & King, 1975). Previous studies have also shown early reflections to be a major contributor to an individual's auditory distance perception and late reflections to generally not contribute to an individual's auditory distance perception (Bronkhorst & Houtgast, 1999; Mershon & King, 1975; Zahorik, 2002b). A limitation of these previous studies, however, was the fact that they were conducted in an enclosed room, limiting the space for the late reflections to travel. Thereby, late reflections tended to be very diffuse in previous studies and not isolated "specular" reflections.

The aim of the present study was to investigate whether late reflections contribute to an individual's auditory distance perception when the sounds propagate in a large space with sparse reflections. To properly conduct this study, three primary distance cues were manipulated: the distance between the loudspeaker and the microphone, the time of the reflection delay, and the type of stimulus noise. A series of screening measures were given to ensure each participant was able to participate in the study. A practice session was also conducted to ensure each participant understood the study task. Within this study, participants were age-matched and gender balanced to rule out any possible gender or age effects.

Reflection Delay, Stimuli, and Distance Interaction

In the current study a three-way interaction between the reflection delay, type of stimulus used, and distance from the sound source was found to have a statistically significant effect on an individual's auditory distance perception. This finding is not surprising and is consistent with previous study findings (Zahorik, 2002a). When a participant is estimating the distance of a sound source in their natural environment, it is rare for the individual to estimate the distance of the sound source using only one of the acoustic and/or non-acoustic cues that are present (Zahorik et al., 2005). Rather, the participant combines the different acoustic and non-acoustic cues, weighs each of them according to their quality and forms one approximate auditory distance judgment (Zahorik, 2002a). The quality of the cue is based on how the cue compares to the other cues that are present and the make-up of the auditory space (Zahorik, 2002a). This "quality" takes into account the sound source distance, the type of stimulus that was used, as well as the acoustics of the room which is what was found in this study.

Reflection Delay as a Main Effect

Contrary to expectations, the main effect of reflection delay was not significant suggesting that the reflection delay did not affect estimated auditory distance judgments. This finding is in sharp contrast with the findings of Bronkhorst and Houtgast (1999) who studied the role of the direct-to-reverberant energy ratio in an enclosed damped room and enclosed reverberant room while using a binaural impulse response. Additionally, Bronkhorst and Houtgast (1999) gave the participants a reference distance of 2 m or 3 m as well as four distance intervals to choose their auditory distance estimate from, used only bursts of pink noise for the stimuli, and six participants per experiment. Bronkhorst and Houtgast (1999) found from their experiment that the number of reflections within the space was significantly related to an individual's auditory distance judgments. The difference between the estimated auditory distance judgments from Bronkhorst and Houtgast (1999) and our study can be seen in Figure 3 below.

