EMBRY-RIDDLE Aeronautical University
SCHOLARLY COMMONS

Theses - Daytona Beach | Dissertations and Theses

Summer 2001

The Effects of Sound Cue Characteristics on Overcoming Front/Back Localization Errors in a 3-D Auditory Display

Robert J. Ehmann
Embry-Riddle Aeronautical University - Daytona Beach

Follow this and additional works at: https://commons.erau.edu/db-theses

Part of the Ergonomics Commons

Scholarly Commons Citation
Ehmann, Robert J., "The Effects of Sound Cue Characteristics on Overcoming Front/Back Localization Errors in a 3-D Auditory Display" (2001). *Theses - Daytona Beach*. 54.
https://commons.erau.edu/db-theses/54

This thesis is brought to you for free and open access by Embry-Riddle Aeronautical University – Daytona Beach at ERAU Scholarly Commons. It has been accepted for inclusion in the Theses - Daytona Beach collection by an authorized administrator of ERAU Scholarly Commons. For more information, please contact commons@erau.edu.

THE EFFECTS OF SOUND CUE CHARACTERISTICS ON OVERCOMING FRONT/BACK LOCALIZATION ERRORS IN A 3-D AUDITORY DISPLAY

By

Robert J. Ehmann

A Graduate Thesis Submitted to the Human Factors and Systems Engineering Department in Partial Fulfillment of the Requirements for the Degree of Master of Science in Human Factors and Systems Engineering

Embry-Riddle Aeronautical University

Daytona Beach, Florida

Summer 2001

UMI Number: EP31929

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.
In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI®

UMI Microform EP31929
Copyright 2011 by ProQuest LLC
All rights reserved. This microform edition is protected against unauthorized copying under Title 17, United States Code.

ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106-1346

THE EFFECTS OF SOUND CUE CHARACTERISTICS ON OVERCOMING FRONT/BACK LOCALIZATION ERRORS IN A 3-D AUDITORY DISPLAY

By

Robert J. Ehmann

This thesis was prepared under the direction of the candidate's thesis committee chair, Dr. Steve Hall, Department of Human Factors and Systems Engineering, and has been approved by the members of his thesis committee. It was submitted to the Department of Human Factors and Systems Engineering and was accepted in partial fulfillment of the requirements for the degree of Master of Human Factors and Systems Engineering

THESIS COMMITTEE:

Steve Hall, Ph.D., Chair

Christina Frederick, Ph.D., Member

Timothy Wilson, Ph.D., Member

MS HFS Program Coordinator

Department Chair, Department of Human Factors and Systems

ACKNOWLEDGEMENTS

The author wishes to express special thanks to the Thesis Chair, Dr. Steve Hall, whose continued assistance and direction, both methodologically and spiritually, during the thesis process allowed for the experience to be an informative and successful endeavor. Appreciation and gratitude must also be given to Dr. Timothy Wilson for his knowledge and assistance in the area of sound and spatial hearing, as well as Dr. Christina Frederick for providing extra credit to participants from her class, and continued encouragement and insight throughout the thesis process. Both were outstanding Thesis Committee Members.

ABSTRACT

Author: Robert J. Ehmann

Title: The Effects of Sound Cue Characteristics on Overcoming Front/Back Localization Errors in a 3-D Auditory Display

Institution: Embry-Riddle Aeronautical University

Degree: Master of Human Factors and Systems Engineering

Year: 2001

The purpose of this study was to investigate the performance effects of adding an additional sound cue characteristic to a 3-D auditory display sound stimulus to increase localization accuracy. Previous literature has provided evidence that localization accuracy for direct front and direct back regions is significantly worse than that of locations in the periphery for virtual 3-D auditory stimuli. In the study conducted, a highpass filter addition or a lowpass filter addition was compared to a "normal" condition for both the front and back locations. Results of the study showed that the best localization performance for the front location occurred with the "normal" sound stimulus, and the best localization for the back occurred with the lowpass filter addition. The increased localization accuracy for lowpass sound stimuli representing the back followed the hypothesis of the experimenter as well as the theory of how humans best localize sound. However, the hypothesis for the front location was not supported, nor followed the theory of how humans best localize sound (higher frequencies from the front). A possible explanation for these results was that there may be an optimal frequency range for localizing front sound stimuli, or the presence of an asymmetrical filtering distribution affected the high-pass and low-pass characteristics.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Three-dimensional auditory displays have become a prominent area of study in the aviation community over the past 20 years. A 3-D auditory display attempts to provide a sound stimulus that can be localized to any area in the surrounding auditory field. Recent attempts at implementation of 3-D auditory displays have been for collision avoidance warnings, threat localization, and communication with multiple persons on one channel (Begault, 1995; Dingus, McGehee, Manakkal, Jahns, Carney, & Hankey, 1997; Bronkhurst, Veltman, & Breda, 1996; Haas, Gainer, Wightman, Couch, & Shilling, 1997). In all of these attempts, the 3-D auditory stimulus is used to represent where the warning, threat, or specific persons are located in relation to the pilot and his or her aircraft. As will be discussed, research on the validity of 3-D auditory displays and their ability to increase localization performance in general shows that it can provide performance benefits (Bronkhurst, et al., 1996; Begault, 1995). There does, however, seem to be a problem in the localization of front/back sound stimuli in virtual 3-D auditory displays (Dolan, Wells, & Osgood, 1993; Perret & Noble, 1997; Wenzel, Arruda, Kistler, & Wightman, 1993). Performance results obtained using 3-D auditory displays often show extremely accurate localization in the peripheral regions of the auditory field, yet errors in correct localization of front/back stimuli are significantly higher. The means by which humans localize sound, as well as the way 3-D sounds are generated, are believed to be the major problems that cause the larger number of errors in the front and back regions. The present study will attempt to provide a way to reduce the number of front/back errors by providing cue specific spatial sounds that will allow users to better discern front and back sound stimuli in virtual 3-D auditory displays.

Current Displays

Many important steps have been taken to ensure that loss of control and low-level flight into terrain accidents do not occur in aviation. Over time, navigational safety aids and warning systems for aircraft have been developed for the purpose of helping pilot(s) reach their destination with a high rate of safety. Auditory cues, visual cues, or both, are currently in used in navigational safety aids to provide the important information required. The current available devices have been very helpful in providing the operational benefits they were designed for (keeping in mind no machine or device is perfect). Like most technologically advanced fields, however, the ongoing research and development into better, more sophisticated warning systems is continuing and the inclusion of an auditory warning in these displays is becoming more prevalent. With the constant mental demands being placed on pilots (e.g. instrument reading, flight procedures, ATC communication), developers believe it is important to provide an adequate warning that will not add to the pilot's workload, but will still provide an appropriate amount of information (Barfield, Cohen, & Rosenberg, 1997; Begault & Wenzel, 1993; Bronkhurst et al. 1996, Perrott, Saberi, Brown, & Strybel, 1990). The human visual system is the most dominant, and perhaps best means of stimulus reception, however, the visual systems workload is already heavily allocated in flight tasks, so the auditory system seems to be the best alternative (Barfield, et al., 1997). The introduction of an auditory warning allows the pilot to perform his or her visual tasks, yet pick-up and perceive warnings using the auditory system. Dividing pertinent information into separate modalities may help to reduce workload levels and increase stimulus perception.

Early Auditory Research

Auditory research has been conducted for at least the last 70 years. Stevens and Newman (1934) conducted a study on the localization of sound sources in an outdoor environment. Although this outside environment may not have been an appropriate environment due to other acoustical distractions, it none-the-less provides evidence for early auditory research. In fact, one of the important conclusions of the study is extremely relevant to the present study: confusion of positions lying in the front quadrant, with those in the back quadrant, occurred frequently during experimentation (Stevens & Newman, 1934).

Auditory Research in Automobiles

The automotive sector has also conducted research with auditory displays. Srinivasin and Jovanis (1997) tested a group of five different route-guidance systems in which one of the displays incorporating auditory information. A second study conducted by Dingus, et al. (1997) focused on headway maintenance/collision avoidance warning and also included five different displays with two of those incorporating auditory information. Results showed that performance was significantly better for displays that included auditory cues relative to those that did not. As stated in the two previous studies, the idea to use auditory displays in the automotive sector was taken from aviation. Due to the similarities in controlling a vehicle, monitoring controls, and situational awareness, any information that can be gathered to improve performance and decrease errors in the aviation community has the ability to be transferred to the 3-D auditory display's use in the automotive community.

Past Research Topics and Proposed Benefits of 3-D Audio

The fact that auditory cues have shown to be beneficial in certain situations (i.e. target localization, warning detection, and speech communication) provides the reasoning behind the continuing research and development that is conducted on auditory displays in the aviation/aerospace sector. With technology being more advanced now than it was 20 years ago, the auditory displays currently being studied most often are three-dimensional in nature. Single-speaker systems have been compared to multiple-speaker systems and it has been demonstrated that both can provide equal performance benefits (Calhoun, Valencia, & Furness, 1987). Auditory displays have been compared to visual displays and combined auditory-visual displays and there is evidence that the inclusion of auditory information provides better performance (Barfield, et al., 1997). For example, auditory displays can aid in target localization of objects in the periphery where eyesight is not effective (Barfield, et al., 1997). However, the inclusion of both types of displays may not be feasible for a majority of environments.

