INVESTIGATING THE EFFECTS OF 3-D SPATIALIZED AUDITORY CUES ON THE DEVELOPMENT OF SITUATION AWARENESS FOR TEAMS

by

LAURA MARTIN MILHAM
B.A. University of Central Florida, 1996

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Psychology
in the College of Arts and Sciences
at the University of Central Florida
Orlando, Florida

Fall Term
2005

Major Professor: Clint A. Bowers

ABSTRACT

This dissertation investigated the effects of spatialized auditory cues on the development of situation awareness for teams. Based on extant research, it was hypothesized that 3-D spatialized auditory cues can be utilized by teams to develop knowledge about team member location in addition to supporting the usage of team behaviors for developing and maintaining situation awareness. Accordingly, the study examined how situation awareness would be differentially influenced by varying the type of auditory cues incorporated into virtual environment (VE) team training scenarios within the context of a MOUT team task.

In general, the results of this study provided partial support for the beneficial effects of 3-D audio cues in facilitating the development of situation awareness and reducing workload. Implications are discussed in the context of design guidance for VE training systems.

This dissertation is dedicated to my mother, without whose sacrifice and support I would not have succeeded.

ACKNOWLEDGEMENTS

The views herein are those of the author and do not necessarily reflect those of the organizations with which the author is affiliated. I would like to thank my advisor, Dr. Clint Bowers, and the other members of my dissertation committee, Drs. Stephen Fiore, Mustapha Mouloua, and Haydee Cuevas for their insightful comments and suggestions. Finally, I want to thank my husband, David, and my son, Dylan, for their patience and love.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

2-D: Two dimensional

3-D: Three dimensional

ANOVA: analysis of variance

APA: American Psychological Association

CS: Cue Sharing

HMD: head mounted display

HRTF: head related transfer function

IM: Information Management

IRB: Institutional Review Board

MOUT: Military Operations over Urban Terrain

NASA-TLX: NASA Task Load Index

PS: Problem Solving

RT: reaction time

SA: situation awareness

SAGAT: Situation Awareness Global Assessment Technique

SALIANT: Situation Awareness Linked Indicators Adapted to Novel Tasks

SO: Spatial Orientation

SSQ: Simulator Sickness Questionnaire

TM: Task Management

VE: Virtual environments

INTRODUCTION

Team training in the military is a challenging task, especially for teams that perform in complex environments which require high levels of physical interaction with other team members (e.g., via physical movements and/or body language.) For example, in Military Operations over Urban Terrain (MOUT) environments, teams are required to physically coordinate (e.g., maintain formation) while searching and eliminating enemy threats in an urban environment (e.g., snipers in buildings). These teams rely on the development of team knowledge regarding where other team members are during the mission, and team skills in building situation awareness and providing information to other team members. Although the development of team competencies related to mission success in these environments require active practice opportunities, live training for these teams is often expensive and impractical (Badique, Cavazza, Klinker, Mair, Sweeney, Thalmann, & Thalmann, 2002). Virtual environments (VEs) provide a practical solution to this problem, allowing flexibility in creating realistic operationally-relevant training scenarios. Further, VEs can provide a unique training opportunity in which environments can provide egocentric (i.e., self-referent point-of-view), spatially accurate information.

Despite the potential of this training medium, however, there is a surprising lack of guidance for VE training designers. The development of VEs is typically characterized by technology-driven approaches rather than founded on a thorough theoretically-based, empirical investigation of how to best design a training environment to achieve desirable team performance outcomes, such as effective coordination, communication, and situation awareness among team members (Kraiger, Ford, & Salas, 1993). Specifically, advances in VE technology allow for presentation of visual, auditory, and haptic cues within training scenarios. Yet, lacking is research to guide the selection of which specific environmental cues may support the development of critical team competencies, as well as *how* and *when* should multisensory cues be incorporated into the training.

For example, extant research focuses on how 3-D spatialized auditory cues can affect target detection, distance judgments, and reaction time, improve object interaction performance, and reduce workload, among other effects in simple environments (Nelson, Bolia, & Tripp, 2001; Begault, 1995). Further, preliminary work on display design with 3-D auditory cues has been found to improve awareness of cue patterns when those cues serve as alarms, thus, assisting operators in developing situation awareness (Endsley & Rosiles, 1995; Kazem, Noyes, Lieven, & 2003). Although auditory cues have been hypothesized to also impact situation awareness for teams (see Kaber, Draper, & Usher, 1999), currently there is no research to support this notion. Given the importance of this competency in complex team environments (Cooke, Kiekel, & Helm, 2001), research on spatialized auditory cues needs to be extended to investigate how presentation of these cues within VE training scenarios influences situation awareness in teams.

To address this issue, this dissertation investigated the effects of spatialized auditory cues on the development of situation awareness (SA) for teams. It was hypothesized that 3-D spatialized auditory cues would be utilized by teams to develop knowledge about team member location in addition to supporting the usage of team behaviors for developing and maintaining situation awareness. Accordingly, the study examined the effects of incorporating different types of auditory cues into VE team training scenarios within the context of a MOUT team task. The organization of this dissertation is as follows. First, VE training systems will be examined, as compared to traditional training approaches, emphasizing how VE design characteristics may facilitate multisensory integration. Second, team knowledge and its relevance to team performance will be discussed within the context of developing situation awareness. The third section will then more specifically describe how auditory cues that provide operators with an egocentric perspective in VEs can facilitate the development of the team knowledge that serves as the foundation for situation awareness. Finally, the design methodology, and results of the research study will be presented.

VIRTUAL ENVIRONMENT APPROACH TO TEAM TRAINING

Although textbooks and lecture are traditionally utilized as a method for imparting basic knowledge and skills, such instructional mediums do not provide opportunity for *practice*, which is key to the development of complex team competencies (Badique et al., 2002). At the other end of the spectrum, 'on-the-job' training does provide practice opportunities, but breakdowns in performance can have severe consequences. While 'live' training exercises do provide practice capability in a safe environment, these exercises are impractical due to their cost and are constrained by the characteristics of the environment (e.g., buildings and other architecture are non-configurable). VEs encompass the advantages of live training, while providing the trainer with the flexibility of being able to reconfigure the training environment.

