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Effects of reverberation conditions and physical versus virtual source placement on localization in virtual sound environments

Anna Catton
University of Nebraska - Lincoln, acatton@unomaha.edu

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by

Anna Christine Catton

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Anna Christine Catton, M.S.

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Advisor: Lily M. Wang

Sound field synthesis systems vary in number and arrangement of loudspeakers and methods used to generate virtual sound environments to study human hearing perception. While previous work has evaluated the accuracy with which these systems physically reproduce room acoustic conditions, less is known on assessing subjective perception of those conditions, such as how well such systems preserve source localization. This work quantifies the accuracy and precision of perceived localization from a multi-channel sound field synthesis system at Boys Town National Research Hospital, which used 24 physical loudspeakers and vector-based amplitude panning to generate sound fields. Short bursts of broadband speech-shaped noise were presented from source locations (either coinciding with a physical loudspeaker location, or panned between loudspeakers) under free-field and modeled reverberant-room conditions. Listeners used a HTC Vive remote laser tracking system to point to the perceived source location.Results show that the system synthesizes source locations accurately for both physical and panned sources, in both azimuth and elevation. Panned sources, though, are localized less precisely than physical sources. Reverberant condition is also found to affect both the accuracy and precision of localization in the azimuthal plane, with dry conditions

producing greater accuracy and better precision. Only accuracy (not precision) of localization in elevation was impacted by reverberant condition, with reverberant cases producing results closer to the target than dry cases. An interaction effect of reverberant condition with elevation on localization in elevation, though, indicates that dry conditions result in better localization in elevation than reverberant ones at an elevation close to head height, but the situations at higher elevations are where subjects localized dry sources lower than the target height, while reverberant ones were more accurately placed. Other laboratories with sound field synthesis systems are encouraged to gather similar data on the accuracy and precision of localization in azimuth and elevation, so that results from studies using these systems can be better interpreted in light of the capabilities of the system to generate accurate and precise reproductions of source locations. [Work supported by NIH GM109023.]

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Chapter 1

Introduction

The sophistication and popularity of three dimensional (3D) audio systems has been growing in the research setting. Different forms of 3D audio have proven useful to hearing and perception research. The goal of this study is to understand accuracy and precision of source localization in a virtual sound environment using 3D techniques.

Multiple approaches have been used to validate 3D audio environments, but there is no consensus on which validation method to use and if the validation results from different approaches are comparable. In order to realistically reproduce an environment, the users of 3D facilities need to be able to understand the accuracy of their systems. Creating virtual sound environments (VSE) usually involves simulating virtual sources, or sources where there physical speaker is not placed, and different environments that have different acoustical properties, like reverberation time. To generate a virtual sound environment, a number of 3D decoding algorithms can be applied.

Determining how perceived source localization is affected by a virtual reproduction method and different simulated conditions is important for system validation. Understanding the complexity and performance of each system improves the reliability and consistency of data collection. In this thesis, such a procedure is presented for a multichannel 3D audio system at Boys Town National Research Hospital (BTNRH) to investigate the effects of different simulated conditions on perceived localization.

1.1 Motivation

Investigators at BTNRH are interested in using the AV Booth to create realistic environments, like classrooms, to test children's hearing. With such a system, different types of hearing technologies could be tested in dynamic space. What needs to be known about the system to create a classroom environment to accurately test a child's performance? With that, how are 3D systems tested or validated currently and how well are they creating a 3D environment? The next chapter explores 3D audio research along with validation techniques to answer these questions.

The choice of 3D audio technique and the reverberant condition of the virtual sound environment are two considerations that will affect the consistency and accuracy of the simulated space. High order ambisonics, virtual based amplitude panning, and wave-field synthesis are commonly used 3D audio techniques that have unique algorithms for simulating virtual sources. The chosen technique will necessitate specific configurations for the speakers with in a space. Speaker configuration has been shown to influence perception ([Grimm et al. 2015], [Wierstorf et al. 2012]). Even though research using 3D audio spaces has become common, there is less published research showing how varying reverberant conditions in virtual sound environments can influence test results.

The 3D audio technique, reverberant condition of the simulated environment, and types of sources simulated impact the subjective localization during a 3D audio based experiment. By following a protocol to determine the error inherent in a specific 3D system, research data can be better evaluated and controlled for future experiments.

The goal of this thesis is to demonstrate a method to validate a 3D audio system by analyzing localization in different conditions. By determining the accuracy and precision of source localization, both in azimuth and elevation, the results from future experiments using that 3D audio system can be better interpreted. Research has been conducted to characterize the realism of simulated auditory environments, but not to determine accuracy and precision for localization of physical sources compared to virtual or panned sources, nor how these differences are influenced by modeled reverberant conditions. Knowing the performance of a 3D audio system provides higher confidence in the simulation of complicated environments as well as provides a means by which different testing facilities can better compare research findings.

1.2 Thesis Overview

The thesis covers a localization study conducted in the BTNRH AV core. A 2 meter radius surround sound speaker system consisting of 24 loudspeakers was constructed in the sound isolated booth. Speakers were placed at two heights every 30° in azimuth. An acoustically transparent curtain was hung in front the speakers to avoid visual cues during testing. Vector based amplitude panning was used to simulate sources at or in between physical speaker locations; these virtual speakers are referred to as panned sources in this thesis.

A total of 39 target source locations were programmed, at three elevations and 13 positions in azimuth. Sources were located from $-90°$ to $90°$ in azimuth, with every 15° switching between physical and panned sources. The three elevations consisted of the top and bottom ring of speakers and a panned ring, programmed in between the two rings of physical loudspeakers.

Speech shaped noise bursts were played in both dry and reverberant conditions. The dry condition was anechoic with no additional reverberation. The reverberant condition was simulated from a modeled classroom with a 0.6 second reverberation time. Subjects were asked to point to the sound source location, for both physical and panned source locations.

After the data were collected, the response data were analyzed for accuracy and precision for each target location. A multivariate analysis was conducted to determine the effects of source type (physical vs. panned) and reverberation condition (dry vs reverberant) on localization. The goal of this analysis was to see if localization was significantly different between conditions.

1.3 Thesis Structure

Chapter 2 presents a brief overview of 3D audio, a literature review of research using 3D virtual sound environments, and previous studies that have sought to validate 3D audio systems. Chapter 3 explains the methodology used in the study. Chapter 4 presents the findings, while Chapter 5 discusses the meaning of those findings. Conclusions and ideas for future research are presented in Chapter 6.

Chapter 2

Literature Review

The goal of this thesis is to determine how accurately and precisely subjects localize sources produced by a 3D virtual sound environment and how reverberation conditions and physical versus virtual source placement affect those results. This chapter begins with an overview of 3D audio system types and how to create them. Next, a brief discussion on what is known to date about localization accuracy and precision for 3D audio systems is presented. Finally, an overview of current techniques for validating other aspects of 3D audio systems is discussed.

2.1 Overview of 3D Audio and Reproduction Methods

For all aspects of 3D audio reproduction, it is important to use appropriate tools to encode, process, and decode the sound signal. Sophisticated microphones can capture desired real audio that can then be programmed into multi-channel reproduction systems. The market for multi-channel or ambisonic recording microphones is growing. The most basic B-Format recording consists of capturing data in the X, Y, Z, and W coordinates, thereby including the data of three spherical harmonics and an omni-directional data (W) [Espitia - Hurtado et al. 2014]. To achieve higher orders of ambisonics, a more complex microphone array with a higher number of channels is needed.

Sound field synthesis refers to using 3D audio techniques to create a virtual sound environment that has the acoustical properties of another space, either measured in real space or simulated. For example, a large cathedral could be modeled in an acoustic simulation program and reproduced in a virtual sound environment so that an anechoic booth sounds like a voluminous, hard surfaced space. If the encoding is performed on a simulation rather than a measurement, the following steps are taken. First, a geometric 3D model is created using a modeling software, like Google SketchUp or AutoCad. Next, this model is imported into an acoustical simulation software, such as ODEON, CATT, or EASE. Similar to light rendering programs, acoustic simulation programs typically use hybrid ray tracing and source image algorithms to calculate the resulting sound field from sound energy traveling through enclosed spaces. The acoustic absorption coefficients of materials are specified to calculate how sound behaves at boundaries. Source and receiver locations are specified for the simulations, and impulse responses are calculated between source and receiver combinations.

From impulse responses, auralizations can be generated. An auralization is a convolved anechoic file that is reproduced with multi-dimensional acoustic attributes like directionality, time structure, localization, and loudness [Volander 2008].

To generate an auralization, the measured or simulated impulse response is convolved with a recording of a source in a dry or anechoic space (voice, instrument, etc), to produce what the dry audio signal sounds like in the simulated room. Auralizations can typically be presented in one of two playback options, binaural and multichannel. Sound field synthesis systems decode the auralizations to create virtual sound environments. For example, a cinema setup uses a standard arrangement of speakers in a surround sound system.

A processing software is needed to play back desired sound signals. MAX/MSP, Matlab, Meyer Constellation [Ellison et al. 2016], and Lora [Cubick & Dau 2016] are commonly used programs that facilitate multichannel audio playback, testing, and data collection. Some of these processing programs allow researchers to manipulate setups in real time and streamline data collection.

The algorithms used for distributing the sound are referred to as decoding techniques [Blauert & Rabenstein 2013]. Within these programs, plugins can be used to decode in a number of different ways. Plug-ins, such as ViMiC (virtual microphone) [Braasch et al. 2008], HOALibrary [Sèdes et al. 2014], SoundScape Renderer [Ahrens et al. 2008], and IRCAM Spat∼ [Carpentier et al. 2015] can be used to manipulate sources within the complexity of a multichannel system.

When the sound has first been gathered, then encoded and programmed by software, and finally processed and decoded to the specific physical loudspeaker system that has been constructed, a virtual sound environment can be created.

The 3D audio knowledge base has grown immensely over the past few decades.

Installation and use of these systems have grown in popularity for a multitude of markets including commercial, entertainment, home, and research markets. Each installation follows a different range of requirements. For example, a movie theater uses surround sound to immerse the audience with sound. For research, there is a need for an accurate and precise system that works well to reproduce the desired sound environment. A variety of 3D methods can be implemented for testing depending on the research needs. Audio reproduction techniques range from basic binaural (two channels) ones to complex ambisonic or vector based amplitude panned arrangements. The following paragraphs discuss a variety of 3D audio techniques and the technology needed to create them.

Binaural systems employ two listening speakers. This technique is referred to by a number of names such as stereo, cross-talk cancellation/trans-aural, or intensity stereophony [Blauert & Rabenstein 2013]. Stereo is one of the most common speaker setups and is the method by which many people typically listen to audio. Stereo panning is common in radio and television mixes, which divides the audio signal into a left and right channel to give a spatial aspect to the media. If the listener is equidistant and equiangular from two speakers, the two channels can produce a virtual source located in between the two physical sources. Precise source position is then determined by the sound intensity balance between the speakers.

A different binaural localization approach uses headphones. To simulate a realistic listening condition, a head related transfer functions (HRTF) must be implemented in the programming. HRTFs account for how sound waves enter the ear due to the reflections from an individual's body, head, and ear shape [Blauert

1997]. HRTFs have been measured using dummy heads, like Bruel and Kjaer's Head and Torso Simulator (HATS) or G.R.A.S. Sound and Vibration's KEMAR or by placing inner ear microphones on humans [Algazi et al. 2001]. Databases, like CIPIC at the University of California - Davis, have measured and released individualistic human HRTFs for different genders, ages and sizes to more realistically represent a subject [Algazi et al. 2001]. These functions are used to modify the audio signal sent to headphones for listening [Blauert 1997].

For multichanel systems, the option called "nearest speaker" (NSP) is the simplest spatial audio reproduction method. Through this method, sound is sent to the speaker located at the minimum distance away from the programmed source location. The nearest loud speaker method limits the number of source locations to the number of speakers installed in the system [Grimm et al. 2015].

High order ambisonics, or HOA, uses spherical harmonics or cylindrical harmonics in either 2D or 3D. A 2D arrangement must encircle the listener in one plane, while 3D is a spherical enclosed system. The following equations are used to determine the highest order of resolution for the spherical harmonics, where M is the order and N is the number of speakers [Hollerweger 2008].

$$2D - Ambisonics : N = (2M + 1) \tag{2.1}$$

$$3D - Ambisonic : N = (M + 1)^2 \tag{2.2}$$

The first order of HOA is known as B-Format. B-Format is collected using four channels of data: X, Y, Z and W and can generate up to three spherical harmonics. Second and third order HOA contain 5 and 7 spherical harmonics respectively. As the ambisonic order increases, the "sweet spot" or the listening area in which the head must be placed to hear the accurate reproduction gets smaller. After the 5th order, the sweet spot is smaller than the average adult head, making such systems impractical [Clapp et al. 2014]. Due to space restriction in the booth at BTNRH, there was not enough height clearance to build an HOA system with the desired resolution to implement ambisonics.

Wave field synthesis (WFS) is a sound reproduction technique that simulates a source position anywhere within or outside the speaker array, giving a depth and spaciousness to the reproduction. WFS relies on time delay sequencing to place the virtual source [Berkhout et al. 1993]. These systems require a high number of speakers, usually arranged in a line or semi-circle. The theory uses a pressure gradient to determine the intensity across the system through the superposition of a monopole behind or in front of the "acoustic curtain" of speakers [Lopez et al. 2011]. WFS requires a high amount of physical speakers in one plane to generate an environment, making this option impractical for testing multiple elevations with the limited number of speakers at BTNRH.

Vector based amplitude panning (VBAP) places the source at an (x, y, z) coordinate in space using intensity vectors [Pulkki 1997]. This method can place sources to be located in between physical loudspeaker locations. A simulated location is typically programmed as the combination of the vectors of three physical speakers and the weighted gains of those speakers. The gain of each speaker pulls the simulated source one way or another in space. Depending on the desired virtual source placement, the method decodes and delivers the audio signal to a set of speakers that surround the intended source placement. The strength of each speaker place the source in virtual space. If the desired location of a simulated source is at a position equidistant from a combination of physical speakers, those physical speakers must produce the same intensity to create that simulated source. The stronger the intensity vector, the closer the simulated source is placed to that specific physical speaker. When a virtual sound is placed between two or more physical speakers, this is referred to as an image source, phantom image/source, or panned image.

VBAP was determined to be the best option for the BTNRH AV Core booth because it allowed flexibility of physical speaker placement as well as versatility of virtual source location and reverberant condition.

2.2 Localization in sound field synthesis systems

Humans rely heavily on binaural cues to localize sources, which are a combination of interaural time differences and interaural level differences. Interaural time difference, ITD, is the time difference in arrival of signal between each ear, measured in milliseconds. Interaural level difference (ILD), or sometimes referred to as interaural intensity difference, is the difference in loudness of signal between one ear and the other, measured in decibels. The head casts a shadow that decreases the loudness at the ear farther from the source which aids in distance and localization cues [Blauert 1997]. ITD and ILD are two quantities have been found to link to how well humans can localize sound sources, particularly in azimuth or the horizontal plane.

Since humans do not have ears on the top and bottom of the head, ILD and ITL provide little assistance in perception of elevation. Humans rely heavily on spectral cues for elevation localization. Additionally, an individual's head related transfer function helps localization. Based on the shape of the head and torso, each body receives and reflects frequencies differently, which determines how sound enters the ear from all angles [Blauert 1997].

Reverberation characterizes built environment, and in the case of virtual sound environments, creates realism and externalization in simulations [Shinn-Cunningham et al. 2005]. For localization in reverberant spaces, humans depend on the precedence effect by using first and secondary reflections to determine a source location. As the decay time, or reverberation time, increases there is a decrease in the ability to localize sources because reverberation degrades interaural cues. Additionally, reverberation increases bias on source localization. Bias indicates the tendency for localization to be overshot either left or right of the target location. Sound reflections provide environmental information of ones surroundings which is important for creating a realistic virtual environment.

In terms of localization in anechoic environments, Perrott and Saberi's 1990 work determined minimum audible angle (MAA) thresholds for sources distributed along the horizontal and elevation plane. MAA is defined to be the smallest detectable angular difference between source location. It was found that the mean minimum audible angle was 0.97° in the horizontal and 3.65° in the vertical plane. Sources were also distributed on the oblique plane from 10 to 60 degrees, and low differences in MAA was observed with means ranged from 0.78° to 1.06°. There were only 4 participants in this study [Perrott & Saberi 1990]. A different approach to studying subjective localization was conducted by Recanzone et al. [1998] to determine if relative and absolute sound localization differed in localization metrics. The ability to determine if the a repeated stimulus has changed postitions determines the relative threshold, where as the absolute threshold is determined by the ability to location of a source with only one stimulus. It was concluded that relative localization is a reliable estimate of absolute spatial localization. This is important to note since it suggests the width of responses do not differ between the two psychometric measures, but they are not thresholds like that measured by Perrott and Savebi [Recanzone et al. 1998].

Carlile et al. [2016] looked into the just noticeable difference (JND) discerning when subjects can tell the source has moved, a relative localization metric. Seven subjects participated in this study, six of whom were untrained listeners [2016]. The JND was tested for each of the following azimuth angles: 0°, 3°, 6°, 12°, 30° and 45° using a constant stimuli. It was found that the mean JND was 6.1°, but the lowest JND of 2.7° occured at the 6° azimuth location. Localization accuracy decreases as the azimuth of the source increases towards the periphery.

Measuring accuracy and precision of subject localization is an effective way to determine localization performance S Dobreva et al. [2012]. This approach quantifies the consistency and spread of responses for all recorded data, extensively describing localization. Accuracy is determined by the mean average of a subject's responses for a specific target. Standard deviation of target responses from one subject for a specific target determines the precision of localization. Another factor of localization is bias which is the tendency to favor a certain direction in location selection. Spatial gain describes how responses for a specific target are either underestimated or overestimated in responses. Additionally, the ability to localize visual target was also investigated by S Dobreva et al. [2012]. The results of this study determined that visual target localization was more accurate and precise than sound localization, therefore a the visual aspect of localization would not interfere with sound source localization.

Hartmann et al [1998] presents analysis techniques used for source identification method, a standard technique to measure source localization ability in rooms. By analyzing the variability and rms error collected from localization responses, and using a decision theory model, which characterize the metrics of width and bias of mean responses. Depending on the speaker array span, Hartmann at. al. provides general guidelines to determine if there are enough speaker sources in the array to provide good analysis.

How localization accuracy and precision differ between immersion 3D audio setups has also been studied. Frank [2014] looked at localization in the frontal horizontal plane for decoding with VBAP, multiple direction amplitude panning (MDAP), and ambisonics. It was determined that VBAP had a 2.35° "average absolute deviation of median experimental results from ideal localization curve," or response average off from the target [Frank 2014]. The average absolute deviation for MDAP and ambisonics were 1.28° and 1.58° respectively. Angle at which panned sources were presented had a statistically significant effect on localization. The test was only conducted from 0° to 45° in 5° intervals. Fourteen subjects participated in this experiment.

Another study gathered the localization error and standard deviation for both real and virtual sources in a flight simulation setup [A. Pedersen & Jorgensen 2005]. The physical sources were real speakers and the virtual were simulated over headphones with a generic HRTF. Subjects included 13 Royal Danish Air Force pilots and 13 civil persons. A total of 58 sources (16 real and 42 virtual) locations were tested at 15 values of azimuth and 9 values for elevation. The stimulus was a dry white noise burst with a duration of 250ms. These data, shown in 2.1, show how much better physical sources were located than virtual in both azimuth and elevation.

	Physical		Virtual	
Direction	Mean	Std. Dev.	Mean	Std. Dev.
Azimuth	0.7	8.8	-2.8	0.9
Elevation	4.4	11.2	13.6	20.5

Table 2.1: Physical and virtual source localization mean and standard deviation in degrees reported by A. Pedersen & Jorgensen 2005

2.3 Validation of sound field synthesis systems

The use of 3D audio systems for research is growing. When using 3D audio for research purposes the main goal is to create a realistic sound field.

A question that continues to be asked is how well do systems reproduce the sound field? Are they accurately and/or precisely simulating sound at the listener location? What measures should be taken to validate such a testing environment?

Currently, there is no standard; each research facility generates virtual sound environments using its own particular system, both hardware and software. It is then difficult to compare data from one lab to that of another since there is no standard protocol that labs follow to report how well their system functions. Due to differences in loudspeaker setup and encoding/decoding techniques, each system may have different levels of reproduction fidelity. There is no consistent method for checking a system's accuracy and precision, but some laboratories have made efforts to validate their systems.

One method of validating encoding and decoding techniques is by measuring binaural cues. Accuracy is quantified by differences in the known ILD/ITD values and those measured in the simulated space during the study. Clapp et al. used this method for evaluating an ambisonic reproduction of a sound-fields by comparing different measurements taken using spherical microphones arrays [2014]. A spherical microphone array measured the natural and simulated ITD and ILD values to compare different 2D sound field reproduction ambisonics to decode the signal to 24 speakers on one horizontal plane. From here the researchers evaluated error using ITD and ILD differences [Clapp et al. 2014]. It was found that error between the natural and simulated stimulus was between 0.17 ms to 0.24 ms for ITD and 3.8 dB to 4.3 dB for ILD. By knowing the differences in simulated and actual binaural cues, the facility can determine the quality of their reproduction. Such a validation produce requires the simulation to be of a physical room from which data for comparison can be acquired.

Algorithms are another approach to validation, where computer generated or hearing aid algorithms are used to determine the quality of systems. Grimm et al. [2015] conducted validation tests on three different 3D audio set-ups (HOA, VBAP and discrete speakers) by measuring different classes of algorithms using spatially distributed microphones and one channel of noise reduction to gather the metrics of beam pattern analysis, signal to noise ratio, perceptual localization prediction and quality modeling to determine the quality of reproduction. Measurements were taken using a HATS manikin wearing hearing aids. A series of computer simulations analyzed the hearing aid algorithms, including static binaural beam former, adaptive differential microphone, binaural noise reduction, and single channel noise reduction, to determine how well 3D audio systems could be used for hearing aid research. It was concluded that depending on the type of desired algorithm analysis and bandwidth, certain decoding methods work better than others for quality testing, such as VBAP and HOA are best for beam pattern analysis but signal to noise ratio behavior is best tested using NSP.

Another validation method compares measured versus simulated acoustical metrics, including reverberation time (T30), speech clarity (C50), speech intelligibility and the interaural cross correlation (IACC). These metrics can be calculated from impulse response measurements. Modeling software, like Odeon, also generates these metrics through 3D model simulations. Researchers Cubick and Dau measured a lecture hall and compared to a measured VSE created in ODEON and reproduced using HOA and Nearest Speaker decoding methods on a 29 speaker spherical array [2016]. A HATS manikin wearing hearing aids was used to compare the actual room and the model space in their 3D virtual sound environment. The results compared acoustic metrics found that the modeled Odeon room and the measured VSE room were nearly identical for reverberation time, while the measured C50 was 2.3 dB lower than the VSE modeled value. IACC measures indicated that the VSE was a more diffuse field than was modeled. Subjective measurements were also taken to determine speech intelligibility differences between the lecture hall and modeled VSE. The intelligibility decreased from the lecture hall to the HOA model, and decreased further when compared to the Nearest Speaker method. The researchers concluded that the desired differences between the real and simulated measurements translated well to real world applications, but at this point nearest speaker is better for simulating an environment for testing hearing aids than HOA.

Lastly, a few researchers have conducted subjective localization studies to determine a system's functionality will be explored. For Wierstroft's 2012 study, subjects participated in trials that compared wave field synthesis and higher order ambisonics simulated over a spherical speaker array to binaural sources simulated through headphones. The goal was to determine if there is a significant difference in azimuth localization abilities between sound field synthesis and binaural synthesis using both an anechoic HRTF and measured HRTF of the testing space [Wierstorf et al. 2012]. This study provided angular results for validations of a line array of loudspeakers. Findings showed small differences between the synthesis techniques, with the loudspeaker mean equals 2.4° and standard deviation equals 2.3° for localization. For standard deviation, the localization blur was the same between real speakers and the room HRTF conditions, showing evidence that diffuse energy from room reflections aids in the localization of virtual simulated sources [2012]. Weirstroft further assessed localization accuracy for sound field systems [2017] . Findings showed the best achieved localization accuracy is 3° at a central listening position for fifth-order HOA employing 12 loudspeakers and a distance between the loudspeakers of appropriately 2 m.

Oreinos and Buchholz used subjective testing to validate their system [2016]. This study had subjects listen in three locations. The first location was the actual room environment, the next an ODEON model of the environment reproduced with a VSE, and the last was a decoded spherical array recording from the actual space also reproduced in the virtual sound environment. Subject performance was evaluated by conducting speech intelligibility tests in each environment and comparing the results between simulations. The ODEON model out-performed the decoded recording, but the actual environment had the best results [Oreinos & Buchholz 2016]. These results indicate the degraded quality of reproduction systems through subjectively comparing different approaches, but do not explicitly provide validation or assessment of the accuracy of the 3D audio system.

After examining these techniques for system evaluation, it is apparent that validation approaches vary widely from one research facility to the next as each research group has different research intentions for their 3D audio system. None of the reviewed studies document localization accuracy and precision of their systems. Additionally, none of the studies have compared how that localization varies between the physical and panned (virtual) source locations nor how significantly reverberation affects results. Even though there may be consistent acoustic characteristics between the real and virtual environments, those do not provide evidence of consistent source localization by listeners. Some of these investigation have provided input on how accurate the system is on a mathematical level, but then miss a link to subjective perception. This thesis presents work on performance at simulating source locations under different source type and reverberant conditions. gathering such data from other 3D virtual sound environment systems will aid in better interpretation of research results from those facilities and help make results more comparable across systems.

2.4 Summary

The intention of this study is to determine a basis for 3D audio system performance through quantifying the accuracy and precision of source localization and to determine effects and interactions between environment conditions, specifically reverberation and source placement. To investigate these issues, this thesis examines the following questions for a specific 3D audio system used for sound field synthesis creating a virtual sound environment at BTNRH:

1. Is there a significant difference in source localization accuracy and precision when sources are placed at physical and panned source locations?

2. Is there a significant difference in source localization accuracy and precision between dry and reverberant room conditions?

3. Does this system and proposed validation process work overall, i.e. does the

work presented effectively quantify localization and validate a 3D VSE system?

Chapter 3

Methodology

This chapter describes the testing facility, equipment, software design, and measurement procedures used for this thesis.

3.1 Testing Facility

Boys Town National Research Hospital in Omaha, Nebraska constructed a specialized audio visual (AV) core facility which can be used for multichannel sound reproduction to conduct various types of hearing research.

The booth (Figure 3.1) is a hemi-anechoic chamber with a measured reverberation time of 0.11 seconds at 1000 Hz. The booth has a cubic volume of 81.4 m^3 (5.8 m x 5.2 m x 2.7 m), and is structurally isolated from adjacent spaces. This is done by attaching the booth construction only to the beam structure of the building so that structural vibrations do not transmit as easily via the structure. The ventilation system for the space is also separated from other spaces providing a low noise floor of 20 dBA (ref 20 μPa). For this study, the AV core facility was outfitted with 24 speakers. Speakers can be attached at any point on pipes attached to the walls using pipe mount connectors, allowing versatile testing configurations.

Figure 3.1: The AV core facility at Boys Town National Research Hospital

Each loud speaker was wired as its own channel to a control station located in a control room outside of the booth. The loudspeakers used are Elipson Planet M. The speakers were chosen for their flat frequency responses. Two computer systems were used shown in Figure 3.1. A MacPro running MaxMSP controlled all audio interfacing. Audio data were distributed by a MADI sound card out to the speakers. Each channel was powered by SLA 4 amplifiers. The second computer was a Puget Serenity PC running Windows 10, used to control the virtual reality software via Ethernet connection to the booth.

3.1.1 Room Configuration

A two meter radius circle of speakers was constructed and installed using a system of PVC piping attached to existing steel pipes and free standing tripods. Speakers were installed every 30° at two heights: 1 m and 2.1 m. A ring of twelve speakers was placed on each elevation for a total of 24 speakers. Figures 3.2 and 3.3 presents 3D model view and a photo of the fully installed speaker arrangement.