Speech intelligibility has also been studied and results show that 3-D auditory speech can be localized as accurately as 3-D tones and sounds (Begault & Wenzel, 1993; Ricard & Meirs, 1994). In addition to those studies mentioned there is a large collection of research that supports the idea that the use of 3-D auditory displays significantly improves performance in localization tasks (Begault, 1995; Perrot, Ambarsoom, & Tucker, 1987; Perrot, et al., 1990; Bronkhurst, et al., 1996).

The results of these studies seem to indicate that there is a performance benefit to 3-D auditory displays and that they have the potential to be an important safety and work aid. In an aviation context, the proposed benefit of a 3-D auditory system is that it will act as a head-up auditory display, allowing the pilot to maintain his or her normal visual attention, yet receive important and precise auditory information. Three specific advantages have also been proposed for the use of a 3-D audio display in conjunction with, or in place of, a visual display. First, by spatially separating signal and noise sources (signal relates to the sound to be perceived where as noise represents any non-specific environmental sound cues) it is possible to lower the threshold at which auditory cues can be detected and discriminated. Second, assigning spatial positions to sound sources improves identification of multiple sounds (Bronkhurst, et al., 1996). Third, in addition to the information contained in the signal itself, relevant directional information can be conveyed using the natural sound-localization ability of humans (Bronkhurst, et al., 1996). If these benefits are achieved, levels of situational awareness and safety should increase significantly due to more accurate and simplified information being presented in a more optimal manner than its current state.

This study (as well as other recent research) is focused on solidifying the third principle explained in the previous paragraph relating to the use of a human's natural ability to localize sound. The problem of front/back errors, specifically with virtual displays, has shown that the natural ability of humans to localize sound is degraded when the sound stimuli are directly in front or back (Dolan, et al., 1993; Perret & Noble, 1997). This is a significant problem that must be handled in order to ensure that localization with 3-D auditory displays can provide high accuracy from all spatial positions. Currently, the front/back error problems that exist in localization research do not strongly support the concept of using the human's natural ability for sound localization.

Fixed Versus Moving-Head Position

The topic of fixed head listening versus moving-head listening is another topic of study that is considered to need further explanation. Little research has been conducted on the effects of head movement versus non-head movement in 3-D auditory displays and it is often included in the discussion section of other studies as "future research". The limited research that has been conducted on head movement does show that there is a performance benefit to allowing and using free head movement to aid in the localization of audio tones or sounds (Sorkin, Wightman, Kistler, & Elvers, 1989; Valencia & Agnew, 1990). However, more importantly, research focusing on head movement and virtual 3-D auditory displays helped to recognize the significance of front/back localization errors that tend to occur in virtual 3-D auditory displays.

The significance of front/back localization errors was discovered while collecting research coinciding with the topic of head movement and localization. In a handful of the literature found on the effects of head movement, the problem of front/back errors came into importance through inferences gained from the performance results of the study being described, or the fact front/back errors were being used as a specific dependent measure for performance.

Research studies that have used front/back errors as a dependent variable have shown that there is a significant decrease in localization accuracy when sound stimuli move from points in the periphery, towards points closer to the direct front or direct back regions (Dolan, et al., 1993; Perret & Noble, 1997; Wenzel, et al., 1993). In conjunction with the specific research that included front/back errors as a dependent variable, other studies conducted on 3-D audio topics have also come to the conclusion that there is a problem of localization in the front/back regions after considering the performance in the studies they conducted (King & Oldfield, 1997; Ricard & Meirs, 1994; Valencia & Agnew, 1990). Taking into account the information provided by these studies, and the way humans localize sound stimuli, there is a definite problem that exists in localizing front and back sound stimuli that must be resolved if virtual 3-D auditory displays are going to be used optimally and efficiently.

Virtual Versus Real Auditory Displays

Three-dimensional auditory displays can be presented using one of two auditory display formats: a virtual display (headphones) or a real display (speakers). In a real display system, the user is surrounded by a network of speakers that will present the 3-D auditory stimulus from a speaker in that region of space. A virtual system, consisting of headphones, must process the sound stimulus through a set of digital filters that will formulate the necessary sound characteristics to make a sound stimulus appear to be coming from a specific area in space. These filters are based on head-related transfer functions (HRTFs).

Research has compared the performance of real displays versus virtual displays. The data support the notion that virtual displays provide equal information relative to real displays when localizing a sound stimuli's general location in space. When more precise localization is needed, however, virtual displays start to degrade in performance as compared to real displays, with one of the most prominent problems being front/back localization errors (Bronkhurst, 1995; Loomis, Hebert, & Cicinelli, 1990; Wenzel, et al., 1993; Doll, 1986). It is believed that the precise ability to generate a 3-D sound through a software program causes the performance difference. When a sound stimulus can be presented from an actual point in space around the listener's head, as opposed to being generated by a program and presented through headphones, there is a much more precise set of sound cue characteristics. Virtual systems must incorporate the use of HRTFs to digitally create a three-dimensional sound through headphones; therefore, the sound cues are not "natural" in their context.

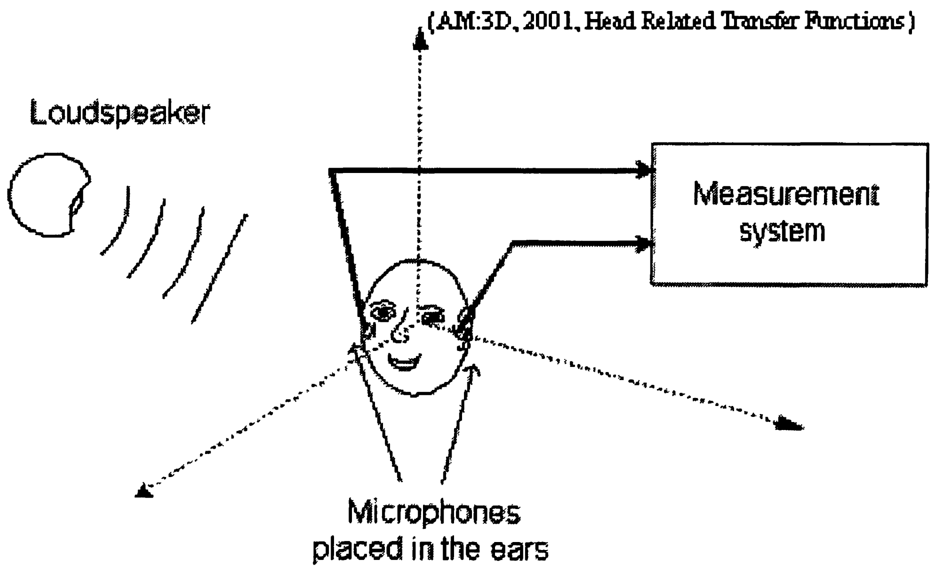
The implementation of "real" 3-D auditory displays is not feasible for many real world applications, such as aircraft cockpits and automobile interiors. Therefore, real world use of 3-D audio displays is limited to virtual type displays, making further development of virtual audio displays very important. For the purpose of this paper, the term "3-D auditory display" refers to a virtual auditory display. This is a critical point to keep in mind due to the fact that there is a performance difference in speaker versus headphone systems and they cannot be used interchangeably.

Head Related Transfer Functions

One specific area of continuing debate in the area of 3-D auditory systems is the topic of HRTFs. Head related transfer functions allow humans to pick up and localize acoustic information as accurately as possible according to their specific sound characteristics. Each person's head, shoulders, and external ear section are all positioned differently and their structure, or layout, is a unique template that allows that person to pick up sounds as accurately as possible. When a virtual 3-D auditory display is used, virtual HRTFs must be applied to the sound source to mimic its characteristics in the real world considering the user's natural capabilities are not viable.

HRTFs for virtual 3-D auditory displays are constructed by performing a complex set of measurements. Using a dummy head (or the head of an actual person), small microphones are placed within the ears to capture sound source information. A monaural sound source is then presented through a loudspeaker from various points in space around the head being measured. For each monaural sound presented a set of listening cues applied to the sound as it travels through the environment, to the microphones, are collected for each ear (left and right) (Kendall, 1998).

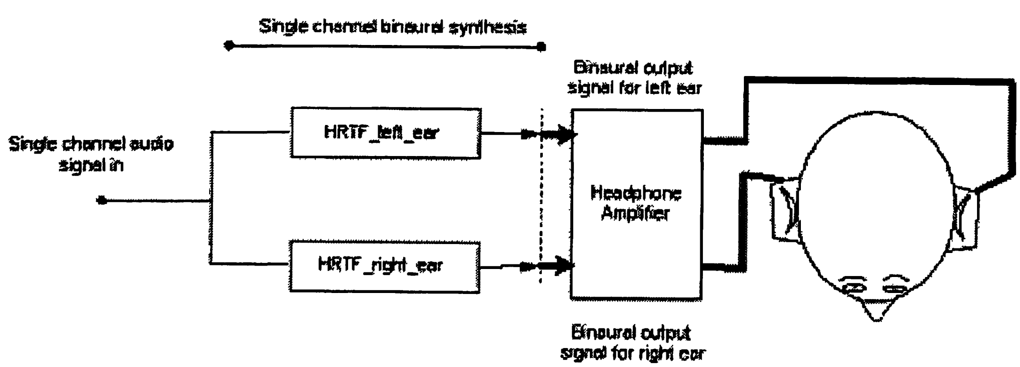
Figure 1
HRTF Measurement



Each set of left and right ear measurements corresponds to a position in space. As more spatial locations are measured, a table is constructed that contains a group of HRTFs for positions around the head. The more locations measured the better, however, seeing that there is an infinite number of three-dimensional points in space it is impossible to obtain HRTFs for every spatial location (AM:3D, 2001).