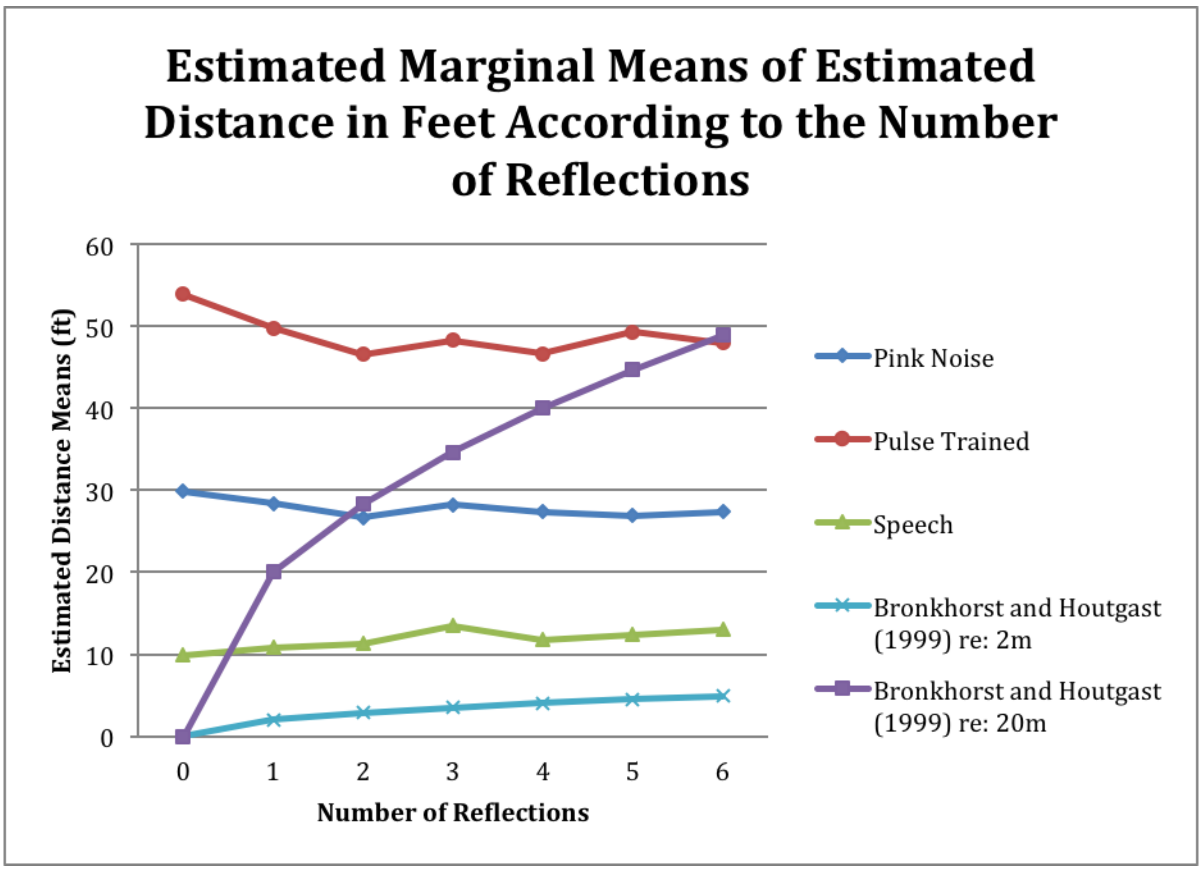

Figure 3. Estimated distance means are shown based on how many reflections were used across the three stimulus conditions. Estimated auditory distance means, using pink noise

stimuli, found by Bronkhorst and Houtgast (1999) are also shown for two reference distances.

Bronkhorst and Houtgast (1999) found a significant correlation between the number of reflections used and estimated auditory distance using the following formula: estimated distance = $\sqrt{n}$ • reference distance, with "n" equaling the number of reflections and the reference distance equaling 2 m and 20 m. Bronkhorst and Houtgast (1999) used a reference distance of 2 m in their study, but to match the scale of our findings a reference distance of 20 m was also used. The findings from Bronkhorst and Houtgast (1999) demonstrate a clear linear relationship, showing that as the number of reflections increase, the estimated distance also increases. Our present findings do not demonstrate the same linear relationship across the three stimulus conditions; no effect of reflection was found.

There were many differences between our study and the study conducted by Bronkhorst and Houtgast (1999), but it is important to compare the present study to Bronkhorst and Houtgast (1999) study since their study is not only one of the few studies in the literature focusing on the direct to reverberant energy ratio, but also the first study to actually quantify a model of how the direct-to-reverberant energy ratio plays a role in auditory distance perception. One difference is that Bronkhorst and Houtgast (1999) conducted their study within an enclosed space whereas the present study simulated reflections in an outdoor free field. Additionally, there are differences between how Bronkhorst and Houtgast (1999) simulated the room acoustics and how the present study simulated the isolated outdoor reflections. Bronkhorst and Houtgast (1999) used binaural impulse responses derived from head-related transfer functions to create a virtual sound space for the listener. This response simulated the characteristics of the space and the loudspeaker, but removed any effect that could have been added due to the headphones (Bronkhorst & Houtgast, 1999). No binaural impulse responses were generated for the present experiment, rather angle of arrival was simulated to be zero degrees incidence, i.e., along the mid sagittal plane of the listener's head. Each participant listened to different clips of sounds where the reflections had been artificially edited to contain one, two, three, four, five, or six reflections. These differences between study methodologies contribute to why the present study did not result in the same conclusions as Bronkhorst and Houtgast (1999).

Estimated Auditory Distance According to Reflection Delay

Speech.