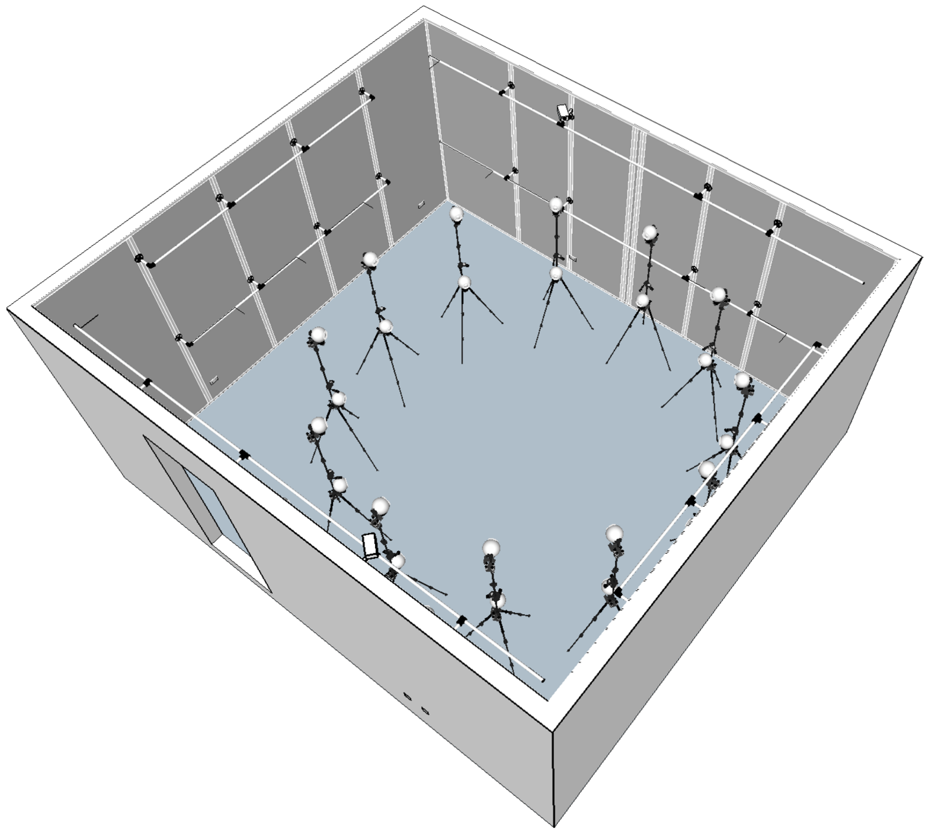


Figure 3.2: 3D model showing speaker placement in the booth

A chair to be used by listeners was placed in the center of the 2-meter radius circle facing one of the physical loudspeakers, designated as 0°. The location of the chair feet were marked with tape on the floor for consistent placement.

A KEMAR head and torso manikin with microphone at each ear position was placed in the testing chair facing forward or 0°. Each speaker was then aimed towards the KEMAR's head at its ear height. An attachment was 3D printed to mount a laser pointer onto each Elipson loudspeaker. The speaker position could then be accurately adjusted to aim the center of its speaker grill directly at the KEMAR's ears via the laser attachment.

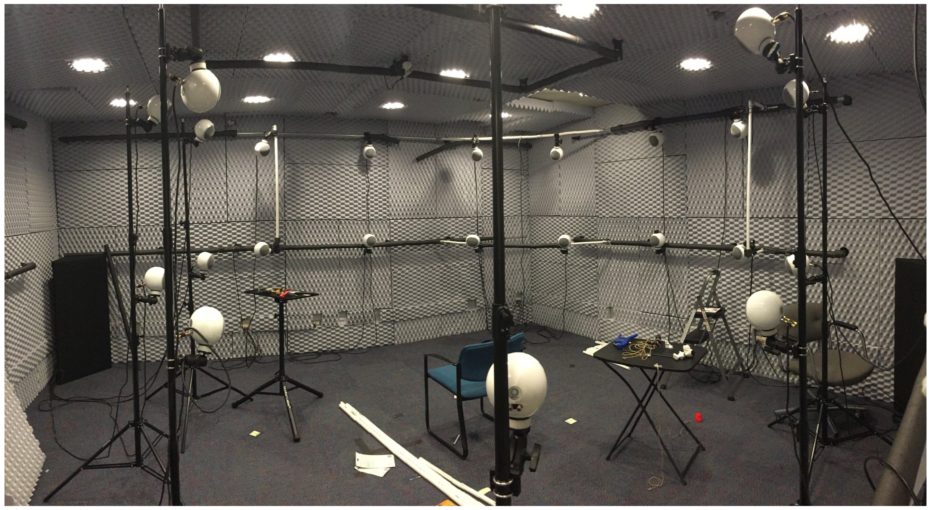


Figure 3.3: Loudspeaker set up

After all speakers were properly aimed, an acoustically transparent black curtain was hung so that listeners would have no visual cues as to physical source locations during experimental testing (Figure 3.4). The curtain material used was Guilford of Maine Anchorage Onyx Fabric. The fabric arrived in 66" wide panels, which was not tall enough to cover the height of the entire booth, so two 42 foot long pieces of the fabric were iron seamed together to create a roughly 10 foot tall curtain which covered from just above the top ring of speakers to the floor. Metal eyelets were installed along the curtain length to attach hooks to hang the fabric. A 16 sided polygon constructed from PVC piping and suspended from steel pipes in the room was installed above the speaker system at a radius of about 1.8 m. The curtain was attached using shower hooks to the PVC pipe ring. Fabric draped right in front of the loudspeaker faces without touching them.

Figure 3.4: Installed acoustically transparent curtain

After placement of the speaker and curtain system was finalized, each loudspeaker was calibrated using a Larson Davis 831 sound level meter (SLM). The sound level meter was placed at the listener location at ear height. White noise was then played from a single speaker, and that speaker's gain was adjusted from the amplifier until the SLM level was 75 (± 1) dBA (ref 20 μPa) with fast time weighting. This calibration process was done periodically throughout the 4 month experimental period to ensure consistent sound levels.

3.2 Experimental Design

The objective of this study is to measure and compare localization accuracy and precision of physical and panned sources in a virtual sound environment, under dry and reverberant conditions. The purpose is to quantify how source type and reverberant condition in this test facility and system impact source localization.

Physical sources refers to a simulated sound source that is located at an actual speaker location. Panned source refers to a simulated sound source that is located in between two or more physical speakers. Dry condition refers to a stimulus sound that has no late reverberation tail. Reverberant condition refers to a stimulus sound that has a reverberation time of .6 seconds, similar to school elementary classroom.

The study used 39 source locations in the frontal hemisphere (Figure 3.5) . These resulted from 3 elevations and 13 positions in azimuth, corresponding to lowest ring, ring 1 = 1 m, of physical speakers, ring 2 = 1.65 m, between the two physical rings, and ring 3 = 2.1 m, corresponding to the highest ring physical speakers. Stimuli were played from each location six times for each reverberation condition. These resulted in 468 trials (39 x 2 x 6) per subject. Six randomized blocks were compiled to create one subjects presentation order. Fifteen orders of the 468 trials were generated and then those 15 were reversed to create a total of 30 presentations orders, allowing some balance in presentation order across the subject pool.

Ring 3	x	o	x	o	x	o	x	o	x	o	x	o	x
Ring 2	o	o	o	o	o	o	o	o	o	o	o	o	o
Ring 1	x	o	x	o	x	o	x	o	x	o	x	o	x
Azimuth	-90	-75	-60	-45	-30	-15	0	15	30	45	60	75	90

x - Physical
o - Panned

Figure 3.5: Physical and panned source locations across azimuth and elevation

The audio signal used was a speech shaped noise burst; six different speech shaped noise bursts were created for use in the experiment. The clips were taken from a long-term average spectrum of speech (LTASS) file at six separate parts of the sentence[Byrne et al. 1994]. Samples were 200 ms in length with 10 ms fade in, 180 ms of constant level, and 10 ms of fade out. Each noise burst stimuli was checked for unwanted peaks or obvious characteristics to ensure all the samples were similar. The six signals were presented in random order throughout the trials.

3.3 Experimental Methods

3.3.1 Subject Response Recording using a Virtual Reality System

An HTC Vive remote controller was used by listeners to select source locations. The HTC Vive Virtual Reality system is one of multiple virtual reality (VR) systems available on the market today. A normal setup for the HTC VIVE system can be seen in Figure 3.6, where a user wears a headset and holds two remotes to interact with the system. To track the remotes in space, two bay stations emit laser pulses to read photo-sensors on the remotes and calculate time differences to determine each remote's orientation and position. For this experiment, only one remote, with no headset, was utilized to record the subject responses. The bay stations, placed in the northeast and southwest corner of the AV core translated the remote position from virtual space to the physical space.

A laser pointer was attached to the VIVE remote so that test subjects could visually see target selection locations (Figure 3.7). The laser was mounted in a 3D

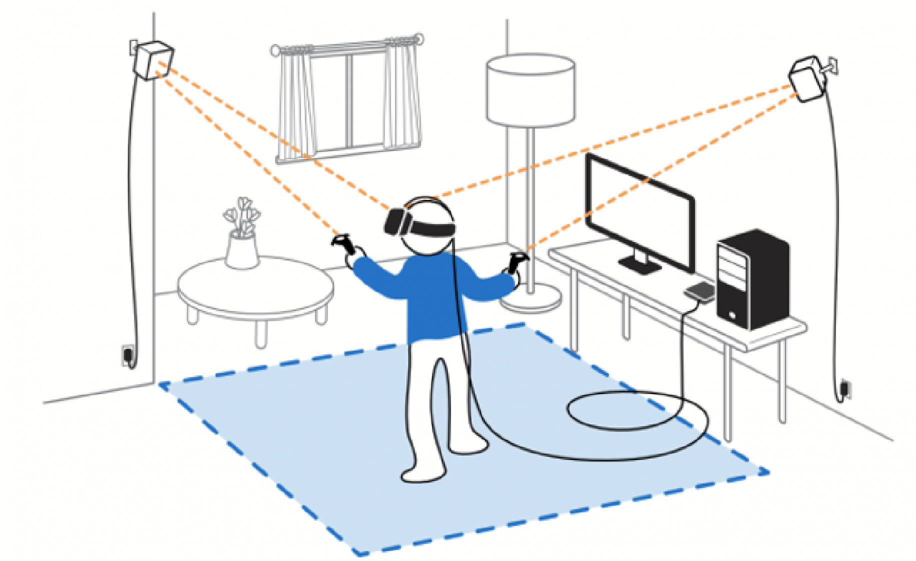


Figure 3.6: An HTC Vive Virtual Reality room setup with bay stations

printed connector, which was glued to the VIVE remote.

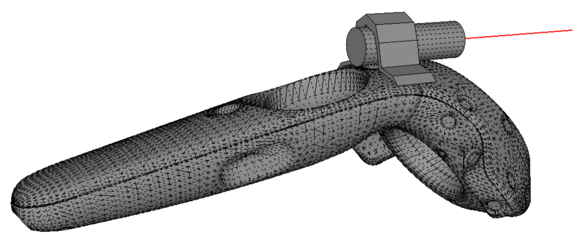
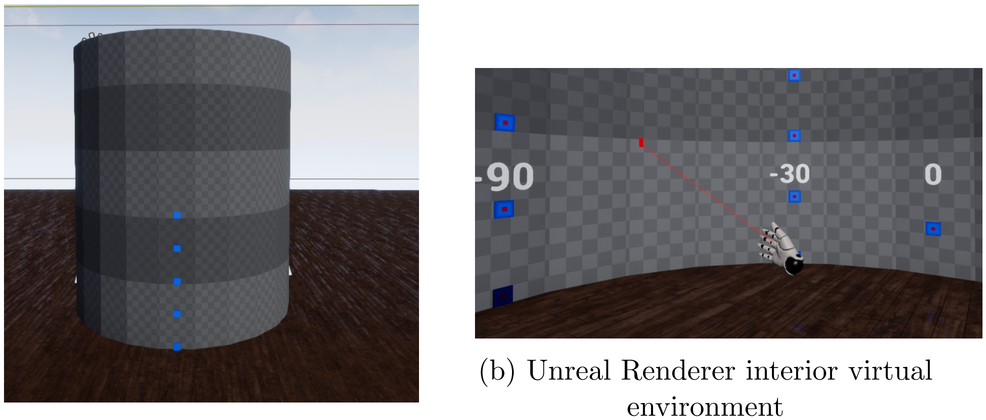


Figure 3.7: Remote with laser pointer attachment

The virtual reality environment was built using the software Unreal Engine Renderer (Epic Games, Cary, NC). The modeled space consisted of a 2 meter radius cylinder that represented the possible source locations placement in the booth (Figure 3.8a). The software tracks the location of the VIVE headset and controllers from two ray tracking bay stations placed behind the curtain, with the tracking box located just above the top edge of the curtain. Although the headset was not used in testing, if the subject were to put on the headset, they would see themselves enclosed in a circular room with a laser pointing out of a virtual hand (Figure 3.8b).

The software “sees” where the remote resides in the virtual environment, both in orientation(pitch, yaw, roll) and location(X, Y, Z). A laser beam was programmed to extend out of the remote/hand to the edge of the cylinder.



(a) Unreal Renderer exterior virtual environment

(b) Unreal Renderer interior virtual environment

Figure 3.8: Unreal Engine Renderer 3D model views

To calibrate the orientation of the HTC Vive system and the Unreal Renderer environment, the headset was placed on a floor marker in the center of the loudspeaker ring facing the subject orientation of 0°. Once the headset was correctly aligned in azimuth, a button on the Unreal Renderer interface set the virtual environment orientation to match the physical.

To confirm that virtual reality environmental coordinates were accurately recorded in the experimental software, a MaxMSP calibration program was written to verify the remote tracking data. The program recorded and displayed the remote’s virtual azimuth degree and height when the remote trigger was pulled. To calibrate the recorded position of the remote prior to each day’s testing, the remote was aimed at a known reference point, marked with a laser affixed to a speaker in the facility, and the resulting azimuth and height was then recorded. If the calibration programs readings were off by less than 2 inches in height ± 1° in azimuth, the system was ready for testing. Otherwise, the process of aiming the headset and aiming the remote was repeated until the reading was within acceptable values.

3.3.2 Face Tracking

To maintain a consistent head position when subjects listen for the noise bursts, a face tracking application was created. This application ensured that the subject was facing forward when the audio signal for each trial was presented. A software called Unity (Unity Technologies, San Francisco, CA) provides a plug-in that reads facial features in real time and reports face angle. A program was then written in Unity to use the face tracking data to report head orientation. The program tracked head orientation using facial features captured with a high resolution web camera placed at the 0° azimuth in front of the curtain at roughly two feet high. Figure 3.9 shows how the software tracks facial features as the head rotates. Subjects were instructed to turn their head to face toward the camera at 0° after selecting a trial source location using the remote. For the next trial to trigger, the face angle had to read between ± 7° for at least three seconds. The application was programmed to read instantaneous facial angles only, no video was recorded.

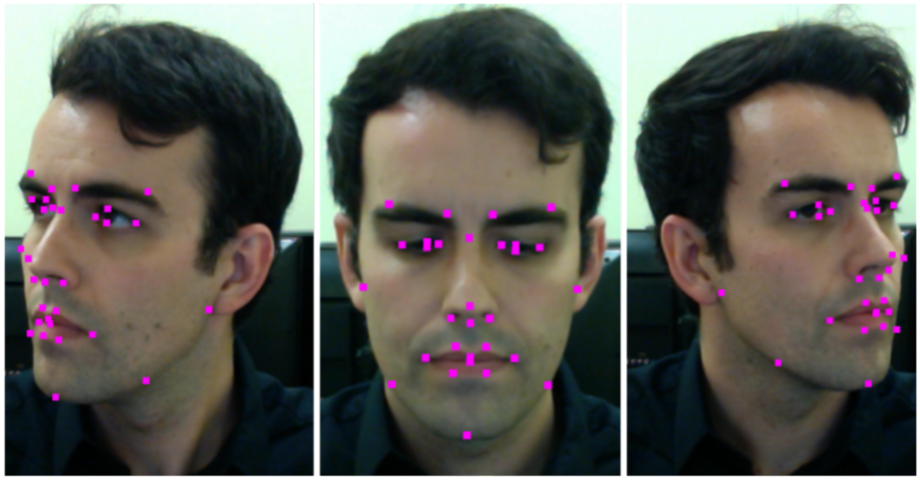
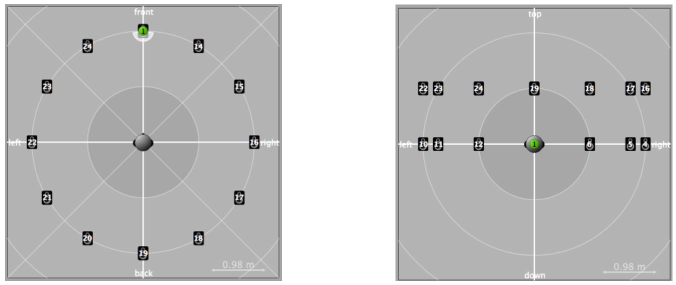


Figure 3.9: Images from the Unity face tracking software, which detecting facial features to measure head placement in azimuth

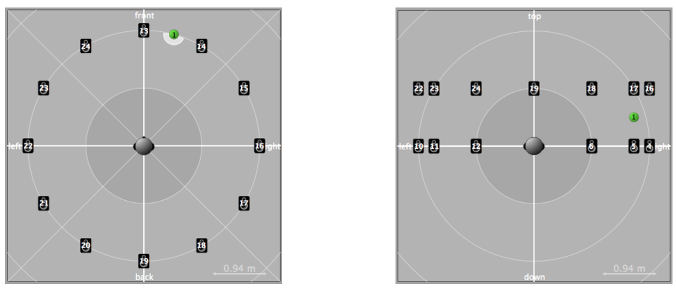
3.3.3 Spatialization software

The MaxMSP plug-in IRCAM (Institut de Recherche et Coordination Acoustique/Musique) Spat∼ was utilized to synthesize the sound fields used in this study. Of the encoding and decoding programs available, this program was chosen because of its ability to decode in multiple methods to a 3D array of speakers and simulate a modeled room reverberation time. With in Spat∼, the locations of physical loudspeakers relative to the listener position were input as (x,y,z) coordinates into the software. Virtual or panned source locations could then be created using the same coordinate system. From there sources could then be programmed to play through the speaker system using a VBAP 3D audio algorithm. Figure 3.10 presents the interface of Spat∼ placing a source at 0° azimuth and the lowest elevation ring (Ring 1). The black numbered dots represent physical loudspeakers in the booth, while the green dot represents the simulated source location. In Figure 3.11a the panned source to be simulated between two physical source locations, is shown as the green dot.



(a) Spat∼ azimuth view (b) Spat∼ elevation eiew

Figure 3.10: Spat∼ source simulation view



(a) Spat∼ azimuth view panned (b) Spat∼ elevation view panned

Figure 3.11: Spat∼ source simulation view panned

A block diagram of hardware and software set up to control the experiment is shown in Figure 3.12. The experiment was run from a MaxMSP user interface on a MacPro. When triggered by face placement, the signal is played and the subject selects their answer using the VR remote. The PC running the Unreal Renderer then records the remote orientation (pitch, yaw, roll and the target's X,Y,Z) coordinate in the booth. Data are then sent back to MaxMSP and recorded within the subject data file and was recorded.

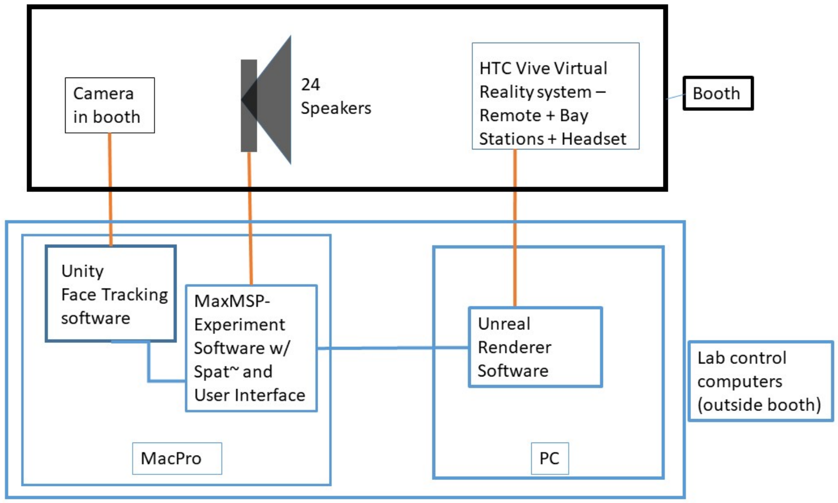


Figure 3.12: Block diagram depicting hardware and software connection for this study

3.4 Subjective Test Procedures

A total of 44 subjects participated in some part of this study. All subjects were recruited through Boys Town National Research Hospital in Omaha, Nebraska. The study was approved by the internal review board at BTNRH. To qualify, subjects must be older than 19 and have hearing thresholds lower than 25HL with normal tympanic function. An audiogram was conducted either on site or within the past six months by an audiologist. A tympanogram was conducted on the day of testing by an audiologist on site. Subjects were paid $ 15/hr for their time.

Nineteen subjects (8 males, 11 females) were able to participate in both rounds of measurements and subsequently used for data analysis. Ages ranged from 19 to 53 years, with an average of 31 years and mode of 21 years.

3.4.1 Pre-Measurements Protocol

After completing an informed consent form and passing the hearing tests, participants were asked to take a musical experience questionnaire. This questionnaire asked a range of questions determining their familiarity with music. Quesetionnaire questions are provided in Appendix D.

The testing procedure was explained to each subject, following a basic script outline. The subject was subsequently asked to enter the booth and sit in the chair facing towards the face-tracking camera. Following given instructions, a few test trials were first deployed to familiarize the subject on the experimental process. For most subjects, a block of 468 trials took less than an hour to complete. Those subjects who were able to perform the task successfully were invited to return on a second day to complete a second block of measurements. The second block followed the same test protocol, except that the 0° azimuth face a panned source, as shown in Figure 3.14.

3.4.2 Measurements Set Up: Round 1

The setup for the first round of experiments placed the subject facing a physical speaker at 0° azimuth (Figure 3.13). Subjects were asked to bring their face back toward 0° before the next trial triggered. Room orientation was constant between round 1 and 2. Figures 3.13 presents these coordinate systems for round 1. Room orientation refers to angular placement of the testing circle based on booth direction, where due west is 0°. Subject orientation refers to the angular placements of the testing circle based of the subject seat position, where the front facing direction of the seat determines 0°.

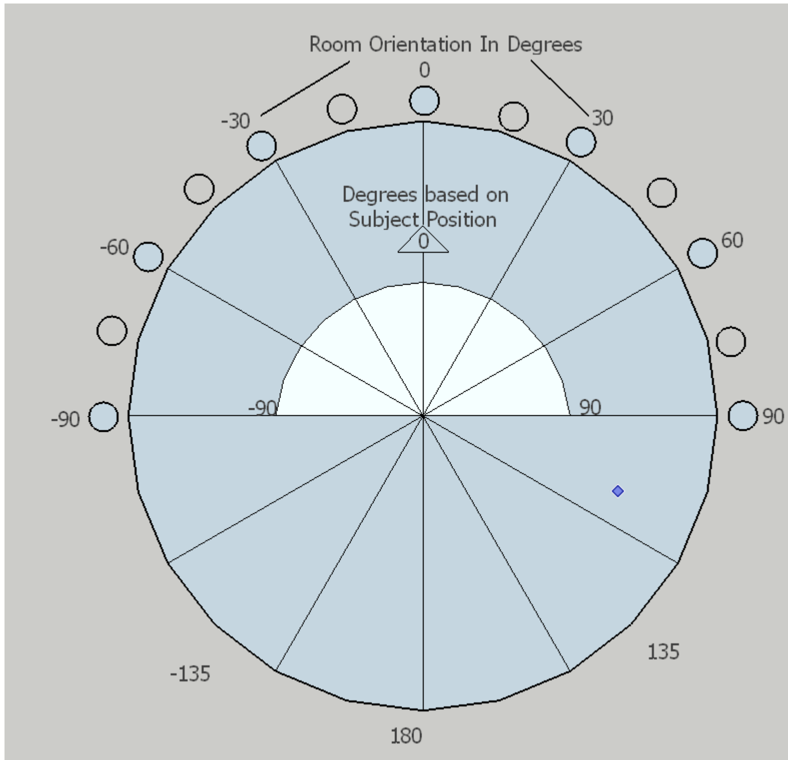


Figure 3.13: Round I: Room and subject orientation

After conducting the first round of measurements multiple subjects were excluded from analysis for various reasons. If a subject reported a localization technique or specific strategy that did not align to the initial instructions, the subject was excluded. Another reason for exclusion was if the subject selected the ceiling or the floor an excessive amount of times, these location selections would report as "0" in the raw data. Finally, a subject were excluded if their overall response rate was greater than 5 percent front-back confusion occurrences. A response qualified as a front-back confusion response if the subject selected an azimuth angle 30° wider than ±90°.

The random number generator used to create the blocks of presentation trials exhibited an error where some location conditions only appeared 5 times and others appeared 7 instead of the intended 6. This issue was resolved before the second round of data collection.

3.4.3 Measurement Set-Up: Round 2

A second round (Round 2) of measurements were taken to gather data that would allow direct comparison between physical and panned sources at the same azimuth locations. Participants whose data were not excluded in round 1 were asked to return to participate in round 2. A total of 19 subjects returned for round 2. The procedure and measurement technique were exactly the same as Round 1. The only adjustment was the subject orientation or the direction the subject face forward. The second setup rotated the subject 15° counter clockwise, placing a panned source at 0° azimuth. Figure 3.14 presents the shifted subject orientation with a panned source located at 0°, relative to the fixed loud speaker presented in room orientation.

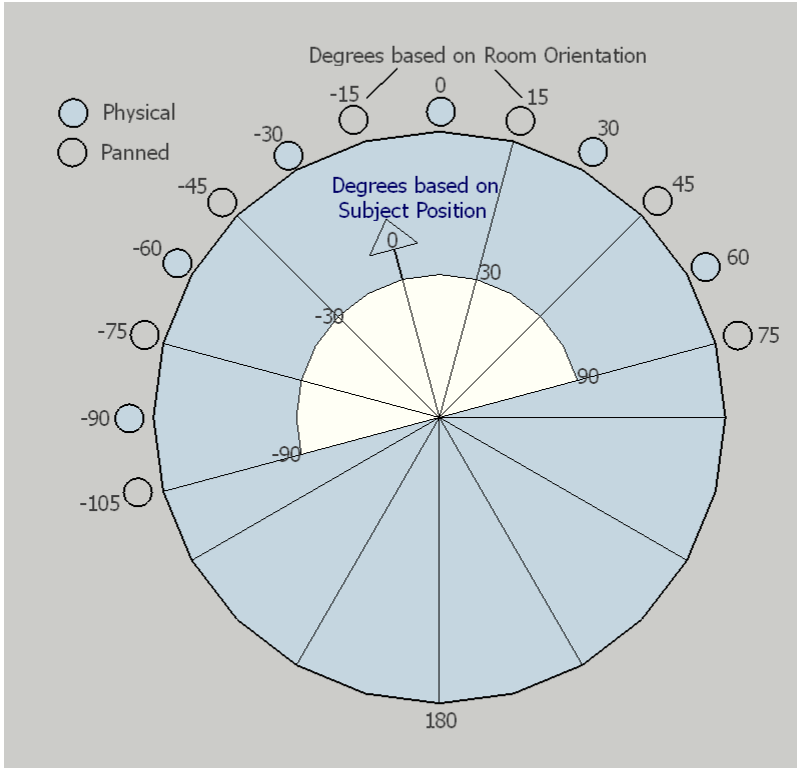


Figure 3.14: Subject orientation was shifted 15° counterclockwise relative to room orientation in Round 2

Ring 3	o	x	o	x	o	x	o	x	o	x	o	x	o
Ring 2	o	o	o	o	o	o	o	o	o	o	o	o	o
Ring 1	o	x	o	x	o	x	o	x	o	x	o	x	o
Azimuth	-90	-75	-60	-45	-30	-15	0	15	30	45	60	75	90

x - Physical
o - Panned

Figure 3.15: Round 2 source placements across azimuth and elevation

3.4.4 Data Collection and Storage

Raw data was stored in csv files by identification subject number. MatLab R2017b (Mathworks, Natick, Ma) was used to process data. A line was recorded after each trial during the experiment. Each subject's data file included details on the follow values: subject number, data presentation line, trial number, group number source location/condition, speech shaped noise burst sample, room coordinates of source location, raw response coordinates, calculated response angle, calculated height response, and date and time. CVS files were saved to a network drive and cloud data storage.

3.5 Data analysis exclusion

Trials that exhibited evidence of front-back confusion were excluded from analyzed data. After these trials were removed, the mean of each location condition (dry and wet) was calculated, i.e. a total of 78 means. Mean outliers were excluded for each individuals subjects responses data, calculated for each of the 78 location conditions. Therefore, some subjects location means were possibly the average of less than 6 trails.

3.6 Concluding Remarks

This chapter provided an overview of the measurement methods used to gather the data presented in subsequent chapters of this thesis. In summary, the objective for this study is to measure localization accuracy and precision under dry and reverberant conditions of physical and panned sources in a virtual sound environment. Normal hearing adults were placed in the center of a 2m radius circle of speakers. Speakers were located every 30° degrees at two elevations. A series of speech shaped noise bursts were played from 39 source locations in the frontal hemisphere from both physical speakers and panned virtual speakers. The panned sources were simulated in between physical source locations using vector based amplitude panning. Noise bursts were presented in a free field (dry) and a modeled classroom condition with a .6 second reverberation time (wet). Subjects used a virtual reality remote control to point to and record the noise burst origin. Nineteen subjects completed the test twice, once with the listening position facing a central physical speaker, and a second time with the listening position rotated 15° degree to the left with the central listening position facing a panned source location. This permitted the comparison between physical and panned sources at same locations relative to the listener.