Once HRTFs have been collected (the number of locations varies according to developer) they are then administered to an auditory display's sound source through a 3-D auditory display software program via computer coding. When a sound source is programmed to be presented from a point in space using the 3-D auditory display, the software references that point to the closest match in the HRTF table. To produce the 3-D auditory sound through headphones, the left and right ear HRTFs for the desired location are synthesized to create a binaural output (Duda, 1996).

Figure 2
Application of HRTFs



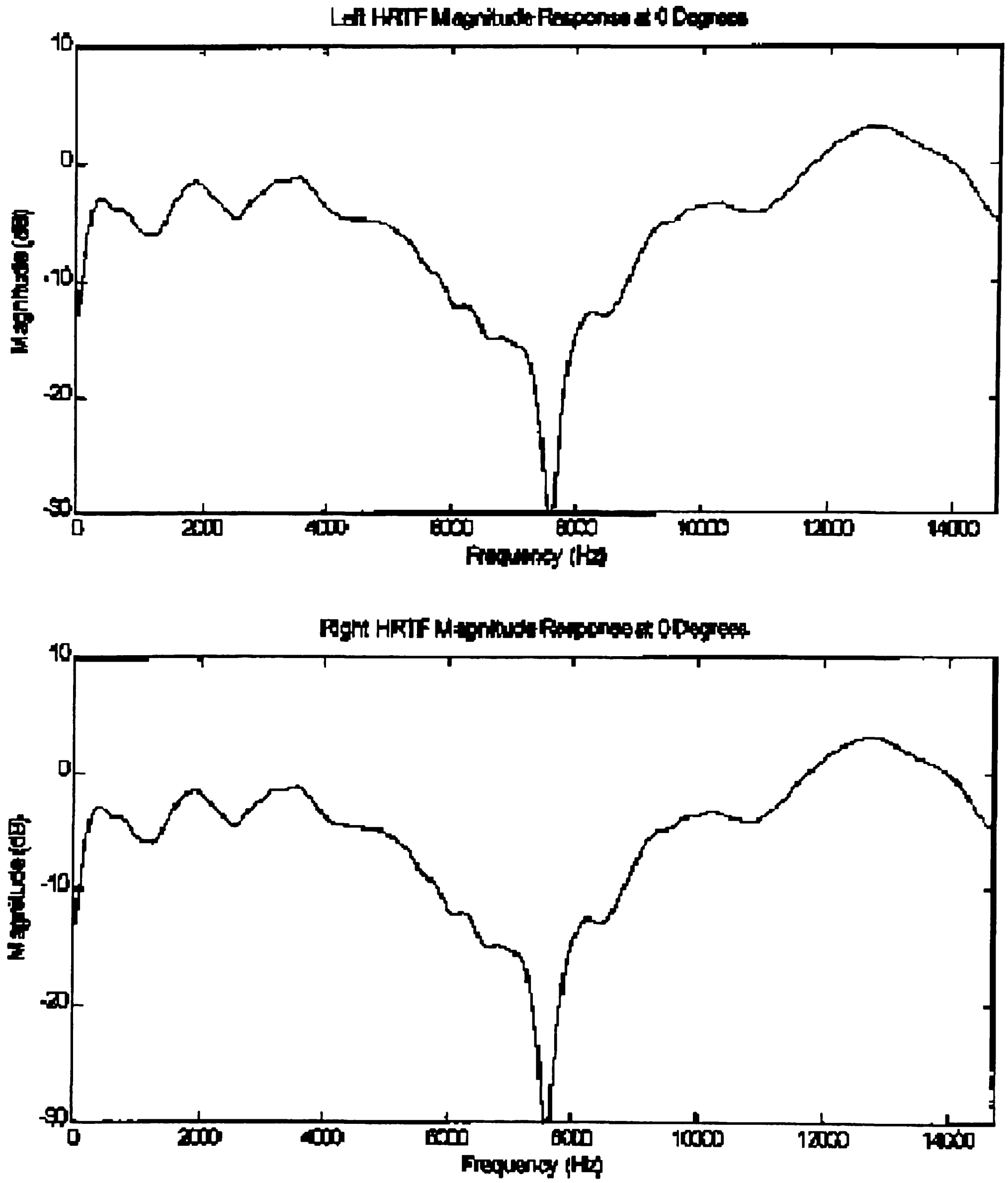
(AM:3D, 2001, Head Related Transfer Functions)

In regard to the continuing debate on HRTFs, the topic in question is whether the display being used should be specifically tailored to the user's HRTFs, or whether a general population average will work just as effectively. A generalized set of HRTFs can be measured from a dummy head or person representing a physiological average of the human population. Should an individualized set be required each potential user of the display would need to be subject to the complex measurements described earlier.

Mixed results have been achieved on HRTF specificity in the three-dimensional audio domain. Some research provides support that tailored systems are superior, whereas other studies show that there is no significant difference in the tailored HRTF design to the non-tailored HRTF design. For example, Bronkhorst (1995) compared real sound sources versus virtual sound sources. The virtual sound source included two conditions, individualized and non-individualized HRTFs. Performance data obtained showed that the individualized HRTFs provided for more error free localization of the sound source than the non-individualized, and were almost as accurate as the real sound sources. On the other side of the debate, Loomis et al. (1990) came to the conclusion that individualized HRTFs are helpful, but not necessary. In their study using a virtual sound source, the performance of five subjects displayed the notion that headphone-based virtual sounds do not necessarily have to implement the individualized HRTFs (Loomis, et al., 1990).

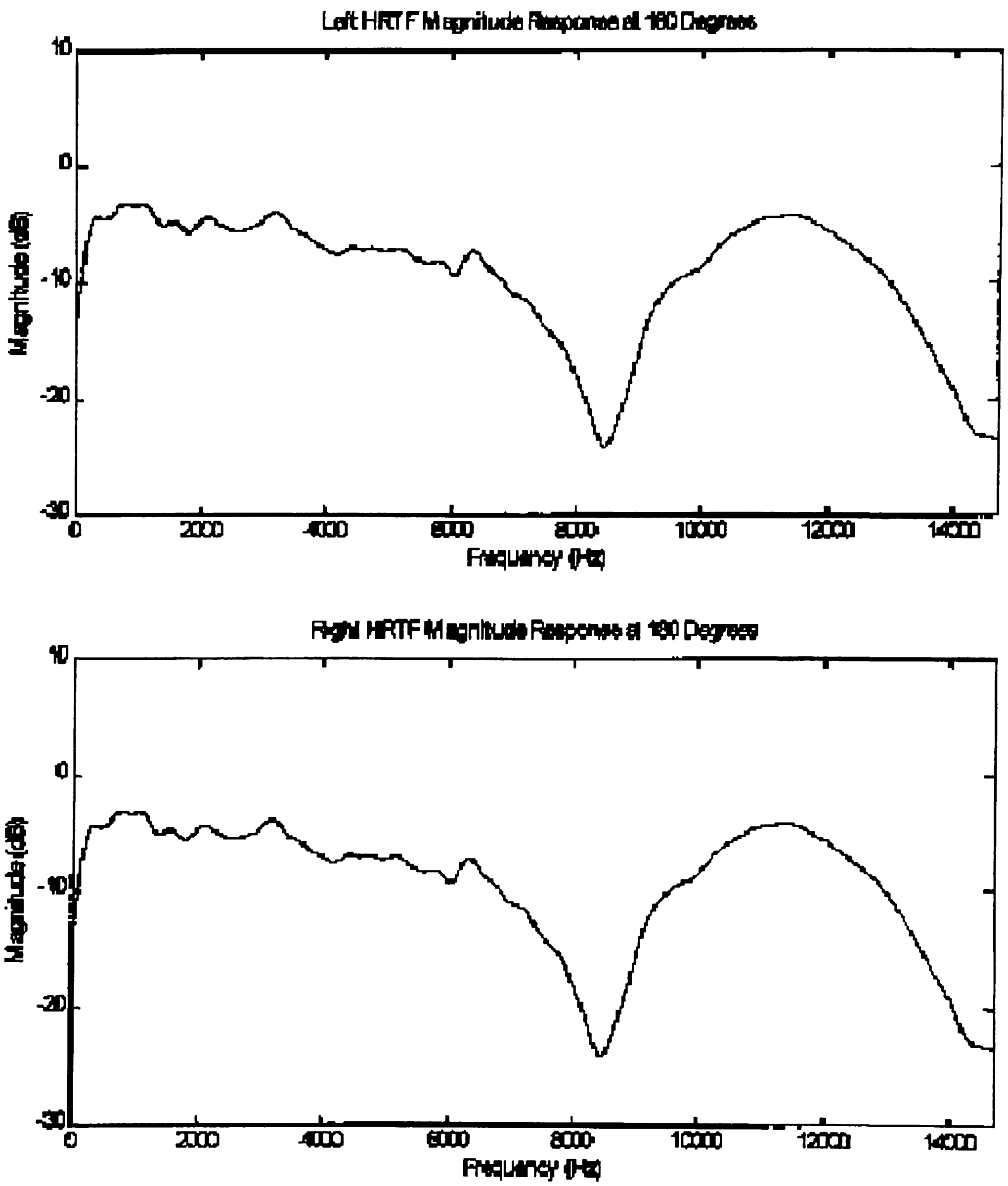
Regardless of whether HRTFs are individualized to each user, one theory of the present study is that baseline HRTFs used to present virtual 3-D audio sounds may not be adequate enough to provide the necessary cues needed to localize front and back sound stimuli. Figures 3 and 4 represent a set of HRTF measurements for direct front (0 degrees) and direct back (180 degrees) locations. Due to the sound source being presented from the direct front or direct back position, both ears are receiving identical measurements in direct front or direct back locations. To further explain this point, Figure 5 represents a set of measurements from a sound source located perpendicular to the right ear (90 degrees). As can be seen, each ear in Figure 5 is receiving a completely different set of sound characteristics due to the fact the sound source is located closer to one ear (in this case the right).

