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ENHANCING THE SITUATIONAL AWARENESS OF AIRFIELD LOCAL CONTROLLERS

by

Samuel P. Mowery

September 2002

Thesis Advisor:	Russell D. Shilling
Second Reader:	Gregory K. Mislick

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In recent years, a number of near midair collisions has shed light on the increased likelihood of mishaps that are partly attributable to traffic density. In air traffic control operations, situational awareness of a local controller at an airfield such as Marine Corps Air Station Camp Pendleton, California, is critical to prevention of catastrophic midair collisions. Spatialized audio technology has the potential to reduce or eliminate temporary losses of situational awareness. Spatialized audio technology allows auditory icons to be presented at perceptual locations external to the head at a complete range of elevation and azimuth locations relative to the listener.

This thesis investigates the use of these spatialized auditory icons to determine if they could be effectively implemented in air traffic control type tasks to benefit local controllers. The research was conducted in the Advanced Auditory Displays Laboratory at NPS. A scenario to exemplify typical airfield operations at Camp Pendleton was written using java-based computer code. A virtual tower environment was created with a head mounted video display, inertial head tracker, and a spatialized audio server. Results indicated that subjects of the experiment responded more rapidly and accurately using spatialized audio.

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ENHANCING THE SITUATIONAL AWARENESS OF AIRFIELD LOCAL CONTROLLERS

Samuel P. Mowery
Major, United States Marine Corps
B.S., United States Naval Academy, 1991

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September 2002

Author: Samuel P. Mowery

Approved by: Russell D. Shilling
Thesis Advisor

Gregory K. Mislick
Second Reader

James N. Eagle
Chairman, Department of Operations Research

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EXECUTIVE SUMMARY

In the 1990s, Congress' Base Realignment and Closure Committees recommended the closure of numerous military installations, to include a number of military airfields. Airfields that remained operational experienced increases in traffic density due to the receipt of more tenant aircraft from the closed installations. Marine Corps Air Station (MCAS) Camp Pendleton, California, for example, received three H-46 squadrons from the closures of MCAS Tustin and MCAS El Toro. As a result, Camp Pendleton's already "crowded" airspace became more congested.

In recent years, a number of near midair collisions have shed light on the increased likelihood of mishaps that are partly attributable to traffic density. In air traffic control (ATC) operations, situational awareness of a local controller at an airfield such as Camp Pendleton is critical to prevention of catastrophic near midair collisions. Spatialized audio technology has the potential to reduce or eliminate temporary losses of situational awareness. Spatialized audio technology allows auditory icons to be presented at perceptual locations external to the head at a complete range of elevation and azimuth locations relative to the listener. This thesis implemented a prototype spatialized audio display and completed a performance evaluation to determine if this technology could be implemented in ATC settings. The prototype used a relatively inexpensive audio server, an inertial head tracking device, hi-fidelity headphones, and a head mounted display. Results from the evaluation show a significant increase in accuracy rates and response rates (degrees per sec of head turn), and a significant decrease in response times. The results also show that this system could be a cost-effective forerunner of a spatialized audio display system for military and civilian ATC. The prevention of one mid-air collision would more than pay for the cost of developing and implementing such a system. The cost-savings in human life is incalculable. However, the impact of this thesis reaches far beyond military and civilian ATC. It has applicability to unmanned aerial vehicle operations and manned aircraft operations as well. Additional research is planned to expand upon the research initiated in this project to further refine the process and deliver an actual product that can be implemented in the operational environment.

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I. INTRODUCTION

A. BACKGROUND

High situational awareness levels are required of all air traffic controllers to maintain safe and efficient operating environments at the world's airports and in the world's airways. Information to sustain high situational awareness levels comes from audio communications, radar displays, and visual sighting of aircraft. In an effort to ensure minimum aircraft separation regulations are met, audio communications are most often used by air traffic controllers to pass directions or announce intentions of flight crews. Aircraft separation becomes an increasingly difficult task for an air traffic controller as the number of aircraft in the controller's airspace grows.

Losing situational awareness, even for a few seconds, can negatively impact the safety of the skies. Unfortunately there are many examples throughout aviation history where the absence of situational awareness has led to the loss of human life.[1] Undoubtedly there are countless other undocumented incidents where human life was luckily spared. One way of reducing or eliminating temporary losses in situational awareness is through the use of spatialized audio communications. In many instances, we believe that spatialized audio communications could have avoided misidentification of aircraft or eliminated the potential for a mid air collision.

Advances in modern technology make it possible to synthesize spatial auditory cues over headphones. Prohibitively large and expensive speaker configurations are no longer necessary to produce a three-dimensional listener space. The headphones would allow air traffic controllers to perceive radio communications as if they emanated from the aircraft's location in three-dimensional space. Controllers could take advantage of research that has been previously completed on radio speech intelligibility. From the 1950s to the present day, researchers have demonstrated the beneficial effects of spatialized audio on radio speech intelligibility (e.g., see Thompson & Webster, 1953; Campbell, 2002). Improvements in radio speech response accuracy have also been

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[1] As recently as July, a midair occurred between a Russian Tupolev 154 and a German Boeing 757 cargo plane that resulted in the loss of 71 lives, including nine young children and 43 youngsters between the ages of 12 and 18 (CNN, 2002).

shown (Speith, Curtis, & Webster, 1954; Thompson & Webster, 1963; McKinley & Ericson, 1995).

However, the impact of this thesis reaches far beyond military and civilian air traffic control (ATC). It has applicability to unmanned aerial vehicle operations and manned aircraft operations as well. Many of the same issues encountered in ATC operations will be encountered by UAV operators as the numbers of UAVs in the skies above battlefields are increasingly populated by combinations of manned and unmanned aircraft. This same technology can be applied to information management inside the cockpit as well. Other research shows that implementing spatialized audio displays in the cockpit can significantly reduce response times to missile threats (Shilling, Letowski & Storms, 2000). Despite the significance of findings from studies such as those mentioned previously, auditory displays are given minimal attention in many operational areas, including ATC.

B. RESEARCH OBJECTIVE

The purpose of this research is to examine the benefits of spatialized audio communications for air traffic controllers. In particular, it investigates the use of spatialized auditory icons to determine if they could be effectively implemented to improve situational awareness in air traffic control type tasks to benefit local controllers. An airfield local controller encounters an environment similar, yet distinctly different, from that of an en route air traffic controller. A local controller is required to acquire aircraft using visual means and audio communications, whereas an enroute air traffic controller (handling the enroute portion of a flight plan) uses a radarscope and audio communications. Research was conducted in the Advanced Auditory Displays Laboratory (AADL) at the Naval Postgraduate School (NPS). This research follows the groundwork laid by previous studies conducted in the AADL (e.g., see Campbell, 2002). A scenario to exemplify typical airfield operations at Camp Pendleton was written using extensive java-based computer code. A virtual tower environment was created with a head-mounted video display, inertial head tracker, and a spatialized audio server. An analysis of results from this experiment and previous studies could lead to new hypotheses and testing for application of superior concepts in both civilian and military aviation and can be extended to situational awareness concerns for the operators of Remotely Piloted Vehicles (RPV) as well. The objective of nearly all research related to air traffic control is to improve the safety and efficiency of aviation operations. Starting in the 1980s, however, several events occurred that made the implementation of spatialized audio in a local airfield environment particularly more attractive to the U.S. military.

C. IMPACT OF BASE REALIGNMENTS AND CLOSURES ON AIRFIELD OPERATIONS

Between 1988 and 1995, the U.S. Department of Defense conducted four rounds of base realignments and closures (BRAC). The rounds were needed to reduce the nation's domestic military basing infrastructure and bring it more in line with its force structure and funding levels. BRAC recommended the closure of a variety of installations to include military airfields. Airfields not selected by BRAC rounds were, nonetheless, affected by BRAC decisions. The airfields that survived experienced increases in traffic density due to the receipt of more tenant aircraft.

One example of an airfield affected by BRAC is Marine Corps Air Station Camp Pendleton (MCAS Camp Pendleton). Prior to 1998, MCAS Camp Pendleton was home to six H-1 squadrons, possessing about 150 aircraft. By the end of 1999, Camp Pendleton inherited two H-46 tactical squadrons from the closures of MCAS El Toro and Tustin. Additionally, in an effort to make room for its V-22 Fleet Replacement Squadron (FRS) at MCAS New River, North Carolina, the Marine Corps moved its H-46 FRS to MCAS Camp Pendleton. Once the helicopter transfers were complete, Camp Pendleton had acquired three H-46 squadrons and its total fleet rose to approximately 180 aircraft. It now owned nine squadrons, including the H-1 and H-46 FRS's—squadrons that typically burden an air space more than "tactical" squadrons due to their inherent training missions. Camp Pendleton's "crowded" airspace, which includes only one runway (6000 feet in length), became more congested.

D. IMPACT OF TRAFFIC DENSITY ON PROPENSITY FOR NEAR MID-AIR COLLISIONS

In recent years, MCAS Camp Pendleton experienced a number of near mid-air collisions at Camp Pendleton. The near mid-air collision hazard reports that resulted from these events gave birth to improved flight routing and altitude restrictions (also known as course rules). Efforts to spread out flight operations more evenly throughout the day have also been implemented. Despite these steps, however, traffic density continues to be a problem at the airfield.

A period of high traffic density poses a challenge to the local controller at an airfield such as Camp Pendleton. Local controllers are highly trained military and civilian air traffic controllers that are responsible for the safe separation of aircraft in the tower's airspace. High traffic density correlates to more aircraft in the controller's airspace. Thus the risk of a mid-air collision is increased. Although ultimate responsibility for aircraft avoidance lies with the aircraft commander (pilots), tower personnel can contribute greatly to safe operating conditions. Local controllers are human and subject to error just as aviators are. A common thread in recent near mid-air events at Camp Pendleton has been the temporary loss of the local controller's situational awareness. The situational awareness of a local controller at an airfield remains critical to prevention of midair collisions, and even more so during inclement weather conditions. This is especially important at Camp Pendleton and other coastal airspaces that must deal with fog and marine layers on a consistent basis.

E. CURRENT AUDIO TECHNOLOGY AND VISUAL ACQUISITION METHODS USED BY LOCAL CONTROLLERS

Local controllers use a single earpiece/microphone device that provides a means of transmitting and receiving radio communications. The monaural audio heard in the blocked meatus earpiece and the controller's eyesight are the primary means of acquiring aircraft in the tower's airspace. Reducing the amount of time to accurately locate an aircraft once it transmits a radio call would have a favorable impact on a local controller's situational awareness. As mentioned previously, one possible way to achieve this reduction is through the use of spatialized sound. To produce spatialized sound for the local controller of an airfield, the azimuth and elevation of aircraft radio transmissions need to be determined. Currently, hardware does not exist to produce spatialized sound in a tower environment. Nonetheless, tools to enhance and maintain the controller's situational awareness are worthy of attention.

F. ORGANIZATION OF THIS STUDY

This thesis is organized into six chapters. Chapter 1 offers initial motivation for pursuing the study of spatialized audio in an air traffic control environment. Chapter 2 provides a basic background on spatialized audio, reviews literature that has applicability to air traffic control, and discusses literature pertinent to the design of the experiment used in the thesis. Chapter 3 describes the methodology behind the airfield tower simulation designed for this thesis. Chapter 4 analyzes the results of the tower simulation. Chapter 5 concludes the thesis and provides recommendations for future study.

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II. HUMAN LOCALIZATION, SPATIALIZED AUDIO, AND PREVIOUS STUDIES

A. LOCALIZATION

Localization refers to a human's ability to make judgments as to the direction and distance of a sound source in the real world environment. Sound waves travel in all directions from a sound source. Thus, the listener must cope with direct and indirect sounds. Direct sound is the most "direct" path that sound travels to reach the listener (straight path). Indirect sound incorporates all of the reflections of the sound that a perceiver hears at a delayed time interval from the direct sound. Humans localize sound through the use of ears and the brain once the direct and indirect sound waves reach the listener. It is possible for humans to localize sound with one ear (for example, on a telephone), but this discussion will focus on binaural hearing. The two localization cues used by humans are interaural intensity difference (IID) and interaural time difference (ITD). IID refers to the fact that sound is louder at the ear to which it is closest. ITD refers to the fact that sound will arrive at one ear earlier than another. Before a sound wave enters the eardrum, it encounters the outer ear structure, or the pinnae. Pinnae act as a "filter" affecting every sound that passes through it. Following the pinnae are the effects of the ear canal (meatus), the middle ear, and finally the inner ear. Many literature sources provide a more detailed explanation of this process (e.g., see Begault, 2000).

Spatialized sound attempts to replicate the "filtering" process of the outer ear through the use of Head-Related Transfer Functions (HRTFs). Sound waves that reach the ears are affected by interaction with the listener's torso, head, pinnae, and ear canals. Head-Related Transfer Functions (HRTFs) account for these acoustical effects by analyzing what happens to a single sound as it arrives to a listener from different angles. HRTFs can be thought of as two audio filters, one for each ear. Every person has a unique set of "individualized" HRTFs, but "generic" (or "non-individualized") HRTFs do exist. HRTFs capture the information necessary to simulate a realistic sound space and produce spatialized sound. However, the measurement of individualized HRTFs can be a difficult, time-consuming process. Most audio systems use a standard set of HRTFs that are not matched to an individual. Such was the case for the audio used in the tower simulation for this thesis. Participants did not have the opportunity for extensive spatial audio training. Even in the worst case, using non-individualized HRTFs does not degrade localization accuracy much more than the listener's inherent ability (Wenzel, 1992).