Chapter 4

Results

This chapter presents the results from data collected in rounds 1 and 2. First the statistical analysis approach is described. Then localization findings across azimuth are presented, followed by results analyzed across elevation. Statistically significant effects and interactions are presented in each section of the analysis.

4.1 Introduction

Statistical analyses were conducted using IBM SPSS Statistics Version 24. A general linear model (GLM) with repeated measures was used to determine the effects between experimental factors. This multivariate analysis of variance assumes each measurement is independent, allowing a subject to participate on multiple occasions (round 1 and 2) to test variations of dependent variables, including elevation, azimuth, source type, and reverberant condition. General linear models also allow for analysis across multiple conditions with an increase of statistical power [Hutcheson & Sofroniou 1999].

The GLM was constructed using multi-levels of within-subject factors, or independent variables. Factors for each statistical run included elevation (2 levels: top ring and bottom ring), source type (2 levels: physical and panned), reverberation condition (2 levels: dry and wet), and azimuth location (13 levels: locations across azimuth). The middle panned ring was excluded in primary analysis because it did not simulate both sources types. The lower and upper ring consisted of both panned and physical sources and will be referred to as Elevation 1 and Elevation 3, respectively. The between-subjects factors were the 19 subjects that participated in both experimental rounds. Azimuth and elevation localization were evaluated independently.

Accuracy and precision are assessed for each target position by evaluating the means and standard deviations of responses for each target location in each condition. A table of the overall mean and standard deviation for each of the 39 azimuth location is provided in Appendix A. Since each location was presented twice (dry and reverberant) for a repetition of six times, each subject's responses were averaged to calculate the mean of each locations responses. Due to an issue in the random number generator, some location conditions were only presented 5 times instead of the intended 6, in those cases the mean is an average of recorded responses. Standard deviation was calculated from the mean of responses for each location condition. Subject mean responses of wet and dry conditions are shown for each location in Appendix B. The accuracy was determine by the difference between the response mean and target location. The standard deviation of responses for each target position determined the precision.

To investigate how subjects may be biased in either direction for azimuth localization responses, the left hemi-field azimuth locations were multiplied by -1. The data then reflects the estimation of center bias. A negative mean indicates a bias towards center or undershooting. A positive mean indicates an overshoot or bias towards the periphery. The elevation data was not multiplied by (-1). For elevation localization, a positive value is an overestimation of the target height while a negative value is an underestimation.

An additional GLM model was ran to determine the functionality of the middle panned ring (Elevation 2). The model included three levels of elevation (top, middle, and bottom ring), 2 levels of round (first and second visit), 2 levels of reverberation condition (dry and wet), and 13 levels of azimuth location. The results of this analysis is discussed at the end of this chapter.

Significant P values and partial eta squared values are reported for each effect or interaction. A criteria of $P < .05$ was selected to be the valid measure of significance. The Wilk's Lambda criterion was used for the testing statistic.

$$\Lambda = \frac{|E|}{|H+E|} = \prod_{i=1}^{p} \frac{1}{1+\lambda_i} \tag{4.1}$$

The criterion measures the percent variance of dependent variables that is not affected by differences between independent variables or in other words a test of how much variance an independent variable adds to the model. The null hypothesis is rejected if the lambda is near zero [Khattree & Naik 1999].

An eta squared value provides an estimate of effect size for each interaction. This "describes the proportion of total variability attributable to a factor" [Levine & Hullett 2002]. Partial eta squared is a less biased approach to effect size than eta squared because the effects of other independent variables and interactions are separated. High partial eta squared values, > .2 [Levine & Hullett 2002], suggest that the sample size is large enough to validate the findings. Partial eta squared, where SS is Sum of Squares, is defined as:

$$\eta_p^2 = \frac{SS_{Effect}}{SS_{Effect} + SS_{Error}} \tag{4.2}$$

The following sections report significant findings from the statistical models. The main effects of results will be presented first, followed by sections describing significant interaction between variables.

4.2 Main Effects in Azimuth Localization

The main effects of elevation, azimuth, reverberation condition, and source type are reported as global variables of the GLM. Table 4.1 presents the P values and partial eta squared values for the main effects on accuracy of localization in azimuth. The shaded cells represent cases with significant effects, with P<.05. Elevation, azimuth, and reverberation are found to have a significant effect on azimuth localization of the accuracy. All of the variables demonstrate main effects on azimuth localization precision, shown in Table 4.2.

Variable	Sig. of Accuracy	Partial Eta Squared
Elevation	.000	.585
Azimuth	.000	.983
Source	.408	.038
Reverb	.000	.683

Table 4.1: Main effects on azimuth localization

Variable	Sig. of Precision	Partial Eta Squared
Elevation	.013	.298
Azimuth	.000	.980
Source	.000	.555
Reverb	.000	.869

Table 4.2: Main effects on azimuth localization precision

The main variables of elevation, azimuth, reverberation condition are significant for both accuracy and precision. Source type is only significant for precision. Each of these are studied in greater detail below.

4.2.1 Elevation localization in azimuth

Elevation has a significant effect on localization accuracy in the azimuthal plane, P<.000 and $\eta_p^2 = .585$. The means of elevation accuracy is shown in Figure 4.1. Standard error is shown by the error bars in all subsequent plots. Responses for Elevation have greater center bias than elevation 1, with elevation 3 responses undershot by about 4° more than elevation 1. The standard error is similar.

Precision is significantly different between elevations (P = .013, η_p^2= .298). The difference between elevations is about 0.25° where elevation 3 is the less precise condition.

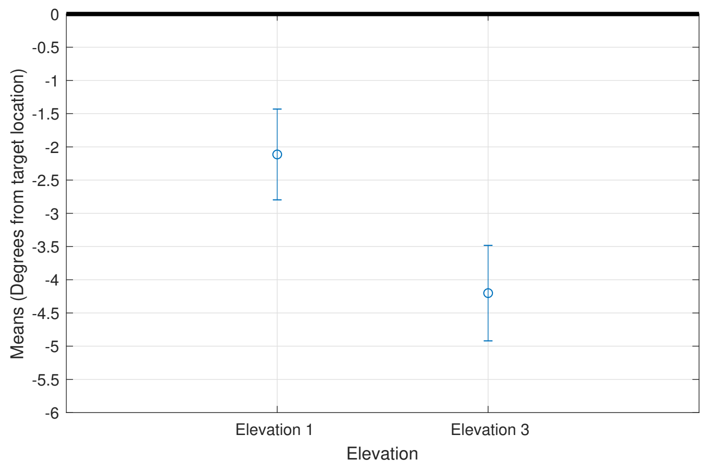


Figure 4.1: Accuracy of azimuth localization as a function of elevation in degrees. Negative values indicate responses that are closer to the center 0°

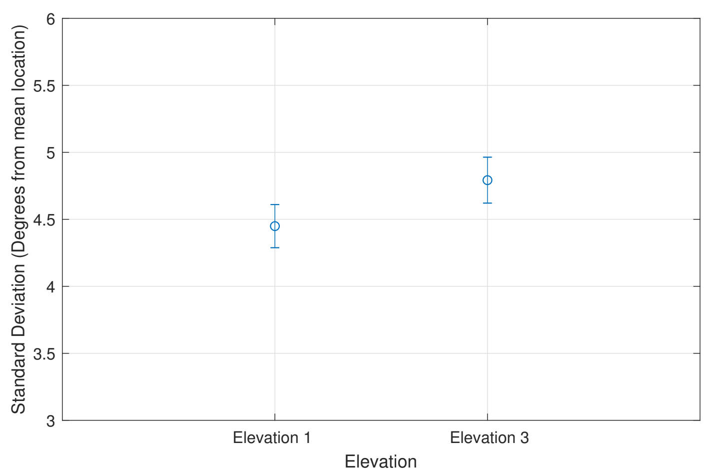


Figure 4.2: Precision of azimuth localization as a function of elevation

4.2.2 Azimuth localization in azimuth

Azimuth has a significant main effect on localization accuracy (P $<$ .000, η_p^2= .983). As seen in Figure 4.3, the means for accuracy are spread in a fairly uniform shape except for at the two edges. Responses at the edges, -90 and 90, have the strongest bias towards center. The absolute value of response across azimuth were analyzed by running additional GLM. Azimuth localization absolute value presents a clearer picture of decrease of accuracy with increase of azimuth location angle value (Figure 4.4).

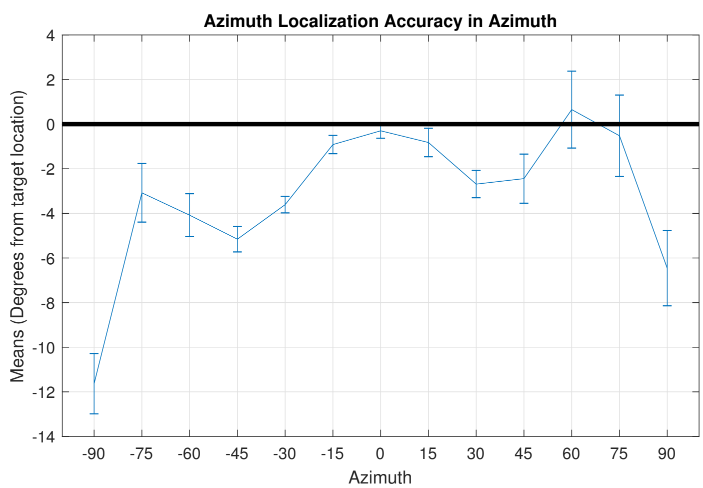


Figure 4.3: Accuracy of azimuth localization as a function of azimuth

Figure 4.5 presents the significant effect of azimuth localization precision (P $<$ .000, η_p^2= .980). Azimuth position greater than $\pm 60°$ have precision values around 5 or 6 degrees, while from $\pm 15°$ to $\pm 45°$, the precision values falls between 3.5 to 4.5 degrees.

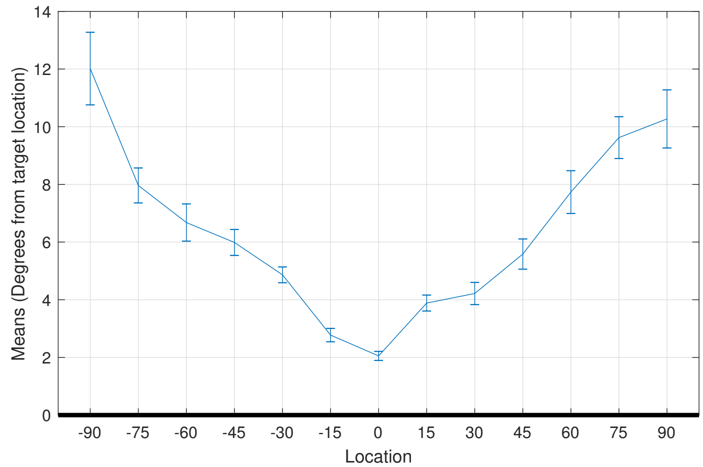


Figure 4.4: Absolute value accuracy of azimuth localization as a function of azimuth

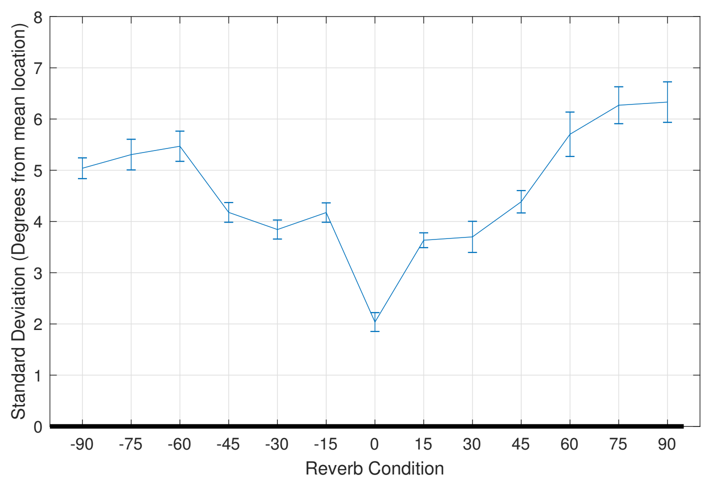


Figure 4.5: Precision of azimuth localization as a function of azimuth

Location 0° is best for localization accuracy and precision.

4.2.3 Source Type localization in azimuth

Source type refers to whether the target was produced at the location of a physical loudspeaker or as a panned virtual source. The source type is not a significant effect azimuth localization accuracy, shown in Figure 4.6, but does have a significant effect for the precision of azimuth localization ($P < .000$, $\eta_p^2 = .555$), shown in 4.7.

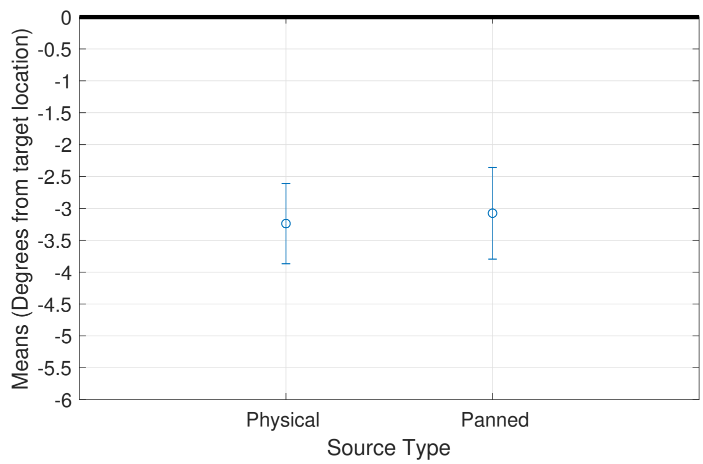


Figure 4.6: Accuracy of source localization as a function of azimuth

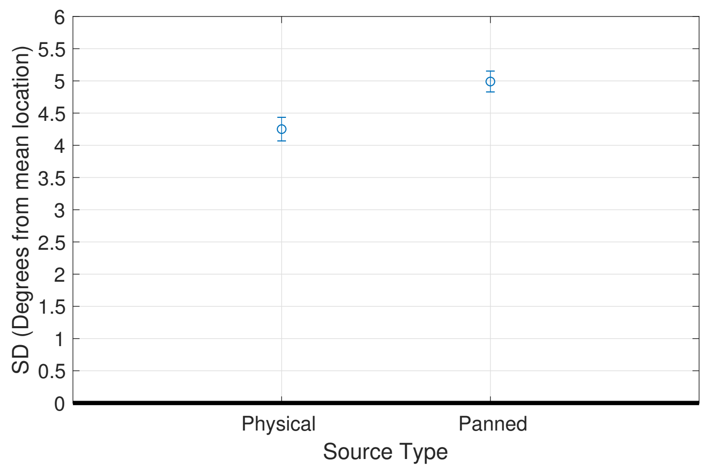
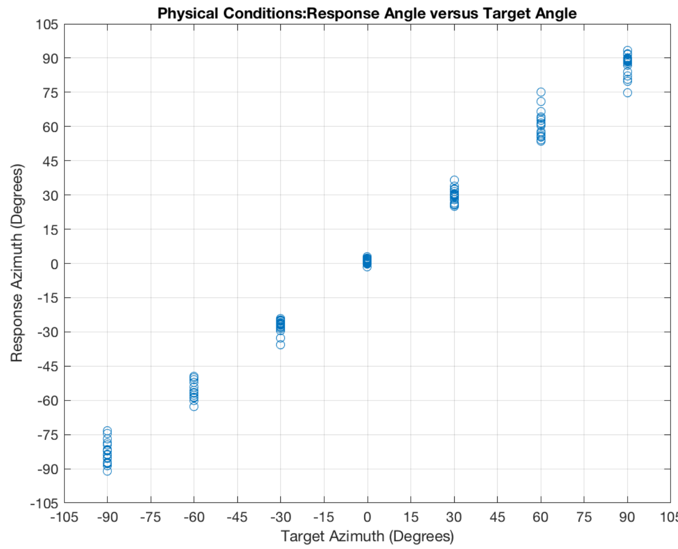


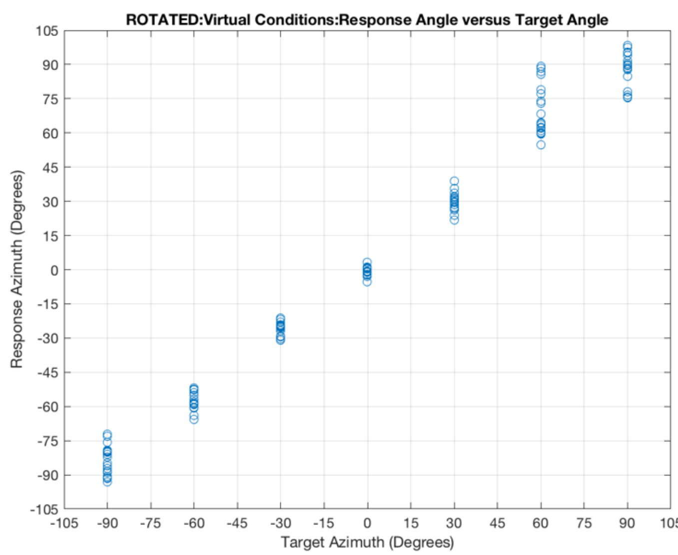
Figure 4.7: Precision of source localization as a function of azimuth

Responses from panned sources have a significantly higher standard deviation than those of physical sources. The panned source condition is about 0.75° less precise than the physical.

Source type does not have significant effect on localization accuracy but it does significantly impact precision. Subjects were able to localize target generated at physical source locations more precisely. Figures 4.8a and 4.8b show scatter plots of raw responses data at elevation 1 where each dot represents the mean of each subjects' responses for every azimuth location. If the plots are compared by each azimuth location, panned responses (4.8b) do seem to have a wider scatter compared to the physical responses (4.8a) presented at the same azimuth location.



(a) Elevation 1 physical source responses from Round 1



(b) Elevation 1 panned source responses from Round 2

Figure 4.8: Comparison of physical and panned dry sources types responses presented at similar azimuth locations for elevation 1

4.2.4 Reverberation localization in azimuth

Dry condition refers to a stimulus sound that has no late reverberation tail. Reverberant condition refers to a stimulus sound that has a reverberation time of .6 seconds, similar to school elementary classroom. Reverberation condition has a significant effect on localization in the azimuthal plane both in terms of accuracy ($P<.000$, $\eta_p^2= .683$) and precision ($P<.000$ and $\eta_p^2= .869$). Subjects respond with greater bias towards the center and less accuracy by about 4° under reverberant condition, as shown in Figure 4.9. Similarly, the precision under the reverberant condition is worse than the dry condition by about 1.5°, shown in Figure 4.10.

The data shows that there is a significant difference between dry and reverberant conditions for localization in azimuth.

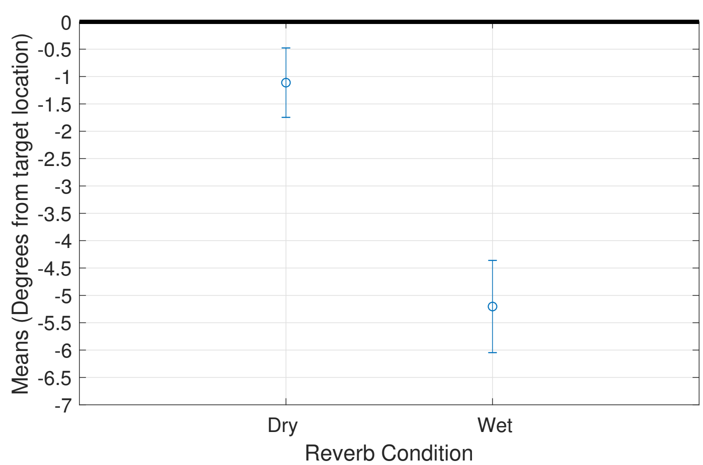


Figure 4.9: Reverberation Condition Means

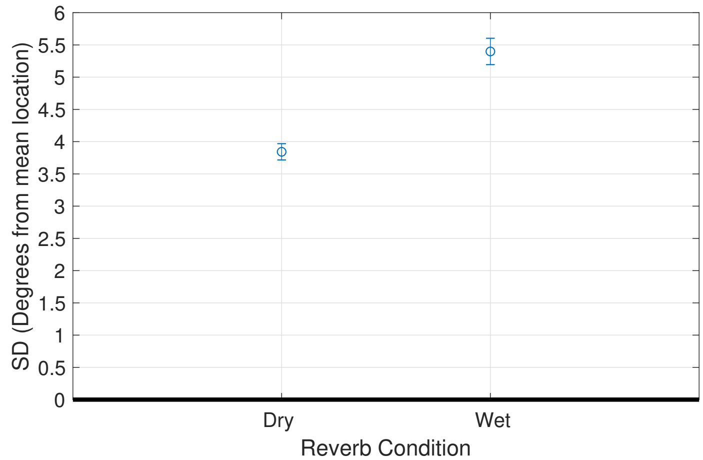
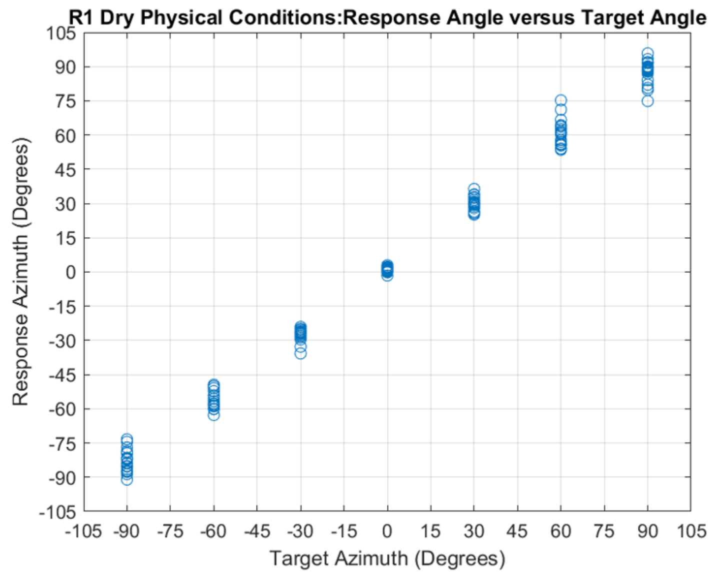
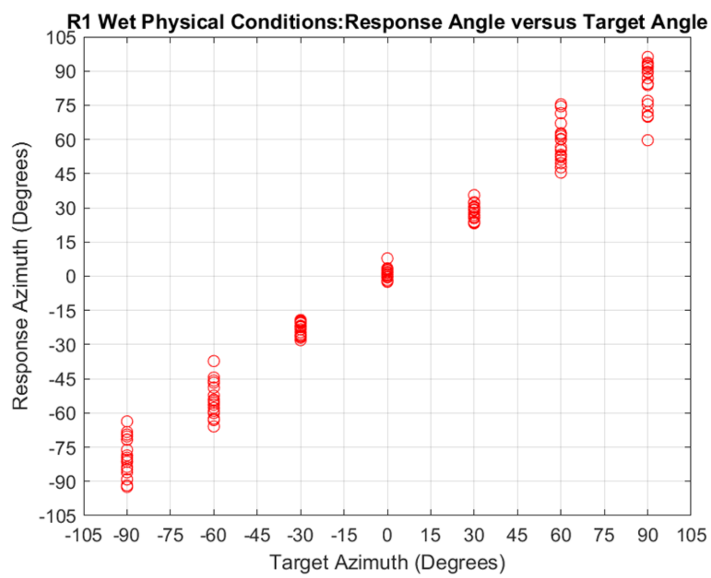


Figure 4.10: Reverberation Condition Standard Deviation

Reverberant condition results are less accurate and less precise than the dry condition, as visually represented in Figure 4.11. Each dot represents the mean of each subjects' 6 responses for each location condition. The wider the scatter at each target azimuth location, the more variation of spread in responses. Data from the reverberant condition is plotted in 4.11b showing more scatter at most locations across azimuth compared to the dry condition (4.11a).



(a) Elevation 1 physical dry source responses from Round 1



(b) Elevation 1 physical reverberant source responses from Round 1

Figure 4.11: Comparison of reverberant condition responses for physical sources on elevation 1

4.3 Two-Way Interactions of the GLM global variables on Azimuth

The following tables present the significant two-way interactions for accuracy and precision of azimuth localization. Significant interactions are found for the following: azimuth localization accuracy for Elevation * Azimuth, Elevation * Source, Azimuth * Source, Elevation * Reverberation, and Source * Reverberation. No significant interactions occur for precision of azimuth localization.

Variable	Sig. of Accuracy	Partial Eta Squared
Elevation * Azimuth	.003	.943
Elevation * Source	.003	.389
Azimuth * Source	.002	.948
Elevation * Reverb	.045	.205
Azimuth * Reverb	.204	.764
Source * Reverb	.022	.258

Table 4.3: Two-Way interactions on azimuth localization accuracy

Variable	Sig. of Precision	Partial Eta Squared
Elevation * Azimuth	.053	.856
Elevation * Source	.929	.000
Azimuth * Source	.130	.802
Elevation * Reverb	.088	.153
Azimuth * Reverb	.471	.653
Source * Reverb	.555	.020

Table 4.4: Two-Way interactions on azimuth localization precision

4.3.1 Elevation * Azimuth interaction in azimuth localization accuracy

Elevation and azimuth has a significant interaction for localization accuracy in the azimuthal plane (P = .003, η_p^2= .943). Table 4.5 presents the significance of elevation for each azimuth location. Target locations that were not significantly different between elevation 1 and 3 include $-75°$, $-60°$, $-15°$, and $0°$, meaning those locations have the same accuracy at both elevations. The majority of azimuth locations were significantly different for azimuth localization accuracy.

The Elevation * Azimuth interaction plot is presented in Figure 4.12 showing the means of Elevation 1 and 3. Elevation 3 tends to have more bias towards center than elevation 1. Majority of locations are not significantly different for azimuth accuracy between elevations. The absolute value data shows a clearer difference between elevations, shown in Figure 4.13. As angle location increases there is an

Degree	Sig. of Elevation
-90	.000
-75	.219
-60	.434
-45	.005
-30	.000
-15	.452
0	.051
15	.000
30	.039
45	.006
60	.000
75	.002
90	.000

Table 4.5: Elevation * Azimuth interactions on azimuth localization accuracy

increases in accuracy error. It is more obvious that Elevation 3 is more affected than Elevation 1 in this graphic.

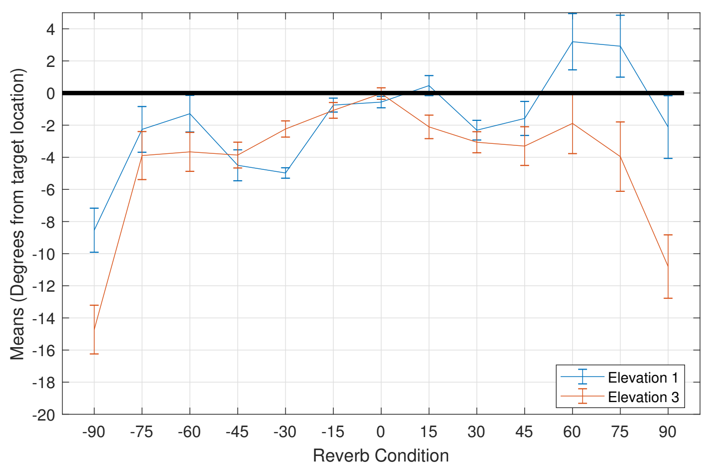


Figure 4.12: Accuracy of azimuth localization as a function of Elevation and Azimuth

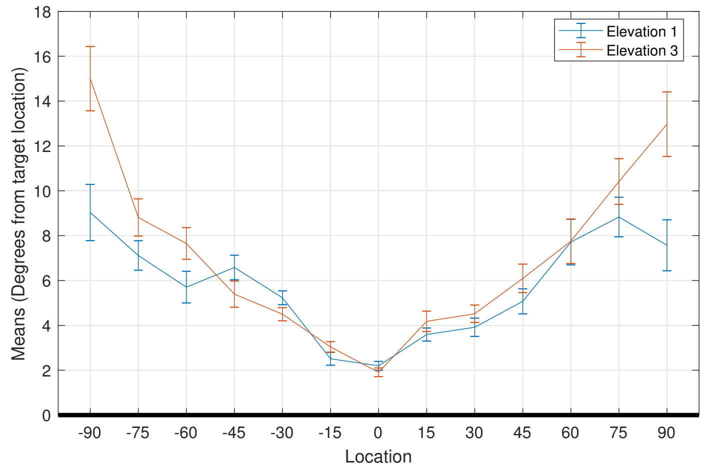


Figure 4.13: Absolute value of accuracy for azimuth localization as a function of Elevation and Azimuth

4.3.2 Elevation * Source interaction in azimuth localization accuracy

Elevation and source have a significant interaction for azimuth localization accuracy (P = .003, η_p^2= .389). Table 4.6 presents the significance of source type at each elevation. Source type is only significant at Elevation 1, therefore physical and panned sources are not significantly different Elevation 3 (Figure 4.14).