Furthermore, VEs provide a unique training opportunity by rendering realistic multisensory environments for trainees to experience. However, to ensure that training is effective, the environment must include those multisensory cues that are critical to performance in the real world. VE training systems rely on processes known as *multisensory integration*, in which individuals sample and combine visual, auditory, and haptic information to build knowledge, assess, and act on the world (Stanney, Samman, Reeves, Hale, Buff, Bowers, Goldiez, Nicholson, & Lackey, 2003). Currently, VEs are comprised of visual, auditory, and haptic cues, although the majority of VEs rely primarily on visual cues. Visual cues provide essential information; however, using them in isolation limits access to the rich environmental stimuli present in the real world. Information is gathered by humans with all of their senses, to help them understand and interpret what is going on in the world. Due to advancing technology, it is possible to incorporate these cues into training environments. However, guidelines do not yet exist to suggest *how* and *when* such multisensory cues should be added.

What Makes a Good VE?

The ultimate goal of any training system is to help facilitate performance, either through development of a competency or competency maintenance. VEs provide an opportunity for training designers to build multisensory environments that allow practice of competencies in an environment authentically similar to the real world, which in turn, may facilitate transfer performance in the operational environment. In and of itself, the VE only provides a practice opportunity, and is only as useful as the training research that is driving its design. Unfortunately, many VEs are technology driven, rather than grounded in design principles that establish the level of fidelity and realism needed to promote successful training outcomes.

There are several types of fidelity that can describe how realism is utilized in VE training systems. *Functional fidelity* is the degree to which a simulation includes representations of relevant information and stimulus-response options present in the real world (Swezey & Llaneras, 1997). With this type of fidelity, the relationships between operator inputs and outputs are interactive, but are not necessarily spatially or physically accurate (e.g., a simulator may utilize a button to represent a switch or knob present in the operational environment). *Physical fidelity* is the degree to which a simulation imitates the multisensory (i.e., visual, auditory, haptic) characteristics present in the real world. Training environment characteristics related to physical fidelity include the use of informational cues that are spatially and temporally accurate, and provide egocentric perspective. Finally, *psychological fidelity* is the degree to which the cues that are present in a simulator model produce psychological, cognitive, and affective responses similar to that of the real world. By utilizing cues to create an affective environment, psychological fidelity can produce the level of realism needed to achieve task-appropriate emotional responses (e.g., operator response to high workload situations).

As evident in the preceding discussion, the appropriate design of the training environment is critical for enhancing fidelity, yet little guidance exists with which to determine how to build an effective VE training system. In general, the overall fidelity of the VE can be enhanced by creating an *interactive*, *affective*, *egocentric* environment, utilizing cues that support the development of multisensory integration, or the usage of more than one of the senses, to create a rich sensory environment (Stanney et al., 2003). Each of these VE characteristics will be discussed in further detail next.

Level of Interactivity

The interactivity of the VE allows trainees to act upon and be acted upon in the environment. Passive interaction (i.e., watching a video, modeling) does not allow trainees to practice key competencies, rather, they allow trainees to view how actions are performed by others (or self, in the case of after-action reviews). It does not provide the opportunity for trainees to develop an understanding of consequential action. Conversely, an *interactive* environment provides the capability of user interaction in real time.

Through the development of relationships between trainee inputs and behavioral responses and changes in the environment, trainees can create links between behaviors and consequences (e.g., hear or see a cue, then perform an action; Badique et al., 2002). Deliberate practice provides trainees with the repetition and control feedback for relational knowledge between inputs and outputs. Given this type of practice, trainees may also be able to develop knowledge regarding the expertise of team members, as they can see both their own and team members' skills performed interactively. Without interaction, they may not know the capabilities or limitations of the team.

Affective Cues

In complex operational environments, teams perform under a variety of stressors, including time pressure, workload, noise, and competing tasks (e.g., monitoring communications while searching a room for enemy targets). In comparison, traditional training programs often present the trainee with a relatively less stressful environment. Yet, without the presence of these affective cues, trainees may not have an opportunity to prepare for and practice their responses to stressful situations, potentially leading to stress-induced performance decrements (e.g., attentional narrowing) in the operational environment. Driskell and Johnston (1998) argue that it is important to introduce stress to trainees to inoculate them from these potentially negative effects. Given the consequences of impaired performance for operational teams, strategies for decreasing such effects can greatly improve operational performance. An affective environment can provide trainees with realistic cues that can facilitate the development of the desired emotional response to a situation.

Egocentric Perspective

VEs can provide an *egocentric* viewpoint, or the ability to experience cues (view, hear, or touch) from a self-reference. The alternative is a bird's eye (*exocentric* or top-down) view, which provides information that would not be experienced in the real world. In first person (egocentric) perspective, trainees view the environment in relation to themselves, and are able to better judge and develop knowledge for placement of objects, landmarks, and routes in the environment. In teams, knowledge can be developed regarding distance information between team members when trying to coordinate action. This information is valuable for trainees who need to develop this knowledge to maintain situation awareness (as will be discussed in the next section). For example, if a team member is to maintain specific distances between himself and other team members to remain in formation, distance information is vital. Without it, he may be able to practice his individual movements, but may not be able to practice how he is performing in relation to others.

Multisensory cues help facilitate an egocentric viewpoint, if rendered in relation to the individual. Visual cues provide an egocentric viewpoint if the scene presents visual information from the standpoint of the trainee (e.g., through a head mounted display or HMD). 3-D spatialized auditory cues, however, can provide information about where other team members are in relation to oneself even when they are out of visual range.

As with any training program, the overall goal of utilizing VE training systems is to successfully achieve training outcomes related to the development of team competencies. This next section will describe how critical environmental cues may provide trainees with the *team knowledge* necessary for the development of situation awareness and effective team performance.