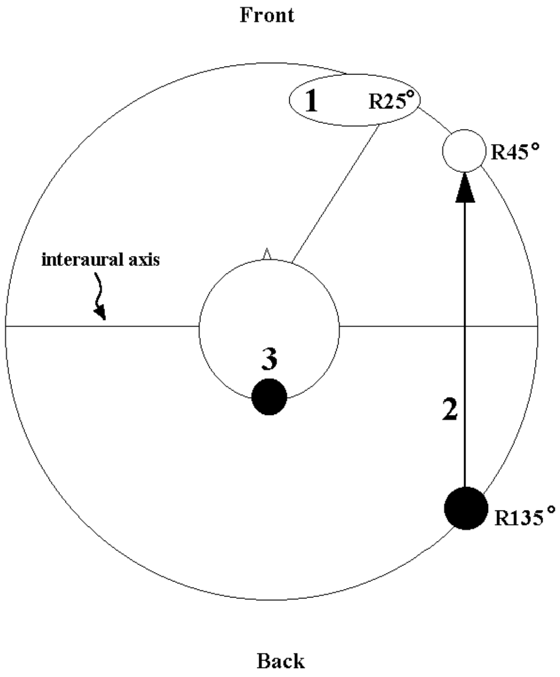
B. SPATIALIZED AUDIO

Spatialized audio is the product of modifying an audio signal for the purpose of making it appear to a human ear to originate from a source outside of a listener's head. It essentially achieves a three-dimensional sound space outside a listener. 3-D sound can be delivered through headphones or loudspeakers that are placed around the listener. Literature indicates headphones are the medium of choice when control over the location of a spatial source is needed (Begault, 1999; Shilling & Shinn-Cunningham, 2002). Spatialized audio is *not* a diotic display (same signal to both ears) or merely a dichotic display (similar to diotic, but the source signal is delayed or scaled at one ear). Both diotic and dichotic displays are normally referred to as "lateralized" rather than "localized' (Shilling & Shinn-Cunningham, 2002). The result of spatialized sound is audio that appears to emanate from 3-D locations, giving an additional cue for the location of particular objects.

Research suggests that localization performance is optimized when the cues used in everyday hearing are reproduced as faithfully as possible (Begault, Wenzel, and Anderson, 2001). Available technology allows this reproduction to be achieved through the use of head trackers, HRTFs, and reverberation. Head trackers allow a sound source to remain in the same relative position to the listener despite his/her head movement. The purpose of HRTFs has been discussed. Reverberation replicates sound propagation and reflection in a particular environment. There have been several studies to identify the effect of any one of these techniques on sound localization performance.

C. COMMON LOCALIZATION ERRORS

Localization performance is measured by the occurrence of three common sound localization errors. These are localization error, externalization error, and reversal error. The following diagram depicts common errors.



1: localization error—perceived source location deviates from exact position (azimuth or elevation)

2: reversal error—source perceived on wrong side of interaural axis

3: externalization error—source perceived as coming from inside head

Figure 1. Common audio localization errors

D. IMPACTS OF HEAD TRACKING, INDIVIDUALIZED HRTF'S AND REVERBERATION

Literature reveals many suggestions about the impact of head tracking, HRTFs, and reverberation. Not all of these suggestions concur with each other. Analysis of Variance (ANOVA) is used in nearly all experiments to see if any method (head tracking, individualized HRTFs, or reverberation) has a main effect on sound localization error rates. Individualized HRTFs are unique HRTFs collected on an individual. Generic HRTFs are used to suit a wider population that exhibits similar physical characteristics, such as head and pinnae size. A number of research studies in the 1980s and 1990s concluded that the use of individualized HRTFs reduced localization and reversal errors (Wenzel, Arruda, Kistler, and Wightman, 1993; Wightman, Kistler, and Perkins, 1987;

Moller, Sorensen, Jensen, and Hammershoi, 1995; Loomis, Hebert, and Cincinelli, 1990; and Mackensen, Fruhmann, Thanner, Theile, Horbach, and Karamustafaoglu, 2000). These same studies showed head tracking enhanced externalization while reducing localization errors. All research attempts strived to see if *one* of the methods reduced sound localization errors.

More recently published research countered many previously held beliefs (Begault, Wenzel, and Anderson, 2001). Perhaps the most striking result was that head tracking and HRTF use had no significant effect on localization error rates. An interaction between the two did exist, but only for azimuth errors. Head tracking was the sole method found to have an impact on reducing reversal rates. Only reverberation was found to have an affect on externalization. This research was the first to compare the relative advantage of each method in a single experiment. The study used a virtual speech source—the source used in many applications of spatialized sound. Use of different sound sources may produce different results.

E. IMPACTS OF SPATIALIZED SOUND ON VISUAL ACQUISITION

Perrott, Cisneros, McKinley, and D'Angelo (1996) evaluated visual search performance in a free-field (anechoic) listening situation using both aurally aided and unaided cues. Not surprisingly, they found that search times were reduced with aurally aided cues. However, their overall approach to the problem of information overload was counterintuitive. Along with other researchers in the 1980s and 1990s, they recognized that "system operators" (pilots) suffered not from too much information but, rather, from too little information regarding which information source was most relevant at any one time. The researchers sought to show how spatial cueing could provide missing information to improve search performance. This type of problem is very analogous to the problems facing tower controllers at military airfields. The surprising part of the research was *how much* the search times were reduced with aural cues. Participants were seated in the center of a large sphere and given sound/visual cues from all azimuths and elevations. Search times of 1500 milliseconds (ms) were common for visual cues near the participant's line of gaze. For those outside the line of gaze, times of 2000 to 3000 ms were common. With aural cueing, these times were reduced to 750 to 1000 ms in the line of gaze, 1250 ms outside the line of gaze. In other words, participants found their targets faster behind them with aural cueing than they found targets in front of them without cueing. Another interesting conclusion found no significant difference in response time using two (azimuth only) or three-dimensional sound. The study used "pink" noise (equal energy at each octave) of broad bandwidth as aural sources. This is not very applicable to radio communications, but the results were still impressive. Few distracters were used to force participants to decide between sources—participants had to either choose which light source was emitting sound, or count the total number of sources (two or three). This type of choice is only partially applicable to airfield tower operations that may have eight to ten detractors. In most cases, local controllers at an airfield know the vicinity of where an aircraft's radio transmission will occur since approach patterns are highly structured. The Federal Aviation Administration deals with deviations from these established and published approach patterns harshly.

F. SPATIALIZED SOUND STUDIES INVOLVING AVIATION AND AIR TRAFFIC CONTROL

Since the 1990s, research has been ongoing at the Spatial Auditory Display Laboratory at NASA Ames Research Center in the area of "head-up auditory displays" for enhancing commercial aviation safety. Similar to a head-up visual display, the use of spatialized audio cues allows pilots to keep their visual gaze out-the-window "head-up" while simultaneously receiving situational awareness information via spatial audio. Crews of commercial airline crews were evaluated in a flight simulator to determine whether the existing Traffic alert and Collision Avoidance System (TCAS) could be improved by including spatial audio cues with the current head-down map display system. The experiment had verbal traffic alerts for TCAS advisories processed so their perceived spatial location corresponded to the location of aircraft traffic seen out of the windshield. Results indicated a significant difference for target acquisition time favoring the spatial audio TCAS condition by 307 ms on average (Wenzel & Begault, 1998).

Additional research has been completed at NASA Ames on the Terminal Area Productivity (TAP) Program. A goal of the TAP program was to show how the implementation of a 3-D Audio Ground Collision Avoidance System (GCAS) could improve the efficiency of airport surface operations for commercial aircraft operating in deteriorated weather conditions while maintaining a high degree of safety. The 3-D audio provided immediate awareness about crossing runways, potential conflicts with other aircraft, and when the aircraft deviated from centerline. Twelve crews were studied in a 747 simulator to see if a significant preference for an audio GCAS system existed on the part of the pilots. The main conclusions of the study were that an audio GCAS system would be useful for avoiding potential conflicts in both low-visibility and normal weather conditions (Wenzel & Begault, 1995). Another conclusion was that taxi times were not reduced significantly with 3-D audio cueing.

New technologies for ATC systems have been under development for implementation in the Federal Aviation Administration's Free Flight program. In the future, the aim of Free Flight is to allow pilots and airlines to set their own courses and resolve conflicts autonomously when possible. Even though pilots would be responsible for maintaining separation and awareness of immediate traffic, ATC would still be required to oversee separation assurance, intervene under emergency situations (e.g., failure of equipment aboard aircraft), and monitor the transition of flights to managed airspace (Metzger, 2001). To assist ATC, researchers have applied 3-D visualization and virtual reality technology to depict the zones around Free Flight aircraft. Spatial audio was then added to this technology. No user studies have been published to show the effect of adding spatial audio but user feedback was mostly positive. Controllers recommended using the spatialized audio features in training new controllers, to help them build a "mental model" of the 3-D nature of the airspace (Azuma, Daily, & Krozel, 1996). A few suggested it might speed up transition time when changing controllers at a station, where the incoming controller must spend time monitoring displays to gain a better understanding of the 3-D situation before he can relieve the controller on duty (Azuma, Daily, & Krozel, 1996).

A review of pertinent literature has shown that spatialized audio is beneficial in many environments, to include those that involve ATC. Upon the arrival of affordable technology that made it possible to synthesize spatial auditory cues over headphones, researchers recognized the potential of spatial auditory displays to enhance both occupational and operational safety and efficiency of aeronautical operations (Begault, 1993). The literature has also shown that localization performance is highly dependent upon a number of factors that include head tracking, HRTFs, reverberation, source and type of aural cues, type of task(s) required of the listener, and listening environment.

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III. METHODOLOGY AND DATA COLLECTION FOR A SIMULATION INVOLVING A LOCAL AIRFIELD CONTROLLER

A. PERFORMANCE MEASURES OF INTEREST FOR A SIMULATION INVOLVING A LOCAL AIRFIELD CONTROLLER

Prior to discussing research methodology for this study, we first must identify our measures of interest. The measures of interest include the following: controller's time to acquire an aircraft from initial aircraft transmission, controller's average angular turning rate (degrees per second) from initial aircraft transmission, and accuracy of controller's responses. In addition to spatialized audio factors mentioned in Chapter II, several additional factors need to be considered when analyzing the performance measures of airfield local controllers.

B. ADDITIONAL FACTORS INFLUENCING PERFORMANCE MEASURES OF AIRFIELD LOCAL CONTROLLERS

Factors affecting controller responses are not limited to whether or not localized sound is used. One factor is the number of aircraft in the pattern. If only one aircraft is in the pattern (performing multiple take offs and landings), it does not take a controller very long to recognize the direction of the radio call. However, if there are six aircraft flying within the controller's airspace, identifying the source of a radio transmission becomes more challenging.

Another factor that impacts the performance of a local controller is the location of the transmitting aircraft. If an aircraft is located directly in front of the controller, the response time to acquire the aircraft will be less than that required to locate an aircraft directly behind the controller because the controller must physically turn around to find the aircraft.

Clarity and quality of a radio call play a factor. A poor quality radio call requires extra thought on behalf of the controller to interpret the radio call. Clear radio calls do not demand such extra effort and are responded to quicker.

Physical attributes and history of the controller play a part in aircraft acquisition. Quality of eyesight, experience level, training, and previous night's sleep are examples of these factors.

At first glance, the next item seems counterintuitive--it takes a controller longer to acquire an aircraft in the daytime than at night. Nighttime aircraft are typically easier to locate because of navigation lights installed on the aircraft. Aircraft manufacturers, for obvious reasons, intentionally design aircraft to be difficult to see during the day against certain types of backgrounds (sky, wooded, or desert camouflage, for example). Other meteorological conditions such as rain, fog, cloud cover, sun position, moon position, and moon phase all impact controller responses. In a real airfield tower environment, the aforementioned factors come into play. In our experiment, all aircraft were high-contrast objects against a blue sky, making them highly detectable with visual cues.

In a simulated tower environment such as the one designed for this thesis, the artificiality of the scenario unavoidably comes into play. Learning effects occur in an experiment. Susceptibility to simulator sickness may affect results. If a particular airfield is modeled after an existing airfield, such as Camp Pendleton, participants may have experience with the airfield and will be familiar with flight operations. Most of the factors listed in this paragraph are considered uncontrollable "noise factors" for purposes of this research.