Estimated auditory distance judgments remained relatively stable across the different reflection delays for the speech stimulus. No increases or decreases in estimated distance judgments were seen as the reflection delay increased from 0 ms to 320 ms. A hypothesis for why no increases in estimated auditory distance were seen as the reflection delay increased is because of the participant's familiarity with the sound source. Brungart & Scott (2001) conducted three experiments on vocal effort, each varying in production and presentation level, and asked each participant to estimate the distance of the pre-recorded speech stimulus. Brungart & Scott (2001) found the participants' familiarity of speech vocal effort affected their estimated distance judgments despite changes in intensity. This finding provides some insight as to why no changes were seen in estimated distance across the varying reflection delays. Each participant may have used their prior knowledge of the different speech vocal efforts that are used at varying distances more heavily than any other acoustic cue. Participants may have used this non-acoustic cue to the point where the intensity and reverberation cues were ignored (Brungart & Scott, 2001). The speech stimulus was recorded at a distance of approximately 10 feet away from the microphone and did not vary. The talker produced her speech at a conversational level with a low amount of vocal effort. The participant's knowledge of how a voice sounds at 10 feet away may have overpowered any possible intensity or reverberation cues that may have been contributing to an estimated auditory distance judgment.

Pink Noise and Pulse Train

There was no effect of reflection delay across the pink noise stimulus condition or the pulse train stimulus condition. Similar effects as to what was observed with the speech stimulus, in that there were minimal increases and decreases in estimated auditory distances with increased reflection delays, were observed with the pink noise and pulse train stimulus conditions. It appears the comb filtering of the reflections was so subtle in the pink noise condition that the only acoustic cue used to estimate auditory distance perception was the cue of intensity. While the same effect was observed across both the pink noise and pulse train stimulus conditions, a large difference in auditory distance estimation was noticed. The energy of the pulse-train stimulus was much less than the energy of both the speech and pink noise stimulus and therefore initially sounded quieter. The participants may have used the relative cue of loudness to aid in their auditory distance estimates for the pulse-train stimulus condition which may account for why the pulse train stimulus was estimated to be so much further off than the speech or pink noise stimulus conditions (Petersen, 1990).

Estimated Auditory Distance According to Actual Sound Source Distance

Estimated auditory distances were shown to increase across all three stimulus conditions as the distance of the actual sound source increased. Literature has previously found the intensity cue to play a large role in auditory distance perception and that as the distance between the listener and the sound source increases, the intensity between the listener and the sound source decreases (Zahorik et al., 2005). A linear relationship can be seen across all three stimulus conditions between the estimated distance and the actual sound source distance. It is hypothesized the participants used the intensity cue across all stimulus conditions when estimating their auditory distance judgments. As the actual sound source distance increased, the estimated distance increased which can most likely be due to the intensity decreasing with the increasing distance (Zahorik et al., 2005). Similarly with the estimated distances that were observed across reflection delays, it can be observed that speech was estimated to be the closest, followed by pink noise, and then pulse-train across the seven sound source distances. This trend is most likely seen because of the following. The vocal effort of the speech was low and therefore always appeared to sound close, the pulse-train stimulus was composed of little energy and therefore always appeared to be sounding farther away than the other stimuli, and the pink noise is a spectrally rich signal which is perhaps why the best relationship between estimated and actual distance is seen.

Clinical Relevance

The present study showed that estimated auditory distance perception, when in an open air outdoor space, is not directly affected by the reflection delay, but is affected by the combined effects of reflection delay, type of stimulus, and sound source distance interacting together. While these results offer no immediate clinical value, they may prove to be clinically relevant and beneficial in the hearing aid fitting process as well as in the development of future hearing aid and hunter and military active hearing protection devices in the future. During the hearing aid fitting process, the hearing aid is usually programmed according to the patient's level of hearing loss across various frequencies. The patient initially tries the hearing aid in an anechoic space or a room that is sound-treated. Many problems in the sound quality are not noticed until the patient leaves the sound-treated space and enters their natural environment. Unlike the sound-treated space, a patient's natural environment is full of reflections that can aid in auditory distance perception. Therefore, further research is needed on hearing aid and hearing protection compression algorithms to see if refinement of these algorithms could allow for better processing of everyday reflections. Hearing aids are known to focus on the amplification of speech, but it would also be important to focus on the compression algorithms processing of reflections to not only make sound more natural, but also improve the chance of distance perception not becoming warped through the use of hearing aids and/or hearing protection. Research in this area may lead to more successful fittings and help to eliminate the common complaint of hearing aid users not thinking the sound quality of a hearing aid is natural.