Elevation	Sig. of Source Type
Elevation 1	.003
Elevation 3	.097

Table 4.6: Significance of source type with respect to elevation in azimuth localization accuracy

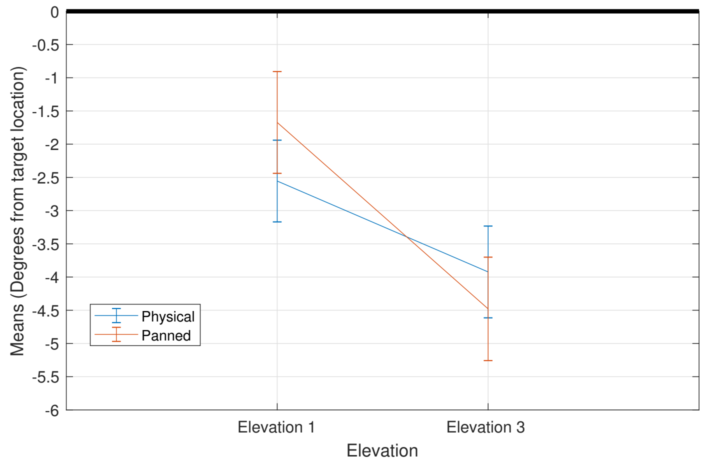


Figure 4.14: Accuracy of azimuth localization as a function of elevation and source, with respect to source

Elevation has a significant effect on azimuth accuracy for both physical and panned sources (Table 4.7). Elevation 1 azimuth localization is more accurate than Elevation 3, but at Elevation 1 panned sources are more accurate than physical shown in Figure 4.15. The opposite is true for elevation 3, where physical are slightly more accurate and less biased than panned.

Source Type	Sig. of Elevation
Physical	.001
Panned	.000

Table 4.7: Significance of elevation with respect to source type in azimuth localization

In conclusion, source type does not affect elevation 3 localization accuracy and panned sources are localized better for elevation 1, where as physical are more accurate at elevation 3.

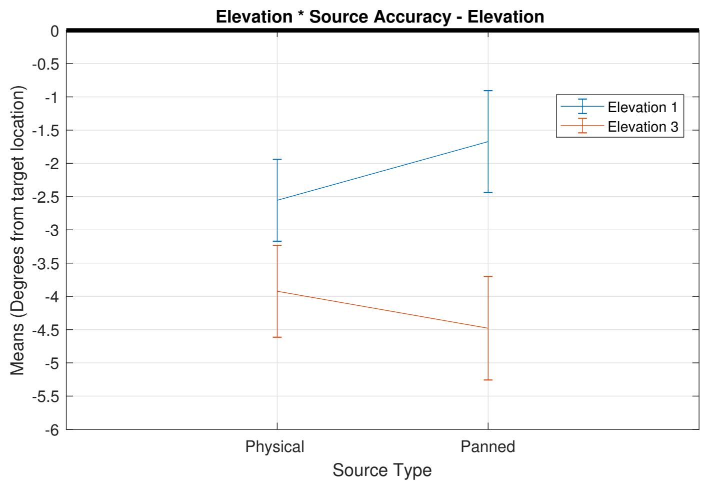


Figure 4.15: Accuracy of azimuth localization as a function of elevation and source, with respect to elevation

4.3.3 Azimuth * Source interaction in azimuth localization accuracy

A overall significance of P $<$ .003, and η_p^2= .948 was found for the Azimuth * Source interaction for azimuth localization accuracy.. Table 4.8 presents the significance of source for each azimuth location.

Degree	Sig. of Source
-90	.295
-75	.026
-60	.680
-45	.108
-30	.121
-15	.697
0	.000
15	.184
30	.018
45	.621
60	.001
75	.015
90	.387

Table 4.8: Azimuth * Source interactions for azimuth localization accuracy

There is a significant difference between source type accuracy for azimuth locations $-75°$, $0°$, $30°$, $60°$, and $75°$. The remaining locations are not affected by differences of source type. Locations are more likely to be significantly different on the right hand side of the frontal hemisphere.

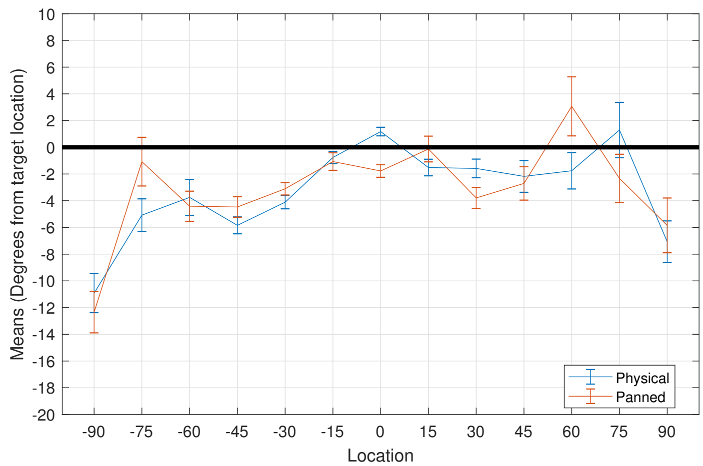


Figure 4.16: Accuracy of azimuth localization as a function of azimuth and source

The majority of locations have no significant difference, although there is a overall interaction between Source * Azimuth for azimuth localization accuracy.

4.3.4 Elevation * Reverberation interaction in azimuth localization accuracy

The interaction between elevation and reverberation is marginally significant for localization accuracy in azimuth (P= .045 and η_p^2= .205). Table 4.9 presents the significance of reverberation condition at each elevation.

The dry condition is more accurate and less center biased than the wet condition, shown in Figure 4.17.

Elevation	Sig. of Reverberation Condition
Elevation 1	.000
Elevation 3	.000

Table 4.9: Elevation * Reverberation interactions on azimuth localization accuracy, significance of reverberation

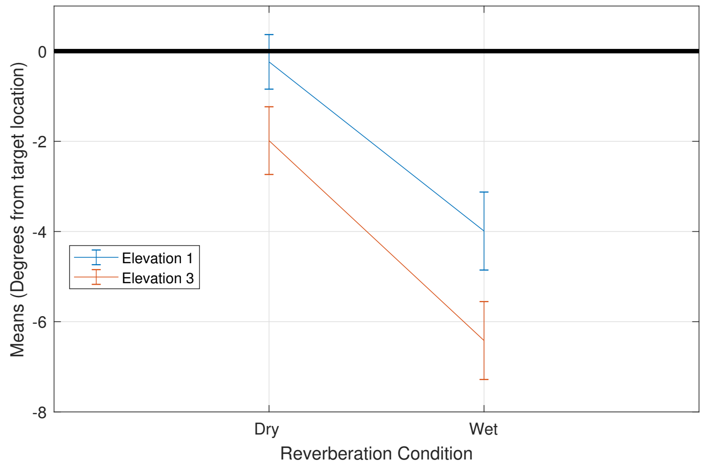


Figure 4.17: Accuracy of azimuth localization as a function of elevation and reverberation, with respect to elevation

Table 4.10 presents the significance of elevation for each reverberant condition. Figure 4.18 shows how the dry condition is more accurate than the wet condition, but both reverberant condition decrease in accuracy with the increases of elevation.

Reverberation Condition	Sig. of Elevation
Dry	.003
Wet	.000

Table 4.10: Elevation * Reverb interactions on azimuth localization accuracy, significance of reverberation

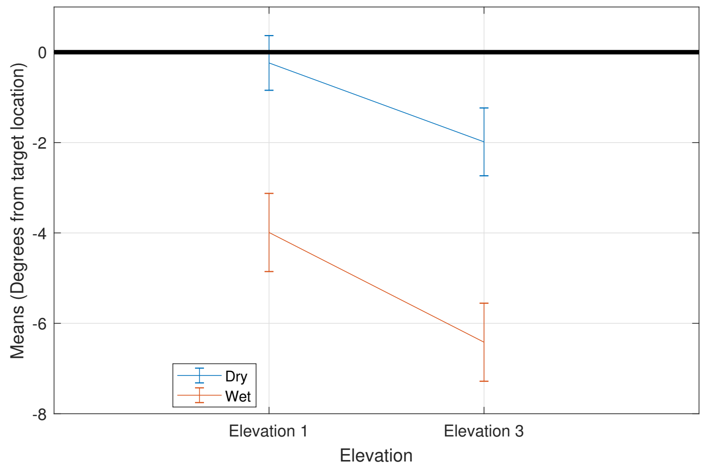


Figure 4.18: Accuracy of azimuth localization as a function of elevation and reverberation, with respect to elevation

This interaction shows that with the increases in elevation and reverberation, accuracy decreases for azimuth localization.

4.3.5 Source * Reverberation interaction in azimuth localization accuracy

There is a significant interaction between source type and reverberation condition for azimuth accuracy (P = .022 and $\eta_p^2 = .258$). Table 4.11 presents the significance of source type for azimuth localization accuracy. The physical condition has a marginal significance of P = .042, where as the panned condition has no significant effect of reverberation. Figure 4.19 shows the accuracy means of each source type, where there is only small differences for physical sources and none for panned sources..

Reverberation Condition	Sig. of Reverberation
Physical	.042
Panned	.403

Table 4.11: Source * Reverberation interactions on azimuth localization accuracy, significance of source

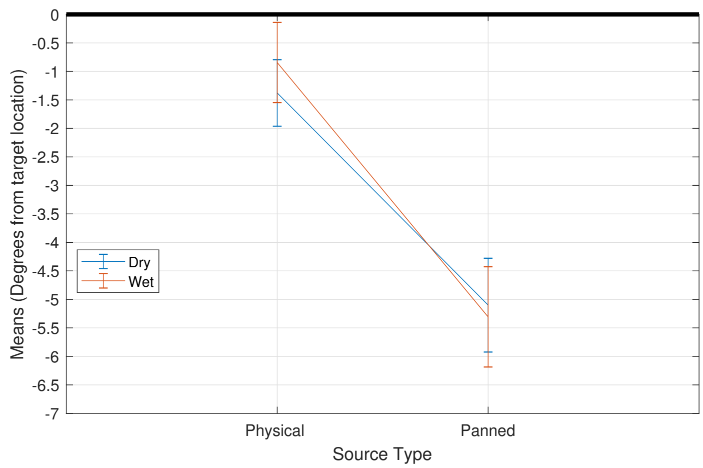


Figure 4.19: Accuracy of azimuth localization as a function of source and reverberation, with respect to source

Table 4.12 presents the significance of source type for each reverberation condition. Both physical and panned sources are affected by the reverberation condition. Figure 4.20 shows the means of the interaction, where the physical sources are more accurate than the panned. The panned source localize worse is the wet condition where as physical localize better in the wet condition for azimuth localization accuracy.

Source Type	Sig. of Source
Dry	.000
Wet	.000

Table 4.12: Source * Reverb interactions on azimuth localization accuracy, significance of reverberation

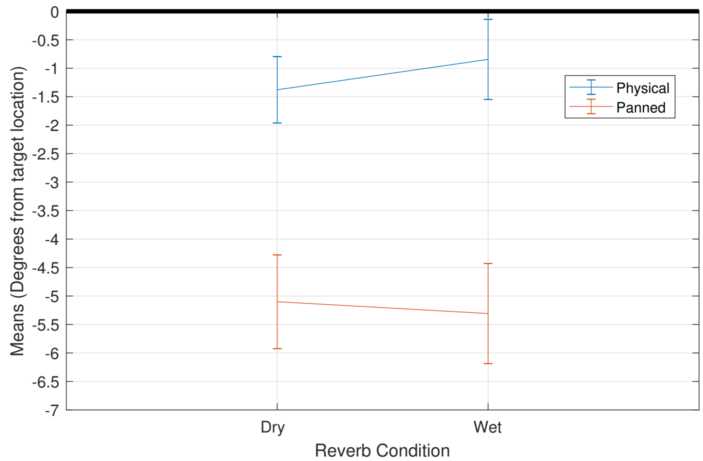


Figure 4.20: Accuracy of azimuth localization as a function of source and reverberation, with respect to reverberation

Source and reverberation have a significant interaction.

4.4 Three-Way Interactions of the GLM global variables on azimuth

Table 4.13 and Table 4.14 present the significance of three way interaction in accuracy and precision for azimuth localization. The significant interactions include Azimuth * Source * Reverberation and Elevation * Azimuth * Source for accuracy. For precision, only the Elevation * Azimuth * Source interaction is significant.

Variable	Sig. of Accuracy	Partial Eta Squared
Elevation * Source * Reverb	.985	.000
Azimuth * Source * Reverb	.023	.892
Elevation * Azimuth * Source	.044	.866
Elevation * Azimuth * Reverb	.401	.680

Table 4.13: Three-way interactions on azimuth localization accuracy

Variable	Sig. of Precision	Partial Eta Squared
Elevation * Source * Reverb	.216	.084
Azimuth * Source * Reverb	.805	.499
Elevation * Azimuth * Source	.017	.903
Elevation * Azimuth * Reverb	.611	.595

Table 4.14: Three-Way interactions on azimuth localization precision

4.4.1 Azimuth * Source * Reverberation interaction in azimuth localization accuracy

Azimuth * Source * Reverberation is the first significant three way interaction (P=.023 and $\eta_p^2 = .892$). The following tables and plots present the interactions for azimuth accuracy localization. Figure 4.26 shows the means of all interaction variable combinations plotted across azimuth. Table 4.15 presents the significance of reverberation for each source type and azimuth location.

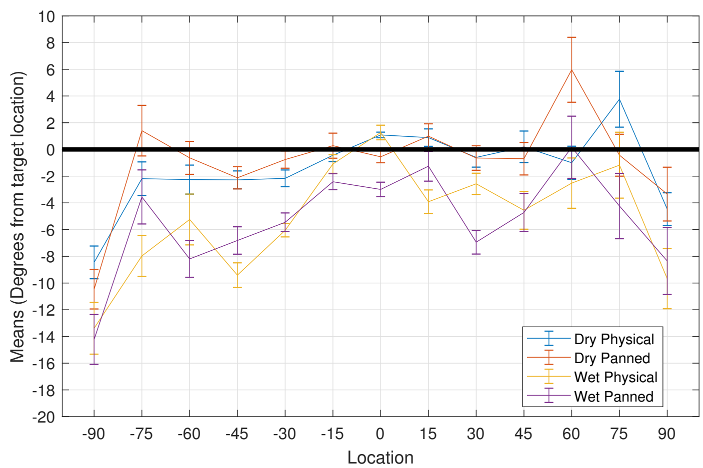


Figure 4.21: Accuracy of azimuth localization as a function of azimuth source and reverberation

Table 4.15 shows for physical locations, only azimuth locations $-60°$, $-15°$, $0°$, and $60°$ are not significantly different. Where as the only insignificant panned location is $75°$. Looking at Figure 4.22 and 4.23, wet conditions undershoot more

	Sig. of Reverb	
Degree	Physical	Panned
-90	.002	.011
-75	.001	.003
-60	.066	.000
-45	.000	.000
-30	.000	.000
-15	.409	.006
0	.730	.000
15	.000	.005
30	.004	.000
45	.000	.000
60	.366	.004
75	.020	.066
90	.011	.020

Table 4.15: Azimuth * Source * Reverberation interactions on azimuth localization accuracy, significance of reverberation

than dry conditions responses. For the most part, the dry physical condition is almost always less center biased than the wet physical. At 0°, the reverberation conditions accuracies are about equal. This is the first time the data shows overshooting in responses, for example 75° for dry physical condition.

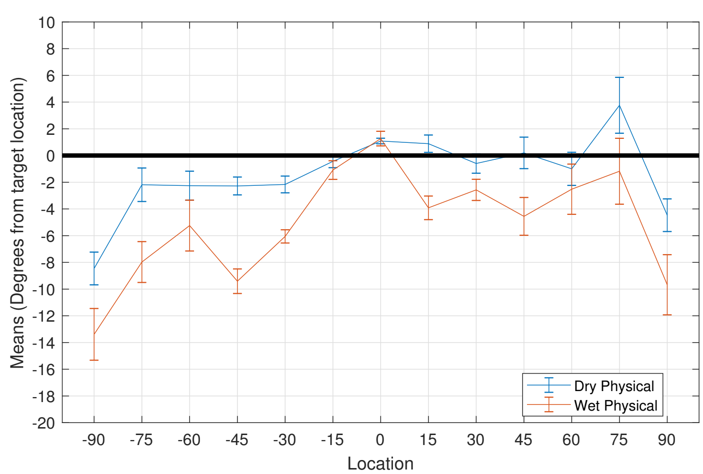


Figure 4.22: Accuracy of azimuth localization as a function of azimuth source and reverberation, with respect to physical sources

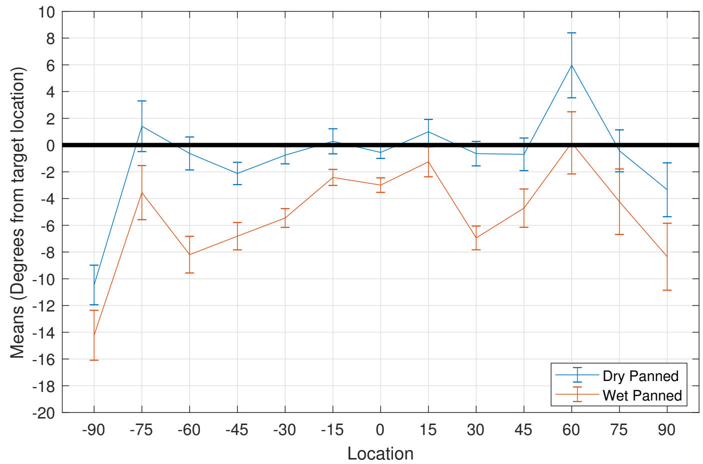


Figure 4.23: Accuracy of azimuth localization as a function of azimuth source and reverberation, with respect to panned sources

Table 4.16 presents the significance of source type for each reverberation condition across azimuth. Significant effects of source type occur in the dry condition at locations 0°, 60°, and 75°. For the wet condition, source type is significant at −75°, −45°, 0°, 15°, and 30°. There are only significant locations for the dry condition on the right hand side.

	Sig. of Source	
Degree	Dry	Wet
-90	.158	.578
-75	.056	.019
-60	.266	.160
-45	.858	.048
-30	.058	.463
-15	.475	.155
0	.004	.000
15	.922	.046
30	.955	.001
45	.407	.915
60	.001	.108
75	.044	.107
90	.517	.518

Table 4.16: Azimuth * Source * Reverb interactions on azimuth localization accuracy, significance of source

Figure 4.24 present the means of physical source type in dry and wet conditions. Performance of azimuth localization alters between panned and physical sources across azimuth, but the dry condition is more consistent than the wet condition.

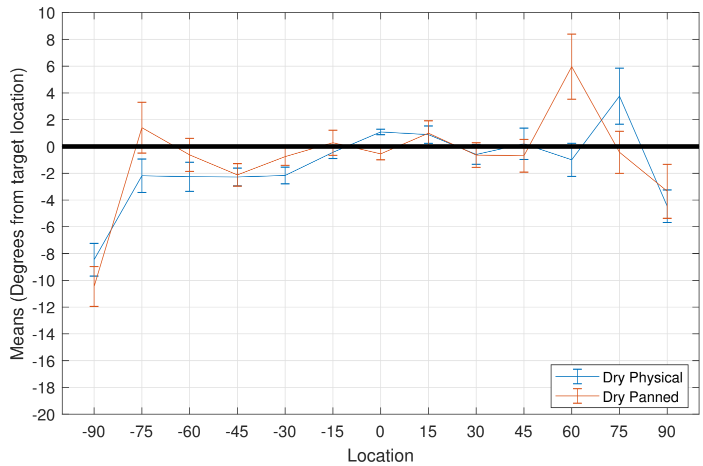


Figure 4.24: Accuracy of azimuth localization as a function of azimuth source and reverberation, with respect to dry sources

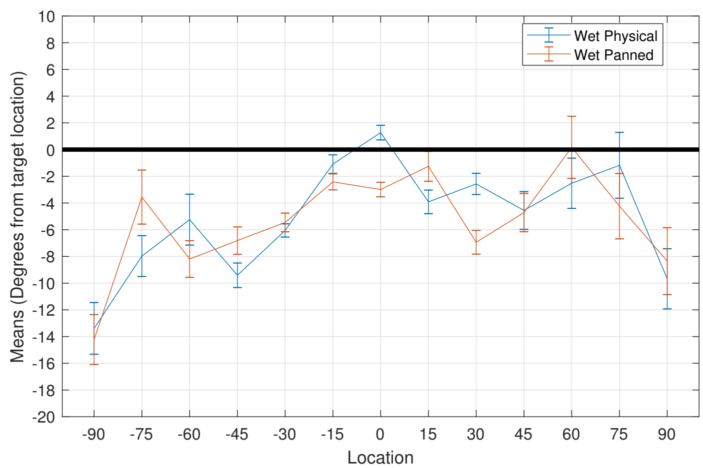


Figure 4.25: Accuracy of azimuth localization as a function of azimuth source and reverberation, with respect to reverberant sources

In summary, dry conditions across azimuth are the most accurate. Wet conditions fluctuate in accuracy and bias more than dry conditions. The source type fluctuate in accuracy across azimuth for both reverberation conditions.

4.4.2 Elevation * Azimuth * Source interaction in azimuth localization accuracy

Elevation * Azimuth * Source is a marginally significant three way interaction (P=.044 and $\eta_p^2 = .866$). The following tables and plots present the interactions of Elevation * Azimuth * Source for azimuth accuracy localization. Figure 4.26 shows the response means plotted across azimuth.

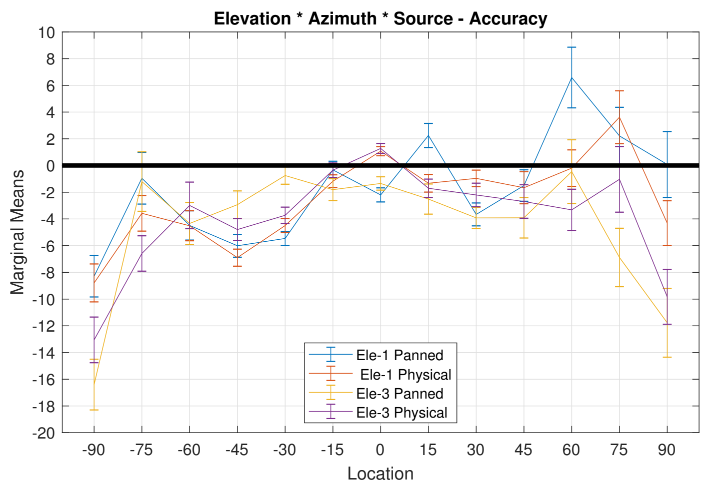


Figure 4.26: Accuracy of azimuth localization as a function of elevation and azimuth and source

Table 4.17 presents the significance of elevation for physical and panned sources across azimuth. Elevation has a stronger impact on accuracy at the outer azimuth edges for the physical conditions. Panned sources are affected by elevation across most azimuth locations, with only $-75°$, $-60°$, and $30°$ not affected by elevation.

Figure 4.27 presents the mean values for Elevation 1 and Elevation 3 for physical sources. Overshooting occurs on the right side azimuth location of 75°, which is only the second time this has occurred in the results. Figure 4.27 presents the mean values for elevation 1 and elevation 3 for panned sources in azimuth.

	Sig. of Elevation	
Degree	Physical	Panned
-90	.002	.000
-75	.010	.903
-60	.205	.923
-45	.010	.013
-30	.197	.000
-15	.088	.044
0	.534	.049
15	.475	.000
30	.056	.615
45	.109	.035
60	.008	.000
75	.012	.001
90	.016	.001

Table 4.17: Elevation * Azimuth * Source interactions on azimuth localization accuracy, significance of elevation

The significance of source for Elevation 1 and 3 across azimuth is presented in Table 4.18. At Elevation 1, the left hand side has no significant locations due to source type, where as elevation 3 has less significant values on the right hand side. Both elevation are significant at location 0°.

Figure 4.29 presents the mean values for physical and panned source locations for Elevation 1. The physical and panned sources for Elevation 1 intertwine across azimuth. The physical tends to be more accurate in means than the panned, especially at 60°. Figure 4.30 presents the mean values for physical and panned source locations at elevation 3. Similar to Elevation 1, the physical and panned means overlap multiple time across azimuth.

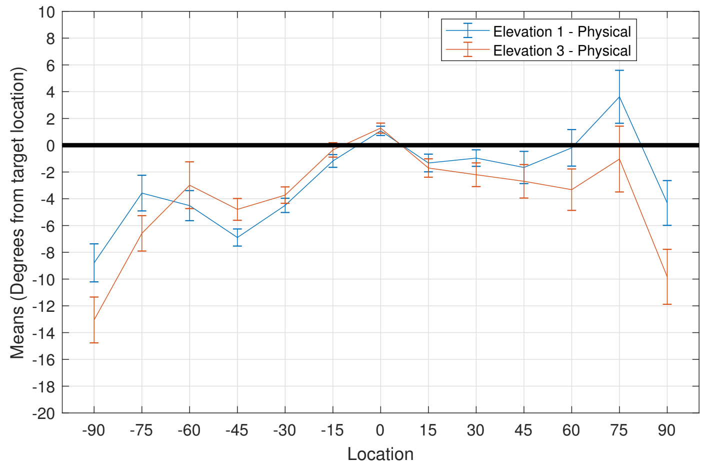


Figure 4.27: Accuracy of azimuth localization as a function of elevation and azimuth and source, with respect to physical sources

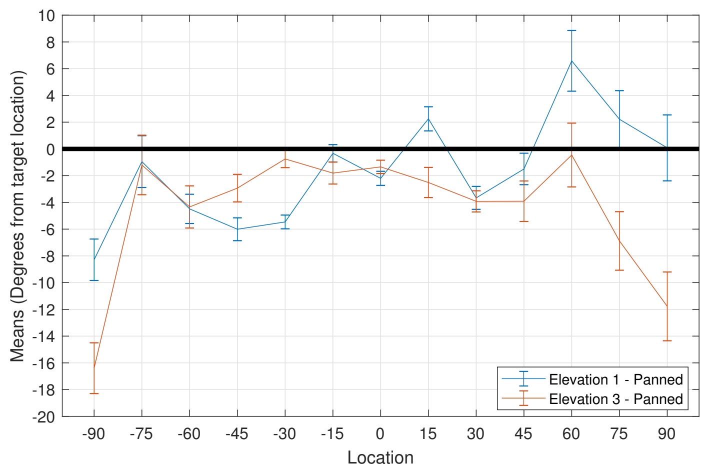


Figure 4.28: Accuracy of azimuth localization as a function of elevation and azimuth and source, with respect to panned sources

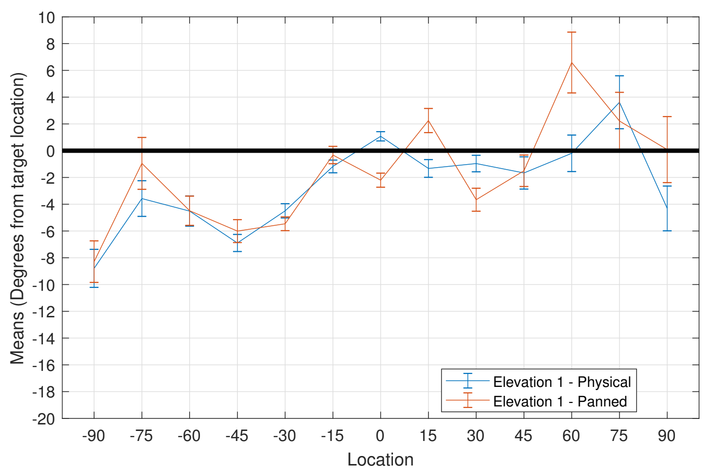


Figure 4.29: Accuracy of azimuth localization as a function of elevation and azimuth and source, with respect to elevation 1

	Sig. of Source	
Degree	Elevation 1	Elevation 3
-90	.668	.107
-75	.144	.020
-60	.980	.561
-45	.375	.059
-30	.254	.001
-15	.264	.154
0	.000	.000
15	.002	.493
30	.005	.119
45	.881	.390
60	.000	.057
75	.353	.004
90	.013	.442

Table 4.18: Elevation * Azimuth * Source interactions on azimuth localization accuracy, significance of source

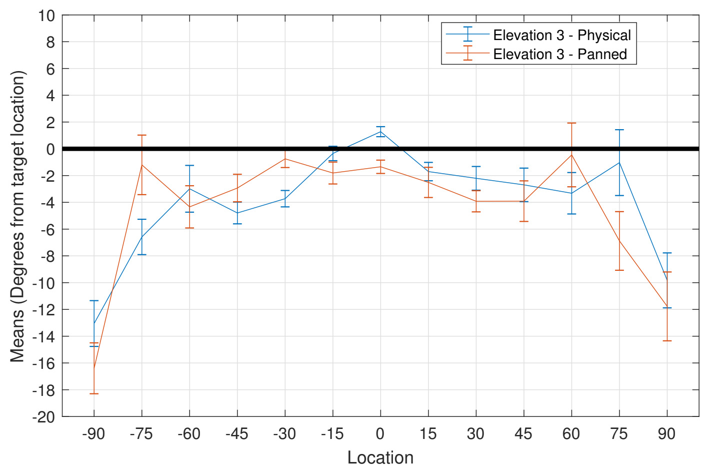


Figure 4.30: Accuracy of azimuth localization as a function of elevation and azimuth and source, with respect to elevation 3

In conclusion, Elevation 1 - Physical is the most accurate of the interaction conditions, followed by either Elevation 3 - Physical or Elevation 3 - Panned. Elevation 1 - Panned has erratic responses. The physical outside azimuth locations are most effected by at elevation 1.