C. PARTICIPANT COMPOSITION AND QUALIFICATIONS

Thirty male graduate students and instructors from NPS were used in the virtual tower scenario. The participants were comprised of the following active duty U.S. military officers: 16 Marine Corps, 13 Navy, and 1 Army. Average age of participants was 35.3 years (SD 4.1 years). Very few students or instructors at NPS have air traffic control experience. Therefore, to understand the content of radio transmission throughout the simulation, participants were required to have either civilian or military flight experience (pilot or naval flight officer). Besides the limited availability of air traffic controllers, the use of aviators allowed them to subjectively evaluate the general utility of spatialized audio in an aviation environment via questionnaire. The average flight experience of the participants was 1597 hours (SD 705 hours). The average time since last flight was 21.9 months (SD 16.7 months). No participant reported any significant hearing loss. Five of the participants had flown at Camp Pendleton. Sixteen of the participants received spatialized sound for the first half of the experiment and non-spatialized sound the second half. The remaining fourteen participants received the opposite treatment, non-spatialized sound followed by spatialized sound. The entire experiment, including time required for paperwork, lasted approximately one hour per participant.

D. EXPERIMENT SETUP AND PROCESS

Upon arrival at the AADL, participants were required to complete required NPS Institutional Review Board forms and a background questionnaire (Appendix A and Appendix B, respectively). Participants were shown all equipment that would be used in the experiment, which included the following hardware: Dell Dimension 8100 client computer with a 1.7 GHz Pentium IV and GeForce4 video card, AuSIM Gold Series spatialized audio server (connected to client via RS-232 port), Sennheiser HD 570 open headphones, InterSense InterTrax^2 inertial head tracker (connected to client via USB port), Olympus FMD-700 Eye-Trek head mounted display (connected to client via S-video cable), and a Logitech cordless optical mouse.

Headphones were used to produce spatialized sound for better control over sound source location. Loudspeakers would be inappropriate in a tower environment because they would interfere with the normal staffing of personnel in the tower. Normal staffing consists of a ground controller, data controller, local controller, and a supervisor. All positions have a requirement to freely communicate with each other. Therefore, Sennheiser HD 570 open headphones were a viable choice for best spatial audio and task performance. As mentioned in Chapter II, it is important to note that generic HRTFs were used since collection of individualized HRTFs was precluded by time constraints on participants.

Head tracking was employed through the use of an InterSense2 inertial head tracker mounted on the top of the Sennheiser headphones. The head tracker fed the participant’s head position data to the AuSIM server for spatialized sound. Head position data was also used to properly update video imaging via the Olympus head mounted display (HMD).

Sound sources for the audio were obtained from actual tower tapes recorded at Camp Pendleton in January 2002. Approximately 45 minutes in length, the cassette was used to produce over 50 individual radio transmissions from AH-1W, UH-1N, and CH-46E aircraft. The individual transmissions were transferred to digital format (44.1 KHz, 16-bit, mono “wav” files) using Sonic Foundry Sound Forge 5.0 software and installed on the AuSIM server.

Considerable effort went into scripting the aircraft events that would simulate a typical day at MCAS Camp Pendleton. An agent-based simulation model called the Multi-Agent Robot Swarm Simulation (MARSS) was used as the main computing software to script twenty-eight minutes of aircraft maneuvers (Dickie, 2002). The original purpose of MARSS was completely unrelated to this research, but the model served as a highly capable platform to produce video imagery of a virtual airfield environment and run a tower simulation. The java-based code possessed a “3D viewer” that could transform a 2-dimensional image into a virtual 3-dimensional environment. Figure 2 shows a screenshot of MARSS with a 1.11-megabyte (2018 x 2016) jpeg image of MCAS Camp Pendleton imported into the program. The 3-dimensional view from the tower is on the left, while the 2-dimensional view is on the right. The direction depicted in the 3-dimensional view is approximated by the dotted line in the 2-dimensional view.

MARSS used the AuSIM Application Programming Interface Java Native Interface (API JNI) to implement spatialized sound by means of the AuSIM server. The head tracker used the API JNI, too, but required the use of AuAST_LT software available from AuSIM. AuAST_LT is a C++ program that ran from the command line, external to MARSS.

The scenario incorporated multiple aircraft takeoffs, approaches, and landings to Runway 21 and the right grass (an area adjacent to the runway). As is the case in real

```
Arena Camera (View 2)
Tgt: (2306.230, 59.067,
Dis: 10.0
Ber: 137.0
Elv: -24.0
```

Figure 2. MARSS screenshot of MCAS Camp Pendleton

life, both left and right-hand traffic patterns were used. Ground controlled approaches (GCAs) to the airfield, low work (hovering) aircraft, and numerous entries and departures to the airfield were scripted. The following visual flight rules reporting points were used: North Initial, LCAC, VORTAC, TALA, delta taxiway, north grass, and south grass. To reduce the number of reporting points that participants were required to learn, Point Canyon, intersection, all taxiways except delta, the fuel pits, and the combined arms loading area (CALA) were not used. The minimum number of aircraft airborne at any one time was one helicopter. The maximum number of aircraft was six. All aircraft abided by local course rules and transmitted required radio calls at appropriate locations, such as “abeam for the grass” or “on the go.” Appendix C contains the individual radio calls heard by participants during the simulation. Before beginning the experiment, participants were exposed to sample radio calls to familiarize themselves with the differences between spatialized and non-spatialized audio, the quality of the audio transmissions, and “refresh” their memories of typical aircraft radio calls. The sequence of seven radio calls and one “inbound GCA” signal was played using the Sennheiser headphones with head tracking enabled. The participants did not wear the HMD for this introduction. Participants were also shown how to adjust volume levels (if needed) on the AuSIM server during this time. The “inbound GCA” signal replicated the sound produced by a console located in the tower of Camp Pendleton. The console allows the local controller to electronically communicate with radar control to sequence instrument flight rules (IFR) aircraft into the tower's visual flight rules (VFR) pattern. Radar controllers are not physically located in the same building as the tower controllers. For example, an aircraft on an instrument approach six miles from the airfield must have tower's permission to enter its airspace. The radar controllers handling the aircraft transmit a signal to the tower that lights up a button on the console located in the tower. The local controller in the tower responds by pressing a button to notify the radar controllers that the aircraft is cleared through tower's airspace (or other buttons that mandate a missed approach, wave off, full stop approach, etc.). Use of this console does not require either controller to talk on the telephone or communicate via radio, but these measures can be taken if necessary.

Next, the participants were given a brief on the general layout of MCAS Camp Pendleton using the 2-dimensional view (see right hand side of Figure 2) of MARSS on the computer monitor. All reporting points mentioned previously were covered in this brief. They were also told of the aircraft that were presently in their airspace. Immediately following this brief the participants donned the HMD and headphones for another brief on the general layout of the airfield, this time in MARSS head tracked 3-dimensional viewer. Once the participants were comfortable and aware of the aircraft in their airspace, the cordless mouse was handed to the participant and the experiment began. To avoid visual distractions underneath the HMD's field of view, the computer monitor was turned away from the participant's line of sight. This also allowed the researcher to see exactly where the participant was looking since the view in the HMD and the client computer's monitor were identical.

When an aircraft transmitted, the participant of the experiment was asked to move their head in order to slew a circular transparent overlay to the immediate vicinity of the aircraft thought to be the source of the radio transmission. Immediate vicinity was defined as approximately twice the width of the overlay. The overlay was always located in the center of the participant's field of view. The participant pressed the left mouse button once the overlay was on the aircraft. The cordless mouse was used to allow the participant to easily rotate in a swivel chair to acquire a "target." At least twelve seconds elapsed between radio calls to allow the participant ample time to respond. Figure 3 shows a video image seen by participants wearing the HMD (and on the client computer monitor). Note the bull's eye, or circular overlay, in the center of the image, and two aircraft, one each to the left and right of the image.

Figure 3. HMD image of MCAS Camp Pendleton runway

During the experiment, the researcher acted as the ground controller and gave appropriate warnings to the participant (the local controller) identical to those used at Camp Pendleton. For example, if an aircraft was taxiing to the hold short line on the delta taxiway for a VORTAC departure, the researcher called out, "Aircraft on Delta, VORTAC departure."

Each participant responded to sixty individual radio transmissions (approximately half were spatialized) during the 28-minute session. At the end of the simulation, participants completed the exit questionnaire located in Appendix D.

E. DATA COLLECTION DURING THE SIMULATION

As noted in the previous section, the researcher was able to see exactly where the participant's line of gaze was located at any time during the experiment. Furthermore, the researcher could hear the click of the mouse button when the participant depressed it. Therefore, the researcher was able to determine if a participant identified the correct aircraft in every response the participant made. The results were recorded on the response accuracy matrix located in Appendix E.

Additionally, MARSS was programmed to record data throughout the experiment. For each participant, the data was written to a unique file upon completion of the experiment. Table 1 shows the data generated by MARSS.

		Simulation Time	**Participant Head Position**	**ID & location of transmitting aircraft**	**ID & location of all aircraft**
Event	**Audio transmission by aircraft or GCA signal**	✓	✓	✓	
	Participant response (mouse click)	✓	✓		✓

Table 1. Data recorded by MARSS for specified events

From the recorded data, participant response time could be calculated as well as the total angular head displacement from aircraft transmission to participant response.

IV. DATA PREPARATION AND ANALYSIS OF RESULTS FROM THE LOCAL CONTROLLER SIMULATION

A. DATA PREPARATION

A significant amount of time was required to collate and prepare the data that was written to text files by MARSS. Numerous Microsoft Excel macros were composed to speed up the process and produce a data set that could be analyzed using analysis techniques available with S-Plus, a commercially available data analysis package. Appendix F contains mathematical formulas applied to the data to obtain response times and angular turning rates.

The final data set consisted of 1,771 user responses. A total of 1,800 radio transmissions were presented, but the computer did not detect some participant responses. Other times, users either failed or forgot to respond to a radio call. Each of the 1,771 user responses had the following attributes as shown by a sample provided in Appendix G: subject number, subject treatment, radio call status, radio call position, response time, response rate, response accuracy, and identification number. Subject (participant) number identified the owner of the response (1-30). Subject (participant) treatment categorized the treatment received by the owner of the response (0 – non-spatialized sound followed by spatialized sound, 1 – spatialized sound followed by non-spatialized sound). Radio call status identified the aircraft audio transmission the user was responding to as either non-spatialized (0) or spatialized (1). Radio call position assigned the location of the radio call into one of seven areas (R – runway or right grass, A – right abeam, N – north initial, GCA, or short final for the runway, L – LCAC or VORTAC, LA – left abeam or TALA, H – hold short line, P – parallel taxiway). Response time was the number of seconds from aircraft transmission to user response (to tenths of a second). Response rate was the number degrees of head turn from aircraft transmission to user response, divided by response time (degrees per second). Response accuracy showed if the user response was correct (1) or not (0). Lastly, the identification number was the time of aircraft transmission (seconds).

B. EFFECT OF SPATIALIZED AUDIO ON ACCURACY RATES

One of the primary areas to be evaluated in the local controller experiment was the effect of spatialized sound on the accuracy of subject responses. Of the 1,771 responses recorded, 884 were taken during non-spatialized segments and 887 were from spatialized segments. 42 out of the total 1,771 responses were incorrect (32 non-spatialized and 11 spatialized). The average accuracies of both non-spatialized and spatialized statuses were quite high, 96.49% and 98.76%, respectively. However, analysis of a one-sided t-test helped determine that a significant difference existed between the two averages (p-value = 0.0009 as shown in Figure 4).

```
            Standard Two-Sample t-Test

t = 3.1414, df = 1769, p-value = 0.0009
alternative hypothesis: true difference in means is greater than 0
sample estimates:
 mean of x mean of y
 0.9875986 0.9649321
```

Figure 4. T-test results for difference in average accuracy rates between localized (x) and non-localized (y) responses

The results of this test are important because they show a significant beneficial effect of spatialized sound on a participant's situational awareness. This translates to fewer cases where an air traffic controller might inadvertently direct an aircraft in an unsafe manner—possibly resulting in the increased potential for a catastrophic mid-air collision and loss of valuable life.

C. EFFECT OF SPATIALIZED AUDIO ON RESPONSE TIMES

The next major item to be analyzed from the simulation was participant response times. The general trend of the data showed most participants tended to have faster reaction times using spatialized sound (see Appendix H). A t-test of the data set showed a significant difference between average non-spatialized audio responses versus spatialized audio responses. Figure 5 shows the results of this one-sided t-test (p-value < 0.00001).

```
      Standard Two-Sample t-Test

t = -5.6382, df = 1727, p-value = 0
alternative hypothesis: true difference in means is less than 0
sample estimates:
 mean of x mean of y
  4.401142 5.112896
```

Figure 5. T-test results for difference in average response times between localized (x) and non-localized (y) responses

A slightly more sophisticated approach to analyzing the effect of spatialized audio on response times was possible through the use of analysis of variance (ANOVA) techniques. Before this approach was taken, it was necessary to eliminate incorrect responses that were discussed in the previous section. Inclusion of incorrect responses in response times did not make logical sense, since a participant could simply click the left mouse button haphazardly to achieve extraordinarily brief response times.

Prior to the application of ANOVA techniques, heteroscedasticity of the data was checked with a plot of participant mean response times versus standard deviations (Figure 6).