TEAM KNOWLEDGE AND THE DEVELOPMENT OF SITUATION AWARENESS

Several team competencies are necessary for effective team performance, including a variety of team knowledge (e.g., egocentric localization), skills (e.g., communication), and attitudes (e.g., collective efficacy) (Cannon-Bowers, Tannenbaum, Salas, & Volpe, 1995). Of particular relevance to this dissertation is the impact of team knowledge on the development of situation awareness and successful execution of teamwork behaviors. Team knowledge facilitates common understandings and coordination among team members (e.g., knowing others' location). Team members must develop some level of team knowledge to coordinate actions, including knowledge of roles held by other members, resources available across the team, and information needed by different members (Cannon-Bowers et al., 1995). Team knowledge may also lead to improved information processing by the team, as well as enhanced process and outcome performance (Liang, Moreland, & Argote, 1995; Moreland & Myaskovsky, 2000; Ren, Carley, & Argote, 2001; Wegner, 1987). Further, Wegner and colleagues (1986; 1991) have found that team knowledge can improve performance time, reduce the number of errors, and increase the overall quality of a team's performance.

In part, this knowledge is used as a foundation to build an understanding of how individuals need to work together in order to complete a task. There are several types of team knowledge that can impact team performance, such as how to coordinate in space and time (Cooke et al., 2001). Knowledge of how the team coordinates spatially and temporally involves an understanding of how team members need to physically synthesize actions within the demands of the task, such the flow of action or what is supposed to occur at different points during the mission. In many environments where timing of actions is critical (e.g., tactical environments), temporal coordination is essential for successful mission performance. Spatial coordination knowledge, in part, includes where to direct attention and where to direct action (e.g., using hand signals to communicate). This describes how team members physically coordinate in the real world (e.g., how a team should move in formation). Given an egocentric perspective, providing spatially accurate cues can facilitate the development of how to coordinate with other team members and objects in the environment.

Situation Awareness in Teams

Team knowledge may also affect team performance via its influence on a team's understanding of a dynamic situation at any one point in time (i.e., situation awareness), as team members must be able to know where others are, know when to act, and be able to know how to assess cue patterns in an environment (Cooke et al., 2001; Cooke, Stout, & Salas, 1997; Martin-Milham & Fiore, 2004; Salas, Cannon-Bowers, Fiore, & Stout, 2001; Stout et al., 1996). Situation awareness can be described as a cognitively demanding process involving cue recognition, assessment, and pattern matching (Endsley, 1995b). Specifically, the cognitive component of SA includes the "perception of elements in the environment, the comprehension of their meaning, and projection of their status in the near future" (Endsley, 1988, p. 7). Thus, team knowledge related to situation awareness (Cooke et al., 2001; Endsley, 1988) includes dynamic and transient knowledge or memory about the current situation (i.e., cue patterns existing in the environment) and the future (i.e., what should be happening next), in addition to long term background knowledge regarding the team and task.

Furthermore, as each individual team member perceives cues in the environment, he can then share that information with other members of the team (Muniz, Stout, Bowers, & Salas, 1998). Thus, collectively, teams often serve as sources of each other's SA by providing information about spatial orientation (where they are), cue sharing (actions taken), problem solving (resolving discrepancies), information management (parsing information flow during task execution), and task management (taking action at the appropriate times) (Muniz et al., 1998).

Measuring Team Knowledge and Behaviors Related to Situation Awareness

Assessing the team knowledge that supports the development of SA is important, as it captures the cognitive components of SA by measuring direct knowledge of the situation (Endsley, 1988). Cooke et al. (2001) examined the validity of measures of team knowledge to evaluate them in terms of their ability to predict team performance and how they reflect skill acquisition. In particular, Cooke and her colleagues examined those measures that evaluated team knowledge associated with situation awareness in the context of a three-person task with both overlapping and distinct task roles. These authors discuss how team knowledge is initially static until it is applied (through the utilization of team process behaviors) during the team's task. The applied knowledge then results in performance outcomes such as time-on-task, accuracy, and efficiency of performance. Specifically, they found that *queries* targeting team situation models (i.e. the dynamic understanding of the current situation) were significantly correlated with team performance.

The Situation Awareness Global Assessment Technique (SAGAT; Endsley, 1995a) is one example of this query method approach that assesses short-term situation team knowledge. SAGAT is a methodology that utilizes simulated scenarios to evaluate the effect of system events on an individual's SA and primarily involves asking the individual questions targeted at assessing his awareness of the cue patterns present in the simulated environment. Specifically, the individual conducts a simulated mission during which the scenario is paused at certain predetermined points. At that time, all of the visual stimuli are removed and the individual is asked to recall key cue patterns. Afterwards, the individual's answers are compared to the actual status of the system/environment to assess the accuracy of his recall.

SAGAT has proven to be a reliable measure of individual-level SA in complex operational environments (Endsley, 1995a; 2000). Further, this technique has been validated in several studies (Endsley, 2000). The strengths of SAGAT are that this technique: provides a "snapshot" of the operator's assessment of the situation, rather than waiting until after the mission is completed; provides an assessment of an operator's global measure of SA based on recall; measures direct knowledge of the situation; and, can be objectively collected and evaluated. Disadvantages are that the simulation must be stopped several times to collect the data, which may disrupt task performance.

Another approach to measuring SA focuses instead on assessing the observable *behaviors* related to SA at the team level. One notable example of this approach is the Situation Awareness Linked Indicators Adapted to Novel Tasks (SALIANT), an *event-based* methodology developed by Muniz and colleagues (1998) as an attempt to capture SA in a team setting. SALIANT describes an event-based assessment process that links observed behaviors to theoretical indicators of SA, resulting in a listing of team process behaviors that support SA (e.g., how information exchange is used as an input for building crewmember SA) (Milham, Barnett, & Oser, 2000). Demonstration of these targeted behaviors suggests that teams are actively building and maintaining their own and team members' SA (Muniz et al., 1998).

Thus far, SALIANT has been successfully validated in both low fidelity simulations (Muniz et al., 1998) in addition to operational task settings (Milham et al., 2000). For example, Milham et al. (2000) evaluated the utility of SALIANT within a dynamic, real world setting (i.e., student navigator training). Specifically, SALIANT was adapted for use in an operational aviation setting by identifying naturally occurring events that *elicit* SA in the environment, rather than introducing trigger events into a simulated training scenario. An event-based behavioral checklist was created, linking observable behaviors to the indicators targeted in SALIANT. Results indicated that the event-based behavioral checklist reliably captured measurement of situation awareness behaviors for teams (Milham et al., 2000), thus providing evidence for the external validity of this modified version of SALIANT.