4.4.3 Elevation * Azimuth * Source interaction in azimuth localization precision

The only significant three way interaction for azimuth localization precision is Elevation * Azimuth * Source (P= .017 and $\eta_p^2 = .903$). The following tables and plots present the significance of each condition.

Table 4.19 presents the significance of elevation for each source type across azimuth. The data shows no significant impact on localization precision for physical sources. The precision of physical sources at each elevation is shown in Figure 4.32. Panned source locations $-15°$ and $90°$ are the only azimuth locations significantly affected by elevation, shown in Figure 4.31.

	Sig. of Elevation	
Degree	Physical	Panned
-90	.950	.218
-75	.863	.528
-60	.958	.289
-45	.581	.076
-30	.763	.877
-15	.085	.004
0	.234	.213
15	.419	.681
30	.123	.837
45	.700	.164
60	.991	.982
75	.478	.926
90	.142	.008

Table 4.19: Elevation * Azimuth * Source interactions on azimuth localization precision, significance of elevation

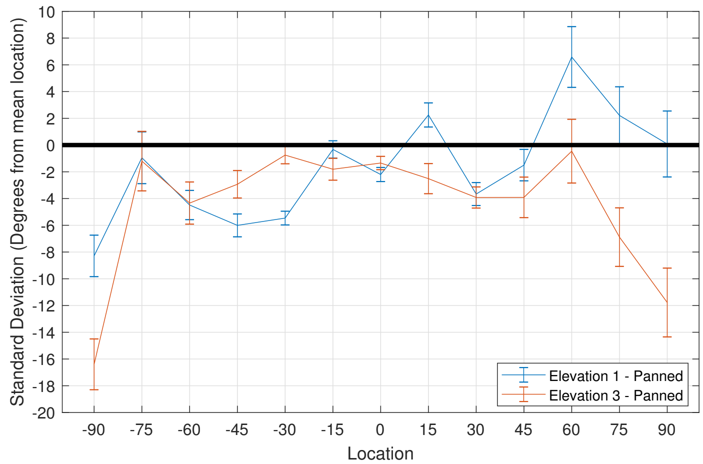


Figure 4.31: Precision of azimuth localization as a function of elevation and azimuth and source, with respect to panned sources

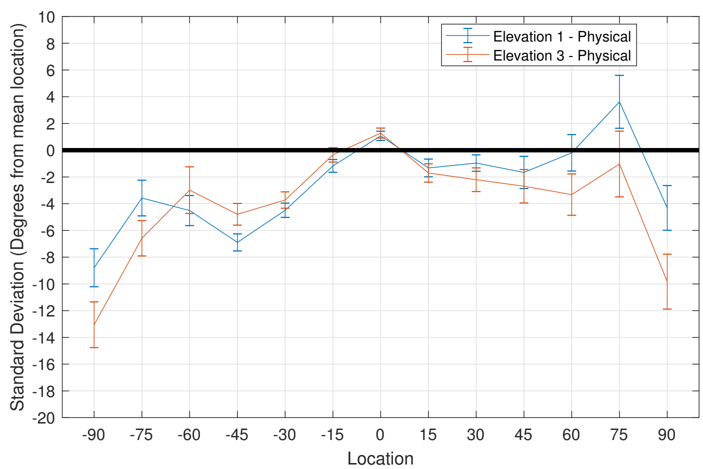


Figure 4.32: Precision of azimuth localization as a function of elevation and azimuth and source, with respect to physical sources

Table 4.20 presents the significance of source type at each elevation across azimuth. Both elevations are significantly affected by source type at $-15°$ and $0°$. For elevation 1, significantly difference locations occur on the right hand side at $30°$ and $90°$. The precision is shown in Figure 4.33 for each source type on elevation 1. Elevation 3 significant locations occur on the left hand side at $-90°$ and $-75°$, plotted in Figure 4.34.

	Sig. of Source	
Degree	Elevation 1	Elevation 3
-90	.792	.034
-75	.081	.002
-60	.650	.710
-45	.688	.611
-30	.831	.382
-15	.015	.000
0	.007	.002
15	.071	.446
30	.003	.481
45	.977	.061
60	.152	.098
75	.860	.876
90	.008	.753

Table 4.20: Elevation * Azimuth * Source interactions on azimuth localization precision, significance of source

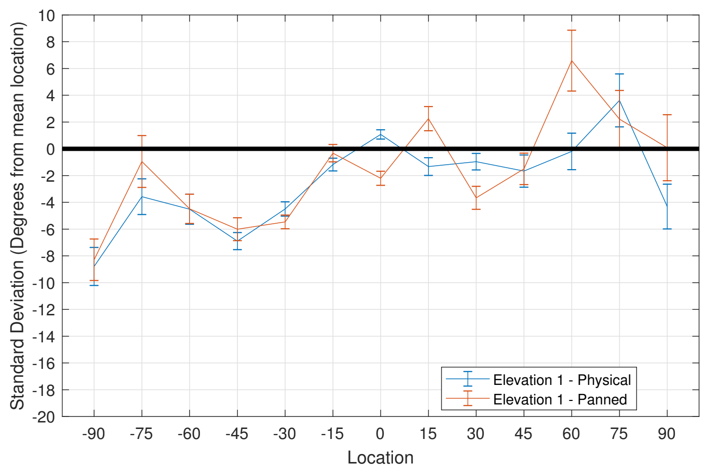


Figure 4.33: Precision of azimuth localization as a function of elevation and azimuth and source, with respect to elevation 1

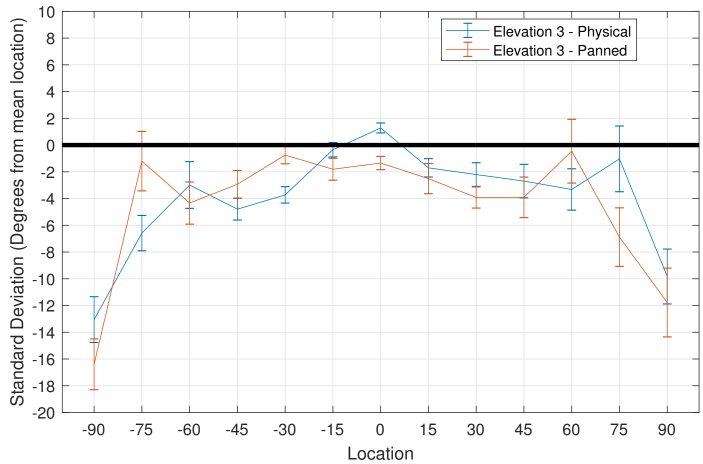


Figure 4.34: Precision of azimuth localization as a function of elevation and azimuth and source, with respect to elevation 3

To summarize, source type has a greater impact on precision than elevation for in azimuth localization precision when analyzing the Azimuth * Source * Elevation interaction.

4.5 Main Effects in Elevation Localization

The main effects of elevation, azimuth, reverberation condition, and source type are reported as global variables of the GLM for elevation localization accuracy and precision. Table 4.21 presents the significance of accuracy and the partial eta squared values for elevation localization. Elevation and reverberation condition are significant global variables.

The main effects for elevation precision are shown in Table 4.22. Source type is the only significant global variable for elevation localization precision.

Variable	Sig. of Accuracy	Partial Eta Squared
Elevation	.000	.938
Azimuth	.433	.668
Source	.423	.036
Reverb	.000	.632

Table 4.21: Main effects on elevation localization accuracy

Variable	Sig. of Precision	Partial Eta Squared
Elevation	.253	.072
Azimuth	.434	.667
Source	.000	.635
Reverb	.255	.071

Table 4.22: Main effects on elevation localization precision

4.5.1 Elevation localization accuracy in elevation

Elevation is a significant effect for elevation localization accuracy (P<.000 and $\eta_p^2 = .938$). Elevation 1 responses were overshot by about 6°, where as Elevation 3 was undershot by 14°, see Figure 4.35. A wide selection of responses for both elevation 1 and 3 are shown in Figures 4.36a and 4.36b. These figures show the target location (black line) versus the elevation responses at each azimuth location. Each dot represents a single response at each azimuth location. Theres figures clearly present the tendencies in subject responses at each elevation which is reflected in the statistical analysis results.

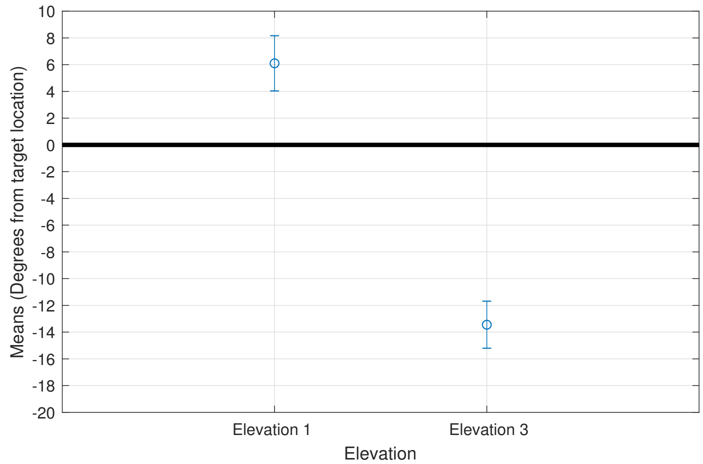
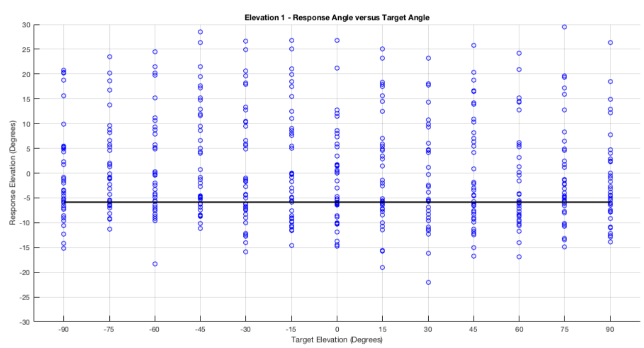
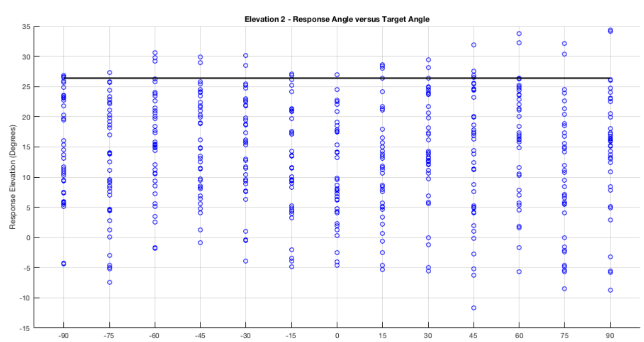


Figure 4.35: Accuracy of elevation localization as a function of elevation in degrees



(a) Elevation 1 scatter of elevation responses across azimuth



(b) Elevation 3 scatter of elevation responses across azimuth

Figure 4.36: Comparison of elevation level responses for elevation 1 and 3

Overall elevation 1 is significantly overshot and elevation 3 is significantly undershot for elevation location accuracy in elevation.

4.5.2 Reverberation localization accuracy in elevation

Reverberation has a significant effect in elevation localization accuracy (P<.000 and η_p^2= .632). Figure 4.37 shows the wet condition is more accurate than the dry condition, with the dry condition responses being undershot by about 6.5° where as the wet is about 0.75°. This shows an differences of roughly 6° between reverberant conditions.

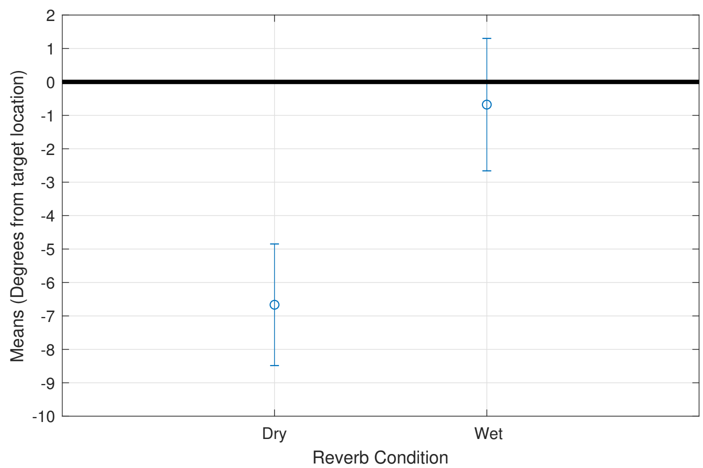


Figure 4.37: Accuracy of elevation localization as a function of reverberation

4.5.3 Source type localization precision in elevation

Source is the only significant main variable for elevation precision (P<.000 and η_p^2 = .635). Similar to accuracy in azimuth localization, physical source have a lower standard deviation than panned sources by almost 1°, shown in Figure 4.37.

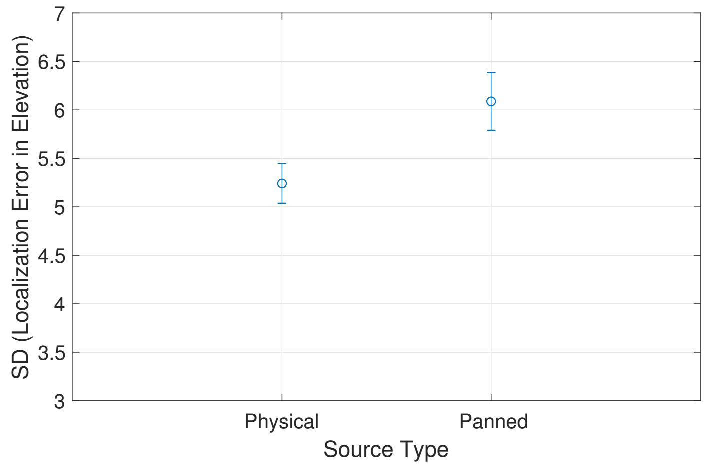


Figure 4.38: Precision of elevation localization as a function of source

4.6 Two Way Interactions of the GLM global variables on elevation

The following tables show the significance of two way interaction for elevation localization. Effects of accuracy are shown in Table 4.23 and precision in Table 4.24. All two way interactions are significant besides Elevation * Azimuth for elevation accuracy. Significant elevation localization precision interactions include Azimuth * Source and Elevation * Reverberation.

Variable	Sig. of Accuracy	Partial Eta Squared
Elevation * Azimuth	.378	.690
Elevation * Source	.000	.630
Azimuth * Source	.027	.886
Elevation * Reverb	.000	.629
Azimuth * Reverb	.024	.890
Source * Reverb	.008	.330

Table 4.23: Two-Way interactions on elevation localization accuracy

Variable	Sig. of Precision	Partial Eta Square
Elevation * Azimuth	.241	.747
Elevation * Source	.913	.001
Azimuth * Source	.005	.932
Elevation * Reverb	.001	.442
Azimuth * Reverb	.352	.700
Source * Reverb	.713	.008

Table 4.24: Two-Way interactions on elevation localization precision

4.6.1 Elevation * Source interaction elevation localization accuracy

There is a significant interaction between Elevation and Source where P<.000 and $\eta_p^2 = .630$. Table 4.25 presents the significance of source for each elevation. Figure 4.40 shows how elevation 1 is overshot and elevation 3 is undershot, but the physical consition is slightly more accurate for both elevations.

Elevation	Sig. of Source
Elevation 1	.000
Elevation 3	.002

Table 4.25: Elevation * Source interactions on elevation localization accuracy, significant of source

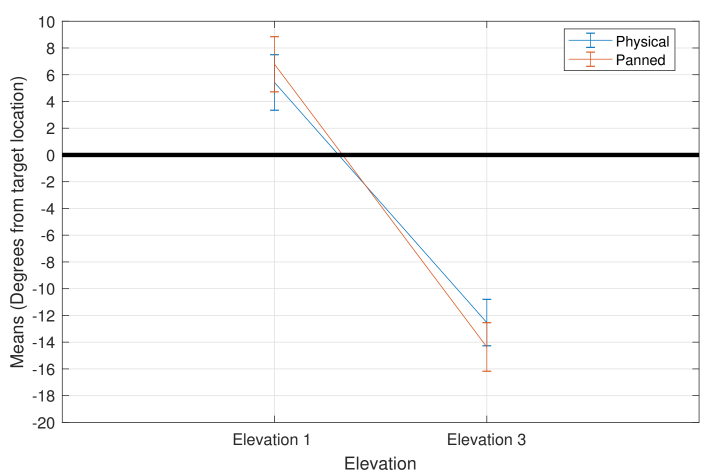


Figure 4.39: Accuracy of elevation localization as a function of elevation and source, with respects elevation

Table 4.26 presents the significance of elevation for each source type. Physical sources are slightly more accurate for both elevations. The panned responses are more likely to overshoot for elevation 1 and undershoot for elevation 3.

Elevation	Sig. of Elevation
Physical	.000
Panned	.000

Table 4.26: Elevation * Source interactions on elevation localization accuracy, significant of elevation

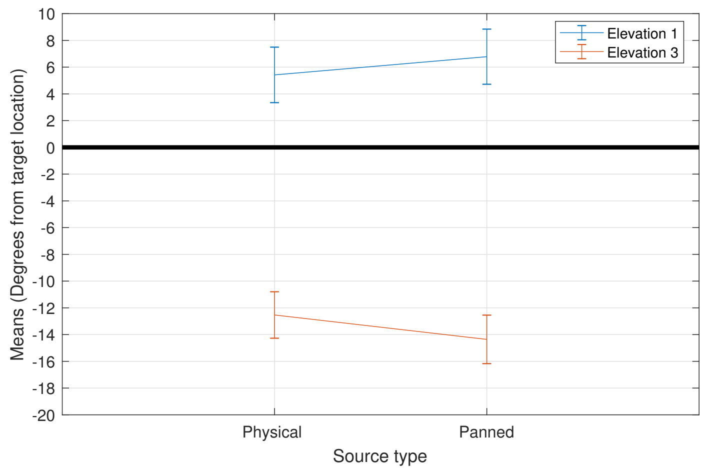


Figure 4.40: Accuracy of elevation localization as a function of elevation and source, with respects source

In summary, at both elevations the physical source is more accurate that the panned.

4.6.2 Azimuth * Source interaction elevation localization accuracy

Azimuth and Source have a significant interaction of P = .024 and η_p^2 = .890. The only significant location is $-45°$, shown in Table 4.27. The trend is unclear between

Azimuth and Source especially since there is overlap of error bars for each azimuth location, shown in Figure 4.41.

Degree	Sig. of Source
-90	.083
-75	.686
-60	.114
-45	.046
-30	.547
-15	.081
0	.598
15	.888
30	.741
45	.243
60	.822
75	.285
90	.525

Table 4.27: Azimuth * Source interactions on elevation localization accuracy

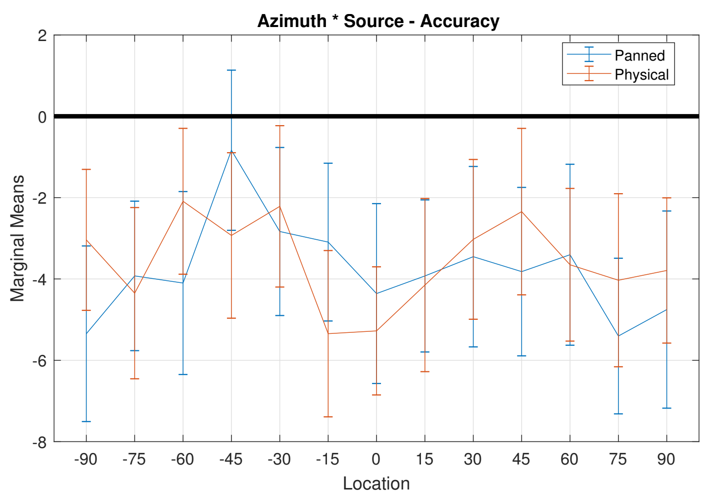


Figure 4.41: Accuracy of elevation localization as a function of azimuth and source, with respects azimuth

4.6.3 Elevation * Reverberation interaction elevation localization accuracy

There is a significant interaction between elevation and reverberant conditions for elevation localization accuracy (P<.000 and $\eta_p^2 = .639$). Table 4.28 presents the significance of reverberation at each elevation. Figure 4.43 shows the means of this interaction. At elevation 1, the dry source are more accurate than wet sources, where as the opposite is true at elevation 3, where the wet condition is more accurate than dry. The reverberant sources are overshot more than the reverberant.

Elevation	Sig. of Reverb
Elevation 1	.000
Elevation 3	.002

Table 4.28: Elevation * Reverberation interactions on elevation localization accuracy, significant of reverberation

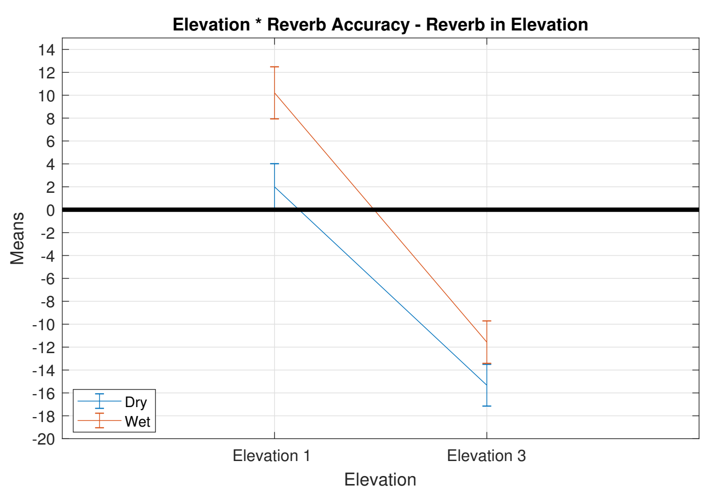


Figure 4.42: Accuracy of elevation localization as a function of elevation and reverberation, with respects elevation

The significance of elevation is shown for each reverberation condition in Table 4.29. Figure 4.43 shows that Elevation 1 decreases in accuracy in the wet condition where as Elevation 3 improves.

Reverb Condition	Sig. of Elevation
Dry	.000
Wet	.000

Table 4.29: Accuracy of elevation localization as a function of elevation and reverb, with respects reverberation

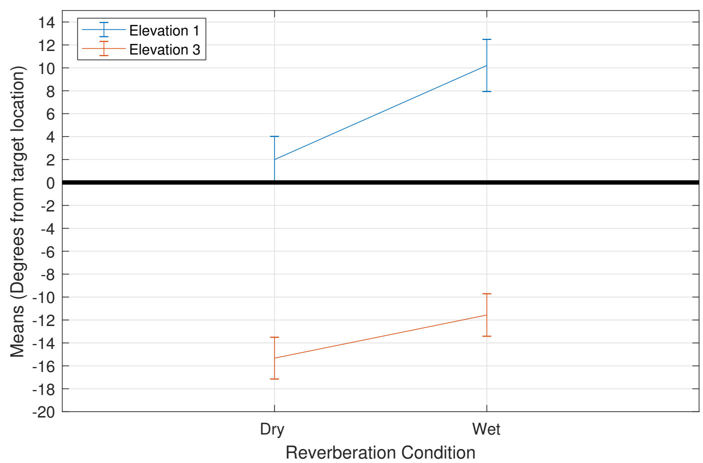


Figure 4.43: Accuracy of elevation localization as a function of elevation and reverberation, with respects reverberation

4.6.4 Azimuth * Reverberation interaction of elevation localization accuracy

The interaction between Azimuth and Reverberation in elevation localization accuracy is significant (P = .024 and $\eta_p^2 = .890$). Table 4.30 presents the significance of reverberation conditions across azimuth. Each location is significantly different between dry and wet conditions. Figure 4.44 show the mean response for each azimuth location with the wet condition more accurate than the dry condition by roughly 6°.

This data suggests that reverberation condition significantly impacts localization accuracy in the elevation plane with wet conditions being more accurate than dry sources.

Degree	Sig. of Reverb
-90	.000
-75	.000
-60	.000
-45	.000
-30	.000
-15	.000
0	.000
15	.000
30	.000
45	.000
60	.001
75	.000
90	.000

Table 4.30: Azimuth * Reverb interactions on elevation localization accuracy

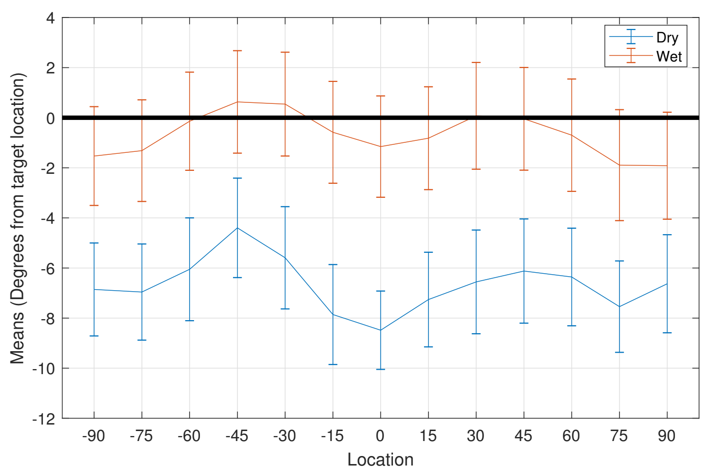


Figure 4.44: Accuracy of elevation localization as a function of azimuth and reverberation, with respects azimuth

4.6.5 Source * Reverberation interaction elevation localization accuracy

Source and reverberation have a significant interaction of P = .008 and η_p^2 = .330. Source has no significant effect of the reverberation conditions, see Table 4.31 and Figure 4.45.

Reverb Condition	Sig. of Source
Dry	.059
Wet	.635

Table 4.31: Source * Reverberation interactions on elevation localization accuracy, significance of source

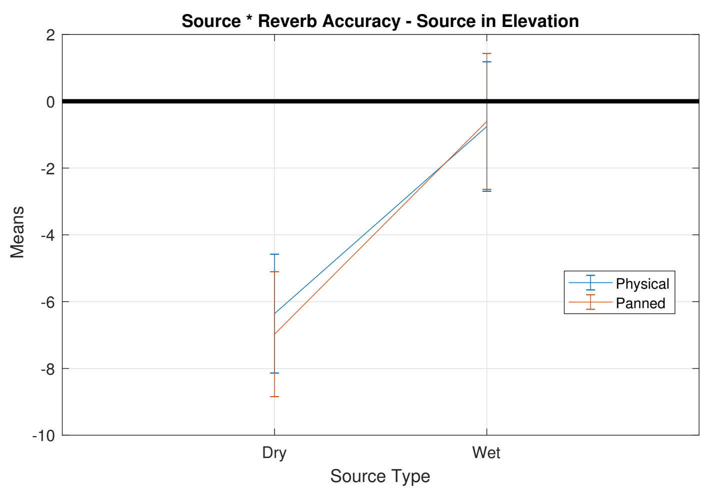


Figure 4.45: Accuracy of elevation localization as a function of source and reverberation, with respects reverberation

Reverberation conditions significantly impact both source types for elevation localization accuracy, see Table 4.32. Similar to previous analysis, panned sources are more accurate in wet conditions. Physical sources are more accurate in the dry conditions and Wet sources are more accurate than dry sourcesFigure 4.46.

This data concludes that source type does not influence elevation localization

Source Type	Sig. of Reverb
Physical	.000
Panned	.000

Table 4.32: Source * Reverberation interactions on elevation localization accuracy, significance of reverberation

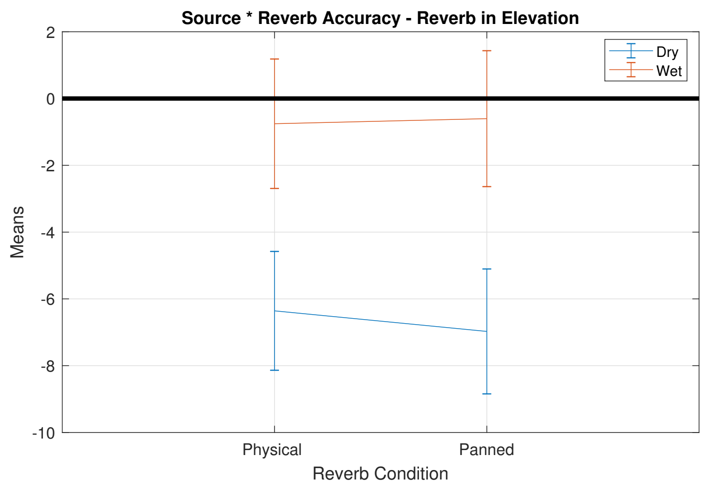


Figure 4.46: Accuracy of elevation localization as a function of source and reverberation, with respects source

accuracy but localization is significantly affected by reverberation conditions.