Figure 3
Set of HRTF Measurements for 0 Degrees



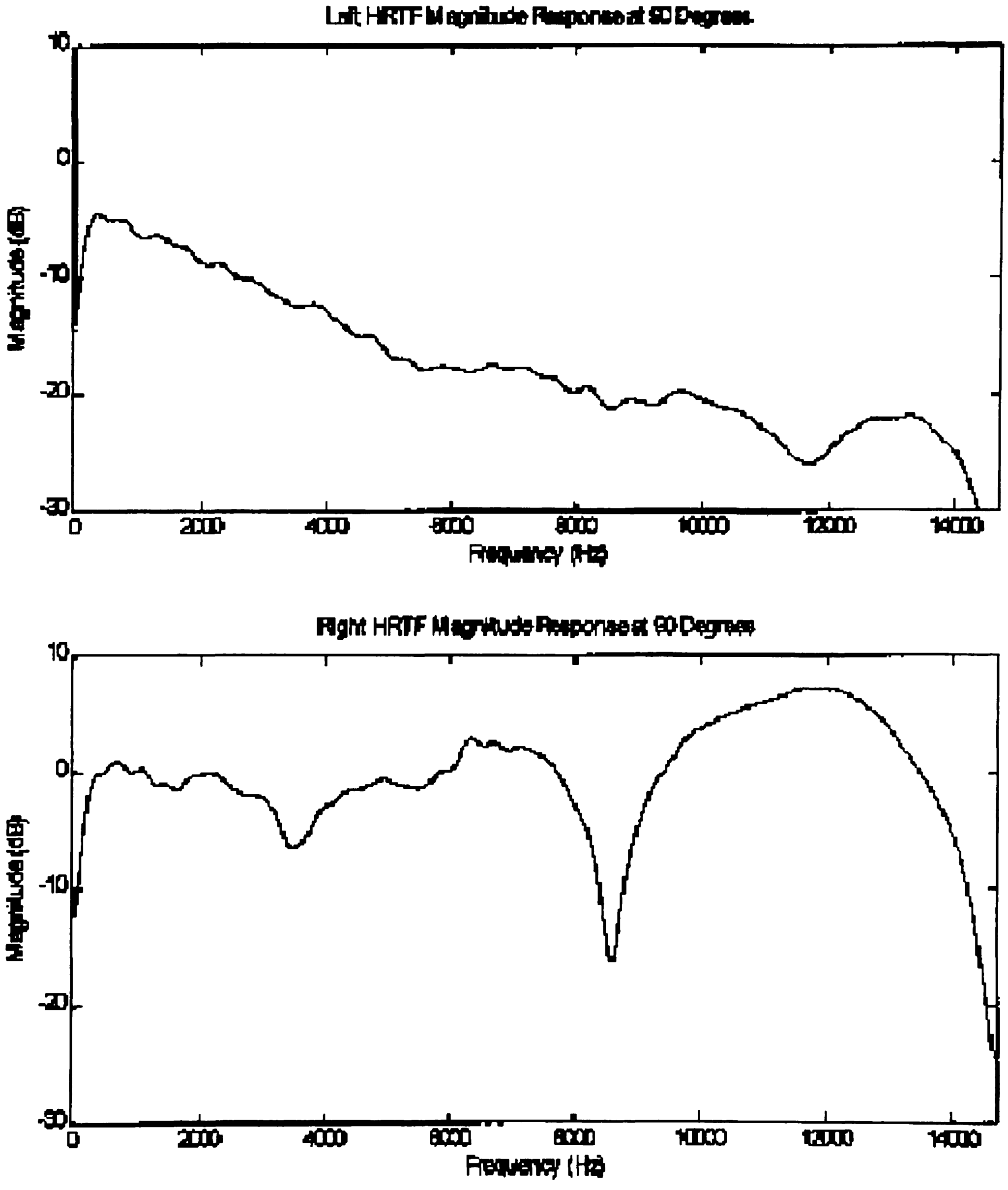
(Hugh, 2000, 3-D Audio Using Head Related Transfer Functions)

Figure 4
Set of HRTF Measurements for 180 Degrees



(Hugh, 2000, 3-D Audio Using Head Related Transfer Functions)

Figure 5
Set of HRTF Measurements for 90 Degrees



(Hugh, 2000, 3-D Audi Using Head Related Transfer Functions)

Further inspection of the HRTF measurements for the direct front and direct back locations show that not only are they identical within their pairing, but if transposed upon one another they are very similar in nature. The major difference between front HRTF measurements and the back HRTF measurements appears to be the majority of frequencies perceived. Direct back HRTFs include more low frequencies as compared to direct front HRTFs that include higher frequencies.

The fact that direct front HRTFs and direct back HRTFs are very similar in nature outside their small frequency differences raised one of the questions being examined by this study. It is believed that the similarity in virtual HRTFs for 3-D auditory displays may play a critical role in the large number of front/back errors that occur in virtual 3-D auditory display localization tasks. Therefore, performance may increase (reducing the number of localization errors) by adding an additional cue to the sound source on top of the HRTF. If these results are true, it may also provide evidence that non-individualized HRTFs can provide extremely accurate localization.

Present Study

The present study will attempt to increase the performance of localizing auditory stimuli in the direct front and direct back regions of the head by adding a highpass or lowpass filter to the sound stimulus. The study will examine whether an additional auditory cue added to a 3-D auditory display's sound stimulus (on top of HRTFs) will allow the user to make more accurate estimates of direct front and direct back sound stimuli. Previously published research in the area of 3-D auditory localization has focused only on the individualized or non-individualized aspect of HRTFs in 3-D auditory displays. The theory behind the current study suggests that the sound cues presented by measured HRTFs may not be distinctive enough to discern front and back sound location, and therefore might not be the best cue for optimal localization performance. Should the study's results support the theory that an additional sound cue provides increased localization accuracy for front and back sound stimuli, an inexpensive design function may be found that can be implemented into future 3-D auditory displays to overcome the problems associated with front/back errors.

The present study will manipulate two variables, Location and Filter, and compare localization performance. The Location variable will consist of a front and back condition, while the Filter variable will consist of a Normal, Highpass, and Lowpass condition. In the Normal condition, sound stimuli presented will contain only the set of HRTFs that are included with the software program. Within the Highpass condition a highpass filter will be added to the sound stimuli, and under the Lowpass condition a lowpass filter will be added to the sound stimuli. For clarification purposes, a sound stimulus presented through a highpass filter will consist only of high frequencies, whereas a sound stimulus presented through a lowpass filter will consist only of low frequencies. A frequency cut off rate regulates the range of frequencies that are presented through each filter. For example, in the current study the frequency cut off rate for each filter will be 1000 Hz. Under the highpass condition frequencies under 1000 Hz will be omitted, and in the lowpass condition frequencies above 1000 Hz will be omitted. Three-dimensional auditory software will be used to incorporate these filters to construct the different experimental sound stimuli. As stated earlier in the paper, HRTFs are needed to represent a virtual 3-D sound, so these filters will be added on top of the necessary HRTFs of the 3-D auditory software.

Manipulating the variables Location and Filter and examining their localization performance will attempt to provide evidence as to whether an additional sound cue, added to the HRTFs, will increase front and back localization performance. The theory of using a high or lowpass filter was developed in accordance with the HRTF description provided earlier. Front and back sound characteristics in virtual 3-D auditory displays appear to differ only slightly, with the difference being the frequency range they contain (Figure 3, Figure 4). Normal front sound stimuli presented in a 3-D auditory display contain higher frequencies than those presented from the back. Therefore, the theory of using a high or lowpass filter as the additional cue is an attempt to "boost" the frequency levels of the HRTFs in order to create a more accurate, salient sound stimulus.