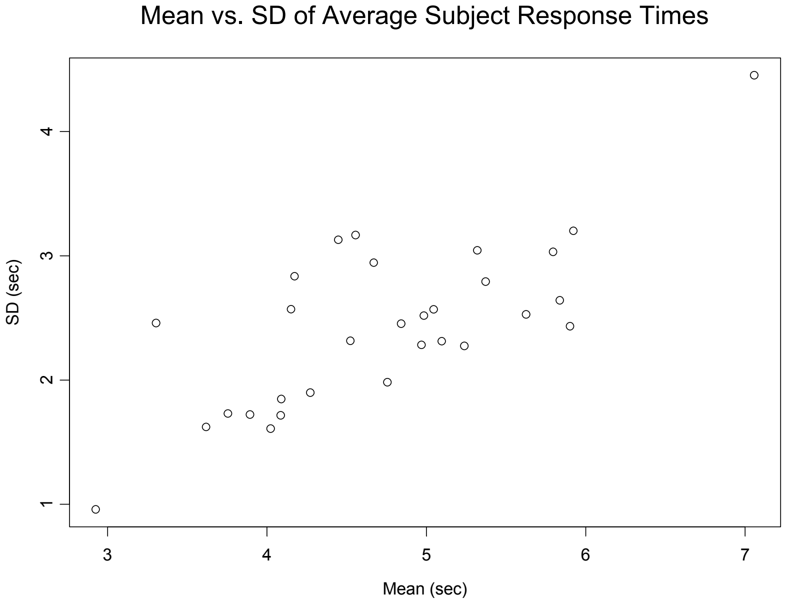

Figure 6. Heteroscedasticity check for response times

This plot shows a general increasing linear trend to the data. Consequently, the logarithm (log) of response time was chosen as an appropriate method to reduce the effect of heteroscedasticity. Figure 7 shows the effect of taking the log of response times.

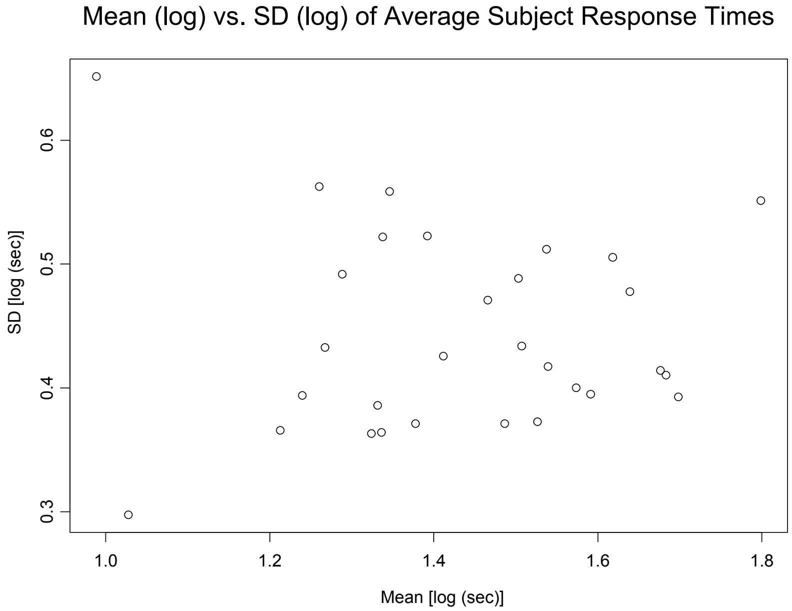

Figure 7. Heteroscedasticity check for log(response times)

The behavior shown in Figure 7 is much more acceptable than the behavior shown in Figure 6.

The first ANOVA model attempted to determine the effect of a number of potential factors that might influence response times. For a particular response, these factors included differences between participants (simply put, some participants will react faster than others), audio status (non-spatialized or spatialized), and position of radio call (one of the seven positions listed in section A of this chapter). Figure 8 shows the results of the initial attempt.

```
Analysis of Variance Table

Response: log(resp.time)

Terms added sequentially (first to last)

                    Df Sum of Sq  Mean Sq  F Value   Pr(F)
as.factor(subject)  29   59.4980  2.05166  15.0693 0.00000
           status    1    7.8880  7.88799  57.9370 0.00000
              pos    6  103.4576 17.24294 126.6487 0.00000
        Residuals 1692  230.3620  0.13615
```

Figure 8. Log of response time ANOVA output (main factors only)

Not surprisingly, this chart shows that participants and positions have a significant impact on response times. Most importantly to this study, however, is the p-value less than 0.00001 associated with status. This means that spatialized audio had an effect on response times. We know this effect was a beneficial one by looking at the coefficient of "status" (-0.13) in the underlying linear regression model (Appendix I). The next step was to analyze the effects of interactions. The ANOVA output in Figure 9 shows the inclusion of interactions.

```
      Analysis of Variance Table

                              Df  Sum of Sq  Mean Sq  F Value     Pr(F)
as.factor(subject)            29  59.4980    2.05166  15.8296  0.000000
status                         1   7.8880    7.88799  60.8599  0.000000
pos                            6 103.4576   17.24294 133.0380  0.000000
as.factor(subject):status     29   7.7001    0.26552   2.0486  0.000873
as.factor(subject):pos       174  29.6740    0.17054   1.3158  0.005541
Residuals                   1489 192.9879    0.12961
```

Figure 9. Log of response time ANOVA output including interactions

In addition to the three factors shown to have an effect in the previous ANOVA output, subject/status and subject/position interactions were shown to be significant (all p-values < 0.006). This was not unexpected since some participants seemed to respond to spatialized sound better than others. The same was true for a participant's particular ability to respond quicker to certain positions. A normal probability plot of the residual errors obtained from the underlying response time model verified the assumption of normality (Figure 10).

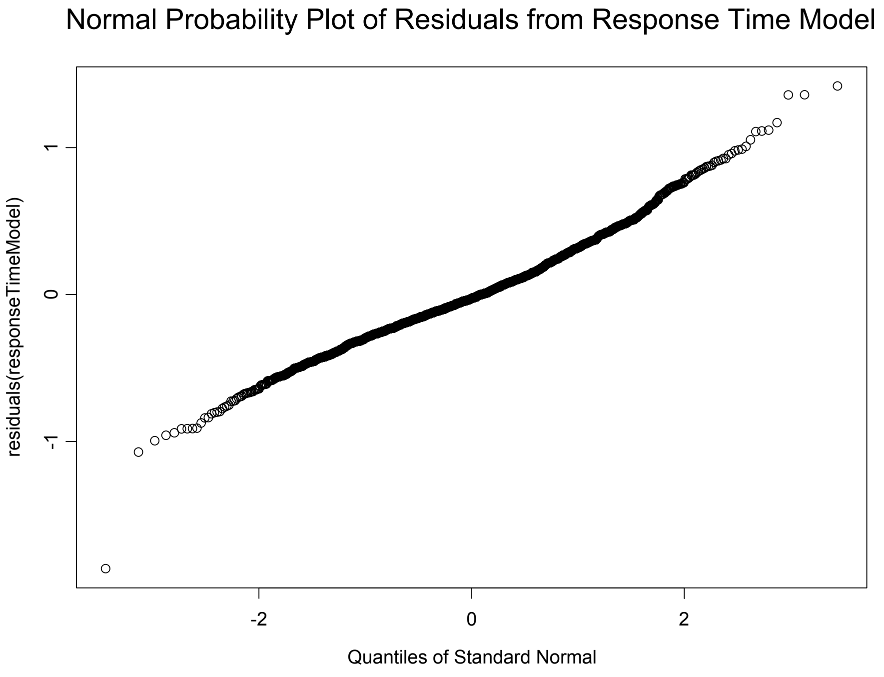

Figure 10. Normal probability plot for response time model

A status/position interaction was not chosen for analysis in the preferred ANOVA due to the lack of sufficient degrees of freedom at some locations (such as left abeam or north initial). Regardless, other ANOVA models showed no interaction between status/position (see Appendix I).

Taking the analysis one step further to account for individual differences, position of aircraft, and statistical interactions has shown that response times are reduced using spatialized sound. The ANOVA and t-tests combined to strongly confirm the beneficial effect of spatialized audio in the local controller simulation.

D. EFFECT OF SPATIALIZED AUDIO ON RESPONSE RATES

An analysis of the effect of spatialized audio on participant response rates followed the same methodology as the previous section's analysis of participant response times. The general trend of the data showed most participants had relatively higher response rates during the spatialized audio segment of the experiment (see Appendix H). A closer look at the data, though, revealed some peculiarities in the data. For instance, why would it take one of our participants a total of 8.7 seconds to move his head 0.89 degrees? There are a number of reasons how this could have happened. After the radio call, the participant may have looked away from his line of gaze to confirm the presence of other aircraft in the airspace before reacquiring the target. Or the participant may have been "leading" the aircraft with the bull's eye in the HMD (analogous to a quarterback "leading" a receiver during a pass play in football), waiting for the aircraft to enter the overlay. Simply stated, interpretation of response rates is not as straightforward as response times. Nonetheless, a t-test of the data set showed a significant difference between average non-spatialized audio response rates and spatialized audio response rates (Figure 11, p-value = 0.0001).

```
      Standard Two-Sample t-Test

t = 3.7356, df = 1727, p-value = 0.0001
alternative hypothesis: true difference in means is greater than 0
sample estimates:
 mean of x mean of y
  11.41584  9.765179
```

Figure 11. T-test results for difference in average response rates between localized (x) and non-localized (y) responses

These results lead one to believe that, on the average, participants move their heads faster toward transmitting aircraft when using spatialized cues.

As was the case with response times, heteroscedasticity of the response rate data was checked with a plot of participant mean response rates versus standard deviations (Figure 12).

Since heteroscedasticity was apparent, the log of the response rates was chosen as the appropriate method for countering heteroscedasticity. The effectiveness of a logarithmic plot for response rates was not as effective as that for response times, but was still chosen (Figure 13).

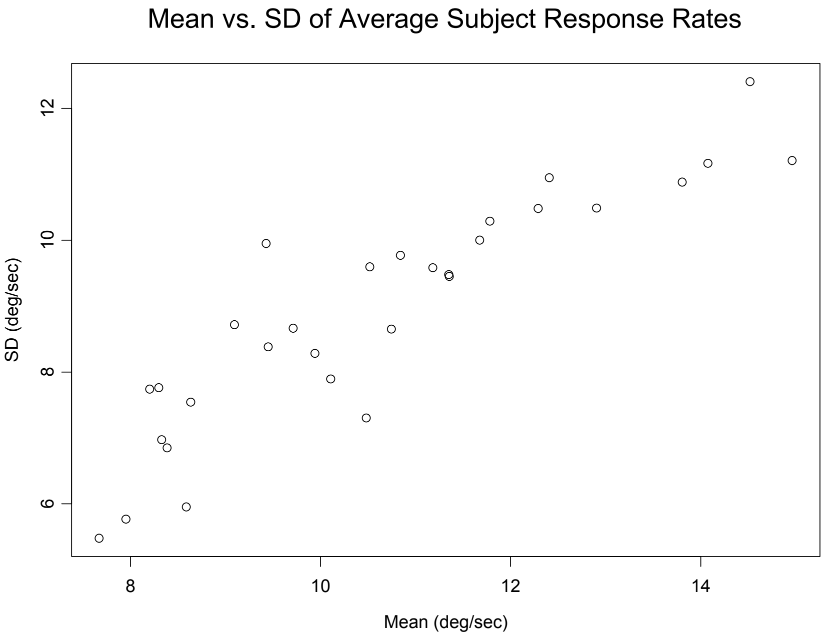

Figure 12. Heteroscedasticity check for response rates

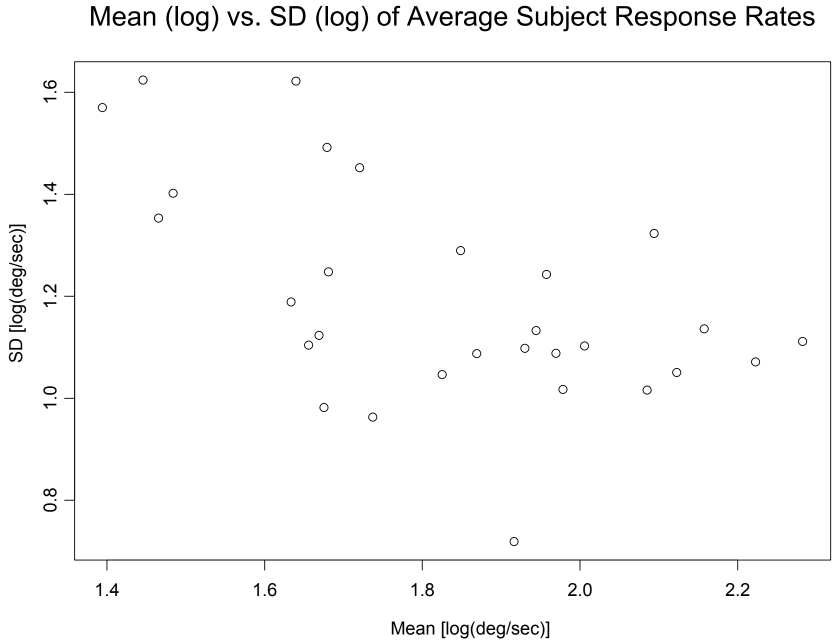

Figure 13. Heteroscedasticity check for log(response rates)

The need to eliminate one more data point became obvious when ANOVA models were attempted. One of the data points had a response rate of 0.000 deg/sec, so applying the log was not an option until that point was removed. Once this was done, the main effects were tested via ANOVA. The S-Plus output is listed in Figure 14.

```
      Analysis of Variance Table

Response: log(resp.rate)

Terms added sequentially (first to last)
                     Df Sum of Sq  Mean Sq  F Value    Pr(F)
as.factor(subject)   29    93.114  3.21084  2.45490 0.0000276876
            status    1    14.333 14.33284 10.95838 0.0009514179
               pos    6   292.115 48.68575 37.22340 0.0000000000
         Residuals 1691  2211.716  1.30793
```

Figure 14. Log of response rate ANOVA (main factors only)

These results point out that participant, status, and position had an effect on response rates during the tower simulation (p-value = 0.00095). Next, an ANOVA with interactions was completed. The results of this ANOVA showed a significant interaction between participant and position (Figure 15).

```
      Analysis of Variance Table

Response: log(resp.rate)

Terms added sequentially (first to last)
                            Df Sum of Sq  Mean Sq  F Value     Pr(F)
       as.factor(subject)   29    93.114  3.21084  2.54637 0.0000128
                   status    1    14.333 14.33284 11.36672 0.0007669
                      pos    6   292.115 48.68575 38.61044 0.0000000
as.factor(subject):status   29    41.850  1.44309  1.14445 0.2728819
   as.factor(subject):pos  174   293.576  1.68722  1.33805 0.0034754
                Residuals 1488  1876.291  1.26095
```

Figure 15. Log of response rate ANOVA with interactions

This interaction is not surprising for the same reason as noted in earlier sections—some participant’s possessed a particular ability to respond quicker to some positions.