Future Directions

The primary aim of this study was to determine if late reflections contributed to an individual's auditory distance perception when in an open-air outdoor space. Even though an interaction involving reflection delay was found to be significant, reflection delay on its own was not found to significantly affect an individual's auditory distance perception. To see if reflection delays have the potential to significantly affect an individual's auditory distance perception, a few changes to the present study should be further investigated.

One change is in regards to the speech stimulus recording. For the present study, the speech stimulus was recorded at a distance of 10 feet away from the microphone. For future studies, researchers should consider recording the speech stimulus at a distance of 64 feet from the microphone to see if any changes in the estimated distance for speech would occur. Another change is in regards to the pulse train stimulus. The individual pulses that made up the pulse train stimulus were approximately 1ms apart from one another. It would be useful to see if an effect on auditory distance perception could be noticed if the individual pulses were spaced farther apart, minimizing the opportunity for the pulses to blend together. Another useful change is in regards to the pink noise stimulus. In the present study the pink noise was played for a few seconds which seemed to eliminate the reflection cue and make the intensity cue more useful to the participant. To see if the reflection cue could be more noticed, a burst, approximately 10 ms, of pink noise should be used rather than the 1 ms to 2 ms that were presented in this study. Even though the study was focused on reflections in a free field, it would be useful to conduct the same study in an enclosed space. The findings from the present study significantly differed from the results of Bronkhorst and Houtgast (1999) which may have been due to methodological differences. Since Bronkhorst and Houtgast (1999) is one of the few studies that model the effects of reflections and auditory distance perception, it would be useful to conduct a study in an enclosed space to see if the results were more in line with their findings.

Conclusions

Reflection delay, on its own, was not found to significantly affect an individual's auditory distance perception which was the primary goal of this study. An interaction between reflection delay, sound source distance, and type of stimuli used was found to significantly affect auditory distance perception which has previously been reported (Zahorik et al., 2005). These results suggest when a listener is presented with multiple acoustic and non-acoustic cues in a simulated outdoor space, the listener combines the cues and weighs them separately to determine one estimated auditory distance judgment. Further research should be conducted in this area to investigate whether the acoustic cue of the direct-to-reverberant energy ratio has the potential to impact an individual's auditory distance perception when in an outdoor environment.

APPENDIX A

TOWSON UNIVERSITY

APPROVAL NUMBER: 14-A052

To: Lisa Guerra
8000 York Road
Towson MD 21252

From: Institutional Review Board for the Proctection of Human Subjects Beth Merryman, Member ALT

Date: Wednesday, January 15, 2014

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

APPROVED
JAN 15 2014
TOWSON IRB

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:

The Effects of Late Reflections on an Individual's Auditory Distance Perception

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: J. Smart
File

Date: Wednesday, January 15, 2014

NOTICE OF APPROVAL

TO: Lisa Guerra **DEPT:** ASLD

PROJECT TITLE: *The Effects of Late Reflections on an Individual's Auditory Distance Perception*

SPONSORING AGENCY:

APPROVAL NUMBER: 14-A052

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: 15-Jan-2014
This research will be reviewed every year from the date of first approval.

Amy Taylor for

Beth Merryman, Member
Towson University Institutional Review Board

APPENDIX B

TOWSON UNIVERSITY

Department of Audiology, Speech-Language Pathology, and Deaf Studies

INFORMED CONSENT FORM

Project title: The effects of late reflections on an individual's auditory distance perception

Principal Investigator:
Lisa A. Guerra
Lguerr1@students.towson.edu

Faculty Sponsor
Jennifer Smart, Ph.D.
Towson University
Dept. of ASLD
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<u>Purpose of the Study:</u>

This study is designed to evaluate the effects, if any, that late reflections have on an individual's auditory distance judgments. Auditory distance judgments, using pulse-train, pink noise, and speech, will be assessed using seven different distances from the speaker and microphone and seven different reflection delays.