Humans tend to localize higher frequencies better from the front and lower frequencies better from the back. One reason for this is the acoustical shadow effect. An example of this can be seen in the HRTF measurements provided earlier. One characteristic of higher frequencies is that they reflect off objects due to their shorter, more compact wavelengths, whereas lower frequencies engulf, or wrap around an object (Goldstein, 1999). When high frequencies reflect off an object an acoustical shadow is created on the opposing side reducing the availability of high frequency sound waves. Due to the protrusion of the external ear on humans, high frequencies originating from behind the head reflect off the back of the ears creating an acoustical shadow on the front side where sound is best suited to enter the ear canal (Goldstein, 1999). This phenomenon formulates the theory within this study that the optimal sound stimuli for virtual 3-D audio localization will be those that are front highpass and back lowpass in nature and coincide with how humans learn to associate sounds. Normal sound stimuli in

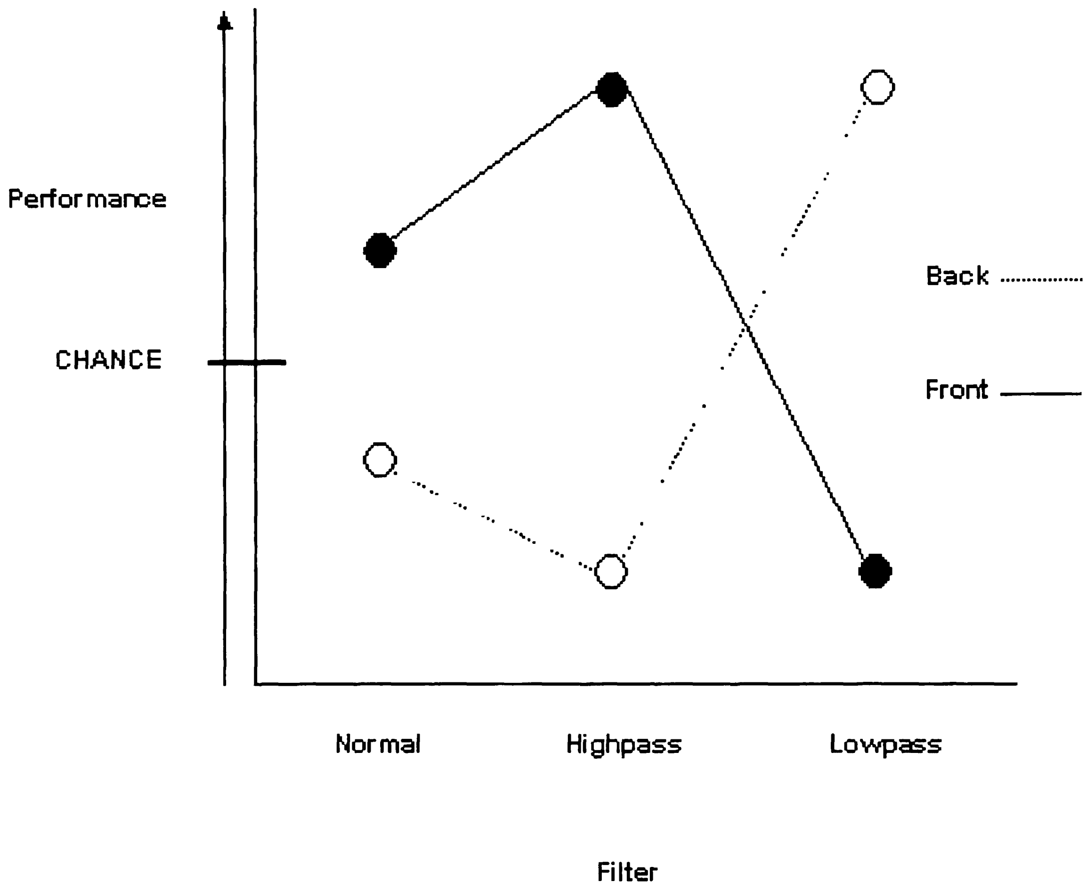
3-D audio displays may not provide strong enough sound characteristics in a virtual auditory display. The added filter "boost" in accordance with how humans best localize sound may be a viable answer to the front/back error problem that exists in 3-D auditory localization.

Hypotheses

Analysis of the data from the current study will not focus on the main effect of Location, or the main effect of Filter, but rather whether or not an interaction exists between the two variables. To be more specific, with the study's theory that an additional sound cue will increase localization performance, the experimenter suggests that a sound stimulus consisting of a highpass filter for the front region and a lowpass filter for the back region will provide the most accurate localization performance.

An interaction effect is hypothesized for the variables Location and Filter. It is hypothesized that the localization performance for front and back sound stimuli will be significantly affected by the filter that is being added. More specifically, optimal localization is expected to occur under the Front-Highpass Filter condition and the Back-Lowpass Filter condition (see Figure 6). With only two location responses available, six comparisons will be conducted for each condition's performance in relation to the possibility it may have occurred by chance alone. It is hypothesized that the Front-Highpass Filter and Back-Lowpass Filter will produce performance results greater than chance, while the Front-Lowpass Filter and Back-Highpass Filter conditions will result in performance below chance. The Front-Normal and Back-Normal conditions are hypothesized to perform equivalent to chance.

Figure 6
Graph of Hypotheses



METHOD

Participants

Participants were recruited from a summer undergraduate course at Embry-Riddle Aeronautical University. Eleven participants, 5 male and 6 female, volunteered to take part in the experiment and were awarded extra credit points by their course instructor for participating. The mean age of the eleven participants was 22.4 years. Participants were asked if their hearing was "normal" to the best of their knowledge. All participants indicated they had normal hearing.

Previously published research in the area of auditory localization was used to estimate the sample size requirement and number of experimental trials required for the study conducted. Studies consisting of similar characteristics were compiled and included in the sample size selection process. The number of independent variables manipulated (2-3), experimental levels within the independent variables (2-3), number of experimental trials conducted (60 or less), and the main task to be performed (auditory localization), were the characteristics that all studies had in common.

Participant totals for the prior research evaluated ranged from four to 16 participants with no clear-cut decision as to which number was ideal. Half of the studies included four to six participants where the other half were spread out from eight to 16 participants. Eight was decided upon due to the fact it was the average of the groups of participants, plus it was equal to or greater than more than half the studies evaluated. With that reasoning, it was believed that eight participants would provide enough empirical data to come to an acceptable conclusion on the experimental conditions performance. Due to the fact extra credit points were provided for voluntary participation in this study, all students in a class of 20 undergraduates were allowed to participate. The number of undergraduate students who chose to participate was greater than eight, therefore all the participants data was included to evaluate the experimental conditions performance (creating the total of 11).

Materials

Two separate software programs were used to formulate and present the auditory sound stimuli for this experiment. The 3-D auditory software that was used to render the experimental 3-D audio sound stimuli consisted of a demonstration version 3-D auditory program downloaded for free via the worldwide web. The software was developed and distributed by Human Machine Interfaces, Incorporated. The demonstration software was titled "InMotion 3D Audio Producer" and was available from the web address www.humanmachine.com (current to the time this study was written) (Human Machine Interfaces, Incorporated, 1999).

The "InMotion 3D Audio Producer" program allowed for wave format files to be reproduced as 3-D audio presentations for playback through headphones or conventional stereo speakers. The "Save", "Save As", and "Render File" settings were not available on the demonstration version software, but wave files meeting the requirements (16 bit, 44,100Hz) of the program could be implemented and various output controls for the sound stimulus could be manipulated. Output controls that were allowed to be manipulated included the sound source's position in space, filter setup, gain level, and delay level. In addition, if a sound clip was long enough in duration it was possible to observe a real-time change of the sound source's location in space during playback if the on-screen virtual speaker was moved to another location. A set of 710 non-individualized HRTFs provided the framework for the digital filters that produced the 3-D auditory effect.

The 3-D auditory software's capability to manipulate the filtering of a sound source was critical to the experimental sound source presentation. The "filter setup" function allowed for no filtering (corresponding to the "normal" condition for the study), lowpass, highpass, band pass, and notch filtering for the sound source being presented. This component was the key factor in the presentation of the 3-D auditory stimuli that were used to test the effectiveness of whether an additional sound cue may provide better localization performance in the front and back regions.

The second audio software program used for this study was Winamp Media Player Version 2.75. Winamp Media Player was a-free software available for download via the worldwide web and was obtained at the web address www.winamp.com (Nullsoft Incorporated, 2001). Winamp Media Player provided for the playback of all computer format sound files and included all basic features found on a real life stereo system. Basic features included a volume control, balance-control, 10-band graphic equalizer, repeat play, shuffle play, and playlist generator.

Two separate computers were used for the rendering process and presentation of the auditory sound stimuli. Rendering of the sound files into the 3-D auditory format took place on a component built PC consisting of an 800 mHz Athlon processor, 128 megabytes of RAM, and SoundBlaster PCI 128 sound card. Because the "Render File" option was disabled in the demonstration software, each experimental condition clip was played in the 3-D audio software and recorded into a separate wave file using Windows Sound Recorder. Experimental presentation with the Winamp Media Player took place on a Dell Optiplex GX150 PC consisting of an 866 mHz Pentium III processor, 256 megabytes of RAM, and an integrated Analog Devices ADI 1885 AC '97 sound device with Yamaha SoftSynthesizer Wavetable. Participants listened to the sound stimuli through a pair of Koss TD61 stereo headphones that were plugged into the front headphone jack of the Dell OptiPlex GX150 PC. Experimental data collection was recorded by the experimenter into an SPSS Statistical Package for PC worksheet, and later analyzed using that same software.

Procedure

The study conducted consisted of a 3 x 2 repeated measures design. Upon arrival, participants read and signed an informed consent paper agreeing to participate in the study. Participants were then given a brief set of instructions as to what was going to take place and what was expected of them in the experiment. After each participant was informed of their duty and had no further questions, they were asked to place the headphones on their head and the presentation of the experimental trials began immediately.