Lastly, a normal probability plot of the residuals from the response rate model reveals a possible left tail (Figure 16).

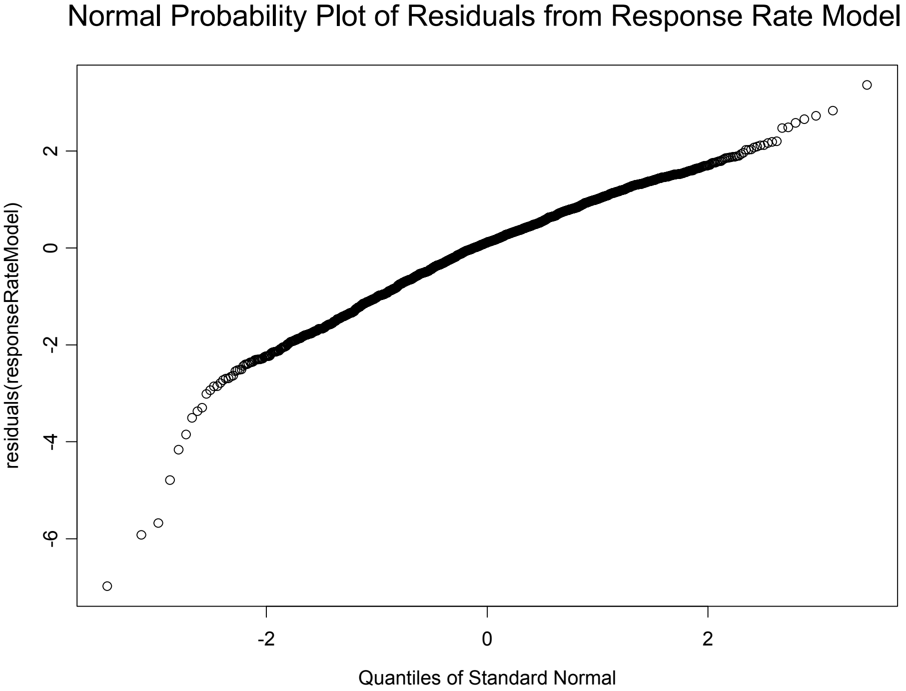

Figure 16. Normal probability plot for response rate model

The points making up the “curved” portion of the plot are relatively few when compared to the overall number. Arguments can be made from many directions about the plausibility of evaluating response rates in the manner that was done in this simulation. The fact of the matter is that response rates were highly dependent upon where a participant was looking at the time of a radio call. The location where a participant’s gaze was directed at the time of an aircraft’s transmission was dependent on factors beyond the scope of this thesis. Further analysis of response rates in this experiment was not warranted. Having said that, there still exists ample evidence to believe that spatialized sound had a positive impact on response rates during the experiment.

E. EFFECT OF TREATMENT RECEIVED ON OVERALL RESULTS

So far, the effect of treatment received by individual participants has not been discussed thoroughly. The inclusion of a treatment factor in ANOVA was infeasible since a participant only received one treatment. Were there differences in a participant’s performance that depended upon treatment received? To find out, each participant's average response time using spatialized sound was subtracted from the same participant's average response time using non-spatialized sound. A t-test was then performed to see if the average difference for those that received non-spatialized audio followed by spatialized audio (treatment "x") was different from those that received the spatialized audio first followed by non-spatialized audio (treatment "y"). The t-test results follow (Figure 17).

```
      Standard Two-Sample t-Test

t = 2.3494, df = 28, p-value = 0.0261
alternative hypothesis: true difference in means is not equal to 0
sample estimates:
 mean of x  mean of y
 0.3870498   1.011051
```

Figure 17. T-test results for difference in average response rates between treatment x (non-3D → 3D audio) and treatment y (3D → non-3D audio)

This t-test shows there is a difference (p-value = 0.0261). On the average, participants that received treatment "y" had a larger difference between average non-spatialized and spatialized response times than did those that received treatment "x." In simple terms, one plausible reason for the difference was that spatialized audio made the aircraft acquisition process an inherently easier task to perform *especially during the first half of the experiment*. Those that received treatment "x" continued to exhibit the benefits of spatialized sound, only to a lesser extent because of familiarity gained from the first half of the experiment. Another plausible reason for the disparity between the treatments could be participant fatigue. During the second half of the experiment, a few participants reported mild eyestrain and/or the effects of a head tracked display on the vestibular system. There is no sure way to tell which case, if either, was the cause of the treatment effect. The only definitive conclusion that resulted from this portion of the analysis was that, on the average, spatialized sound helped participants acquire targets faster regardless of treatment received.

F. SUBJECTIVE FEEDBACK FROM PARTICIPANTS

Each participant completed a questionnaire following the simulation that queried him about perceived levels of situational awareness throughout the experiment (Appendix D). A scale of 1 (worst) to 10 (best) was used. 26 of 30 participants rated their situational awareness during the spatialized portion of the experiment higher than that during the non-spatialized portion. Three participants rated them equal. One participant felt that his situational awareness was higher during the non-spatialized portion because he "had to actually listen to the content of the radio call." The average rating of situational awareness during spatialized sound was 8.63. The average rating for non-spatialized sound was 6.17 (see Appendix J). In no case did a participant feel spatialized sound was a bad idea. Some participants came out of the experiment quite enthusiastic about the potential of spatialized sound in the tower, as well as in the potential applicability in the cockpit (see Appendix K).

V. CONCLUSIONS AND RECOMMENDATIONS

A. ANALYTICAL CONCLUSIONS

This thesis investigated the use of spatialized auditory icons and radio communications to determine if they could be effectively implemented in air traffic control tasks to benefit local controllers. The research provides quantitative evidence that spatialized audio helps to improve the accuracy of a local controller's identification and acquisition of aircraft that are communicating with the tower. It also provides quantitative evidence that spatialized audio helps to reduce the amount of time required by the local controller to visually locate an aircraft emitting a radio transmission. Lastly, it shows that local controllers exhibit faster head turn rates using spatialized audio.

B. IMPACT OF THIS STUDY

The impact of this thesis reaches far beyond military and civilian ATC. It has applicability to remotely piloted vehicle (RPV) operations and manned aircraft operations as well. It is hypothesized that this technology can be used to increase the situational awareness of pilots for mental and physical perceptions of other aircraft in their airspace. Judging from the responses of participants that took part in the experiment, the question to be answered is not, "Should we have spatialized sound in the cockpit," but rather, "Why don't we have spatialized sound in the cockpit?"

C. RECOMMENDATIONS FOR FUTURE STUDY

The prototype used in this research used a relatively inexpensive audio server that can supply audio for four or more independent listeners. The study implemented an inexpensive inertial headtracking device and HMD. The analysis shows that this system could be a cost-effective forerunner of a spatialized audio display system for military and civilian air-traffic control. The prevention of one mid-air collision would more than pay for the cost of developing and implementing such a system. The cost-savings in human life is incalculable.

Finally, this thesis significantly impacts future research to be conducted at NPS and the Operations Research Department. Additional research is planned to expand upon the research initiated in this project to further refine the process and deliver an actual product that can be implemented in the operational environment. To avoid anomalies encountered during the analysis of head turn rates, it is recommended that future studies focus on the *initiation* of head turn rates (i.e., number of degrees of head turn in the first two seconds following a radio call). If possible, the HMD should be replaced with a full 360-degree visual display. To this end, additional research funding is being sought to supplement the research initiated here and to develop specific requirements documents to drive the Small Business Innovation Research (SBIR) process for delivering a product to the operational world.

APPENDIX A. NPS INSTITUTIONAL REVIEW BOARD FORMS

The following pages contain all forms that were completed by each participant prior to the commencement of the airfield local controller experiment. They include a Participant Consent Form, Minimal Risk Consent Statement, and a Privacy Act Statement.

NAVAL POSTGRADUATE SCHOOL, MONTEREY, CA 93943
PARTICIPANT CONSENT FORM

1. **Introduction.** You are invited to participate in a study of the situational awareness of air traffic controllers aboard a military airfield. With information gathered from you and other participants, we hope to evaluate the effectiveness of localized sound on situational awareness. We ask you to read and sign this form indicating that you agree to be in the study. Please ask any questions you may have before signing.

2. **Background Information.** This study is part of ongoing effort on behalf of naval aviation, and aviation in general, to enhance safety and efficiency at airfields. The study is also a contributor to the Human Systems Integration Laboratory's efforts to investigate virtual displays.

3. **Procedures.** If you agree to participate in this study, the researcher will explain the tasks in detail. There will be two fifteen-minute sessions: 1) a simulation using localized sound and 2) a simulation using non-localized sound. The order of the simulations will vary from participant to participant. Overall time of the study will be approximately forty-five minutes to one hour.

4. **Risks and Benefits.** This research involves no risks or discomforts greater than those encountered by playing an ordinary video game. The benefits to the participants are exposure to techniques for enhancing spatial knowledge in an aviation environment.

5. **Compensation.** No tangible reward will be given. A copy of the results will be available to you at the conclusion of the experiment.

6. **Confidentiality.** The records of this study will be kept confidential. No information will be publicly accessible which could identify you as a participant.

7. **Voluntary Nature of the Study.** If you agree to participate, you are free to withdraw from the study at any time without prejudice. You will be provided a copy of this form for your records.

Points of Contact. If you have any further questions or comments after the completion of the study, you may contact the research supervisor, Dr. Russell Shilling, (831) 656-2543 rdshilli@nps.navy.mil.

8. **Statement of Consent.** I have read the above information. I have asked all questions and have had my questions answered. I agree to participate in this study.

--- --------------------------

Participant's Signature Date

--- --------------------------

Researcher's Signature Date

NAVAL POSTGRADUATE SCHOOL, MONTEREY, CA 93943
MINIMAL RISK CONSENT STATEMENT

Participant: VOLUNTARY CONSENT TO BE A RESEARCH PARTICIPANT IN: Enhancing the Situational Awareness of Local Airfield Controllers

1. I have read, understand and been provided "Information for Participants" that provides the details of the below acknowledgments.

2. I understand that this project involves research. An explanation of the purposes of the research, a description of procedures to be used, identification of experimental procedures, and the extended duration of my participation have been provided to me.

3. I understand that this project does not involve more than minimal risk. I have been informed of any reasonably foreseeable risks or discomforts to me.

4. I have been informed of any benefits to me or to others that may reasonably be expected from the research.

5. I have signed a statement describing the extent to which confidentiality of records identifying me will be maintained.

6. I have been informed of any compensation and/or medical treatments available if injury occurs and is so, what they consist of, or where further information may be obtained.

7. I understand that my participation in this project is voluntary; refusal to participate will involve no penalty or loss of benefits to which I am otherwise entitled. I also understand that I may discontinue participation at any time without penalty or loss of benefits to which I am otherwise entitled.

8. I understand that the individual to contact should I need answers to pertinent questions about the research is Dr. Russell Shilling, Principal Investigator, and about my rights as a research participant or concerning a research related injury. A full and responsive discussion of the elements of this project and my consent has taken place.

Medical Monitor: Flight Surgeon, Naval Postgraduate School

____

Signature of Principal Investigator Date

____

Signature of Volunteer Date

____

Signature of Witness Date

NAVAL POSTGRADUATE SCHOOL, MONTEREY, CA 93943
PRIVACY ACT STATEMENT

1. Authority: Naval Instruction

2. Purpose: Situational awareness data will be collected to enhance knowledge, and to develop tests, procedures, and equipment to improve the development of Virtual Environments.

3. Use: Situational awareness data will be used for statistical analysis by the Departments of the Navy and Defense, and other U.S. Government agencies, provided this use is compatible with the purpose for which the information was collected. The Naval Postgraduate School in accordance with the provisions of the Freedom of Information Act may grant use of the information to legitimate non-government agencies or individuals.