4.6.6 Azimuth * Source interaction elevation localization precision

There is a significant interaction between Azimuth and Source condition in elevation localization precision (P = .005 and $\eta_p^2 = .932$). Locations $-75°$, $-45°$, $-15°$, $0°$, $45°$, and $75°$ are significantly different. Figure 4.47provided evidence that panned and physical sources from Round 1 are less accurate than round 2. Round 1 physical sources were $\pm 90°$, $\pm 60°$, $\pm 30°$, and $0°$, the remaining azimuth location were panned. This implie that subjective localization improved between round 1 to round 2 for elevation accuracy.

Degree	Sig. of Source
-90	.706
-75	.000
-60	.414
-45	.002
-30	.252
-15	.000
0	.000
15	.001
30	.899
45	.000
60	.472
75	.108
90	.755

Table 4.33: Azimuth * Source interactions on elevation localization precision, significance of source

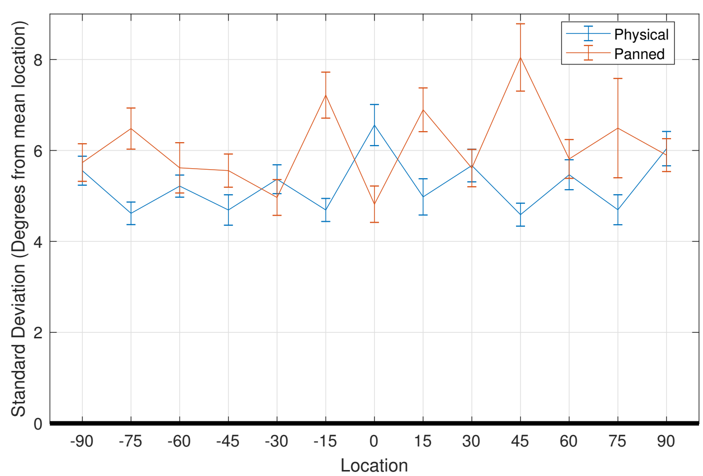


Figure 4.47: Precision of elevation localization as a function of azimuth and source, with respects azimuth

A GLM was con ducted to compare round 1 and 2 to determine if subjects had improved in elevation precision between visits. The results determined that subjective localization for elevation precision did improved. Figure C.3 shows that precision increased by about 1° from the first to the second round in all cases besides elevation 3 wet. A full analysis is provided in C.

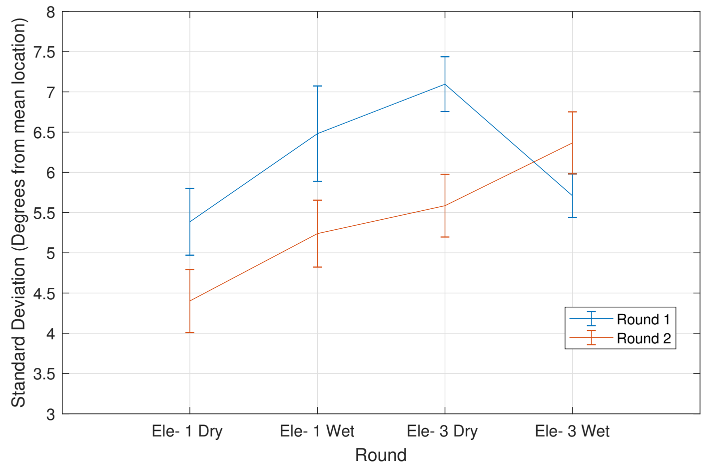


Figure 4.48: Elevation Precision - Round * Elevation * Reverb

4.6.7 Elevation * Reverberation interaction elevation localization precision

There is a significant interaction between elevation and reverberation condition for elevation localization precision (P=.001 and $\eta_p^2 = .442$). Figure 4.49 presents the interaction between elevation and azimuth standard deviations where the dry condition is more precise at elevation 1 but the wet condition is more precise at elevation 3.

Elevation	Sig. of Reverb
Elevation 1	.012
Elevation 3	.001

Table 4.34: Elevation * Reverberation interactions on elevation localization precision, significance of reverberation

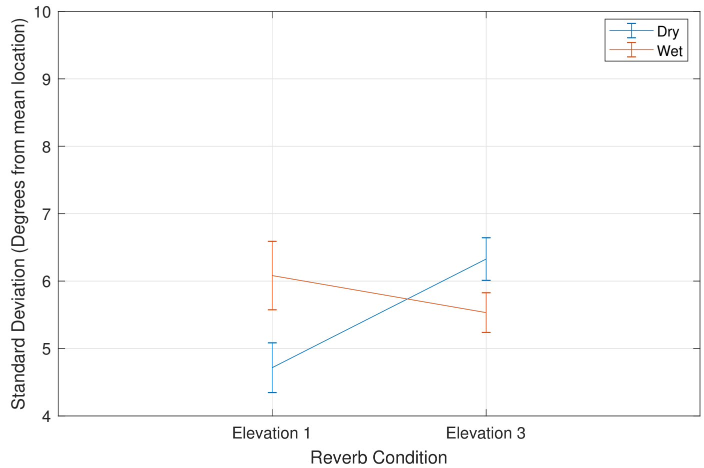


Figure 4.49: Precision of elevation localization as a function of elevation and reverberation, with respects elevation

4.7 Three-Way Interactions of the GLM global variables in elevation

The three way significance of elevation accuracy and precision are presented in Table 4.35 and Table 4.36. There are no significant interactions for localization accuracy and precision in elevation localization.

Variable	Sig. of Accuracy	Partial Eta Squared
Elevation * Source * Reverb	.221	.082
Azimuth * Source * Reverb	.690	.560
Elevation * Azimuth * Source	.065	.846
Elevation * Azimuth * Reverb	.134	.800

Table 4.35: Three-Way interactions on elevation localization accuracy

Variable	Sig. of Precision	Partial Eta Squared
Elevation * Source * Reverb	.786	.004
Azimuth * Source * Reverb	.159	.786
Elevation * Azimuth * Source	.450	.661
Elevation * Azimuth * Reverb	.120	.808

Table 4.36: Three-Way interactions on elevation localization precision

4.8 Investigation of all elevations localization

An additional GLM model was ran to investigate the performance of accuracy and precision of elevation 2 for both azimuth and elevation localization. As previously mentioned, elevation 1 and 3 consisted of physical and panned sources but elevation 2 consisted of only panned simulated sources generated using a combination the lower and upper ring of speakers using VBAP. The levels of this model consisted of round (2 visits), elevation (3), reverberation condition (2), and azimuth (13). The following sections present the significant effects of elevation from the statistical model.

4.8.1 Elevation localization in the azimuth

Elevation is a significant effect of azimuth localization when all three elevations are investigated. Accuracy of azimuth localization, shown in Figure 4.50 , has a $P <$ $.000$ and $\eta_p^2 = .935$. As elevation increases the tendency to undershoot increases.

Additionally, accuracy gets worse with increase of elevation. Precision is also a significant effect of elevation localization (P=.002 and $\eta_p^2 = .513$). Figure 4.51 shows elevation 1 is the most precise elevation, followed by closely by elevation 2 and 3 which have similar standard error.

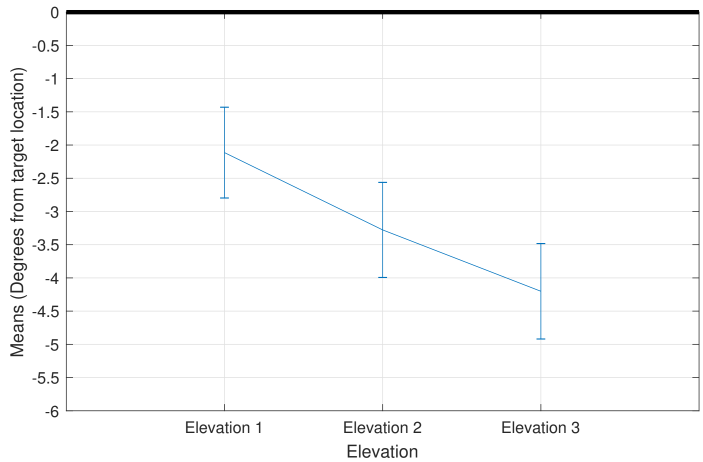


Figure 4.50: Elevation accuracy for all elevations in azimuth localization

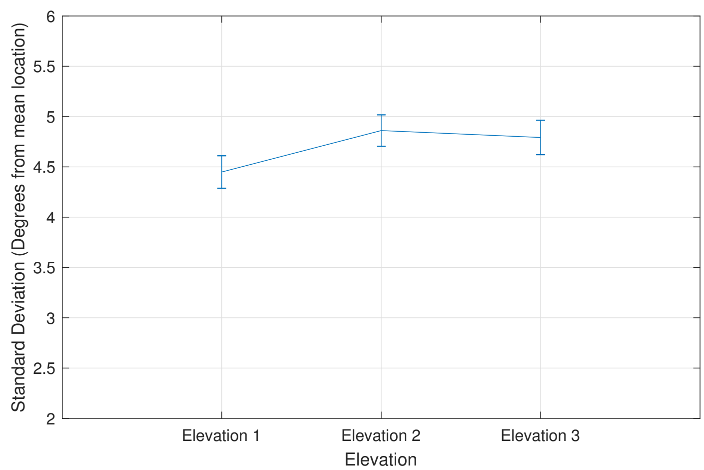


Figure 4.51: Elevation precision for all elevations in azimuth localization

4.8.2 Elevation * Reverberation interaction in the azimuth accuracy

The interaction of Elevation * Reverberation in accuracy is the only significant two way interaction for elevation localization (P<.000 and $\eta_p^2 = .766$). The shape of the two reverberation conditions reflect each other, showing that elevation 1 and 2 preform similarly in the dry condition and elevation 2 and 3 perform similarly in the wet condition (Figure fig:AllEle-AziEleReverb). There is little difference between elevation 1 and 2 in the dry condition and elevation 2 and 3 for the wet condition. The significance between each elevations is shown Table 4.37.

Variable	Sig. of Elevation 1 and 2	Sig. of Elevation 1 and 2	Sig. of Elevation 1 and 2
Dry	.863	.013	.003
Wet	.000	.992	.000

Table 4.37: Elevation * Reverberation in Elevation Comparison for Azimuth Accuracy

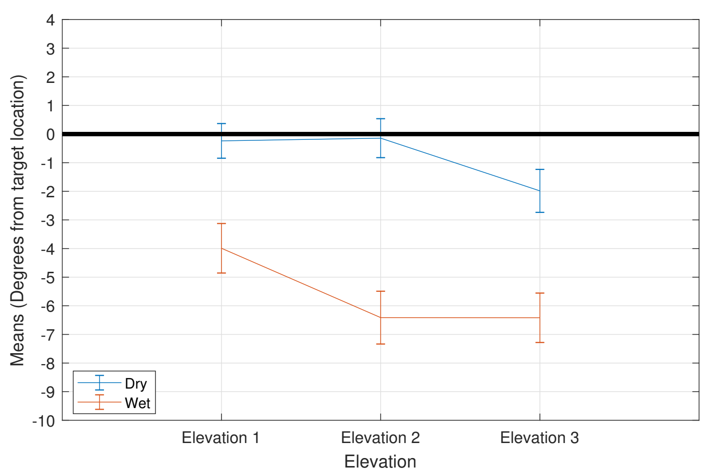


Figure 4.52: Elevation * Reverberation Accuracy for all Elevations in Azimuth Localization

4.8.3 Elevation localization in the elevation

Elevation accuracy and precision is significant for elevation localization (P $<$ .000 and $\eta_p^2 = .942$). Elevation 2 means fall linearly in between the upper and lower rings, shown in Figure Figure 4.53. The effect for precision is P = .018 and $\eta_p^2 =$ .376. Figure Figure 4.54 shows elevation 2 has the greatest standard deviation and also largest standard error of all three elevations, shown by the error bars.

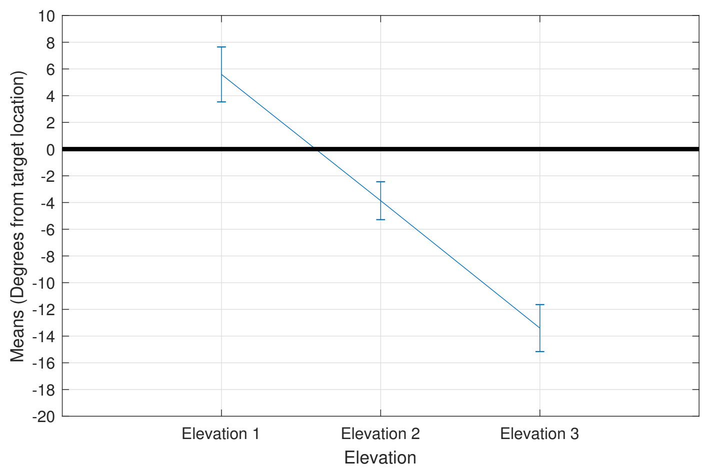


Figure 4.53: Elevation Accuracy for all Elevations in Elevation Localization

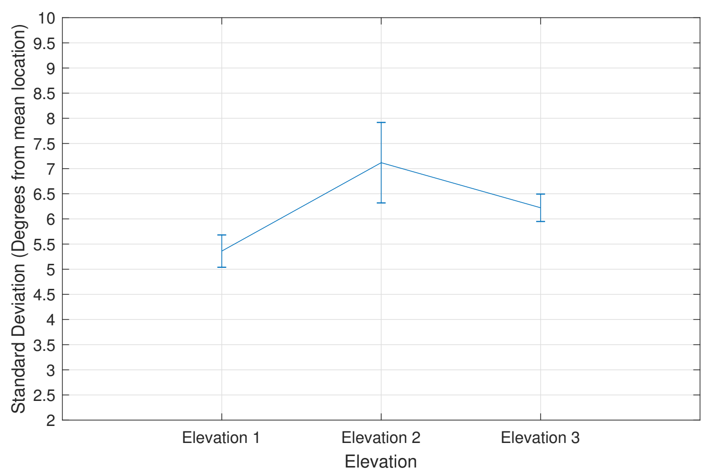


Figure 4.54: Elevation Precision for all Elevations in Elevation Localization

4.8.4 Elevation * Reverberation interaction the elevation localization accuracy

There is a also significant interaction between Elevation * Reverberation for accuracy in the elevation plane (P $<$ .000 and $\eta_p^2 = .608$). Figure 4.55 shows a fairly linear response for both the dry and the wet condition with the dry condition having lower mean values than the reverberant condition for all elevations.

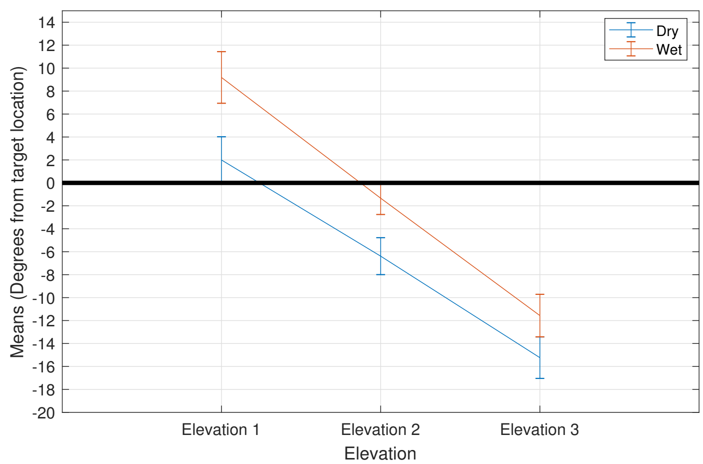


Figure 4.55: Elevation * Reverberation Accuracy for all Elevations in Elevation Localization

4.9 Concluding Remarks

In this chapter the statistical analysis process is discussed. A brief overview of the statistical model was described. Then, significant interactions were presented, first in azimuth and then in elevation. Finally, the analysis of the elevation including elevation 2 was discussed. In the next chapter, these results are discussed in detail.

Chapter 5

Discussion

This chapter discusses the results presented in the previous chapter. Localization findings are discussed first in the azimuthal plane, followed by the elevation plane. The effects of reverberant condition and panned source type are discussed in each plane respectively. Finally, the overall validation process and functionality of the system are discussed.

5.1 Effects on Localization in the Azimuth Plane

In regard to localization in the azimuthal plane, the results present a few consistent trends in subject responses. The accuracy and precision both decrease for azimuth localization as target locations progressively increase with distance from the mid-line, which agrees with the findings of Carlile et al. [2016]. The bias towards center increases at larger azimuth and is increasingly worse at higher elevations (Figure 4.50). These findings align with previous localization studies [Blauert 1997], [Perrott & Saberi 1990]. The following sections specifically discuss the impact of physical vs panned sources and reverberant conditions on azimuth localization.

5.1.1 Does Source Type Impact Azimuth Localization?

Source type has an effect on localization in the azimuthal plane. Accuracy was not significantly different overall between physical and panned sources, implying that this sound-field synthesis system creates an equally accurate simulated centroid for both physical and panned sources. However, the precision of localization in the azimuthal plane is significantly different between source types, with standard deviations for panned sources being greater than for physical sources by about 0.75°. Differences in precision may be due to the physical booth setup and or the virtual based amplitude panning algorithm.

The apparent source width of physical versus panned sources may explain this significant difference in localization precision. A physical loudspeaker has an apparent width or image source size that can be tied to the physical width of the one loudspeaker producing the sound, while the VBAP algorithm uses a combination of multiple physical loudspeakers to generate a focal point/centroid for each panned source. Subsequently the simulated source image could appear wider as the combination of physical speakers are in use to generate a focal point. Increasing the total number of physical loudspeakers in the 3D audio system would reduce virtual image width by decreasing the distance between physical loudspeakers. Since there is no difference in accuracy, it can be determined that VBAP as applied in the

BTNRH system is simulating sources well, but the significant difference in precision indicates that panned sources appear wider compared to physical ones.

The impact of source type on localization accuracy in the azimuthal plane is different across elevation. A significant difference is found between source types at elevation 1, but not at elevation 3 where both source types result in higher center bias. Accuracy of azimuth localization decreases at higher elevation. The interaction of elevation with source type shows panned sources being localized with greater accuracy at elevation 1 but with less accuracy at elevation 3 (Figure 4.14).

The impact of source type on localization accuracy in the azimuthal plane is significantly different across azimuth locations. There are more significant azimuth locations on the right hand side of the tested frontal hemisphere. Handedness could explain the differences for azimuth localization accuracy for source types. Subjects' hand dominance was not collected but it could be assumed the remote was held in the dominant hand (most likely right). By holding the remote with only one hand there would be a restriction in the crossover movement when selecting a response, where as a dominant side location has no arm restriction. With no restriction, source responses could be more accurate which would make varying responses more likely to be significant. The wide variation, especially shown in the error bars, could reflect a more laissez-faire response technique that comes with the extra effort of locating a target.

The impact of source type on localization accuracy in the azimuthal plane is also marginally different across reverberant conditions. The results show differences between source type only in the dry condition but not the reverberant one.

Referring to Figure 4.19, physical sources were located with marginally greater accuracy in the presence of reverberation than in dry conditions, but the panned sources produced similar (worse) results in either reverberant condition.

The other interaction between source type and azimuth position on localization accuracy in the azimuthal plane is also statistically significant. A few locations demonstrate significant differences between source types more often than others, including $-75°$, $0°$, $30°$,$60°$, and $75°$. The center location of $0°$ produces the most accurately and precise results, as expected, and is significant in most analyses.

One hypothesis to explain the significant effects at other angles is that there could be a room effect that highlights those angles in the physical space. Elements in the physical room, like installed piping or loudspeaker placement relative to room boundaries could create reflections that impacted binaural cues. More investigations would need to be conducted to ascertain if shifting the placement of loudspeakers in the room would change this effect.

To summarize, there was no effect of source type on accuracy localization in the azimuthal plane but physical sources were generally located more precisely than panned ($\eta_p^2 = .555$). Effects of source type were apparent at elevation 1, but not at elevation 3($\eta_p^2 = .389$). And physical sources were located more accurately in reverberant versus dry condition, which panned sources did not show an effect($\eta_p^2 = .288$). Finally, there may be a handedness effect that results in the significance different results across of azimuth locations.

5.1.2 Does Reverberation Condition Impact Azimuth Localization?

Reverberation does have effects on both the accuracy and precision of localization in the azimuthal plane. The dry condition localization was found to be more accurate and precise than one with a 0.6 second reverberation time, as expected. Additionally, the reverberant condition resulted in greater bias towards the center with an average around 5°. Previous studies support these findings; that as the reverberation time in a space increases, the ability of humans to localize sources decrease [Shinn-Cunningham et al. 2005].

The interaction of reverberation and elevation is also only marginally significant ($\eta_p^2 = .205$). The difference in bias towards the center is greater at elevation 3 than elevation 1, with dry conditions producing less bias towards center than wet (Figure 4.18). The analysis of all three elevations shows results from the dry conditions being similar for elevation 1 and 2 while results from the reverberant condition are similar for elevations 2 and 3 conditions (Figure 4.52). Reverberant conditions produce larger error at elevation 2, unlike dry condition. The longer reverberation time combined with the wider source image of a panned source for all locations on elevation 2 could explain this difference. This also agrees with known research that there is a decrease in localization accuracy with increased reverberation times [Shinn-Cunningham et al. 2005].

As discussed in the previous section, the presence of reverberation marginally impact localization accuracy in azimuth for physical sources, but not for panned.

To summarize, reverberation does clearly affect localization accuracy and precision in the azimuthal plane but not as often as source interactions. This is a known effect in real reverberation room, it is difficult to tease out how much is due to virtual simulation process and how much matches true reverberation room effects.

5.2 Effects on Localization in Elevation

The localization responses in elevation were more widely scatter than those in azimuth, but overall subjects did perceive some consistent shifts in where sources were located in elevation.

The investigation of all three elevations shows how the elevation localization progressively becomes worse with higher elevations.

The responses for the lowest ring (elevation 1) were consistently overshot by about 6°, the middle ring (elevation 2) undershot by roughly 3° and upper ring (elevation 3) was undershot by an average of 14°. It is important to note that the actual difference between elevations 1 and 3 is 32.4°. Responses for elevation 3 were thus consistently around 50 percent of the total ran off, ergo the collected elevation responses varied greatly and inconsistently for elevation localization.

It is interesting to point out that there was no effect in elevation precision when elevation 2 was not included in the statistical analysis. When elevation 2 was included (Figure 4.54), there was significantly higher standard deviation in the precision results, at elevation 2 likely due to elevation 2 being all panned sources. Even though simulated sources were located at different elevations, the responses were very spread causing accuracy data around $-4°$ overall but wide precision at $7°$. It is unclear if subjects performed this way due to not understand that the task involved sources at different elevation or poorer performance in localization sources at higher elevations occurred.

The following section specifically discuss the impact of physical versus panned sources and reverberant conditions on elevation localization.

5.2.1 Does Source Type Impact Elevation Localization?

Source type has an effect on the precision of localization in elevation but not accuracy, when comparing elevation 1 and 3. This result is similar to that on localization in azimuth.

When localizing the elevation of panned sources, subjects demonstrate worse precision than with physical by roughly $1.5°$ more, suggesting a larger perceived source sizes. An interaction was also found for Elevation * Source, whereby physical sources are more accurately localized in elevation than panned (Figure 4.39).

There is a significant interaction of Source * Azimuth on elevation localization precision; looking closer at the data plotted in Figure 4.47, interesting trends appears. The panned and physical sources alternate in precision performance, e.g. at $0°$ panned is better, at $15°$ physical is better, and so on. The source type with higher precision at each azimuth location aligns to the source type used for round 2 of the study, suggesting that subject's performance improved from round 1. A post hoc analysis was run to determine if there was a statistically significant difference in responses between round 1 and 2.

The analysis determined that subjects did improve in precision in round 2. This effect may be due to subjects did understanding the possible range of elevations when the protocol was explained in round 1, but understanding more clearly in round 2. Subjects could have also improved with practice over time in the study. Appendix C shows the complete statistical results of this analysis.

In summary, source type is found to affect elevation localization. As expected, localization panned sources is less precise than of physical ones, most likely due to source image size. Additionally, subjects did demonstrate better precision in round 2, which impacted the interaction of source type and azimuth localization.

5.2.2 Does Reverberation Condition Impact Elevation Localization?

Generally reverberant conditions result in more accurate localization in elevation than dry conditions. Perhaps due to the reverberation adding spectral cues that aid in elevation localization accuracy. The localization accuracy improves by about 7°, which is a considerable difference in accuracy considering maximum angle difference is the 30° between the highest and lowest elevation Figure 4.37.

The significant interaction of reverberation * elevation shows in greater detail the accuracy of elevation localization for the dry condition being closer to the actual target for elevation 1 (within 3°) but farther for elevation 3 (Figure 4.43). So at both elevations subjects located the reverberant condition at higher elevations than the dry. At the lower heights though the dry result is more accurate the the target elevation, while it is much worse at elevation 3. this indicates that subjects are better at localizing dry stimuli, if presented on head plane, but once elevation increases, the reverberant stimuli produce results that are both more accurate (Figure 4.42) and precise (Figure 4.49).

Studying elevation localization results on how reverberation interacts with azimuth location presents a clearer picture with the wet condition wavering around 0 degrees, whereas the dry condition is underestimated at all azimuth angles (Figure 4.44). This interaction suggests, again, that extra spectral cues in the wet condition supports localization accuracy in the elevation plane. Note the similar trends across azimuth angles for both reverberant conditions peaks occurring between +- 30° to 60°. This could be due to the room effects triggered by sources at these angles, such as reflections off of mounting hardware or room boundaries.

The final interaction between source * reverberation does not have as strong as effect as other in the study ($p = 0.008$, $\eta_p^2 = 0.330$), but points to how physical sources are more accurate in elevation localization than panned in dry conditions, but they are switch in reverberant conditions (Figure 4.46). The change between the source type is small in degrees though.

Lastly, the comparison of results between round 1 and 2 shows that precision of elevation localization increased for dry sources in round 2, much more than for reverberant sources Figure C.3. Looking even further at the Round * Elevation * Reverberation interaction on precision of elevation localization, all conditions show an approximate 1° improvement in precision except for the reverberant sources presented at elevation 3.

In summary, the reverberant conditions generally result in greater accuracy than dry conditions most likely due to spectral cues provided by the increase in reflections contributing to the longer reverberation time, except for on an elevation at head height where dry sources results in greater accuracy and precision.

5.3 Do This System and Validation Process Work?

This study has provided information on the accuracy and precision of source localization in azimuth and elevation from physical or panned sources in dry or reverberant conditions, using a specific loudspeaker setup and decoding software (IRCAM-SPAT) in the BTNRH AV Core Facility. The following provides a summary of what the results indicate about this sound field synthesis system's performance and functionality.

The system appears to synthesize source locations accurately for both physical and panned sources, in both azimuth and elevation. Panned sources, though, are localized less precisely than physical sources, in both azimuth and elevation; so while they are still located on average at the correct target location, the precision or standard deviation is larger across multiple trials for panned sources (5° in azimuth, 6.1° in elevation) than for physical sources (4.25°, 5.25° in elevation). These precision values would be expected to vary from one synthesis system to the next, depending on the number of loudspeakers, their placement relative to where sources are generated, and the software used to decode the desired signal to the speakers. For example, a greater number of loudspeakers covering the same region where target sources may be located would be expected to produce better precision in localization.

Reverberant condition is also found to affect both the accuracy and precision of localization in the azimuthal plane from the BTNRH sound field synthesis set-up, with dry conditions producing greater accuracy (1° compared to 5° off target biased towards center) and better precision (3.85° versus 5.4°). Only accuracy (not precision) of localization in elevation was impacted by reverberant condition, with reverberant cases producing results closer to the target (0.68° on average) compared to 6.7° off for dry cases. The precision of localization in elevation was found to be on average the same for dry (5.5°) and reverberant (5.8°) conditions. An interaction effect of reverberant condition with elevation on localization in elevation, though, indicates that dry conditions result in better localization in elevation than reverberant ones at an elevation close to head height, but the situations at higher elevations are where subjects localized dry sources lower than the target height, while reverberant ones were more accurately placed (Figure 4.55).

How much of the differences in accuracy and precision between the dry and reverberant conditions are due to additional cues or smearing from room reflections (as would occur in the real physical space) versus from the sound field system's particular synthesis process is difficult to parse out from the data acquired in this particular study. Additional calibration and testing is recommended in future investigations, such as comparing simulated (within sound field synthesis facility) and measured (from physical space upon which simulation is based) impulse responses.