Taken together, these two distinct yet related methodologies can provide a multi-faceted approach to assessing a team's SA (see Table 1). Queries presented using the SAGAT methodology can be used to assess individual team member's current knowledge of the situation during task performance. The event-based SALIANT methodology can be used to objectively collect data during scenarios to assess team behaviors related to SA. Within the context of this dissertation, these measures can be utilized to assess the utility of auditory cues on the development of SA in complex team environments. The next section discusses more specifically how auditory cues can facilitate the development of team knowledge that serves as the foundation for SA and summarizes relevant research findings supporting the importance of auditory cues for performance in a variety of tasks.

Table 1.

Summary of Selected Situation Awareness Measures

Measure	**Utility**
Query-based measures (SAGAT)	Self-report assessment of an individual's knowledge or awareness of the current situation
Event-based measures (SALIANT)	Objective assessment of team behaviors related to situation awareness

AUDITORY CUES IN VE SYSTEMS AND SITUATION AWARENESS

In complex task environments, it can be challenging for operators to determine where to focus attention, as incoming information may exceed information processing capability (Endsley, 1997). These constraints force operators to expend greater mental effort as they attempt to build their situation awareness of the system's state, resulting in slower reaction times to emerging events (Milham, Cuevas, Stanney, Clark, & Compton, 2004). Further, research suggests that individuals sample a host of sensory cues to detect and assess cue patterns (Endsley, 1995b). The detection of patterns of cues is based on the human's ability to perceive and remember common patterns of visual, auditory, and tactile stimuli that together represent an emerging situation. These patterns may be obvious (an auditory alarm) or subtle (hearing a sound behind you, seeing a shadow, and remembering where your team member is supposed to be in a planned formation). Visual cues alone may provide some measure of representing how an event would play out in the real world. However, auditory cues often represent pieces of the situation that allow an individual to more quickly interpret what is happening. As such, auditory cues are often vital to the interpretation of an event.

Some research supports this notion, as the *redundant signal effect* suggests that a weaker stimulus becomes strengthened when it is paired with another stimulus (Meredith & Stein, 1986). This effect indicates that it is possible that a visual cue that is difficult to detect would become more 'magnified' when paired with an auditory stimulus. Further, as auditory signals draw the operator's attention (Strybel, Boucher, Fujawa, & Volpe, 1995), it can be expected that targets will be detected faster. As situation awareness is dependent on the quick assessment of a situation, such improved cue detection can result in better SA and lead to mission success (as measured by performance time and target detection accuracy) (Endsley, 1995b). In particular, auditory cues are critical for many military tasks, providing soldiers with the ability to locate objects in their environment in relation to themselves (egocentric localization) (Cohn, Schaffer, Milham, & Stanney, 2004). Further, audition is one of the most far-ranging senses, allowing humans to collect sensory information that is outside of the immediate visual range. In close quarters battle, for example, soldiers may have a very limited viewpoint, and may need to rely more heavily on audition. Further investigation of the major role that auditory cues play in cue pattern detection within military training and operational environments is clearly warranted (Graeber, Stanney, & Milham, 2002). This issue will be discussed in greater detail next.

Information Processing and Multisensory Cues

In VE training systems, visual cues provide the majority of environmental stimuli, thereby minimizing multisensory integration and the powerful impact of the rich array of visual, auditory, and haptic cues present in the real world environment. Yet, there are theoretical and practical advantages to providing multisensory information during training, as such cues may lead to more efficient information processing. Information processing describes the way that individuals perceive and interpret sensory information. Information is perceived through sensory processors, encoded, processed in working memory with the input of long term memory, after which a decision is made and action is taken (Baddeley 1990; 2000; Wickens, 1992). Recent studies indicate that information presented via different sensory modalities (e.g., audio and visual channels) does not compete for resources, as the incoming information is coded and stored in separate areas of the brain (Miyake & Shah, 1999; Schneider, 1999). Further, empirical work has found that tasks that are spread across different senses (minimizing the competition between senses) are managed better (i.e., faster performance, less errors) than tasks that are designed with a single modality (Stanney et al., 2003). This is also important for tasks or jobs that tend to overload a single channel, such as when providing numerous competing visual stimuli. In these environments, presenting some of the data in auditory format may decrease the workload experienced by individuals (Stanney et al., 2003).

Also, as discussed previously, pairing weaker sensory stimuli with another stimulus can actually enhance the weaker stimuli when presented via multiple modality channels (Meredith & Stein, 1986). As such, during times when visual cues are obscured (e.g., fog, darkness), the visual cues that are visible may be more perceptible when paired with auditory stimuli. Further, auditory cues have an added advantage in that sound has a natural tendency to draw attention (Strybel et al., 1995). In either case, auditory cues can lead to further processing using focused attention to facilitate perception (Endsley, 1995b). In sum, in both busy and impoverished visual environments, auditory information can provide the necessary cueing to increase target detection, and in turn, improve task performance. Yet a critical issue remaining is determining which type of auditory cues (e.g., 3-D spatialized versus 2-D non-spatialized) results in the most benefit, a topic turned to next.

Three-Dimensional Spatialized versus 2-Dimensional Non-Spatialized Auditory Cues

The human's ability to perceive sounds spatially in the environment and selectively attend to spatially separated acoustic signals results from the structure of the auditory system (Abouchacra, Breitenbach, Mermagen, & Letowski, 2001). As the ears are separated in distance, listeners can use interaural differences and sound wave intensity to determine from where the sound source is originating. The ear that detects the sound first and with higher intensity determines that the sound is coming from that side of the individual. Further, individuals make head movements, allowing outer ear differences to help determine if the sound is coming from the front or back and if it is higher or lower than the individual's head (Abouchacra et al., 2001).

When sounds are reproduced or routed through earphones, this information is no longer present, rather the same sound signal is presented to both ears, and the sound is perceived as coming from a location inside of the head (Abouchacra, Breitenbach, Mermagen, & Letowski, 2001). This eliminates the utility of using sound to determine object location. The sound of gunfire, enemies, and team members, however, can still provide some value to the training environment, as two-dimensional sound may still create an affective environment, even though the sounds do not provide information in relation to the individual. From the information processing standpoint, 2-D auditory cues may *attract* attention, but not *direct* it, as would a 3-D spatialized auditory cue. The direction of attention is important for some types of military teams (e.g., MOUT) that rely heavily on localization of sounds. For these teams, it is important to investigate the relative importance of auditory cues for team competencies related to the development and maintenance of SA. With this information, training designers will have information about the costs and benefits of utilizing various forms of auditory cues.