4. Disclosure/Confidentiality:

   a. I have been assured that my privacy will be safeguarded. I will be assigned a control or code number, which thereafter will be the only identifying entry on any of the research records. The Principal Investigator will maintain the cross-reference between name and control number. It will be decoded only when beneficial to me or if some circumstances, which are not apparent at this time, would make it clear that decoding would enhance the value of the research data. In all cases, the provisions of the Privacy Act Statement will be honored.

   b. I understand that a record of the information contained in this Consent Statement or derived from the experiment described herein will be retained permanently at the Naval Postgraduate School or by higher authority. I voluntarily agree to its disclosure to agencies or individuals indicated in paragraph 3 and I have been informed that failure to agree to such disclosure may negate the purpose for which the experiment was conducted.

   c. I also understand that disclosure of the requested information, including my Social Security Number, is voluntary.

____

Signature of Volunteer   Name, Grade/Rank (if applicable) DOB   SSN   Date

____

Signature of Witness   Date

APPENDIX B. BACKGROUND QUESTIONNAIRE

Subject Number: ____

Age: ______ Sex: ______ Service: __________

Years in service: ______ Branch/MOS: ___________

Do you have any aviation or air traffic control related experience? ___________

If yes, please briefly explain here (military / civilian, type aircraft, number of hours, last flight, and air traffic control qualifications): ___________________________

____

____

____

Do you have any significant hearing loss? ___________

If yes, explain here: ____

____

____

____

Circle the number that best estimates your video game ability:

1 – Poor	(What's Doom, Asteroids, or Space Invaders?)
2 – Below Average	(My kids have PlayStation 2, Game Cube, or X-box, but I rarely play [be honest])
3 – Average	(I can hold my own)
4 – Above Average	(I've read game manuals to learn special tricks)
5 – Expert	(Carpel Tunnel Syndrome is a certainty)

Circle any of the following symptoms you are presently experiencing:

Stomach awareness

Headache

Difficulty focusing

I feel like a champ

Yawning

Eye strain

General body fatigue

Burping

Nausea

Dizziness

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APPENDIX C. RADIO CALLS

This appendix contains the time, file name and message content of all radio calls heard by participants during the airfield local controller experiment.

Time	Audio File	Message
30.0	Atlas22OnTheGoRtDownStart.wav	"Tower, Atlas 22 on the go for the right downwind"
55.0	Atlas35OnTheGoRtGrass.wav	"Tower, Atlas 32 is on the go, right grass"
142.4	Atlas22AbeamDuty.wav	"Tower, Atlas 22 abeam for duty"
173.4	Atlas35AbeamRightGrass.wav	Tower, Atlas 35 abeam for right grass
225.4	Atlas22OnTheGoRtDown.wav	"Tower, Atlas 22 on the go for the right downwind"
260.4	Atlas35OnTheGoRtGrass.wav	"Tower, Atlas 32 is on the go, right grass"
277.0	Coyote32NorthInitFullStop.wav	"Campen Tower, Coyote 32 North Initial inbound full stop"
321.9	Coyote32FullStopArmDearm.wav	"Coyote 32 will be full stop off at the arm / dearm"
334.8	Atlas22AbeamGrass.wav	"Campen Tower, Atlas 22 abeam for the grass "
377.9	Knightrider00LCACfullStop.wav	"Campen Tower, Knightrider 00 is at the LCAC, inbound, landing full stop"
398.2	Atlas35AbeamRightGrass.wav	"Tower, Atlas 35 abeam for right grass"
421.8	Atlas22OnTheGoRtDown.wav	"Tower, Atlas 22 on the go for the right downwind"
433.4	Knightrider00AbeamFullStop.wav	"Knightrider 00 approaching abeam, full stop"
447.3	Atlas49Num1Delta21RightDown.wav	"Campen Tower, Atlas 49 number 1 hold short delta for 21, right downwind"
480.3	Atlas32TalaLocalBounce.wav	"Tower, Atlas 32 is a single huey from the TALA for local bounce"
512.5	Atlas35OnTheGoRtGrass.wav	"Tower, Atlas 35 is on the go, right grass"
532.2	Atlas32AbeamDuty.wav	"Tower, Atlas 32 is abeam for duty"
559.6	Atlas22AbeamDuty.wav	"Tower, Atlas 22 abeam for duty"
589.8	Atlas49AbeamRtGrass.wav	"Tower, Atlas 49 is abeam, right grass"
628.2	Atlas32OnTheGoDuty.wav	"Tower, Atlas 32 on the go, duty"
648.4	Atlas35AbeamExtendStuckPedals.wav	"Tower, Atlas 35 request extended downwind for stuck pedals"
676.8	Atlas49OnTheGoRtGrass.wav	"Tower, Atlas 49 is on the go, right grass"
694.2	Atlas35TurningBase.wav	"Tower, Atlas 35 turning base"
737.6	Atlas32OnTheGoRtGrass.wav	"Tower, Atlas 32 is on the go, right grass"
763.3	Atlas35OnTheGoDuty.wav	"Tower, Atlas 35 on the go from the duty"
779.2	Swift04DeltaVortac.wav	"Tower, Swift 04 is number one hold short, delta, for a VORTAC departure"
814.6	Atlas49AbeamRtGrass.wav	"Tower, Atlas 49 is abeam, right grass"
851.9	Atlas32AbeamGrass.wav	"Tower, Atlas 32 is abeam, right grass"
892.1	Atlas35AbeamDuty.wav	"Atlas 35 abeam, duty"
909.6	Swift04Vortac.wav	"Campen Tower, Swift 04 is VORTAC for the switch"
931.3	Atlas49OnTheGoRtGrass.wav	"Tower, Atlas 49 is on the go, right grass"
952.2	Knightrider03TakeoffLeftDownwind.wav	"Campen Tower, Knightrider 03 takeoff, left downwind"
975.6	Atlas32AbeamDuty.wav	"Tower, Atlas 32 is abeam for duty"
1009.7	Swift12ParallelHoverChecks.wav	"Campen Tower, Swift 12 on the parallel, hover checks, north grass"
1051.1	Atlas49AbeamRtGrass.wav	"Tower, Atlas 49 is abeam, right grass"
1075.4	InboundGCAsignal.wav	"none (sequence of five audio beeps)"
1082.9	Atlas68PapaSouthGrass.wav	"Tower, Atlas 68 papa for the south grass, ten minutes"
1108.3	Knightrider03LeftAbeamPracticeAuto.wav	"Tower, Knightrider 03 is left abeam, practice auto"
1120.3	Viper34GCALocal.wav	"Tower, Viper 34 GCA handoff for local bounce"
1138.1	Atlas49OnTheGoRtGrass.wav	"Tower, Atlas 49 is on the go, right grass"
1151.8	Viper34OnTheGoWithTraffic.wav	"Tower, Viper 34 on the go with traffic"
1189.0	InboundGCAsignal.wav	"none (sequence of five audio beeps)"
1209.1	Knightrider03OntheGo.wav	"Tower, Knightrider 03 is on the go"
1258.3	Viper34AbeamGrass.wav	"Viper 34 abeam, practice auto, grass"
1275.9	Atlas49AbeamRtGrass.wav	"Tower, Atlas 49 is abeam, right grass"
1345.3	Viper34OnTheGoRtGrass.wav	"Tower, Viper 34 on the go, right grass"
1354.6	Knightrider03LeftAbeamPracticeAuto.wav	"Tower, Knightrider 03 is left abeam, practice auto"
1390.2	Atlas49TakeoffRightGrass.wav	"Tower, Atlas 49 takeoff, right grass"
1455.4	Knightrider03OntheGo2.wav	"Tower, Knightrider 03 is on the go"
1483.1	Viper34AbeamPracAutoRtGrass.wav	"Viper 34 abeam, practice auto, grass"
1513.9	Atlas49AbeamRWY21.wav	"Tower, Atlas 49 is abeam for runway 21"
1537.9	Dragon00LCACforTheBreak.wav	"Campen Tower, Dragon 00 flight of four, LCAC inbound request extended downwind for the break"
1562.6	Knightrider03LeftAbeamPracticeAuto.wav	"Tower, Knightrider 03 is left abeam, practice auto"
1597.4	Viper34OnTheGoRtGrass.wav	"Tower, Viper 34 on the go, right grass"
1615.1	Dragon00AbeamBreak.wav	"Tower, Dragon 00 is abeam for the break"
1627.8	Knightrider03TakeoffVortac.wav	"Campen Tower, Knightrider 03 takeoff, VORTAC departure"
1651.1	Swift12LowWorkComplete.wav	"Campen Ground (Tower), Swift 12 is low work complete "
1667.7	Dragon00LakeBreak.wav	"Tower, Dragon 00 and flight is Lake O'Neill inbound, request mid field break"
1705.5	Viper34Abeam21.wav	"Viper 34 is abeam for 21"
1715.5	Knightrider03VortacClear.wav	"Tower, Knightrider 03 is VORTAC clear"

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APPENDIX D. EXIT QUESTIONNAIRE

Subject Number:____

1. During the ***spatialized*** sound portion of the experiment, rate your overall situational awareness.

Low					Medium					High
0	1	2	3	4	5	6	7	8	9	10

2. During the ***non-spatialized*** sound portion of the experiment, rate your overall situational awareness.

Low					Medium					High
0	1	2	3	4	5	6	7	8	9	10

3. How well were you able to understand the audio transmissions of the aircraft?

None					Some					Very Well
0	1	2	3	4	5	6	7	8	9	10

4. Circle any of the following symptoms you are presently experiencing:

Stomach awareness

Headache

Difficulty focusing

I feel like a champ

Yawning

Eye strain

General body fatigue

Burping

Nausea

Dizziness

5. Any additional comments:

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APPENDIX E. RESPONSE ACCURACY MATRIX

This matrix shows the accuracy of each participant's response during the airfield local controller experiment. Columns labeled 1-30 correspond to participant number.

T= 3d --> non-3d F = non-3d --> 3d

					T	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T	F	T
#	Time	Left	Pos	Transmitting	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	30	28.1	R	Atlas22																			X											
2	55	27.7	R	Atlas35																														
3	142.4	26.2	A	Atlas22																														
4	173.4	25.7	A	Atlas35																											X			
5	225.4	24.8	R	Atlas22																														
6	260.4	24.3	R	Atlas35																														
7	277	24.0	N	Coyote32													X	X																
8	321.9	23.2	N	Coyote32			X				X					X							X											
9	334.8	23.0	A	Atlas22																														
10	377.9	22.3	L	Knightrider00																													X	
11	398.2	22.0	A	Atlas35																														
12	421.8	21.6	R	Atlas22											X																			
13	433.4	21.4	A	**Knightrider00**																														
14	447.3	21.1	H	Atlas49																														
15	480.3	20.6	LA	Atlas32	X			X												X	X						X					X		
16	512.5	20.0	R	Atlas35					X																									
17	532.2	19.7	LA	Atlas32									X				X				X				X		X				X			
18	559.6	19.3	A	~~Atlas22~~																														
19	589.8	18.8	A	Atlas49																														X
20	628.2	18.1	R	Atlas32																						X								
21	648.4	17.8	A	Atlas35																														
22	676.8	17.3	R	Atlas49																														
23	694.2	17.0	N	Atlas35																														
24	737.6	16.3	A	Atlas32																														
25	763.3	15.9	R	**Atlas35**																														
26	779.2	15.6	H	Swift04																														
27	814.6	15.0	A	Atlas49																														
28	851.9	14.4	R	Atlas32																														
29	892.1	13.7	A	~~Atlas35~~																														
30	909.6	13.4	L	Swift04																														
31	931.3	13.1	R	**Atlas49**																														
32	952.2	12.7	H	Knightrider03						X																						X		D
33	975.6	12.3	A	**~~Atlas32~~**																														D
34	1009.7	11.8	P	Swift12							X																							
35	1051.1	11.1	A	Atlas49																														
36	1075.4	10.7	N	**Viper34**												D																		
37	1082.9	10.5	P	Atlas68																							X							
38	1108.3	10.1	LA	Knightrider03																														
39	1120.3	9.9	N	Viper34																														
40	1138.1	9.6	R	Atlas49																X														
41	1151.8	9.4	R	Viper34																				X										
42	1189	8.8	N	GCAplane						X																		X						
43	1209.1	8.4	R	Knightrider03																														
44	1258.3	7.6	A	Viper34																				X										
45	1275.9	7.3	A	Atlas49																														
46	1345.3	6.2	R	Viper34																														
47	1354.6	6.0	LA	Knightrider03																														
48	1390.2	5.4	R	Atlas49											X																			
49	1455.4	4.3	R	Knightrider03																														
50	1483.1	3.9	A	Viper34																														
51	1513.9	3.4	A	~~Atlas49~~																														
52	1537.9	3.0	L	Dragon00Dash1																														
53	1562.6	2.5	LA	Knightrider03																														
54	1597.4	2.0	R	Viper34																														
55	1615.1	1.7	A	Dragon00Dash1																														
56	1627.8	1.5	R	Knightrider03																														
57	1651.1	1.1	P	~~Swift12~~																								X						
58	1667.7	0.8	N	~~Dragon00Dash1~~																														
59	1705.5	0.2	A	Viper34																														
60	1715.5	0.0	L	Knightrider03						X										X														

Positions
R = runway or right grass
A = right abeam
LA = left abeam or TALA
N = north initial, short final, or GCA
H = hold short at Delta
L = LCAC or VORTAC
P = parallel taxiway

bold = ground controller notification required for next aircraft call
~~strikethrough~~ = aircraft is full stop this approach

D = did not respond
X = mistake made

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APPENDIX F. APPLICABLE MATHEMATICAL FORMULAS

The following equations were used to produce response times and response rates from the data collected during the experiment.