Each participant listened to a set of 60 randomized sound stimuli presented through the stereo headphones via a playlist generated with the Winamp Media Player. The sound stimulus consisted of a four second helicopter clip and the characteristics of its sound were dependent on the trials experimental condition. There were a total of six different sound stimuli tested: Front-Normal, Front Highpass, Front-Lowpass, Back-Normal, Back-Highpass, and Back-Lowpass. Each of the six different sound stimuli was presented 10 times (creating 60 total trials). Randomization of the sound stimuli presentation was conducted by generating a set of random numbers in Microsoft Excel and associating them to an experimental condition. It must be noted that the trial presentation order was randomized, but each participant received the same playlist. Participants were not provided with feedback as to whether their estimate was correct, therefore no learning took place.

Each sound stimulus was separated by 2 seconds of silence in order to provide an adequate, yet controlled, amount of time to provide a localization estimate. Upon presentation of a stimulus, the participant was asked to announce whether they believed the sound stimulus to be originating from the front or from the back. The participants were instructed that only the answers "front" or "back" should be given. Participants were allowed to move their head, close their eyes, or perform any other task during the experimental trials so long as they remained seated and provided a front or back answer. During the trial presentation the experimenter recorded the participant's answers in an SPSS worksheet. Following the final trial presentation participants were allowed to remove the headphones. The experimenter then provided the participant with a debriefing sheet and explained the basic theoretical background of the study.

The decision to use the helicopter clip as the sound stimulus, rather than a pure tone like most previous research has used (lack of research was found comparing complex sound stimuli to pure tone's in virtual 3-D audio), was due to its easy implementation into the 3-D auditory program. The helicopter sound clip was included with the demonstration version, met the requirements of the software, related to the field of aviation, and was an adequate duration to hear and understand, yet not long enough to totally fixate upon. Frequencies contained within the four-second "normal" helicopter clip ranged between 500 Hz and 4000 Hz. The frequency cut-off rate for each filter condition (Highpass, Lowpass) was 1000 Hz. Under the highpass condition frequencies below 1000 Hz were omitted, and in the lowpass condition frequencies above 1000 Hz were omitted once the filter was imposed on the normal sound stimulus.

RESULTS

Performance was analyzed by computing the total number of correct location responses each participant made for each experimental condition. Six experimental conditions, presented 10 times each, formulated the sixty trials presented. The total number of correct location responses per 10 experimental trials was recorded into an SPSS data worksheet. Table 1 provides the mean and standard deviation for each experimental condition.

Table 1
Number of Correct Localization Estimates

	Location					
	Front		**Back**		**Total**	
Filter	***M***	***SD***	***M***	***SD***	***M***	***SD***
Normal	8.82	1.89	2.00	1.95	5.41	3.96
High	5.36	3.53	6.64	3.04	6.00	3.28
Low	2.36	2.98	8.27	2.69	5.32	4.10
Total	5.51	3.87	5.64	3.90		

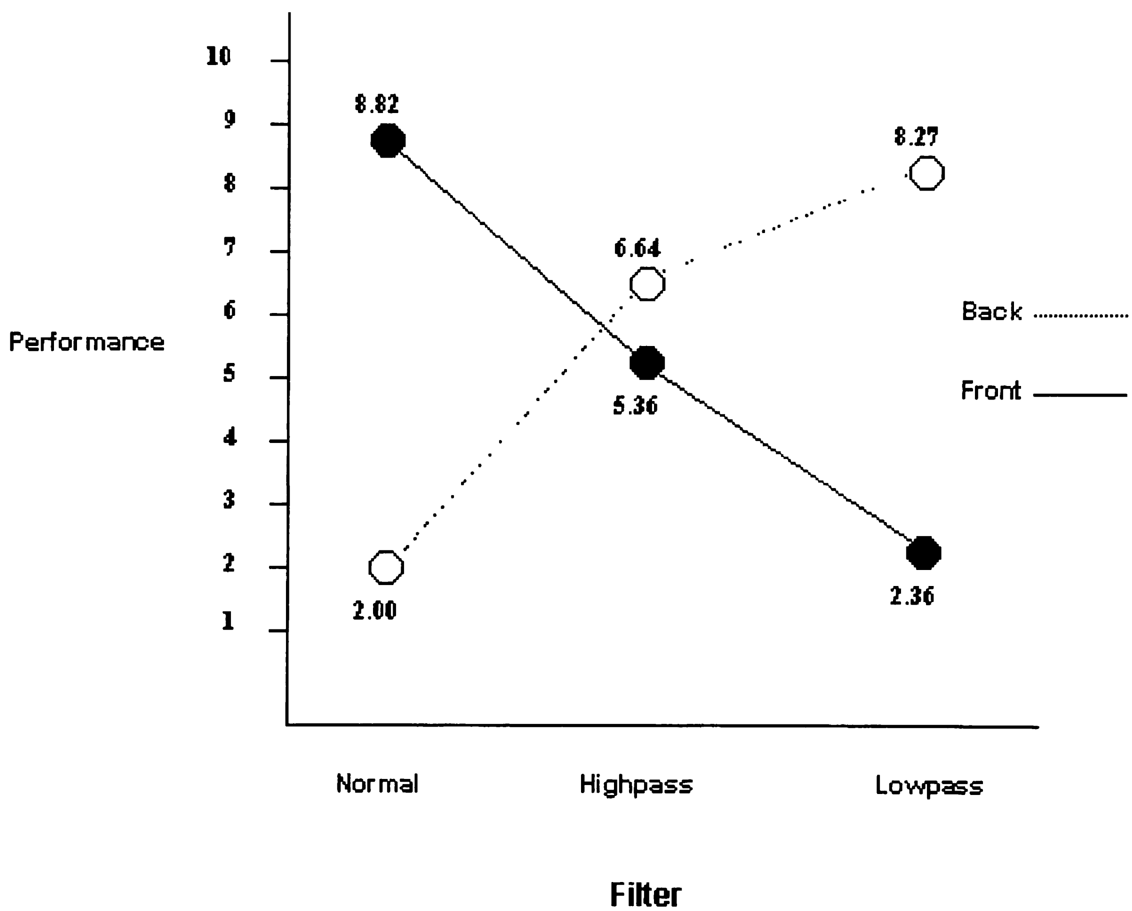
Note. n = 11

A repeated measures ANOVA was performed on the number of correct localization estimates. Results indicated that there was no significant main effect of Location, $F(1,10) = 0.071$, *ns*. Results also failed to find a significant main effect of Filter, $F(2,20) = 3.124$, *ns*. Results did indicate a significant interaction, $F(2,20) = 12.002$, $p = 0.000$. Table 2 provides the repeated measures ANOVA table while Figure 7 provides a graph of the significant interaction.

Table 2
Analysis of Variance for Correct Localization Estimates

Source	**SS**	**df**	**MS**	**F**	**p**	**Eta Squared**	**Observed Power**
Location	0.242	1	0.242	0.071	0.795	0.007	0.057
Error	34.091	10	3.409				
Filter	6.03	2	3.015	3.124	0.066	0.238	0.534
Error	19.303	20	0.965				
Location * Filter	456.394	2	228.197	12.002	0.000	0.545	0.987
Error	380.273	20	19.014				

Figure 7
Localization Performance by Location and Filter



A post hoc analysis, consisting of a two-tailed t-test with Bonferroni correction, was conducted comparing scores in each experimental condition to performance expected to occur by chance alone (i.e. 5.0). Significant differences were obtained for the Front-Normal, Back-Normal, and Back-Lowpass conditions (Table 3). Significant differences for the Front-Normal and Back-Lowpass conditions were better than chance, and the Back-Normal condition was below chance.

Table 3
Post Hoc Comparison of Performance Scores to Chance Performance of 5.0

Condition	Mean Difference	$\underline{t}$
Front		
Normal	3.82	6.71*
High	0.36	0.34
Low	-2.64	-2.94
Back		
Normal	-3.00	-5.11*
High	1.64	1.79
Low	3.27	4.04*

Note. Bonferroni correction was used, $\underline{t}_{crit} = 3.277$
* $p < 0.05$

A second post hoc analysis, consisting of a two-tailed t-test using Tukey's HSD correction, was performed to conduct pair-wise comparisons within each Location variable to evaluate whether Filter had an effect on performance. Significant differences between means were found for all pair-wise comparisons except the Back-Highpass/Back-Lowpass conditions (Table 4).

Table 4
Post Hoc Comparison of Performance Scores Within Location

Condition	Mean Difference
Front	
Normal – High	3.46*
Normal – Low	6.46*
High - Low	3.00*
Back	
Normal – High	-4.64*
Normal – Low	-6.27*
High - Low	-1.63

Note. Tukey HSD = 2.59
* $p < 0.05$

DISCUSSION

The addition of a 3-D auditory cue to displays that present warning information or verbal communication can improve localization performance and situational awareness (Begault, 1995; Dingus, McGehee, Manakkal, Jahns, Carney, & Hankey, 1997; Bronkhurst, Veltman, & Breda, 1996; Haas, Gainer, Wightman, Couch, & Shilling, 1997). However, research has shown that there is a performance problem with 3-D auditory displays when localizing front/back sound stimuli from virtual sound sources (headphones) compared to real sound sources (speakers) (Bronkhurst, 1995; Doll, 1986). Previously published research has concluded that virtual 3-D auditory displays provide accurate localization for sound stimuli located in the periphery, but localization accuracy significantly degrades for sound stimuli located in the direct front or direct back regions (Barfield, et al., 1997). Implementing a "real" 3-D auditory display into many real world settings (i.e. aviation cockpits or automobile interiors) is not feasible, therefore, it is important that virtual displays perform as accurately as real displays. Research to date has provided evidence that there is a significant problem with localizing front and back sound stimuli in a virtual display. Until this performance problem can be overcome, the objective of virtual 3-D auditory displays to decrease workload levels and increase situational awareness cannot be obtained.