Spatialized Auditory Cues in Virtual Environments

In a virtual environment, auditory cues are spatialized by replicating two cues known to be important for sound source localization: interaural difference cues and cues related to the action of the pinna (i.e., the external ear) on incoming sources (Wenzel, Wightman, & Foster, 1988; Wightman & Kistler, 1989). The pinna cues are developed by utilizing a *head related transfer function* (HRTF) representing the transformation of the sound source by the head, torso, and pinna. The pinna cues are replications of the magnitude and phase characteristics of the HRTF and produce the perception of externalized sound images at a particular elevation and azimuth when presented via earphones.

Unlike visual information presentation, use of auditory cues in user interfaces requires that the auditory information is *individualized* to the user, due to the interaction of the acoustic wave with the body of the listener (Fouad, 2004). These interactions are characterized with the HRTF, which describes the characteristic changes in the spectrum of the signal as it gets scattered by the listener's anatomy (Wenzel et. al., 1988). Currently, most VEs that include auditory cues utilize *generalized* HRTFs, developed using generic head models. As noted above, however, this approach is not ideal as it does not account for individual differences in the listener's physiology. The effects of generalized HRTFs rather than individualized HRTFs have been found to lead to front-back reversals (e.g., a sound is perceived to be coming from the front of the listener, when in fact, the sound occurred at the back of the listener; Wightman & Kistler, 1989). Further, localization performance is impacted, as there is a discrepancy between actual and perceived sound source locations (Wenzel et. al., 1988).

Despite this advantage, individualized HRTFs are a challenge to utilize as they require time, effort, and specialized equipment to build the individualized models. To address this, *best-fit* HRTF selection approaches attempt to match the user's HRTF to a database of HRTFs to find one that is a close match (Fouad, 2004). Such best-fit HRTFs are hypothesized to provide improved visual search and localization performance (Bolia, D'Angelo, & McKinley, 1999; Wightman & Kistler, 1989b; Wenzel, et al., 1991, 1993). This and other potential benefits of auditory cues on performance will be further discussed next.

Benefits of Auditory Cues on Task Performance

The benefits of spatialized signal presentation have been demonstrated in a number of simple environments (Abouchacra, Tran, Besing, & Koehnke, 1997; Bronkhorst & Plomp, 1992; Ericson & McKinley, 1997; Hawley, Litovsky, & Colburn, 1999; Peissig & Kollmeier, 1997; Webster & Solomon, 1955). Current research into auditory cues suggests there are considerable benefits with regards to localization, visual search performance, and communications. These and other related findings will be discussed in more detail next.

Localization

Research supports the notion that auditory cues can facilitate the localization of objects in a virtual environment (Nelson, Bolia, & Tripp, 2001). Localization through auditory cues is a critical aspect of team performance, especially for teams who need to keep track of the location of team members. Team members who are maintaining formation, monitoring mission status, status of team members' progress, or who need to communicate with others nonverbally (e.g., hand signals) need to develop and maintain knowledge of where other team members are at all times. As basic research provides strong evidence that 3-D spatialized auditory cues facilitate object localization (Nelson et al., 2001), this finding should extend to moving objects and/or individuals.

Navigation

Auditory cues have also been used as navigational cues in virtual environments (Mulgund, Stokes, Turieo, & Devine, 2002). In a study of visually-impaired individuals, Loomis and colleagues (1994) found that spatialized auditory waypoints facilitated navigation through a VE. Further, the ZForm Company developed a VE game consisting of auditory-only environments, in which spatialized auditory cues replaced the sounds of objects (e.g., doors) for a task that requires players to navigate through buildings and environment, choose pathways, open doors, locate and pick up equipment from the floor, while fighting enemy forces. When this game was used in a visual format versus auditory format, it was found that visually-impaired users with the auditory version of the game performed better than sighted users with the visual version of the game (Cook, 2002).

Detection/Alerting

There has been some research into the impact that 3-D spatialized auditory displays have on avoidance of collisions (Begault, 1993; Begault, Wenzel, Shrum, Miller, 1996; Foyle, Andre, McCann, Wenzel, Begault, Battiste, 1996; Kazem, Noyes, & Lieven, 2003). These efforts utilize auditory cues to alert an operator about various events that require attention, resulting in higher detection of events, a precursor to SA.

Visual Search Performance

Bolia, D'Angelo, and McKinley (1999) investigated the impact of pairing auditory cues with visual cues while performing a visual search task. These authors compared virtual spatialized audio, free field audio, and no audio conditions under different levels of competing visual distracters. The redundant-signal effect proposes that reaction time (RT) to stimuli containing redundant bimodal information is shorter than to unimodal stimuli (Meredith & Stein, 1986). This effect was supported by the results, which indicated that both spatialized audio and free field audio led to reductions in RT for detecting visual targets, while maintaining accuracy. The free field audio group performed faster than those in the spatialized audio group, and their search times did not increase as the number of distracters increased, as did the spatialized audio group. The authors hypothesize that the differences in search times were possibly due to imperfect virtualization of the auditory cues, suggesting that best-fit HRTFs would lead to better search performance than generalized spatialized audio.

Workload

Pairing audio stimuli with visual targets can also reduce workload (Flanagan, McAnally, Martin, Meehan, & Oldfield, 1998; Nelson et al., 1998; Perrott, Cisneros, McKinley, & D'Angelo, 1996). The visual channel is often overloaded with stimuli, with so many competing stimuli that it is difficult to find and engage a target (Nelson, Bolia, & Tripp, 2001). In the training environment, the natural cueing effect of spatialized auditory cues can reduce workload and allow trainees to focus attention of other aspects of the task (e.g., looking for additional threats).