RESPONSE TIME = time of user response – time of aircraft transmission

For example, an aircraft begins its transmission at time $t_1 = 55.0$ seconds and the participant responded at time $t_2 = 60.0$ seconds, then

RESPONSE TIME = $t_2 - t_1 = 60.0 - 55.0 = 5.0$ seconds.

RESPONSE RATE = # of degrees of head turn / RESPONSE TIME

The # of degrees of head turn (theta) was a little more complex to compute. Calculus was used to determine the angle, theta, between the head position at the time of aircraft transmission and the head position at the time of user response.

$\text{theta} = \cos^{-1}[(A \cdot B) / (|A|\,|B|)]$ where " $\cdot$ " represents a dot product, and $|A|$ = magnitude of the vector A.

The equation reduces to the following if the magnitudes of A and B are equal to 1:

$$\text{theta} = \cos^{-1}(A \cdot B)$$

For example, let az_A and $elev_A$ equal the azimuth and elevation, respectively, of the user's head at the time of an aircraft transmission. Then vector A is determined by these formulas (in right-handed X, Y, Z coordinate system):

X component = $-\cos(elev_A) * \sin(az_A)$,
Y component = $\sin(elev_A)$
Z component = $-\cos(elev_A) * \cos(az_A)$

Similarly, these formulas apply to determine the vector that represents the head position at the time of user response as well. Finally, the trivial calculation $\cos^{-1}(A \cdot B)$ determines the angle theta.

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APPENDIX G. SAMPLE DATA

This appendix is an example of the data gathered from participant #1 during the airfield local tower scenario. Inclusion of all experimental data would be quite lengthy. For a complete data set, please contact Dr. Russell Shilling at the Naval Postgraduate School, (831) 656-2543.

subject	treatment	status	resp time	pos	resp angle	resp rate	accuracy	id
1	1	1	1.9	R	37.9476	19.97242	1	55
1	1	1	1.6	A	6.118595	3.824122	1	142.4
1	1	1	0.6	A	2.482774	4.137957	1	173.4
1	1	1	2.8	R	3.60466	1.287379	1	421.8
1	1	1	3.1	A	12.55633	4.05043	1	433.4
1	1	1	2.4	H	14.31875	5.966146	1	447.3
1	1	1	3	T	74.43727	24.81242	0	480.3
1	1	1	2.9	R	81.55037	28.12082	1	512.5
1	1	1	6.5	LA	122.7071	18.87802	1	532.2
1	1	1	1.1	A	1.784293	1.622085	1	559.6
1	1	1	1.3	A	9.085597	6.988921	1	589.8
1	1	1	2.9	R	51.31325	17.69422	1	628.2
1	1	1	2.6	A	13.40196	5.154601	1	648.4
1	1	1	1.9	R	31.12465	16.38139	1	676.8
1	1	1	2.9	N	4.684776	1.61544	1	694.2
1	1	1	0.7	A	3.279536	4.685051	1	737.6
1	1	1	3	R	6.814918	2.271639	1	763.3
1	1	1	1.1	H	1.704386	1.549442	1	779.2
1	1	1	1.8	A	57.16414	31.75785	1	814.6
1	1	1	2.1	R	80.6997	38.42843	1	851.9
1	1	1	2.5	A	8.055538	3.222215	1	892.1
1	1	1	5.1	L	62.36669	12.22876	1	909.6
1	1	1	2.7	R	81.9266	30.34319	1	931.3
1	1	0	3.3	H	4.478749	1.357197	1	952.2
1	1	0	2.9	A	74.12908	25.56175	1	975.6
1	1	0	4.8	P	80.52682	16.77642	1	1009.7
1	1	0	0.8	A	0.612634	0.765793	1	1051.1
1	1	0	5.9	N	153.951	26.09339	1	1075.4
1	1	0	6.3	P	114.2211	18.13034	1	1082.9
1	1	0	5.2	LA	132.6342	25.50657	1	1108.3
1	1	0	4.9	S	128.9458	26.31548	1	1120.3
1	1	0	1.2	A	5.804066	4.836722	1	1258.3
1	1	0	2.2	A	12.49496	5.679529	1	1275.9
1	1	0	2.6	R	19.94666	7.671794	1	1345.3
1	1	0	5.9	A	108.501	18.38999	1	1483.1
1	1	0	3.7	A	19.38602	5.239465	1	1513.9
1	1	0	6.2	L	42.46573	6.849312	1	1537.9
1	1	0	2.4	R	35.9508	14.9795	1	1597.4
1	1	0	15.3	R	162.5618	10.62496	1	1600.9
1	1	0	4.6	A	147.4996	32.06513	1	1615.1
1	1	0	1.9	N	14.64398	7.707356	1	1667.7
1	1	0	3.6	N	87.50718	24.30755	1	1689.6
1	1	0	1.7	L	18.48977	10.87633	1	1721.1
1	1	0	2.3	L	32.83853	14.27762	1	1777
1	1	0	4.2	L	15.23521	3.627431	1	1786.9

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APPENDIX H. AVERAGE RESPONSE TIME AND RATES

The table below lists average response times and rates for each participant. It is important to keep in mind that every participant did not have the same number of responses recorded during the experiment. For example, participant 1 only had 45 responses, participant 2 had 59, and participant 3 had 58. These averages are only to show the reader general trends of the data.

	average times		**average rates**	
Subject	**non-3d**	**3d**	**non-3d**	**3d**
1	4.177	2.457	13.984	12.391
2	5.114	4.017	9.559	10.312
3	4.993	3.871	10.788	16.409
4	6.186	5.397	7.773	9.549
5	5.148	5.586	8.041	8.567
6	4.697	3.603	11.465	13.603
7	5.519	3.634	7.623	12.859
8	3.783	3.465	14.614	15.288
9	4.981	4.476	8.888	13.310
10	5.348	4.368	9.436	10.735
11	7.061	6.924	5.423	11.339
12	6.189	5.097	8.642	6.809
13	6.326	5.841	11.056	10.277
14	4.983	5.219	10.260	9.358
15	5.074	3.175	9.683	15.177
16	5.448	3.916	12.047	11.725
17	4.352	4.836	7.007	11.319
18	6.221	5.603	8.826	7.623
19	4.048	3.683	8.335	14.089
20	7.504	4.803	8.529	7.161
21	5.465	5.310	6.879	12.149
22	6.179	4.435	8.396	7.983
23	4.687	4.045	12.498	16.027
24	4.700	3.674	11.048	7.811
25	4.229	3.941	8.797	13.028
26	4.769	3.448	11.927	11.647
27	5.768	4.375	6.697	10.318
28	3.341	2.584	15.045	13.893
29	4.913	5.097	8.516	12.799
30	5.204	4.771	11.477	11.497

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APPENDIX I. S-PLUS DATA ANALYSIS OUTPUT

This appendix contains S-Plus output for each t-test and AVOVA model. Linear regression models are also included to fully interpret the ANOVA models. For reference, `status = 0` is non-spatialized sound, `status = 1` is spatialized sound, `treatment = 1` is spatialized→non-spatialized, and `treatment = 2` is non-spatialized→ spatialized.

One-sided t-test for difference in accuracy rates

```
> t.test(sam2$accuracy[sam2$status == 1],
sam2$accuracy[sam2$status == 0], alt = "greater")

      Standard Two-Sample t-Test

data:  sam2$accuracy[sam2$status == 1] and
       sam2$accuracy[sam2$status == 0]
t = 3.1414, df = 1769, p-value = 0.0009
alternative hypothesis: true difference in means is greater than 0
sample estimates:
 mean of x mean of y
 0.9875986 0.9649321
```

One-sided t-test for difference in response times

```
> t.test (sam2$resp.time[sam2$status == 1],
sam2$resp.time[sam2$status == 0], alt = "less")

      Standard Two-Sample t-Test

data:  sam2$resp.time[sam2$status == 1] and
       sam2$resp.time[sam2$status == 0]
t = -5.6382, df = 1727, p-value = 0
alternative hypothesis: true difference in means is less than 0
sample estimates:
 mean of x mean of y
  4.401142  5.112896
```

ANOVA model for main effects of log(response time)

```
> anova (lm (log(resp.time) ~ as.factor(subject) + status + pos,
data = sam2))
Analysis of Variance Table

Response: log(resp.time)

Terms added sequentially (first to last)
                          Df Sum of Sq  Mean Sq  F Value         Pr(F)
      as.factor(subject)   29   59.4980  2.05166  15.0693 0.000000e+000
                  status    1    7.8880  7.88799  57.9370 4.474199e-014
                     pos    6  103.4576 17.24294 126.6487 0.000000e+000
               Residuals 1692  230.3620  0.13615
```

Regression model for main effects of log(response time)

```
*** Linear Model ***

Call: lm(formula = log(resp.time) ~ as.factor(subject) + status + pos,
data = sam2)
Residuals:
    Min      1Q   Median    3Q   Max
 -2.308 -0.2103 -0.03184 0.201 1.736

Coefficients:
                          Value Std. Error  t value Pr(>|t|)
         (Intercept)    0.8121   0.0577    14.0834   0.0000
 as.factor(subject)2    0.3421   0.0735     4.6528   0.0000
 as.factor(subject)3    0.3894   0.0750     5.1922   0.0000
 as.factor(subject)4    0.6495   0.0744     8.7347   0.0000
 as.factor(subject)5    0.5833   0.0735     7.9326   0.0000
 as.factor(subject)6    0.2781   0.0741     3.7525   0.0002
 as.factor(subject)7    0.4183   0.0741     5.6462   0.0000
 as.factor(subject)8    0.2175   0.0733     2.9682   0.0030
 as.factor(subject)9    0.4961   0.0735     6.7464   0.0000
as.factor(subject)10    0.4706   0.0733     6.4219   0.0000
as.factor(subject)11    0.7968   0.0738    10.7957   0.0000
as.factor(subject)12    0.6267   0.0738     8.4898   0.0000
            .
            .  (output edited for space)
            .
as.factor(subject)29    0.5345   0.0736     7.2663   0.0000
as.factor(subject)30    0.5053   0.0741     6.8188   0.0000
              status   -0.1302   0.0178    -7.3269   0.0000
                posH    0.2934   0.0425     6.8953   0.0000
                posL    0.6312   0.0374    16.8640   0.0000
               posLA    0.7246   0.0356    20.3279   0.0000
                posN    0.3585   0.0305    11.7379   0.0000
                posP    0.6924   0.0432    16.0233   0.0000
                posR    0.1794   0.0222     8.0932   0.0000

Residual standard error: 0.369 on 1692 degrees of freedom
F-statistic: 34.86 on 36 and 1692 degrees of freedom, the p-value is 0
```

ANOVA model showing no status:position interaction effect in log(response time)

```
> anova (lm (log(resp.time) ~ as.factor(subject) * status + pos +
status:pos, data = sam2))
Analysis of Variance Table

Response: log(resp.time)

Terms added sequentially (first to last)
                            Df Sum of Sq  Mean Sq  F Value     Pr(F)
       as.factor(subject)   29   59.4980  2.05166  15.3396 0.0000000
                  status     1    7.8880  7.88799  58.9761 0.0000000
                pos          6  103.4576 17.24294 128.9201 0.0000000
as.factor(subject):status   29    7.7001  0.26552   1.9852 0.0014158
              status:pos     6    1.0398  0.17329   1.2957 0.2558217
               Residuals 1657  221.6221  0.13375
```

Final ANOVA model for main effects and interactions of log(response time)

```
>  anova  (lm  (log(resp.time)  ~  as.factor(subject)  *  status  +
as.factor(subject)*pos, data = sam2))
Analysis of Variance Table

Response: log(resp.time)

Terms added sequentially (first to last)
                              Df Sum of Sq  Mean Sq  F Value       Pr(F)
        as.factor(subject)   29   59.4980  2.05166  15.8296 0.000000000
                    status    1    7.8880  7.88799  60.8599 0.000000000
                       pos    6  103.4576 17.24294 133.0380 0.000000000
 as.factor(subject):status   29    7.7001  0.26552   2.0486 0.000873557
    as.factor(subject):pos  174   29.6740  0.17054   1.3158 0.005541997
                 Residuals 1489  192.9879  0.12961
```