The present study examined the performance effects of adding an additional sound cue characteristic (i.e. highpass filter or lowpass filter) to a virtual 3-D auditory display sound stimulus in an attempt to increase localization performance for the front and back regions. Three different sound cue characteristics were tested for the front and back locations: normal (software's HRTFs), Highpass (addition of a highpass filter), and

Lowpass (addition of a lowpass filter). The number of correct localization estimates served as the dependent measure.

Hypothesis one of the study stated that there would be a significant interaction between the location of the sound stimulus and the sound cue characteristic (Filter variable). Specifically, the hypothesis stated that the Front-Highpass filter would provide optimal performance for front sound stimuli and the Back-Lowpass filter would provide optimal performance for back sound stimuli. Hypothesis one was partially supported by the performance results obtained. There was a significant interaction between the location of the sound stimulus and the filter administered (or lack there of in the "normal" condition), however, the interaction did not completely match the specifics of the hypothesis. Optimal localization performance for the front location occurred under the Normal Filter condition, with the worst localization performance occurring under the Low Filter condition. Optimal localization performance for the back location occurred under the Low Filter condition while the worst localization performance was shown to exist in the Normal Filter condition. There was no statistical difference found between the Back-Highpass condition and Back-Lowpass condition, however, the Back-Lowpass condition scores were found to occur significantly greater than chance. These results provide evidence for the partial support of the interaction hypothesis. The Back-Lowpass condition did provide the best localization performance for the back location as hypothesized, however, the Front-Normal condition provided the best localization for the front location, and that does not match the experimenter's hypothesis.

Post hoc comparisons using two-tailed t-tests with Tukey's HSD were conducted across the Filter variable for each level of the location variable. The Highpass and

Lowpass Filter conditions both showed evidence of providing significantly better localization performance than the Normal Filter condition for the back location. Although the Lowpass condition did provide the best localization performance for the back location, and partially supported the experimental hypothesis, according to the results of the Tukey's HSD there was no significant statistical difference between the Back-Lowpass scores and Back-Highpass scores. These results pose two important questions for the back location: (1) Why is it the Highpass Filter condition provided significantly better localization performance than the Normal condition when it would be expected to provide the worst performance (due to its characteristics being the opposite of how humans best localize sound)? (2) Is the Lowpass Filter realistically the best sound stimulus for optimal localization performance in the back region?

In relation to the first question, there are no clear explanations that answer the question. According to the post hoc comparisons conducted on the performance of Back-Highpass score's to chance alone, the performance results could have occurred due to the fact the participants were guessing on the sound stimuli's location. No other valid explanation can be formulated that would relate the performance obtained to a physiological or procedural factor.

The performance scores in relation to chance alone provide support for the explanation to question two in the previous paragraph. Although there is no significant difference between scores in the Back-Highpass condition and Back-Lowpass condition, the scores in the Back-Lowpass condition show to occur significantly better than chance whereas the Back-Highpass condition's score's are only equal to occurring by chance alone. Therefore, according to these results participants were making a more informed estimate for the Back-Lowpass condition as opposed to the Back-Highpass condition. This evidence provides further support that the Back-Lowpass condition was the most optimal sound stimulus for localizing back sound stimuli.

Post hoc comparisons using two-tailed t-tests with Tukey's HSD across Filter for the front location showed that each condition and its scores were significantly different than each other. However, reverting back to the partial support of the interaction hypothesis, the front location did not perform as expected. It was hypothesized that the Front-Highpass condition would provide the best localization performance and the Front-Lowpass the worst. In actuality, the Front-Normal condition provided the best localization performance, followed by the Front-Highpass condition and Front-Lowpass condition. An explanation for the results may be gathered by referring back to the 3-D auditory software program and the sound characteristics of each condition stimulus. Examining the sound characteristics of each sound stimulus condition, it is apparent that an asymmetrical distribution during the filtering process may provide an explanation into the performance results. Each four-second-helicopter clip contained a frequency range of 500 Hz to 4000 Hz. When a filter was applied, a cut off level of 1000 Hz was applied to the frequency range. Therefore, a lowpass sound stimulus included a frequency range between 500 Hz and 1000 Hz, and a Highpass sound stimulus included a frequency range between 1000 Hz and 4000 Hz. This information provides evidence that a larger portion of frequencies were subtracted when a lowpass filter was administered as opposed to when a Highpass filter was administered. With a larger portion of frequencies being subtracted for the Lowpass filter conditions, those lowpass filters may have been perceived from Normal conditions more distinctively than the highpass filters. Had an equal amount of frequency range been subtracted when producing the Highpass filter conditions, the sound quality of the stimulus would have been much more dramatic in its effect compared to the Normal condition and may have provided the performance results hypothesized for the front location. One way to fix the problem of an asymmetrical filter distribution would be to apply low and high-pass filters that produce frequency ranges that are more equivalent to one another in quantity, intensity, or both.

Hypothesis two of the study stated that the Front-Highpass condition and the Back-Lowpass condition would provide localization that was significantly better than chance alone, whereas the opposite of the two (Front-Lowpass, Back-Highpass) would provide localization that was significantly worse than chance alone. The normal condition was expected to perform equivalent to chance alone. Hypothesis two, for the most part, was not supported. Of the six comparisons made relating performance scores to chance performance alone, only one of the six comparisons supported the second hypothesis. The Back-Lowpass Filter localization performance was significantly better than chance alone. The two remaining comparisons conducted on the back location showed that the Normal Filter performed significantly worse than chance alone and the Highpass Filter performed equivalent to chance alone. According to these results, it is believed that the addition of the Highpass Filter to the software's back HRTFs caused confusion in determining the correct location of the sound stimulus. Although the results do not match the hypothesis that the condition would perform significantly worse than chance alone, it still provides support that it is not beneficial in providing consistent, accurate localization performance for the back location. Results for the Back-Normal condition do not support the second hypothesis as well, however, they do fall in line with previously published accounts of significantly worse localization in the back location with "normal" (consisting of only the software's HRTFs) sound stimuli.

In the front location, none of the comparisons conducted on performance results to chance alone supported those that were hypothesized. The Front-Highpass and Front-Lowpass conditions performed equivalent to chance alone and the Front-Normal condition performed significantly better than chance alone. An explanation for these results may be that there is an optimal frequency range that humans localize best for front sound stimuli. If the sound stimulus contains frequencies that are too low or too high performance may be poor. Humans generally attempt to address sounds or objects from their front perspective, and in the real world natural sounds are not filtered as they pass through the environment. Therefore, the Front-Normal condition may have provided the best performance due to the fact it is most representative of how humans perceive sounds on a daily basis. A second explanation for the front performance results, which is somewhat more questionable, could be that the asymmetrical filter distribution affected performance.

Results of the present study show support that an additional sound cue added to the back sound stimuli (specifically one that is low-pass in its characteristics) in a virtual 3-D auditory display will increase localization accuracy for the back region. In relation to the front location, results support the notion that "normal" sound stimuli (software's HRTFs) provide the best localization for front sound stimuli in a virtual 3-D auditory display. This evidence would suggest that a virtual 3-D auditory display that provides a "normal" sound stimulus to represent front stimuli, and a lowpass sound stimulus to represent back stimuli, would provide the most accurate and beneficial localization performance for real world implementation. Although these conclusions are true based upon the results obtained in the present study, the issue pertaining to the asymmetrical filter distribution may provide a caveat to the true accuracy of the scores that were obtained and what sound characteristics are optimal.

In addition to the asymmetrical filter distribution expressed, other possible limitations may exist with the study that was conducted. As has been stated earlier, a demonstration version 3-D audio software package was used to develop the 3-D audio cues, which were then recorded and played over the Winamp Media Player. The process of rendering the 3-D audio cues and presenting them over a separate program may have affected the clarity and perception of the sound stimuli and their characteristics. Creating and presenting sound stimuli through a single 3-D audio software program may provide more accurate performance results.

Another limitation of the study may be the presentation order of the experimental trials. The trials were randomized, but each participant received the same randomized order. The first initial set off trials may have affected how each participant perceived each type of sound stimulus. Through the first few trials participants may have developed a strategy or thought relating to each sound stimulus that they used throughout the rest of the experimental presentation. Separate, randomized trial presentations for each participant may provide more accurate results for this type of sound stimuli localization task.

One other limitation that cannot be ruled out is the possibility of experimenter bias. Participants were positioned facing the experimenter as he entered their localization estimate into an SPSS worksheet. Although the participant could not view the screen that the experimenter was facing, there is still the chance that the experimenter was displaying some sort of behavioral cue when correct estimates were given as opposed to non-correct estimates. These bavioral cues, if present, would generally not be noticeable by the experimenter himself but nevertheless could affect the participants estimation strategy.