Still, quantifying a sound field synthesis system's loss or gain in accuracy and precision of localization in azimuth and elevation resulting from generating a reverberant scenario versus a dry scenario is helpful in being able to understand and compare performance between systems used by different labs. Other laboratories with sound field synthesis systems are encouraged to gather similar data on the accuracy and precision of localization in azimuth and elevation, so that results from studies using these systems can be better interpreted in light of the capabilities of the system to generate accurate and precise reproductions of source locations.

Chapter 6

Conclusion and Recommendations for Future Work

6.1 Conclusion

This thesis presented a method to validate a multichannel 3D audio system at Boys Town National Research Hospital (BTNRH) to investigate the effects of different simulated conditions on perceived localization. This was accomplished by conducting a subjective localization experiment in a virtual sound environment. A series of sound bursts were presented from 3 elevations and 13 azimuth locations. The burst were presented in dry and reverberant .6-second reverberation time conditions. Two rounds of measurements were collected to compare simulated physical and panned sources, this permitted the comparison between physical and panned sources at same locations relative to the listener. A virtual reality system was used to collect subject localization responses. The results were then analyzed for accuracy and precision.

For azimuth localization, the center locations perform best and then deceases in performance as locations move towards the periphery. Dry locations are more accurate than wet and physical sources are more accurate than panned sources. As location increase in height, the bias towards center increases. Panned sources have the same accuracy as physical but are less precise in both azimuth and elevation. The wet conditions are less accurate and precise in azimuth localization. It was also determined that simulated source type affects localization more than reverberant conditions in azimuth.

In elevation, there is a decrease in accuracy as elevation increases. Elevation 1 was consistently over shot while elevation 3 in significantly undershot. The wet conditions performed much better than the dry, due to spectral cues. Source type did not affect accuracy, but there was a significant difference in precision with panned sources having a larger standard deviation. The elevation data shows specific trends but was overall quite varied with many response averages reporting about 50 percent error.

In conclusion, this process provides a quantitative analysis of accuracy, precision, center bias, and significance of conditions for the implemented VSE. With the collected data, a systems functionality and limitations can be more fully understood. This validation process could ease the comparison of studies between different facility based on known performance metrics. This protocol would be beneficial for facility using a 3D audio system to conducted research.

6.2 Future Work

Future research to build off this study would attempt to understand more specific factors incorporated in the validation protocol. First would be the addition of more speakers in both azimuth and elevation to reduce the distance between speakers, reducing apparent source width for panned sources. The measurement booth is another factor. Repeating the experiment in a taller booth or a fully anechoic chamber would help avoid the ceiling affect that is reflected in presented results. The extra space would help isolate the wet conditions responses differences. Additionally, bias on condition could be more thoroughly investigated.

For future studies it would be helpful to test for handedness, to determine how much of an effect hand dominance has on localization in a VSE. Further more, adding eye-tracking to the localization responses collection would help determine the differences in the pointing mechanism and sound localization. Virtual reality systems are very versatile with the environment visualization. Eye tracking software can be implemented with the VR headsets. Eye tracking with localization tasks show the movement of the pupil as a way to track stimulus responses. This matched with the remote provides insight of localization from multiple strategies. After the sound elements are understood, the virtual reality could be built in to visually block the speakers. So not only is the curtain now unnecessary, but the wearer can be placed in any setting.

As mentioned, one of the goals at Boys town National Research Hospital in to create a realistic environment to test children. To accomplish this, the next steps for this research would incorporate a realistic auralizations and speech. This could be done by building an environment using an ODEON model and classroom sounds effects, like a teacher's voice, building systems noise, and other elements as needed. As each stimulus is added, more studies can asses the quantitative functionality of the virtual sound environment.

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Appendix A

Means and Standard Deviations in Azimuth Localization

This appendix presents the measured means and standard deviations from both rounds across azimuth and elevation. The data are reported as the average of the response angle for each target azimuth location at each elevation. Tables of the overall means, dry condition means, and reverberant condition means are presented first followed by tables of the coinciding standard deviations.

Degree	-90	-75	-60	-45	-30	-15	0	15	30	45	60	75	90
Elevation 1	-80.79	-72.23	-54.96	-38.47	-25.04	-14.36	-0.91	15.35	27.48	43.48	62.18	76.53	86.52
Elevation 2	-78.10	-67.13	-53.85	-35.86	-23.02	-15.74	-1.66	17.74	29.55	47.75	65.04	68.96	80.81
Elevation 3	-74.87	-70.75	-56.59	-41.16	-27.92	-13.93	-0.22	12.90	26.79	41.43	56.97	70.32	77.91

Table A.1: Overall mean responses in azimuth localization

Degree	-90	-75	-60	-45	-30	-15	0	15	30	45	60	75	90
Elevation 1	-83.20	-73.76	-58.21	-41.74	-25.91	-14.19	-1.00	15.72	29.53	45.91	69.72	80.33	91.16
Elevation 2	-81.53	-71.89	-58.28	-39.38	-25.01	-16.94	-1.12	20.16	32.65	51.51	69.45	73.60	85.72
Elevation 3	-77.56	-73.92	-60.13	-44.42	-30.37	-14.96	0.44	14.78	28.89	43.55	58.72	72.69	81.68

Table A.2: Overall dry condition means responses in azimuth localization

Degree	-90	-75	-60	-45	-30	-15	0	15	30	45	60	75	90
Elevation 1	-78.97	-67.78	-51.73	-34.37	-22.76	-13.34	-3.32	11.65	22.97	40.21	62.20	75.51	86.68
Elevation 2	-74.68	-62.38	-49.43	-32.33	-21.04	-14.54	-2.21	15.31	26.46	43.98	60.63	64.33	75.91
Elevation 3	-72.17	-67.57	-53.05	-37.90	-25.47	-12.91	-0.88	11.03	24.70	39.30	55.23	67.95	74.13

Table A.3: Overall reverberant condition means responses in azimuth localization

Degree	-90	-75	-60	-45	-30	-15	0	15	30	45	60	75	90
Elevation 1	4.71	4.56	5.40	4.41	3.94	3.36	2.22	3.61	3.82	4.43	5.33	5.92	5.22
Elevation 2	4.93	6.24	6.17	5.07	4.08	3.64	2.96	4.04	4.00	5.20	6.10	6.49	6.58
Elevation 3	5.14	5.56	5.78	4.71	3.92	3.77	2.31	3.55	3.69	4.10	5.75	6.29	7.35

Table A.4: Overall standard deviation of responses in azimuth localization

Degree	-90	-75	-60	-45	-30	-15	0	15	30	45	60	75	90
Elevation 1	4.02	3.75	5.25	3.54	3.37	2.60	1.60	2.87	3.59	3.91	4.39	4.64	4.50
Elevation 2	3.59	5.00	6.15	3.90	3.58	3.02	2.25	3.10	3.05	4.09	4.69	5.06	5.11
Elevation 3	4.13	4.52	5.24	3.84	3.39	2.62	1.89	2.93	3.18	4.02	4.70	5.30	5.86

Table A.5: Overall dry condition standard deviation responses in azimuth localization

Degree	-90	-75	-60	-45	-30	-15	0	15	30	45	60	75	90
Elevation 1	5.40	5.38	5.55	5.27	4.52	4.11	2.84	4.34	4.05	4.95	6.26	7.20	5.94
Elevation 2	6.27	7.48	6.18	6.24	4.58	4.25	3.68	4.98	4.96	6.31	7.51	7.92	8.05
Elevation 3	6.14	6.60	6.32	5.59	4.45	4.91	2.74	4.17	4.19	4.19	6.80	7.27	8.84

Table A.6: Overall reverberant condition standard deviation responses in azimuth localization

Appendix B

Raw Data

This appendix presents the raw data of subject responses (response azimuth vs response elevation) for each round and location. For every figure, a blue dot represents one subject's average response for the dry condition, where as the red dots represent the average response for the reverberant conditions trials. A total of 19 dots are shown for each condition (19 red dots and 19 blue dots). The cyan and pink triangles represent the response mean of all subjects average response for the dry and reverberant responses. The large black dot represents the target location.