<u>Procedures:</u>

If you take part in this study, a series of assessments will be performed. The study will consist of one session, which should take two hours. During this session, you will receive a free hearing screening and a free visual depth perception screening. If the hearing screening or the visual depth perception screening reveals non-normal hearing and/or visual depth perception, you will be excluded from the remainder of the study and you will be referred to an audiologist and/or opthamologist for a complete evaluation. If you pass the hearing screening and the visual depth perception screening, you will be able to participate in a series of listening tasks. For the listening tasks, you will click through 147 sound bites on a laptop computer. A sound will be presented, either a pulse-train, pink noise, or speech stimulus, and you will be required to estimate the distance, in feet, that you think the sound source is from you. For each estimation you make, you will be required to write your response on a provided piece of paper that is numbered 1 to 147. After you have listened to all 147 sound bites and recorded your responses, you will be required to listen to the 147 sound bites again using the same protocol. All testing will be performed at the Hearing and Listening Lab (HALL) in Van Bokkelen Hall on Towson University's campus.

Risks/Discomfort:

There are no known risks for participating in this study. The tests included in this study are a part of routine clinical and research test batteries. It should be noted that some of the sounds presented through the earphones may be perceived as "loud" but none of the sounds will be presented at a harmfully loud level. Additionally, a hearing loss may be uncovered during the hearing screening and/or difficulties with visual depth perception may be uncovered during the hearing screening and/or visual depth perception screening portion of this research project. The discovery of a hearing loss and/or visual depth perception problem may be troubling and if either issue should arise, the principal investigator will discuss the results of the hearing screening and/or visual depth perception screening with you and you will be referred complete evaluation to further investigate a hearing loss and/or visual depth perception problem. You may go to an ophthalmologist of your choice for the vision evaluation. For the audiological evaluation, you may also go to an audiologist of your choice or contact the Towson University Speech, Language, and Hearing Center. Contact information for the Towson University Speech, Language, and Hearing Center as well as the Counseling Center will be provided.

Benefits:

The results from this research study will have no direct benefit to you. Results from previous research studies do not provide a clear picture regarding the possible effects late reflections have on an individual's auditory distance perception. This study will help researchers to develop a further understanding about auditory distance judgments in an open-air space and whether late reflections continue to have no effect or rather begin to have an effect on those auditory distance judgments. These findings can then be used to make predictions about how a soldier can use his environment to make accurate auditory distance judgments.

Alternatives to Participation:

Participation in this study is voluntary. You are free to withdraw or discontinue participation at any time.

Cost Compensation:

Participation in this study will involve no costs or payments to you.

Confidentiality:

All information collected during the study period will be kept strictly confidential and will be located in a locked cabinet in the Hearing and Listening Laboratory (HALL). You will be identified through identification numbers. No publications or reports from this project will include identifying information. If you agree to join this study, please sign your name below:

_____ I have read and understood the information on this form.

_____ I have had the opportunity to ask questions about the information on this form.

____

Participant's Name (printed)

_______________________________________ ___________________

Participant's Signature Date

_______________________________________ ___________________

Principal Investigator Date

If you have any questions regarding this study please contact the Principal Investigator, Lisa A. Guerra, email: lguerr1@students.towson,edu, the Faculty Sponsor, Dr. Jennifer L. Smart, phone: (410) 704-3105 or email: JSmart@towson.edu or the Institutional Review Board Chairperson, Dr. Patricia Alt, Office of University Research Services, 8000 York Road, Towson University, Towson, Maryland 21252; phone (410) 704-2236.

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CURRICULUM VITA

Lisa A. Guerra

[redacted]

Audiology

Doctor of Audiology

Education:

- **TOWSON UNIVERSITY –** Towson, MD
  - **Doctor of Audiology (Au.D.), August 2011 – Present.**
  - **Anticipated graduation: May 2015**
- **TOWSON UNIVERSITY –** Towson, MD
  - **Bachelor of Science in Speech Language Pathology and Audiology, May 2011**

Clinical Experience:

- **Penn State Milton S. Hershey Medical Center** – Hershey, PA
  - **Audiology Student Clinician, January 2014 - May 2014**

- **Lincoln Intermediate Unit #12 –** New Oxford, PA
  - **Audiology Student Clinician, September 2013 – December 2013**

- **Harmony Hearing** – Bel Air, MD
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- **The Lancaster Cleft Palate Clinic** – Lancaster, PA
  - **Audiology Student Clinician, May 2013 – August 2013**

- **AC Associates: Tinnitus, Hyperacusis, and Balance Center** – York, PA
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