Other limitations that may relate to this study include: the population sampled (young adults), lack of task or relevant environment to which the 3-D auditory display would be implemented, type of sound used for the presentation stimuli (complex as opposed to a tone), and the required response of either "front" or "back". Better hearing capabilities may exist for younger adults, there was no added workload while performing the localization task, a complex sound includes multiple frequencies as opposed to a tone, and the "front" or "back" response may have limited the participant's true estimate of where they believed the sound to originate from. All of these factors have the capability to play a role in the localization performance of virtual 3-D auditory displays and have an effect on experimental results. It must also be noted that 3-D auditory displays and the topic of individualized versus non-individualized HRTFs are still in their own respective stage of development. All of these limitations should be considered in future research.

Future research focusing on the addition of another sound cue in accordance with HRTFs is needed to build upon the evidence obtained from the present study. Although this study provided support that lowpass filters added to sound stimuli originating from the back increased performance, the problem of an asymmetrical filter distribution must be dealt with and re-examined. Future research may want to study the effects of different filter cut-off levels on performance of localizing front and back sound stimuli. According to the results obtained, a beneficial cut-off level for a back-lowpass sound stimulus has been established, but further research must assess the cut-off levels for the highpass filter and how they will affect localization performance in the front region. In addition to examining frequency cut-off levels, it may be advantageous to conduct research that will include sound stimuli that vary in angle from the front centerline and the back centerline, or would include some form of vigilance task to perform while localizing the filter specific sound stimuli. Studying sound stimuli that vary in angle off the front and back centerlines will assist in defining the point at which additional sound cues are not needed or can be "blended" out of the sound stimulus. Research including the addition of a vigilance task during localization will allow researchers to study whether or not the performance benefits achieved by additional sound cues will still show to be beneficial once workload is increased and the user does not have an abundance of perceptual resources available.

In addition to the previously mentioned topics that should be considered for future research, it would also be beneficial to conduct a study comparing virtual sound stimuli (with the manipulated filters) to real sound stimuli. A study of this nature would provide evidence as to how effective the filter addition is to increasing virtual sound stimuli's performance to match that of real sound stimuli. Once data from the two displays is collected together and compared, it may be the case that the addition of filters to the virtual sound stimuli does not increase localization performance as much as expected when compared to real sound stimuli performance. However, on the other side of the equation, results for virtual sound stimuli without added filters may show that the HRTFs need to be exaggerated more for sound stimuli being presented from direct front or direct back locations. For either outcome to be evaluated, real sound stimuli performance needs to be collected in order to compare the performance results of virtual sound stimuli and real sound stimuli

To recap the proceedings of the study, previously published research has expressed the notion that 3-D auditory displays provide beneficial localization performance for warning information and verbal communication. However, virtual 3-D auditory displays have shown to provide degraded localization performance for sound stimuli located in the direct front or direct back regions. Due to the fact "real" displays are not feasible in most real world environments, it is important to continue research that will enhance the accuracy of virtual 3-D audio displays. The study that was conducted examined the localization performance for direct front and direct back sound stimuli in a virtual 3-D audio environment when an additional sound cue was added to the stimuli. Results provided evidence that an additional sound cue added to back sound stimuli, specifically one that is lowpass in nature, will increase localization performance for the back location. Results for the front location supported the use of "normal" sound stimuli, or those that contain only HRTFs, as providing the best localization accuracy for sound stimuli representing the front region. After examining the results of the study, an asymmetrical filter distribution was noticed for the administration of the high and lowpass filter stimuli. The asymmetrical filter distribution may provide evidence for the results not completely supporting the experimenter's hypothesis that a front-highpass sound and a back-lowpass sound would provide the best localization accuracy for their respective location. Future research that adjusts the filter distribution process may provide evidence that the experimenter's hypothesis is correct once the highpass and lowpass filters are equivalent in their effect size. Although future research is needed, the results of the study conducted show that adding an additional sound cue characteristic to front and back sound stimuli in a virtual 3-D audio display may provide a means to overcome the front/back localization error problem.

REFERENCES

AM:3D. (2001). Head related transfer functions. Retrieved June 29, 2001, from AM:3D Website: *http://www.am3d.com/inside/inside_head.htm*

Barfield, W., Cohen, M., & Rosenberg, C. (1997). Visual and auditory localization as a function of azimuth and elevation. *The International Journal of Aviation Psychology, 7(2)*, 123-138.

Begault, D.R. (1995). Head-up auditory display research at NASA ames research center. *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting*, 114-118.

Begault, D.R., & Wenzel, E.M. (1993). Headphone localization of speech. *Human Factors, 35(2)*, 361-376.

Bronkhurst, A.W. (1995). Localization of real and virtual sound sources. *Journal of the Acoustical Society of America, 98*, 2542-2553.

Bronkhurst, A.W., Veltman, J.A., & Breda, L. van. (1996). Application of a three-dimensional auditory display in a flight task. *Human Factors, 38(1)*, 23-33.

Calhoun, G.L., Valencia, G., & Furness, T.A. (1987). Three-dimensional auditory cue simulation for crew station design/evaluation. *Proceedings of the Human Factors and Ergonomics Society 31st Annual Meeting*, 1398-1402.

Dingus, T.A., Hulse, M.C., Mollenhauer, M.A., Fleischman, R.N., McGehee, D.V., & Manakkal, N. (1997). Effects of age, system experience, and navigation technique on driving with an advanced traveler information system. *Human Factors, 39(2)*, 177-199.

Dingus, T.A., McGehee, D.V., Manakkal, N., Jahns, S.K., Carney, C., & Hankey, J.M. (1997). Human factors field evaluation of automotive headway maintenance/collision warning devices. *Human Factors, 39(2)*, 216-229.

Dolan, N.J., Wells, M., & Osgood, R. (1993). A comparison of performance with visual and auditory displays in a simulated target localization task. *7th International Symposium on Aviation Psychology,* 1, 49-53.

Doll, T.J. (1986). Synthesis of auditory localization cues for cockpit applications. *Proceedings of the Human Factors and Ergonomics Society 30th Annual Meeting,* 1172-1176.

Duda, R.O. (1996). 3-D audio for HCI. Retrieved June 29, 2001, from the Department of Electrical Engineering, San Jose State University Website: *http://www.engr.sjsu.edu/~knapp/HCIROD3D/3D_home.htm*

Goldstein, E.B. (1999). Sensation and Perception (5th ed.). California: Brooks/Cole Publishing Company.

Haas, E.C., Gainer, C., Wightman, D., Couch, M., & Shilling, R. (1997). Enhancing system safety with 3-D audio displays. *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting,* 868-872.

Hugh, P. (2000). 3-D audio using head related transfer functions. Retrieved June 29, 2001, from the Digital Signal Processing Laboratory, Florida International University, Department of Electrical and Computer Engineering Website: *http://dsplab1.eng.fiu.edu/MSIP/3D_Audio.html*

Human Machine Interfaces, Incorporated. (1999). InMotion 3D Audio Producer. Retrieved December 1, 2000, from the Human Machine Interfaces, Incorporated Website: *www.humanmachine.com*

Kendall, G. (1998). Physical Acoustics. Retrieved June 29, 2001, from the 3D Sound at Northwestern University Website: *http://www.northwestern.edu/musicschool/classes/3D/pages/dhPhyAcst.html#anchor243576*

King, R.B., & Oldfield, S.R. (1997). The impact of signal bandwidth on auditory localization: Implications for the design of three-dimensional audio displays. *Human Factors, 39(2)*, 287-295.

Loomis, J.M., Hebert, C., & Cicinelli, J.G. (1990). Active localization of virtual sounds. *Journal of the Acoustical Society of America, 88*, 1757-1763.

Nullsoft Incorporated. (2001). Nullsoft Winamp Version 2.75. Retrieved June 25, 2001 from the Nullsoft Winamp Website: *www.winamp.com*

Perrett, S., & Noble, W. (1997). The contribution of head motion cues to localization of low-pass noise. *Perception and Psychophysics, 59 (7)*, 1018-1026.

Perrot, D.R., Ambarsoom, H., & Tucker, J. (1987). Changes in head position as a measure of auditory localization performance: Auditory psychomotor coordination under monaural and binaural listening conditions. *Journal of the Acoustical Society of America, 82*, 1637-1644.

Perrot, D.R., Saberi, K., Brown, K., & Strybel, T.Z. (1990). Auditory psychomotor coordination and visual search performance. *Perception & Psychophysics, 48(3)*, 214-226.

Ricard, G.L., & Meirs, S.L. (1994). Intelligibility and localization of speech from virtual directions. *Human Factors, 36(1)*, 120-128.

Sorkin, R.D., Wightman, F.L., Kistler, D.S., & Elvers, G.C. (1989). An exploratory study of the use of movement-correlated cues in an auditory head-up display. *Human Factors, 31(2)*, 161-166.

Srinivasin, R., & Jovanis, P.P. (1997). Effect of selected in-vehicle route guidance systems on driver reaction times. *Human Factors, 39(2)*, 200-215.

Stevens, S.S., & Newman, E.B. (1934). The localization of actual sources of sound. *American Journal of Psychology, 48*, 297-306.

Valencia, G, & Agnew, J.R. (1990). Evaluation of a directional audio display synthesizer. *Proceedings of the Human Factors and Ergonomics Society 34th Annual Meeting*, 6-10.

Wenzel, E.M., Arruda, M., Kistler, D.J., & Wightman, F.L. (1993). Localization using nonindividualized head-related transfer functions. *Journal of the Acoustical Society of America, 94 (1)*, 111-123.