B.1 Part 1:Raw Data

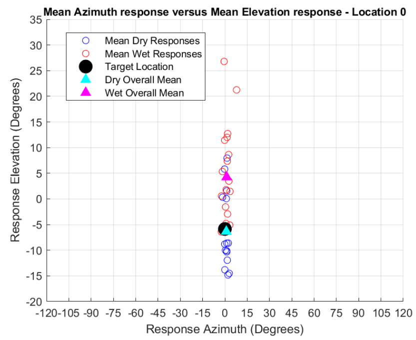

Figure B.1: Adults-Modified Mean for each Subject, Location 0

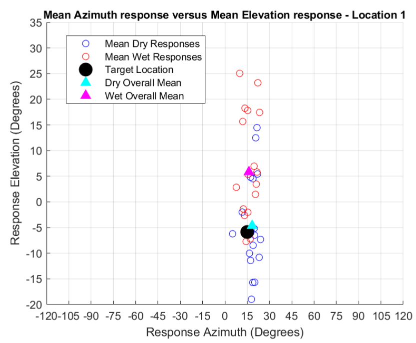

Figure B.2: Adults-Modified Mean for each Subject, Location 1

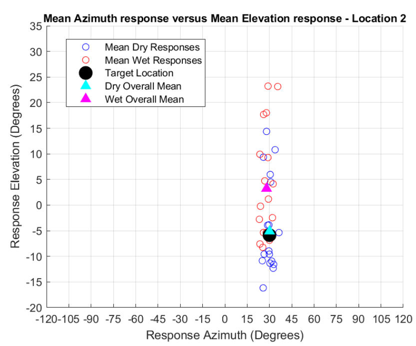

Figure B.3: Adults-Modified Mean for each Subject, Location 2

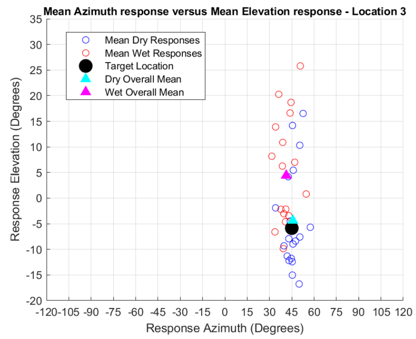

Figure B.4: Adults-Modified Mean for each Subject, Location 3

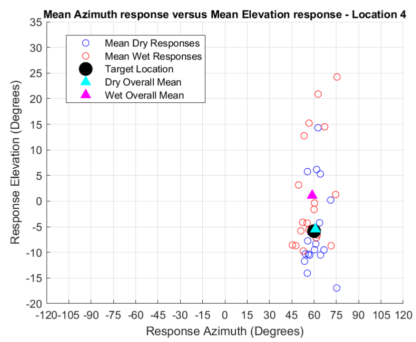

Figure B.5: Adults-Modified Mean for each Subject, Location 4

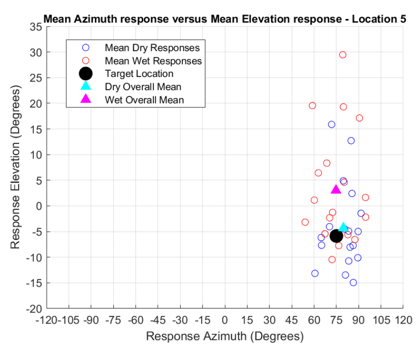

Figure B.6: Adults-Modified Mean for each Subject, Location 5

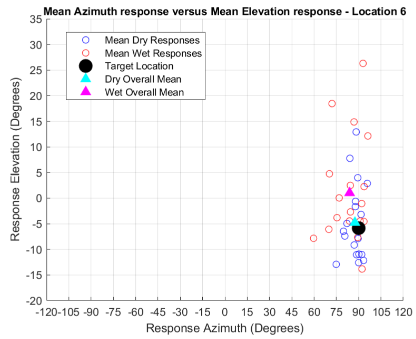

Figure B.7: Adults-Modified Mean for each Subject, Location 6

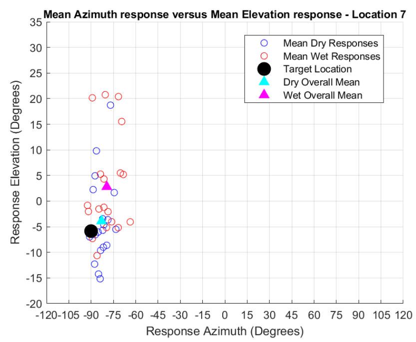

Figure B.8: Adults-Modified Mean for each Subject, Location 7

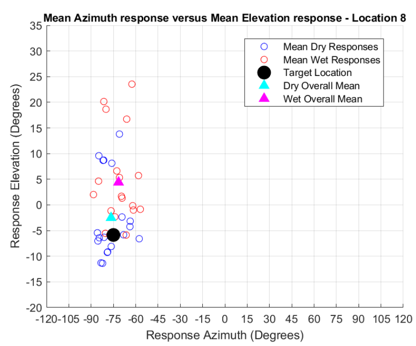

Figure B.9: Adults-Modified Mean for each Subject, Location 8

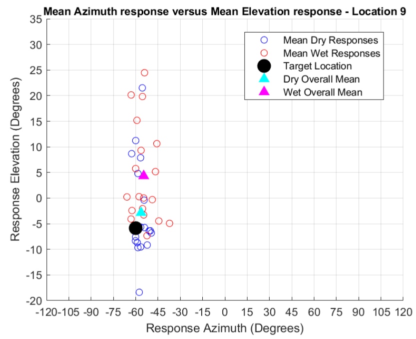

Figure B.10: Adults-Modified Mean for each Subject, Location 9

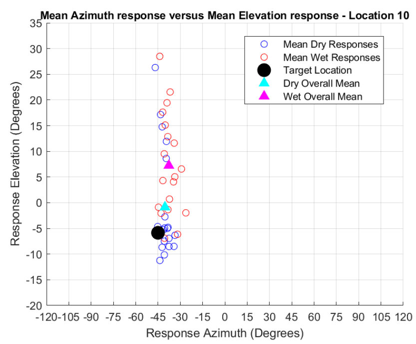

Figure B.11: Adults-Modified Mean for each Subject, Location 10

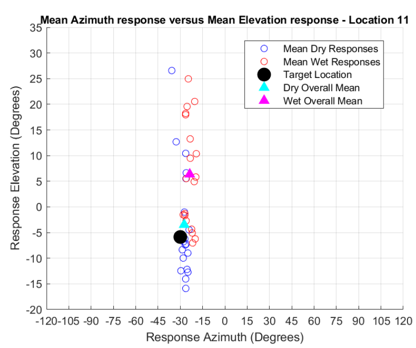

Figure B.12: Adults-Modified Mean for each Subject, Location 11

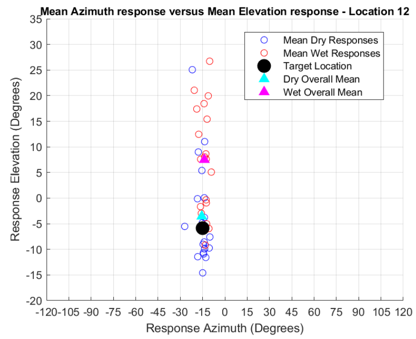

Figure B.13: Adults-Modified Mean for each Subject, Location 12

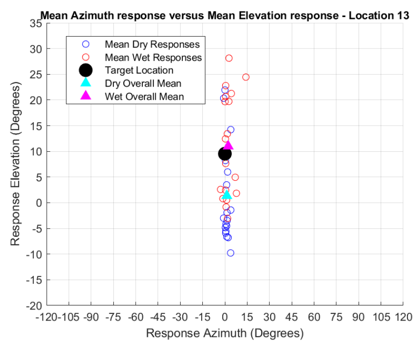

Figure B.14: Adults-Modified Mean for each Subject, Location 13

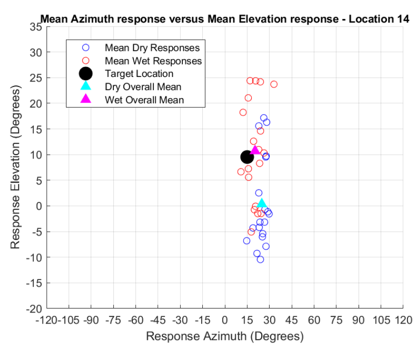

Figure B.15: Adults-Modified Mean for each Subject, Location 14

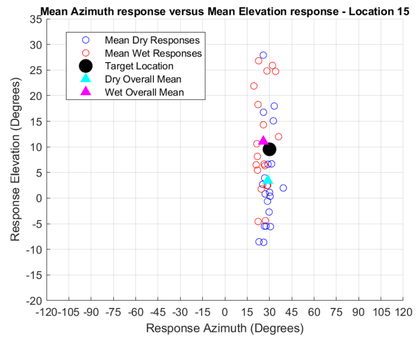

Figure B.16: Adults-Modified Mean for each Subject, Location 15

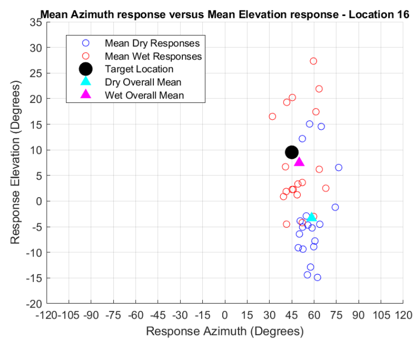

Figure B.17: Adults-Modified Mean for each Subject, Location 16

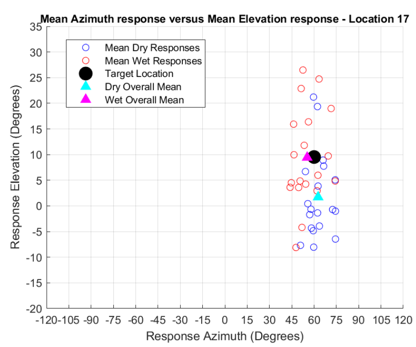

Figure B.18: Adults-Modified Mean for each Subject, Location 17

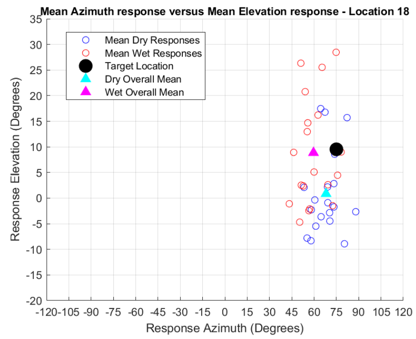

Figure B.19: Adults-Modified Mean for each Subject, Location 18

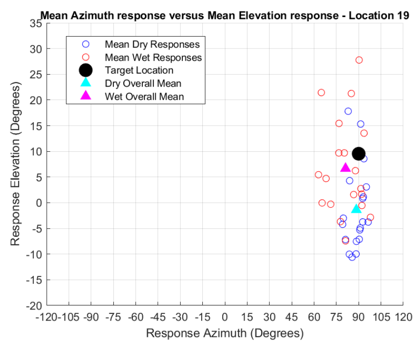

Figure B.20: Adults-Modified Mean for each Subject, Location 19

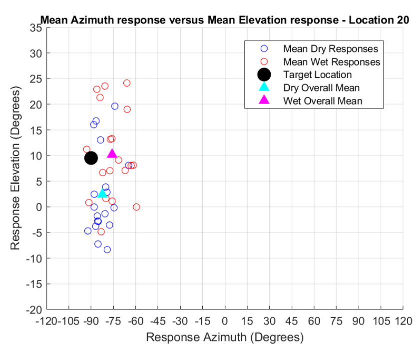

Figure B.21: Adults-Modified Mean for each Subject, Location 20

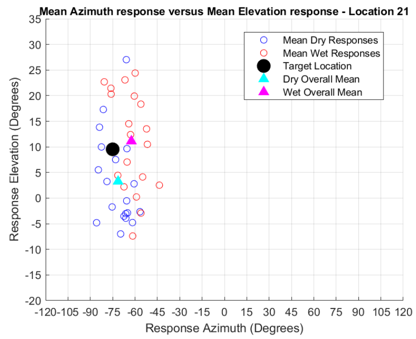

Figure B.22: Adults-Modified Mean for each Subject, Location 21

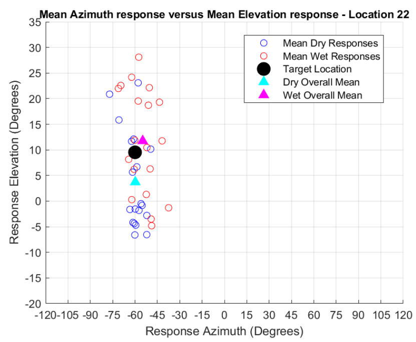

Figure B.23: Adults-Modified Mean for each Subject, Location 22

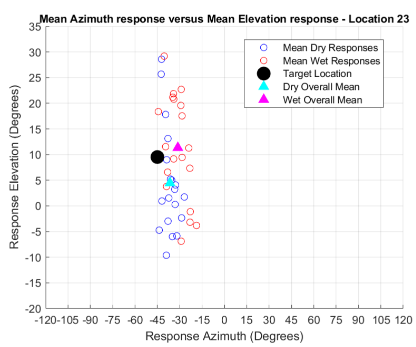

Figure B.24: Adults-Modified Mean for each Subject, Location 23

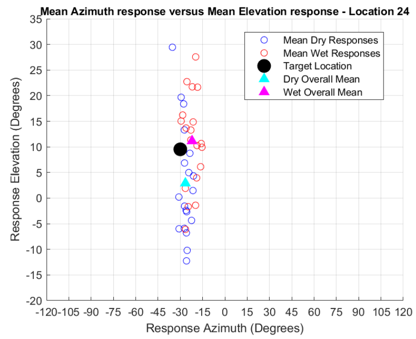

Figure B.25: Adults-Modified Mean for each Subject, Location 24

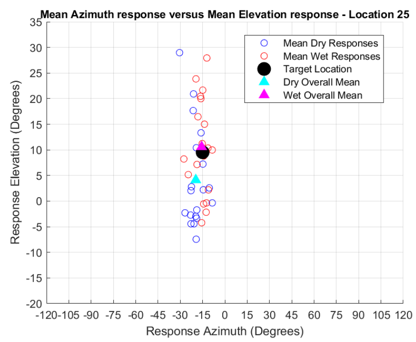

Figure B.26: Adults-Modified Mean for each Subject, Location 25

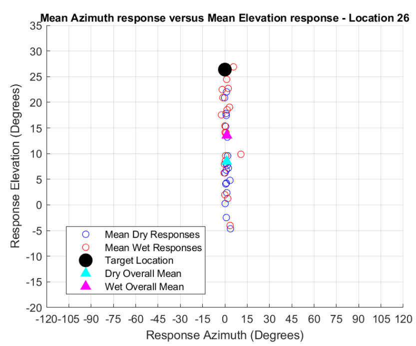

Figure B.27: Adults-Modified Mean for each Subject, Location 26

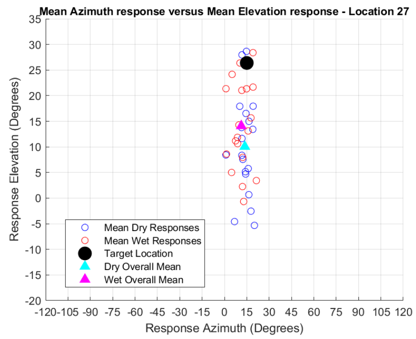

Figure B.28: Adults-Modified Mean for each Subject, Location 27

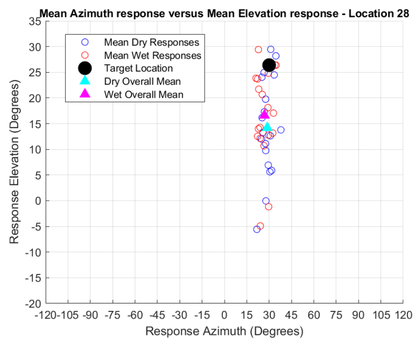

Figure B.29: Adults-Modified Mean for each Subject, Location 28

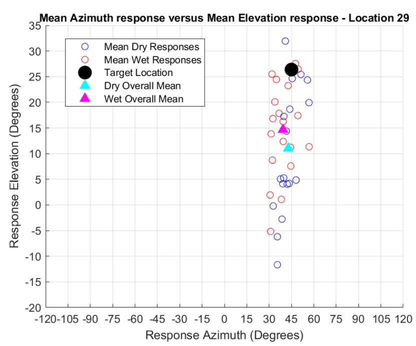

Figure B.30: Adults-Modified Mean for each Subject, Location 29

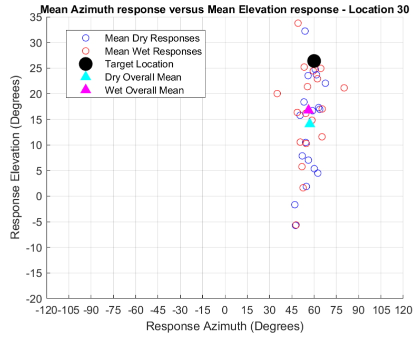

Figure B.31: Adults-Modified Mean for each Subject, Location 30

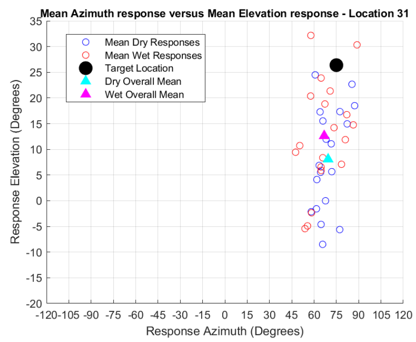

Figure B.32: Adults-Modified Mean for each Subject, Location 31

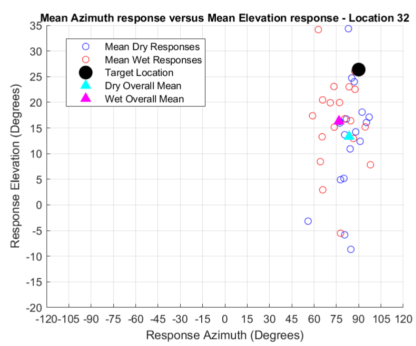

Figure B.33: Adults-Modified Mean for each Subject, Location 32

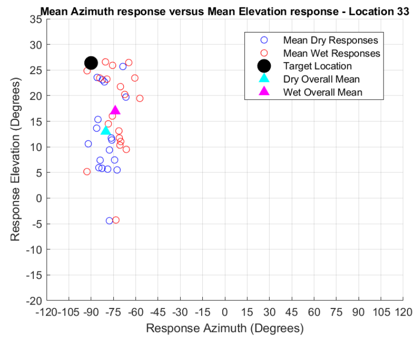

Figure B.34: Adults-Modified Mean for each Subject, Location 33

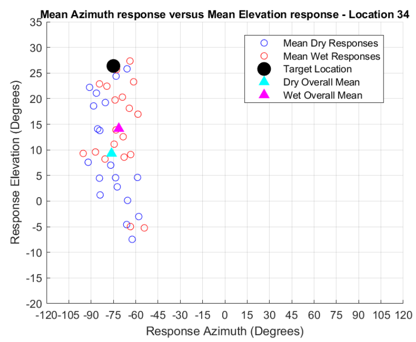

Figure B.35: Adults-Modified Mean for each Subject, Location 34

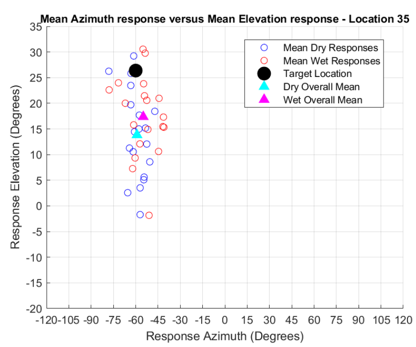

Figure B.36: Adults-Modified Mean for each Subject, Location 35

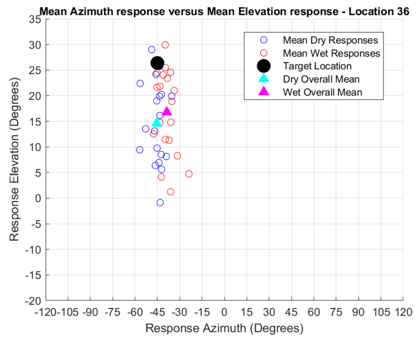

Figure B.37: Adults-Modified Mean for each Subject, Location 36

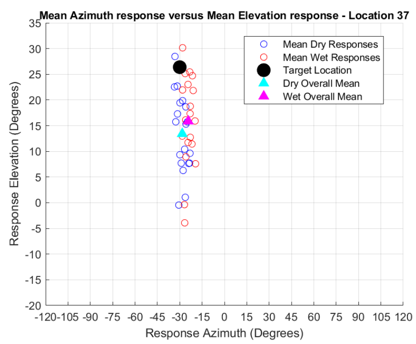

Figure B.38: Adults-Modified Mean for each Subject, Location 37

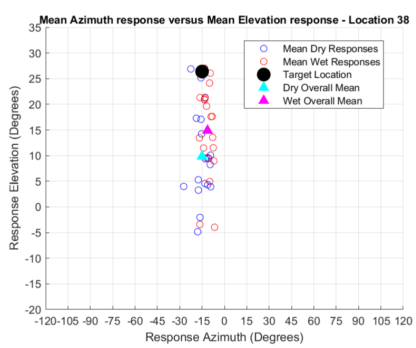

Figure B.39: Adults-Modified Mean for each Subject, Location 38

B.2 Part 2: Rotated Raw Data

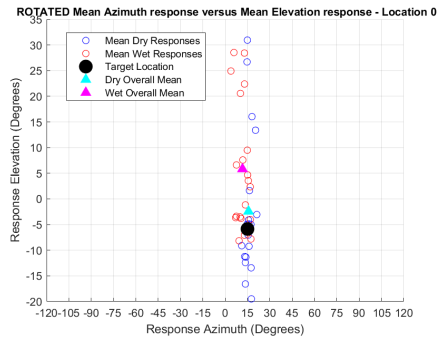

Figure B.40: Rotated: Adults-Modified Mean for each Subject, Location 0

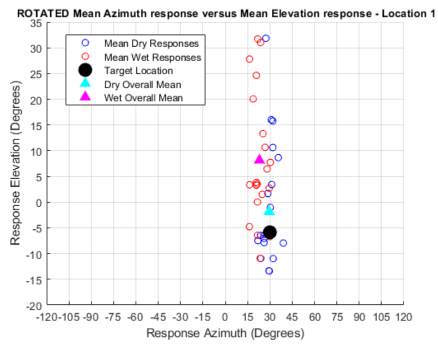

Figure B.41: Rotated: Adults-Modified Mean for each Subject, Location 1

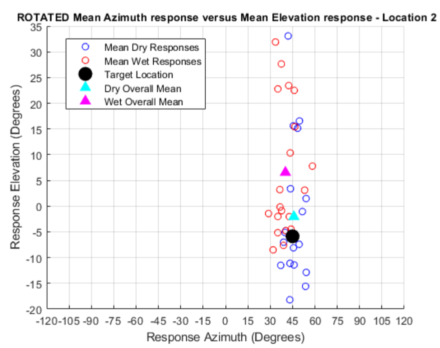

Figure B.42: Rotated: Adults-Modified Mean for each Subject, Location 2

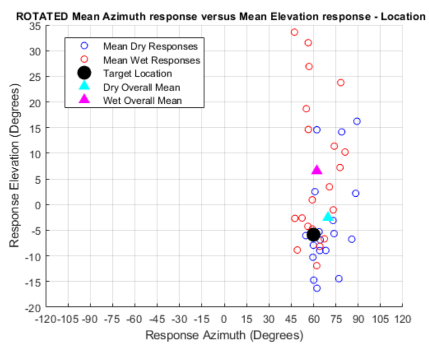

Figure B.43: Rotated: Adults-Modified Mean for each Subject, Location 3

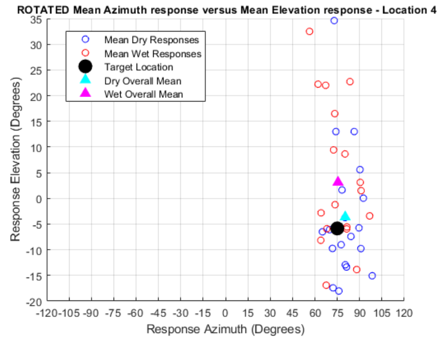

Figure B.44: Rotated: Adults-Modified Mean for each Subject, Location 4

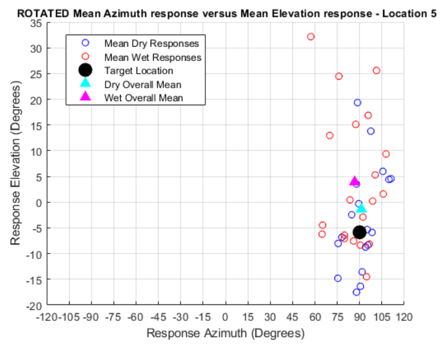

Figure B.45: Rotated: Adults-Modified Mean for each Subject, Location 5

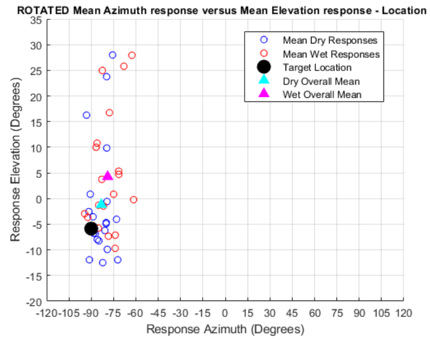

Figure B.46: Rotated: Adults-Modified Mean for each Subject, Location 6

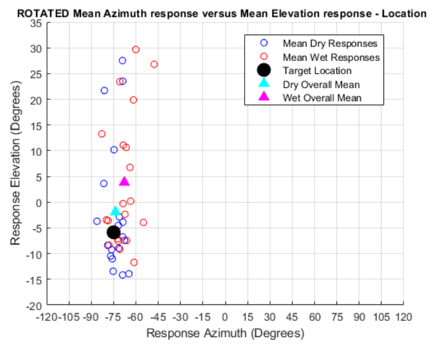

Figure B.47: Rotated: Adults-Modified Mean for each Subject, Location 7

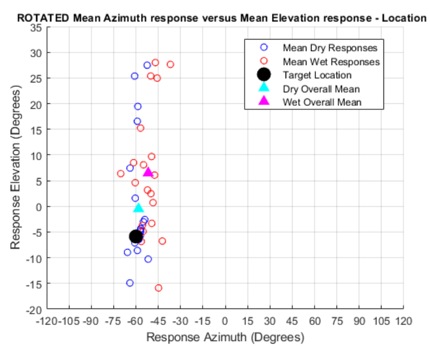

Figure B.48: Rotated: Adults-Modified Mean for each Subject, Location 8

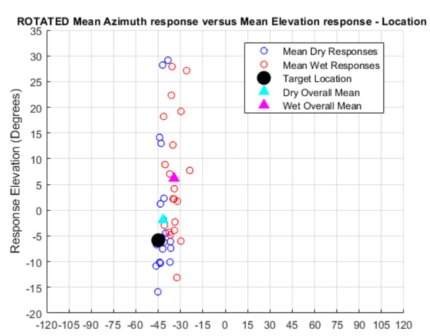

Figure B.49: Rotated: Adults-Modified Mean for each Subject, Location 9

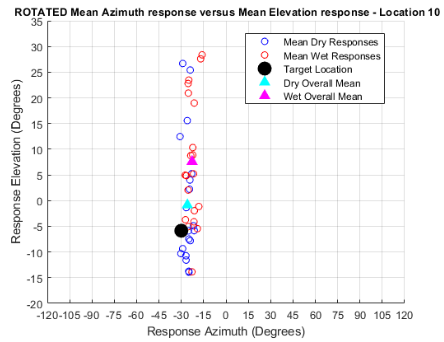

Figure B.50: Rotated: Adults-Modified Mean for each Subject, Location 10

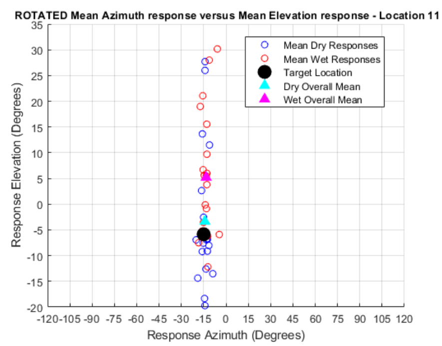

Figure B.51: Rotated: Adults-Modified Mean for each Subject, Location 11

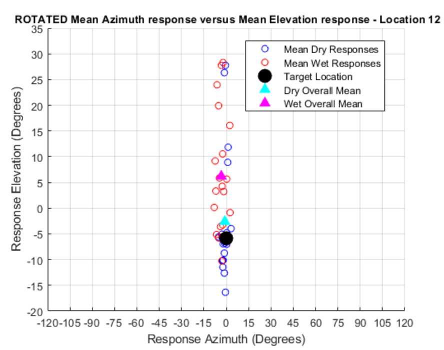

Figure B.52: Rotated: Adults-Modified Mean for each Subject, Location 12

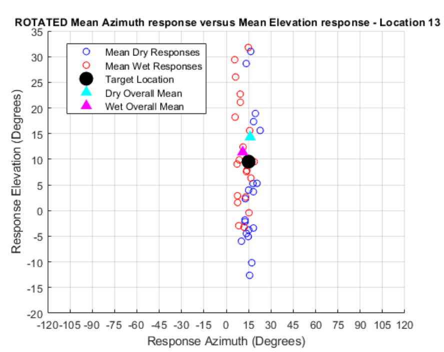

Figure B.53: Rotated: Adults-Modified Mean for each Subject, Location 13

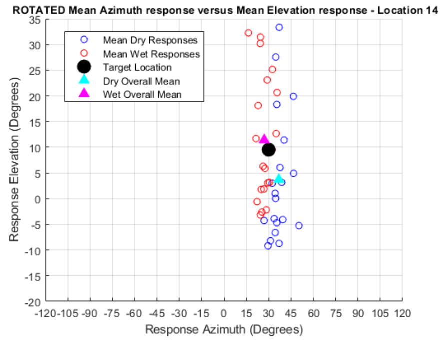

Figure B.54: Rotated: Adults-Modified Mean for each Subject, Location 14

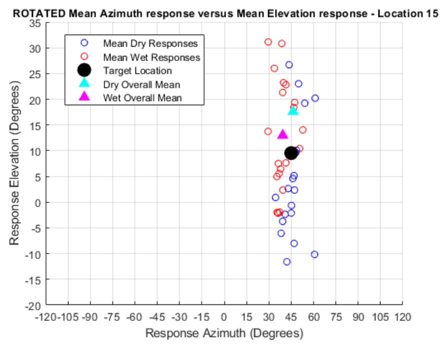

Figure B.55: Rotated: Adults-Modified Mean for each Subject, Location 15

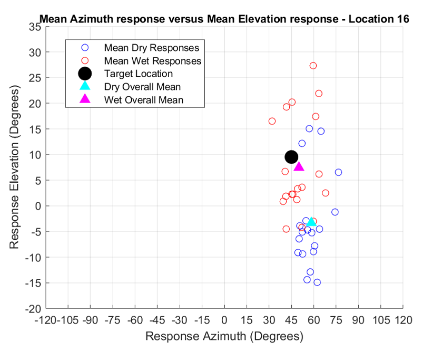

Figure B.56: Rotated: Adults-Modified Mean for each Subject, Location 16

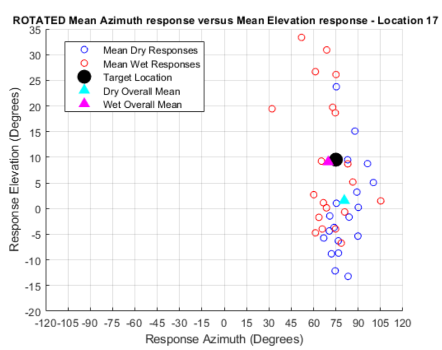

Figure B.57: Rotated: Adults-Modified Mean for each Subject, Location 17

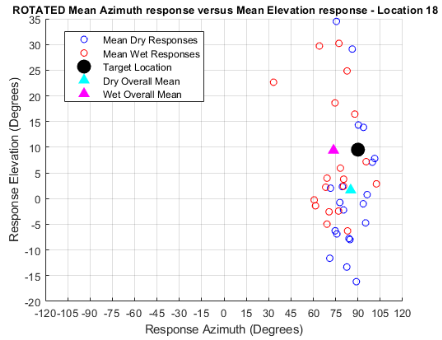

Figure B.58: Rotated: Adults-Modified Mean for each Subject, Location 18

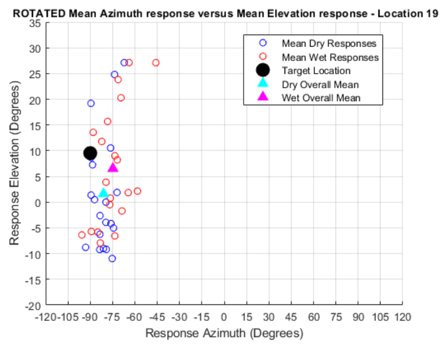

Figure B.59: Rotated: Adults-Modified Mean for each Subject, Location 19

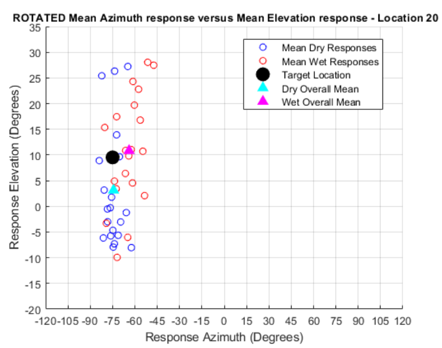

Figure B.60: Rotated: Adults-Modified Mean for each Subject, Location 20

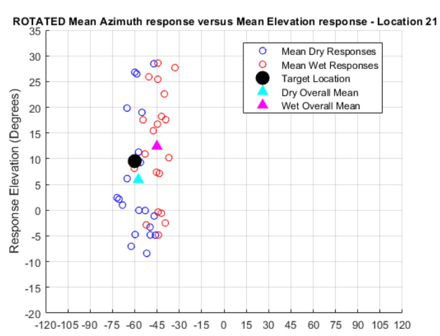

Figure B.61: Rotated: Adults-Modified Mean for each Subject, Location 21

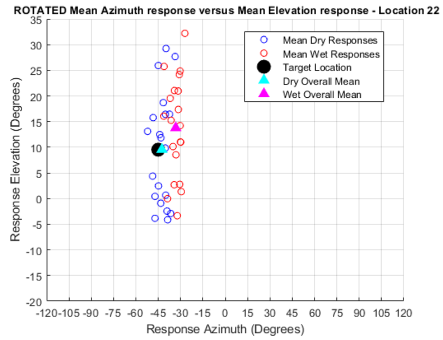

Figure B.62: Rotated: Adults-Modified Mean for each Subject, Location 22

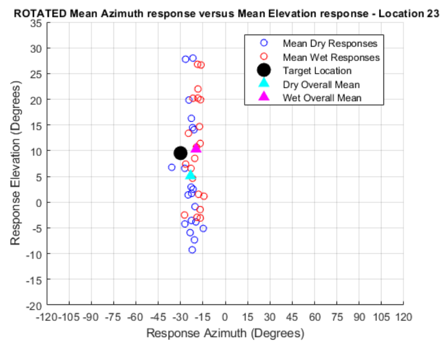

Figure B.63: Rotated: Adults-Modified Mean for each Subject, Location 23

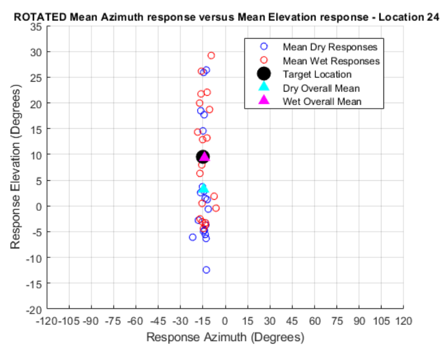

Figure B.64: Rotated: Adults-Modified Mean for each Subject, Location 24

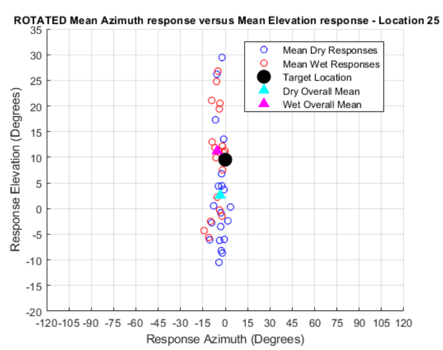

Figure B.65: Rotated: Adults-Modified Mean for each Subject, Location 25

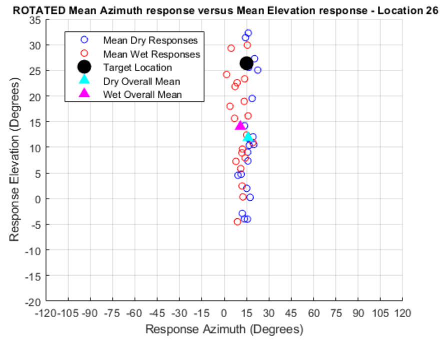

Figure B.66: Rotated: Adults-Modified Mean for each Subject, Location 26

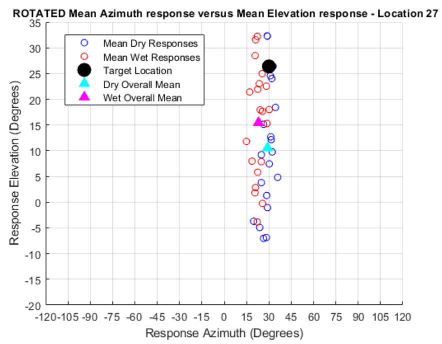

Figure B.67: Rotated: Adults-Modified Mean for each Subject, Location 27

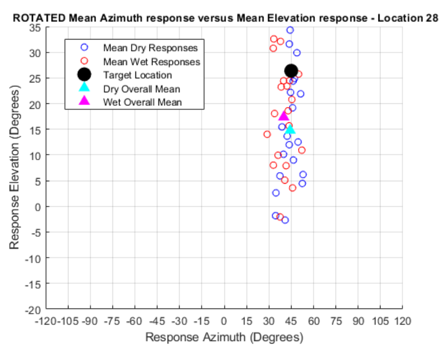

Figure B.68: Rotated: Adults-Modified Mean for each Subject, Location 28

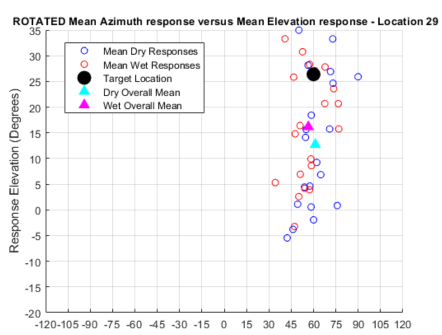

Figure B.69: Rotated: Adults-Modified Mean for each Subject, Location 29

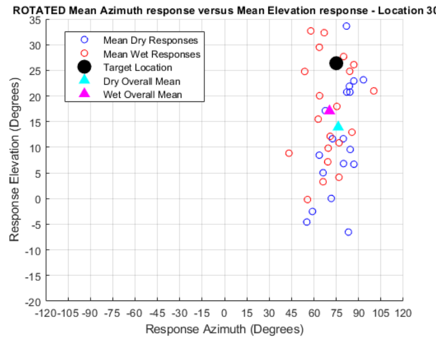

Figure B.70: Rotated: Adults-Modified Mean for each Subject, Location 30

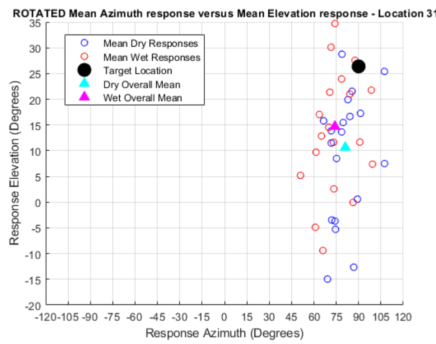

Figure B.71: Rotated: Adults-Modified Mean for each Subject, Location 31

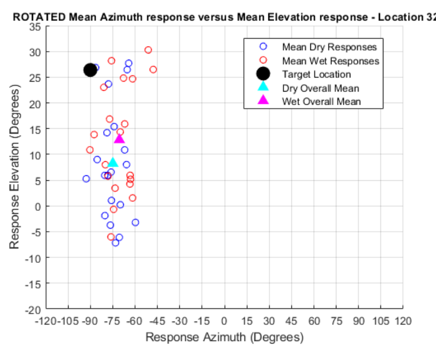

Figure B.72: Rotated: Adults-Modified Mean for each Subject, Location 32

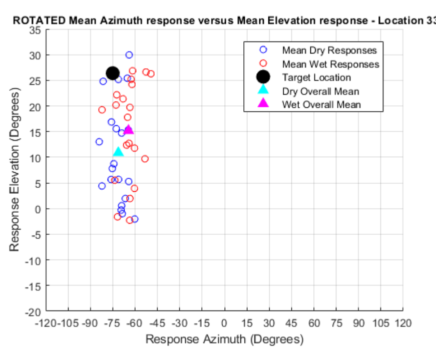

Figure B.73: Rotated: Adults-Modified Mean for each Subject, Location 33

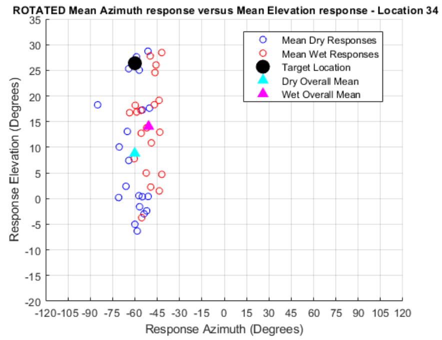

Figure B.74: Rotated: Adults-Modified Mean for each Subject, Location 34

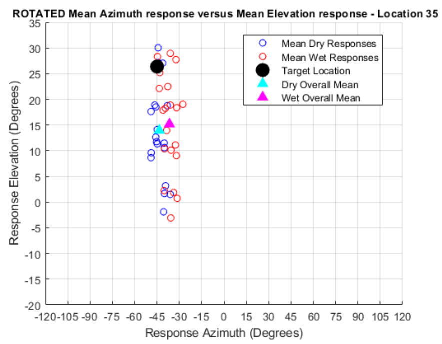

Figure B.75: Rotated: Adults-Modified Mean for each Subject, Location 35

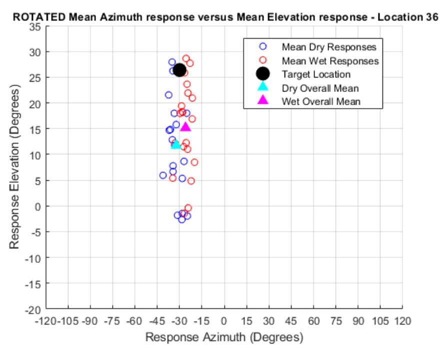

Figure B.76: Rotated: Adults-Modified Mean for each Subject, Location 36

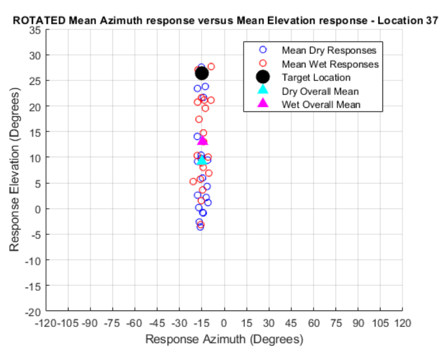

Figure B.77: Rotated: Adults-Modified Mean for each Subject, Location 37

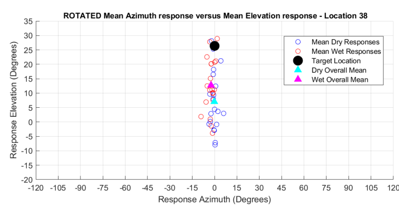

Figure B.78: Rotated: Adults-Modified Mean for each Subject, Location 38

Appendix C

Comparison of Rounds

A comparison round was done to check for significant changes occurred between the two visits, referred to as Round 1 and Round 2. There is no significant effect of part for azimuth accuracy or precision and elevation accuracy (Table C.1). The precision in elevation is a significant effect for Round, Round * Reverberation, and Round * Elevation * Reverberation, shown in Table C.2.

Variable	Sig. of Part	Partial Eta Squared
Azimuth Accuracy	.630	..013
Azimuth Precision	.678	.010
Elevation Accuracy	.321	.055
Elevation Precision	.004	.37

Table C.1: Accuracy - Azimuth Part Comparison Main Effect

Variable	Sig. of Precision	Partial Eta Squared
Part	.004	.37
Part * Reverb	.001	.460
Part * Elevation * Reverb	.001	.448

Table C.2: Precision Elevation Part Comparison Main Effect

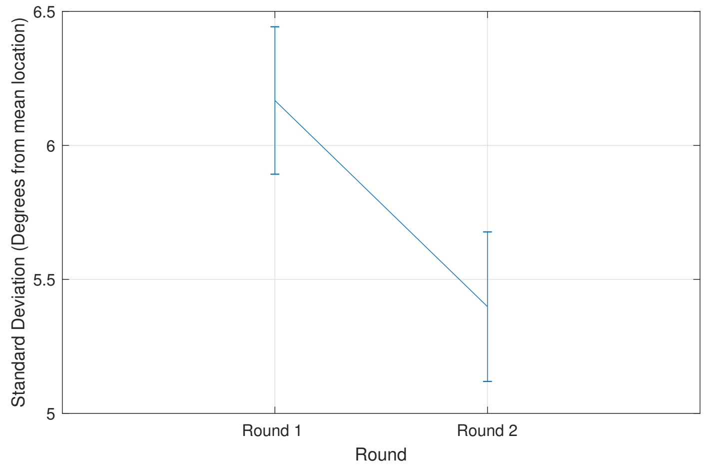

Figure C.1: Round Elevation Precision

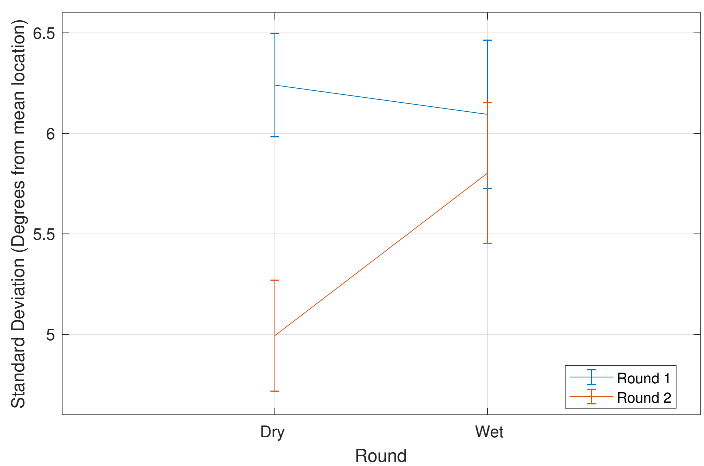

Figure C.2: Elevation Precision - Round * Reverb

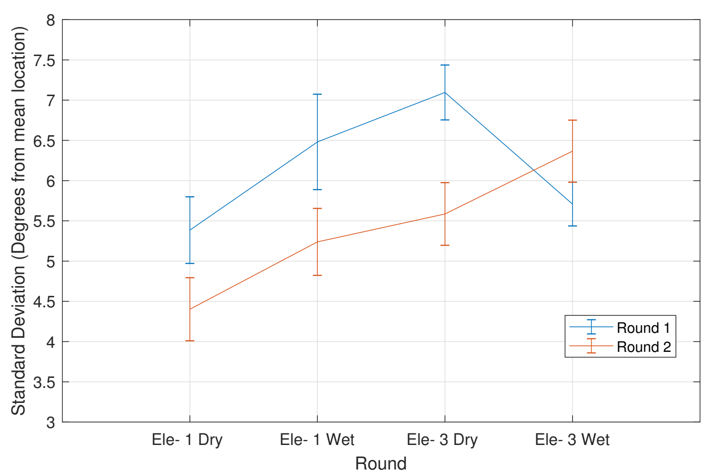

Figure C.3: Elevation Precision - Round * Elevation * Reverb

The significant interaction of precision presents evidence of improvement between the first and second visit. Figure C.1 shows that the second visit (Round 2) improved by roughly 0.5° in precision. The two way interaction between round and reverberation, the dry condition improved significantly between round while the wet condition was only marginal (Figure C.2). Finally, the three way interaction of Round * Elevation * Reverberation, shown in C.3, there was significant improvement of about 1° for each condition except for the Elevation 2 Wet condition.

Appendix D

Musical Experience Questionnaire

Questions were as follows:

Please circle the letter of the most appropriate response for each question, but do not mark more than one response per question.

1. On average how often do you listen to music in a week?

    (a) Less than 1 hour

    (b) Between 1 and 4 hours

    (c) Between 4 and 10 hours

    (d) Between 10 and 40 hours

    (e) More than 40 hours

2. On average, how many hours do you purposely listen to music in a day?

    (a) Never

    (b) Less than 30 minutes

(c) Between 30 minutes and 2 hours

(d) Between 2 and 4 hours

(e) More than 4 hours

3. Have you played or do you play a musical instrument?

(a) No

(b) Yes

4. Have you sung as a soloist or performed in a musical ensemble since high school?

(a) No

(b) Yes

If you answer No to question 3 and question 4, then you need not answer the remaining questions.

5. The peak of your interest, how many hours per day did you play practice the musical instrument or sing rehearse ?

(a) Not applicable

(b) 1 hour or less

(c) 1 to 2 hours

(d) 2 to 6 hours

(e) 6 or more hours

6. How long since you last regularly played a musical instrument or, what is the highest level of formal music training have you received?

    (a) Not applicable

    (b) 10 or more years ago

    (c) 5 to 10 years ago

    (d) Less than 5 year ago

    (e) I regularly play an instrument at the present time

7. What is the highest level of formal music training you have received?

    (a) Not applicable

    (b) Up to 1 year

    (c) 1 to 5 years

    (d) 5 to 10 years

    (e) More than 10 years