Regression model for significant main effects & interactions of log(response time)

```
*** Linear Model ***

Call: lm(formula = log(resp.time) ~ as.factor(subject) * status +
as.factor(subject) * pos, data = sam2)
Residuals:
    Min     1Q   Median    3Q   Max
 -1.865 -0.208 -0.02773 0.187 1.418

Coefficients:
                             Value Std. Error t value Pr(>|t|)
             (Intercept)  0.8497  0.1128     7.5357  0.0000
       as.factor(subject)2  0.0561  0.1537     0.3649  0.7152
       as.factor(subject)3  0.4518  0.1504     3.0035  0.0027
       as.factor(subject)4  0.5438  0.1514     3.5911  0.0003
       as.factor(subject)5  0.5683  0.1458     3.8984  0.0001
       as.factor(subject)6  0.1629  0.1516     1.0748  0.2826
```

```
            .
            .  (output edited for space)
            .
      as.factor(subject)30  0.4665  0.1545     3.0188  0.0026
                    status -0.4026  0.1208    -3.3333  0.0009
                      posH  0.1402  0.2269     0.6180  0.5367
                      posL  0.4812  0.1896     2.5385  0.0112
                     posLA  1.1118  0.2701     4.1159  0.0000
                      posN  0.5011  0.1896     2.6433  0.0083
                      posP  0.8548  0.2784     3.0703  0.0022
                      posR  0.5190  0.1424     3.6443  0.0003
 as.factor(subject)2status  0.4240  0.1552     2.7311  0.0064
 as.factor(subject)3status  0.1652  0.1578     1.0469  0.2953
 as.factor(subject)4status  0.3902  0.1572     2.4816  0.0132
            .
            .  (output edited for space)
            .
as.factor(subject)29status  0.3882  0.1555     2.4964  0.0127
as.factor(subject)30status  0.3215  0.1575     2.0405  0.0415
   as.factor(subject)2posH  0.5219  0.3199     1.6314  0.1030
   as.factor(subject)3posH  0.2168  0.3201     0.6772  0.4984
   as.factor(subject)4posH  0.3699  0.3187     1.1606  0.2460
   as.factor(subject)5posH  0.1302  0.3187     0.4087  0.6828
   as.factor(subject)6posH  0.0571  0.3534     0.1617  0.8716
   as.factor(subject)7posH -0.1477  0.3194    -0.4624  0.6439
   as.factor(subject)8posH  0.1143  0.3187     0.3586  0.7199
   as.factor(subject)9posH  0.1372  0.3187     0.4304  0.6669
            .
            .  (output edited for space)
            .
  as.factor(subject)29posR -0.3530  0.1842    -1.9166  0.0555
  as.factor(subject)30posR -0.3953  0.1863    -2.1215  0.0340

Residual standard error: 0.36 on 1489 degrees of freedom
F-statistic: 6.722 on 239 and 1489 degrees of freedom, the p-value is 0
```

One-sided t-test for difference in response rates

```
> t.test (sam3$resp.rate[sam3$status == 1],
sam3$resp.rate[sam3$status == 0], alt = "greater")

      Standard Two-Sample t-Test

data:  sam3$resp.rate[sam3$status == 1] and
       sam3$resp.rate[sam3$status == 0]
t = 3.7646, df = 1726, p-value = 0.0001
alternative hypothesis: true difference in means is greater than 0
sample estimates:
 mean of x mean of y
  11.42889  9.765179
```

ANOVA model for main effects of log(response rate)

```
> anova (lm (log(resp.rate) ~ as.factor(subject) + status + pos,
data = sam3))
Analysis of Variance Table

Response: log(resp.rate)

Terms added sequentially (first to last)
                            Df Sum of Sq  Mean Sq  F Value        Pr(F)
      as.factor(subject)   29    93.114  3.21084  2.45490 0.0000276876
                  status    1    14.333 14.33284 10.95838 0.0009514179
                     pos    6   292.115 48.68575 37.22340 0.0000000000
               Residuals 1691  2211.716  1.30793
```

Regression model for main effects of log(response rate)

```
*** Linear Model ***

Call: lm(formula = log(resp.rate) ~ as.factor(subject) + status + pos,
data = sam3)
Residuals:
    Min      1Q Median    3Q   Max
 -7.111 -0.6954 0.2052 0.839 2.766

Coefficients:
                        Value Std. Error  t value Pr(>|t|)
         (Intercept)   1.9459  0.1787    10.8870   0.0000
 as.factor(subject)2  -0.5409  0.2279    -2.3733   0.0177
 as.factor(subject)3  -0.0485  0.2324    -0.2088   0.8346
 as.factor(subject)4  -0.5110  0.2305    -2.2170   0.0268
 as.factor(subject)5  -0.5263  0.2279    -2.3093   0.0210
 as.factor(subject)6  -0.2717  0.2297    -1.1825   0.2372
 as.factor(subject)7  -0.5139  0.2296    -2.2379   0.0254
 as.factor(subject)8   0.0774  0.2271     0.3407   0.7334
 as.factor(subject)9  -0.3337  0.2279    -1.4640   0.1434
            .
            .  (output edited for space)
            .
as.factor(subject)28   0.0174  0.2288     0.0762   0.9393
as.factor(subject)29  -0.2262  0.2280    -0.9921   0.3213
as.factor(subject)30  -0.2618  0.2297    -1.1397   0.2546
              status   0.1868  0.0551     3.3916   0.0007
                posH  -0.9089  0.1319    -6.8920   0.0000
                posL  -0.0900  0.1160    -0.7758   0.4380
               posLA   1.2245  0.1105    11.0830   0.0000
                posN   0.3938  0.0947     4.1595   0.0000
                posP   0.5005  0.1339     3.7369   0.0002
                posR   0.1294  0.0687     1.8816   0.0601

Residual standard error: 1.144 on 1691 degrees of freedom
F-statistic: 8.486 on 36 and 1691 degrees of freedom, the p-value is 0
```

Final ANOVA model for main effects & interactions of log(response rate)

```
>  anova  (lm  (log(resp.rate)  ~  as.factor(subject)  *  status  +
as.factor(subject) * pos, data = sam3))
Analysis of Variance TableResponse: log(resp.rate)

Terms added sequentially (first to last)
                           Df Sum of Sq  Mean Sq  F Value     Pr(F)
       as.factor(subject)   29    93.114  3.21084  2.54637 0.0000128
                   status    1    14.333 14.33284 11.36672 0.0007669
                      pos    6   292.115 48.68575 38.61044 0.0000000
as.factor(subject):status   29    41.850  1.44309  1.14445 0.2728819
   as.factor(subject):pos  174   293.576  1.68722  1.33805 0.0034754
                Residuals 1488  1876.291  1.26095
```

Regression model for significant main effects & interactions of log(response rate)

```
*** Linear Model ***

Call: lm(formula = log(resp.rate) ~ as.factor(subject) * pos + status,
data = sam3)
Residuals:
    Min      1Q Median     3Q   Max
 -7.089 -0.6257 0.1336 0.7465 3.434

Coefficients:
                            Value Std. Error t value Pr(>|t|)
              (Intercept)  1.6941  0.2830     5.9865  0.0000
      as.factor(subject)2 -0.6903  0.3918    -1.7620  0.0783
      as.factor(subject)3  0.3907  0.3918     0.9972  0.3188
      as.factor(subject)4 -0.1628  0.3816    -0.4265  0.6698
      as.factor(subject)5 -0.2654  0.3817    -0.6954  0.4869
      as.factor(subject)6  0.6621  0.3816     1.7349  0.0830
      as.factor(subject)7 -0.2796  0.3865    -0.7234  0.4696
      as.factor(subject)8  0.2768  0.3816     0.7253  0.4684
      as.factor(subject)9  0.1923  0.3817     0.5037  0.6145
     as.factor(subject)10 -0.1443  0.3816    -0.3782  0.7053
     as.factor(subject)11 -0.3660  0.3817    -0.9588  0.3378
     as.factor(subject)12 -0.6473  0.3816    -1.6962  0.0900
     as.factor(subject)13  0.2806  0.3817     0.7350  0.4624
             .
             .  (output edited for space)
             .

                     posH -0.9708  0.7077    -1.3719  0.1703
                     posL  0.4223  0.5766     0.7323  0.4641
                    posLA  1.3045  0.8436     1.5464  0.1222
                     posN  0.7188  0.5766     1.2466  0.2127
                     posP  1.1647  0.8442     1.3797  0.1679
                     posR  0.6517  0.4406     1.4790  0.1394
                   status  0.1798  0.0568     3.1660  0.0016
  as.factor(subject)2posH  1.3695  0.9984     1.3717  0.1704
  as.factor(subject)3posH -0.4429  0.9985    -0.4436  0.6574
  as.factor(subject)4posH -0.6176  0.9945    -0.6210  0.5347
  as.factor(subject)5posH  0.6545  0.9945     0.6581  0.5106
```

```
                .
                .   (output edited for space)
                .
 as.factor(subject)29posR -0.5769  0.5721    -1.0083  0.3135
 as.factor(subject)30posR -0.6989  0.5789    -1.2073  0.2275

Residual standard error: 1.125 on 1517 degrees of freedom
F-statistic: 2.606 on 210 and 1517 degrees of freedom, the p-value is 0
```

T-test for difference in treatments

```
> t.test (sam2$diff[sam2$treatment == 2],
sam2$diff[sam2$treatment == 1])

      Standard Two-Sample t-Test

data:  sam2$diff[sam2$treatment == 2] and
       sam2$diff[sam2$treatment == 1]
t = 2.3494, df = 28, p-value = 0.0261
alternative hypothesis: true difference in means is not equal to 0
sample estimates:
 mean of x  mean of y
 0.3870498  1.011051
```

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APPENDIX J. SUBJECTIVE RATINGS OF SITUATIONAL AWARENESS

This chart shows the subjective rating of situational awareness by participants during spatialized and non-spatialized segments of study. Also included is a subjective rating of radio call clarity.

subject	spatialized	non-spatialized	clarity
1	8	4	6
2	9	7	8
3	8	4	6
4	10	7	6
5	9	9	8
6	8	6	5
7	10	8	9
8	10	8	9
9	9	5	6
10	8	7	7
11	8	4	6
12	9	6	7
13	9	8	9
14	7	8	7
15	8	5	6
16	8	5	7
17	9	5	8
18	9	7	9
19	10	8	8
20	10	4	6
21	8	5	7
22	9	7	7
23	9	4	8
24	8	8	6
25	8	7	6
26	9	7	5
27	9	4	9
28	7	5	5
29	8	5	9
30	8	8	8

average	8.63	6.17	7.10

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APPENDIX K. PARTICIPANT COMMENTS

Participant Comments
Very realistic simulation.
Spatial has a plus in resolving locations of a/c.
I think the spatialized sound provided good azimuthal cues, but not necessarily elevation cues. I believe spatialized auditory cueing was very helpful during my experiment.
My response times for non-spatialized portion seemed to be less. This could be partially due to the fact that it is an unfamiliar field to me. Once the spatialized sound was turned on, sa was enhanced 10 fold. Knowledge of the surrounding areas was not necessary to locate calling aircraft.
The spatialized sound definitely helped in initially acquiring the aircraft if it was an initial call or I was not sure where they were in the pattern. The more I got used to using it and having it help me direct my eyes the more my SA improved.
Spatialized portion seemed significantly easier to locate subject when part of radio transmission was not completely heard. Head-tracked spatialized audio was most effective when the controller is constantly moving his / her head if stationary when a call comes in; must move the head to discriminate fore / aft differences. After a while started continuously moving head -- radio calls received then were very quickly discriminated and located.
I responded better on the non-spatialized segment because I had become much better oriented in the spatialized segment. If I had done the non-spatialized segment first, I think I would have understood much less and been more disoriented.
Very cool graphics. Spatialized portion -- was very helpful when Knightrider called left abeam & Dragon called for the midfield break to hear it in the right ear (plus beeping for north initial). Really helpful to orient you.
During spatialized portion I relied more heavily on the sound to guide me to the target and actually paid less attention to the content of the transmission, particularly call signs. During non-spatialized phase I relied more heavily on the content of the call to locate the target and felt I spent more time scanning the airspace and trying to sort call signs so I thought my overall SA was a bit higher.
Eyeglasses have horrible nosepiece.
Much easier to manage traffic with spatialized sound. I could look where the transmission was coming from and anticipate the aircraft's request based on its position.
Spatialized helped with cueing during the transmission, especially when an unexpected call (near aircraft) was received.
Spatialized - hope all towers get this someday.
It was clear to me that spatializing the sound enhanced my situational awareness.
Spatialized sound made a big difference in ability to quickly and accurately localize the source of a transmission. It helped make up for unfamiliarity with the operating area and unfamiliarity with typical radio calls used at the operating area.
Interesting. Would be nice to have spatialized sound in the cockpit. Definitely improves your SA when you have a busy lookout duty.
I felt very little SA difference from spatialized to non-spatialized. This seems to be more from training (lack of) than cues available. The sound cue was there at beginning of transmission but I found myself not determining position until partially through transmission.
Spatialized sound helped with faster acquisition of targets.
Spatialized sound helped. Quicker to spot aircraft. Sound gave general direction to look before radio call told you their position.
I tended not to memorize call signs of the aircraft but rely on position calls and the spatialized direction of arrival to find the aircraft as they called for clearances.
Distance dependent radio calls could be confused with a bad transmitter otherwise the idea is great. Great idea, I felt much more aware of the aircraft.
I could hear and understand the radio calls better during non-spatialized portion. I could definitely turn my head quicker and locate the trarget faster during the spatialized portion (however, I had more trouble understanding).

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