Object Interaction

Another benefit of adding auditory cues in virtual environments includes allowing a more natural object interaction pattern. In the real world, interacting with objects often has an accompanying sound (e.g., hearing a key depress when it is pressed). This auditory feedback provides valuable information as to whether or not the intended action occurred. Research indicates that auditory cues can speed manipulation tasks when paired with visual and kinesthetic feedback (Apostolos et al., 1992). Further, Begault (1995) found that pilots needed an auditory cue to tell them if they had engaged a control. In these cases, a control may be repeatedly selected if the operator is uncertain as to whether the system had accepted the response.

Communications

The ability to hear team communications is critical to mission success (Garinther, Whitaker, & Peters, 1995). Degraded speech communications have been associated with mission failure, personnel loss, engagement of incorrect targets, and navigation to the incorrect location (Garinther et al., 1995). Listening for specific information in a noisy environment is limited by the information processing resources available to the listener. Spatialized audio has been found to facilitate recognition of target messages when competing auditory stimuli are present. Abouchacra, Breitenbach, Mermagen, and Letowski (2001) found that when diotic presentation is compared with spatialized presentation, improvements in speech recognition performance range from 20-40% in a quiet environment to 10-35% in a noisy environment (with competing auditory stimuli). As clarity of team communications is a behavior noted for its importance to team performance (Smith-Jentsch, Zeisig, Acton, & McPherson, 1998), this finding is critical, as it suggests that two dimensional sound representations may mask important auditory communications in a noisy environment.

Presence

Hendrix and Barfield (1996) and Vastfjall (2003) have shown that the addition of spatialized sound significantly increased the reported sense of presence in a VE, although it did not increase the apparent realism of that environment. As presence is related to the development of an affective environment, this benefit of audio cues could provide individuals with a greater experience of involvement in the VE.

Summary

As indicated in the preceding discussion, 3-D auditory cues help operators determine where they are and where others and objects are in relation to themselves (egocentric localization). Further, auditory cues may facilitate navigation, decrease workload, increase perceived presence and increase transmission of team communications. Currently, much of the work on audition has not been extended to complex operational settings, especially team environments. Given the aforementioned findings regarding 3-D spatialized auditory cues, it can be hypothesized that such cues can be utilized to foster team knowledge and behaviors related to SA. Specifically, improved localization performance can support team knowledge regarding where team members are located, in addition to other knowledge related to SA (e.g., providing information about enemy location to team members) (Cooke et al., 2001). The visual search and navigation benefits of auditory cues can facilitate team behaviors associated with SA (Muniz et al., 1998). This next section further discusses the utility of auditory cues, but more specifically in VE training systems.

Auditory Cues in VE Training Systems

Auditory cues can be utilized to create a VE training system that is interactive, affective, and egocentric, three principle characteristics for enhancing fidelity and multisensory integration in VEs. An *interactive* environment is supported when auditory cues are used to accompany actions taken (e.g., typing, turning on lights, etc.). Further, when interacting with objects, auditory feedback provides valuable information as to whether or not the intended action occurred. Auditory cues can, therefore, assist trainees in creating links between their behavioral responses (e.g., 'shoot' at a target) and the environmental consequences of those behaviors (e.g., hear the sound of the weapon firing and then 'hitting' the target) (Badique et al., 2002).

An *affective* environment is created when auditory cues are used to render sounds of gunfire, enemy and team member communications, among others, which can all feed into the degree of stress experienced by a trainee in a VE (Cannon-Bowers & Salas, 1998). By introducing operationally-relevant stressors into the training environment, such exposure may decrease automatic physiological (e.g., increased heart rate) and psychological (e.g., narrowed attention) responses and allow trainees to develop more adaptive ways of dealing with stress (Driskell & Johnston, 1998). As these cues are present in the real world, auditory cues combine to support a realistically stressful environment, providing practice opportunities that may minimize performance decrements due to stress in the operational environment (Vastfjall, 2003).

Auditory cues can also promote an *egocentric* environment, that is, provide information regarding where objects and individuals are in relation to the trainee. This egocentric spatial information is critical to SA, as it allows individuals to develop an understanding of distance to objects, placement of objects, and, consequently, how to interact with objects. This information can provide highly accurate directional information, allowing listener's to identify where objects (including people) are located in the environment.

Further, auditory cues can provide valuable data for teams who may not be in sight of each other, but must maintain dynamic knowledge of where team members are and what they are doing. They can use this knowledge to determine where to go, if an area is safe, and to judge how others' tasks are being accomplished. The addition of auditory cues can help support the visuals in a VE to improve location and distance judgments. This is accomplished as auditory events are localized in reference to the position of the listener (Perrott, Saberi, Brown, & Strybel, 1990; Fisher & Freedman, 1968). As SA is developed through a process of directing and focusing attention, identifying situations faster, and perceiving cue patterns, it is hypothesized that 3-D spatialized auditory cues can facilitate SA.

Limitations of Auditory Cues

The preceding discussion suggests that incorporating auditory cues into VE training systems may be advantageous for numerous reasons. However, these beneficial effects have their limitations, specifically with regard to how auditory cues may interact with other sensory cues as well as influence an operator's perceived workload.

Visual Dominance Effect. It is important to note that the use of auditory cues may be limited by the level of visual fidelity present in the environment. Referred to as the visual dominance effect, studies have found that individuals tend to rely primarily on visual cues when present in the environment, overlooking cues presented via other modalities (e.g., audio) (see Cooper, 1998; also Colavita, 1974). For example, Colavita (1974) found that when auditory and visual stimuli were presented together, individuals tended to attend to the visual stimuli and were often unaware of the auditory stimuli. Of particular relevance to this study is that when auditory and visual cues both provide localization information, it is possible that the auditory information may not be utilized (Stein & Meredith, 1993). In fact, in cases where visual information is in opposition or in contrast to auditory information, individuals tend to 'believe' the visual information (McGurk & MacDonald, 1976). Conversely, auditory cues may be more useful for localization when visual cues are less salient. In this case, individuals may rely more on the stronger auditory cues, which may provide a clearer indication of how they impact localization.

Perceived Workload. The relation between auditory cues and perceived workload is still unclear. On the one hand, the addition of multimodal cues into the training environment may provide some opportunities to practice how to deal with overload, leading to potentially less perceived workload with practice, and less physiological reaction in the operational environment than would be expected by not providing this exposure. Further, by building training environments that mimic the natural pairing of sound cues with visual cues (e.g., hearing footsteps of a team member behind you), perceived workload may be lower when trying to locate said team member, than in an environment without natural sound cueing. On the other hand, presentation of auditory cues has been identified as sources of stress in 'busy' auditory environments (Cannon-Bowers & Salas, 1998). Auditory cues that provide target detection information, alarms, or communications may draw attention to an object. However, if there is already a high level of auditory information present in the environment, then the addition of auditory cues can result in sensory overload, increasing perceived workload (Cannon-Bowers & Salas, 1998). Given this equivocal relationship, further research is warranted to better understand how different types of auditory cues may influence perceived workload and under what conditions.

Present Study

The development and maintenance of situation awareness in complex team environments is a critical training goal. To accomplish this, the training environment must provide multisensory cue patterns for trainees to assimilate. Yet, there is little known regarding how the effects of 3-D spatialized auditory cues, in particular, impact dynamic team knowledge and team behaviors related to situation awareness. To investigate this issue, this dissertation investigated the effect that the following three levels of auditory cues had on team performance related to SA: 3-D spatialized built with best-fit HRTFs, 3-D spatialized built with generalized HRTFs, and 2-D non-spatialized. To control for the potential influence of the visual dominance effect, the proposed study varied the level of visual fidelity of the task environment. Specifically, the effects of aurally-rendered cues regarding objects and individuals in a virtual environment was examined under both high (well-lit) and low (dimly-lit) visual fidelity conditions. Further, given the equivocal impact of auditory cues on perceived workload, independent measures of workload were used to investigate the relationship between the different types of auditory cues and perceived workload in a VE complex team task. In addition, given findings regarding the impact of auditory cues on presence, audio presence was evaluated to examine the degree to which the manipulation led to greater experiences of involvement in the environment.

This dissertation extended findings regarding demonstrated beneficial effects of auditory cues in simple environments to the development of situation awareness and task performance of teams operating in complex situations, namely that of the Military Operations over Urban Terrain (MOUT) environment. MOUT teams include two to four individuals who search and eliminate enemy threats in urban terrains (e.g. buildings). To successfully accomplish this task while minimizing the threat to the team, team members must avoid danger areas, coordinate to make sure that all areas of the environment are cleared of threats and quickly detect and engage enemies. The following hypotheses were examined.

Hypotheses

Team Knowledge Related to Situation Awareness

3-D spatialized sound has been implicated in the development of localization of objects in the environment, improving visual search performance (e.g., through the direction of attention) (Nelson, Bolia, & Tripp, 2001). These beneficial effects of auditory cues would be expected to extend to localization of individuals in the environment, facilitating the development of team knowledge related to team member location. Cooke et al. (2001) further suggest that team knowledge is related to situation awareness, as team members must be able to know where others are, know when to act, and be able to know how to assess cue patterns in an environment. 3-D cues that facilitate team member localization were, thereby, hypothesized to increase dynamic team knowledge related to situation awareness. Further, 3-D spatialized audio cues built with best-fit HRTFs have been found to result in better localization performance, with fewer errors in judgment (Wightman & Kistler, 1989).

Hypothesis 1a: Presentation of 3-D spatialized auditory cues, overall, will lead to significantly better dynamic team knowledge related to situation awareness (e.g., distance and location judgments of team members) than presentation of 2-D non-spatialized auditory cues.

Hypothesis 1b: Presentation of 3-D spatialized auditory cues built with *best-fit* HRTFs will lead to significantly better dynamic team knowledge related to situation awareness than presentation of 3-D spatialized auditory cues built with *generalized* HRTFs.

Team Behaviors Related to Situation Awareness

Providing coincident auditory stimuli with visual stimuli leads to quicker cue detection (Bolia, D'Angelo, & McKinley, 1999), which is hypothesized to lead to increased use of SA behaviors in teams related to cue detection and cue sharing among team members. As indicated previously, 3-D spatialized audio cues built with best-fit HRTFs have been found to result in better localization performance, with fewer errors in judgment (Wightman & Kistler, 1989). The improved localization of critical cues is hypothesized to result in better cue detection performance, and use of indicators of situation awareness in teams.

Hypothesis 2a: Presentation of 3-D spatialized auditory cues, overall, will lead to significantly more observable team behaviors related to situation awareness than presentation of 2-D non-spatialized auditory cues.

Hypothesis 2b: Presentation of 3-D spatialized auditory cues built with *best-fit* HRTFs will lead to significantly more observable team behaviors related to situation awareness than presentation of 3-D spatialized auditory cues built with *generalized* HRTFs.

Task Performance

Use of spatialized auditory cues has been related to improved visual search (Bolia, D'Angelo, & McKinley, 1999) and localization (Nelson, Bolia, & Tripp, 2001) performance. In a MOUT environment, task performance is related to the speed and accuracy of combatant detection and engagement. Given this, the use of spatialized auditory cues is hypothesized to improve MOUT performance. This effect was expected to be greater for 3-D spatialized audio cues built with best-fit HRTFs, as they have been found to result in better localization performance, with fewer errors in judgment (Wightman & Kistler, 1989).

Hypothesis 3a: Presentation of 3-D spatialized auditory cues, overall, will lead to significantly better task performance, as measured by faster task completion and greater target detection accuracy, than presentation of 2-D non-spatialized auditory cues.

Hypothesis 3b: Presentation of 3-D spatialized auditory cues built with *best-fit* HRTFs will lead to significantly better performance, as measured by faster task completion and greater target detection accuracy, than presentation of 3-D spatialized auditory cues built with *generalized* HRTFs.

Visual Dominance Effect

The visual dominance effect (i.e., the tendency to rely on visual cues when they are present) suggests that auditory cues may be most helpful when visual cues are less clear (Cooper, 1998; also Colavita, 1974). Working in dimly-lit conditions is operationally realistic, as soldiers perform night time operations, as well as in fog, smoke or rain. In these situations, auditory cues provide an even more critical role, as individuals cannot rely on their muted vision. Given this, the specific effects of spatialized audio may be greater when the visual channel is obscured.

Hypothesis 4: The beneficial effects of 3-D spatialized auditory cues on situation awareness and task performance will stronger when the visual fidelity of the task environment is low (i.e., dimly-lit VE).

Perceived Workload

Auditory cues have been related to higher perceived workload in busy auditory environments, but to lower perceived workload when auditory cues are used to provide redundant cueing to visual targets (Flanagan, McAnally, Martin, Meehan, & Oldfield, 1998; Nelson et al., 1998; Perrott, Cisneros, McKinley, & D'Angelo, 1996). In the proposed study, auditory cues are coincident with visual targets (i.e., unidentified individuals in the MOUT environment). As 3-D spatialized auditory cues built with best-fit HRTFs provide more accurate mapping between visual and auditory cues, they will result in lower workload than spatialized auditory cues modeled with generalized HRTFs.

Hypothesis 5a: Presentation of 3-D spatialized auditory cues, overall, will lead to significantly less perceived workload than presentation of 2-D non-spatialized auditory cues.

Hypothesis 5b: Presentation of 3-D spatialized auditory cues built with *best-fit* HRTFs will lead to significantly less perceived workload than presentation of 3-D spatialized auditory cues built with *generalized* HRTFs.

METHOD

Participants

Seventy-seven two-member teams of undergraduate students (154 participants in all) were asked to participate in this experiment for course credit. Participants were recruited from the General Psychology department subject pool at the university. Participants were randomly assigned, in pairs, to conditions using a Latin squares technique to ensure that participants had an equal chance of being assigned to any one of the three experimental groups. In addition, because studies have shown differential performance in spatial tasks depending upon participants' gender (e.g., Kramer & Smith, 2001), teams were matched by gender (i.e., male-male, female-female) across experimental conditions to control for potential effects due to gender. Treatment of these participants was in accordance with American Psychological Association (APA) ethical standards (see Appendix A for the IRB Committee approval letter).

Design

A 2 x 3 mixed (between-within) factorial design was utilized in this study (see Table 2). The between-groups factor was the type of auditory cues presented in the VE scenarios, manipulated at three levels: 2-D non-spatialized, 3-D generalized HRTF spatialized, and 3-D best-fit HRTF spatialized. The within-groups factor was the level of visual fidelity (lighting condition) present in the VE scenarios, manipulated at two levels: low (dimly lit) or high (well lit). The presentation order of the within-groups factor (visual fidelity) was counterbalanced to control for potential order effects.

Table 2.

Experimental Design

		Auditory Cue		
		2-D	3-D	3-D
Visual	Low (dimly lit)	Non- Spatialized	Generalized HRTF	Best-fit HRTF
Fidelity	High (well lit)		Spatialized	Spatialized

Dependent measures included both query-based (SAGAT) and event-based (SALIANT) measures of situation awareness, and task performance measures (time on and target detection accuracy). Self-reports of perceived workload during the task were assessed using the NASA Task Load Index (NASA-TLX) and the SA Workload subscale of the Mission Awareness Rating Survey (MARS). Auditory presence was assessed using the corresponding subscale in the Presence questionnaire. The Simulator Sickness Questionnaire (SSQ) was administered to participants before and after the experiment to minimize any potential risks involved in interacting in VEs.

Materials

Description of MOUT Team Task

The overall goal of the MOUT team is to search and eliminate enemy threats in an urban environment (e.g., a building). To accomplish this, a fire team enters a building, moves rapidly along a hallway while covering the entire area with their guns to maintain security. If people are encountered, they must be quickly evaluated and engaged if hostile. The team clears from one end of the hallway to the other; thus, it is essential that all rooms are cleared as they are reached. As the team members cross the threshold of a doorway into a room that has not been cleared, they perform immediate target engagement of any enemies detected. Upon entry, each team member clears a designated area of responsibility, such as the left, right, or overhead areas of the room. Next, team members enter the room to search behind furniture or other obstacles to ensure that enemies are not hiding behind them (Milham, Stanney, Gledhill-Holmes, & Jones, in preparation).

For this dissertation, 2-person teams were presented with two scenarios that utilized identical environments, but varied with respect to the number and placement of enemies, noncombatants, and furniture (see Appendix B for illustrative layout the MOUT facility). In addition, the visual fidelity of the rooms was varied, with one of the scenarios utilizing well-lit rooms (high visual fidelity), and the other scenario utilizing dimly-lit rooms (low visual fidelity), though with enough visibility so that the participant could still identify and discriminate between enemy targets and noncombatants. The virtual environment contained 15 rooms off of a hallway, with varying numbers of enemies and noncombatants in each room (from 1-3). Furniture was in most rooms, as were windows. In several of the rooms, there were holes in the wall, which represented danger areas (i.e., enemies can peer through the holes and shoot at the team). Enemies and noncombatants were stationary, and looked similar except for one important characteristic, namely the presence of a gun.

Teams were asked to move down the hallway and clear each room as they came to it, while minimizing their team's exposure to danger areas (operationalized as windows, open doorways, holes in the wall, and enemies). Task roles were not assigned, however; participants received task information and were asked to select either a front man or back man role. The front man is the first to enter the room, and is exposed to danger areas first. The back man maintains rear security by identifying and engaging threats that are behind the team. Both roles are required to scan an assigned area of each room (i.e., left or right area), and identify and engage enemy targets while minimizing time in front of windows and holes in the walls. To accomplish this, participants have to detect individuals in the room (who are either kneeling or standing, in clear view or hiding behind furniture), discriminate between combatants and noncombatants, engage combatants and clear noncombatants. After clearing each room, they return to the hallway and clear the next room, following the same procedure.

Each participant was seated while wearing a helmet mounted display (HMD) with the cables held over their heads to prevent tangling when turning. The HMD was used to look left and right, up and down, and a joystick was used to move forward and backward throughout the environment. The gun viewpoint followed the participants' eye gaze, and the joystick buttons were used to shoot targets and clear noncombatants. Both team members were seated in the same room, but communicated with headphones and headsets. Voice communications (in the spatialized auditory conditions) appeared to be coincident with avatar location in the VE. Video and audio data were captured for analysis.

Rendering of Auditory Cues

For each of the experimental conditions, an auditory cue was coincident with communications and movements (e.g., footsteps) of team members, enemies, and noncombatants. The 3-D best-fit HRTF auditory cues had a spatial component that was fitted to each individual participant's physiological characteristics. The 3-D generalized

HRTF auditory cues had a non-individualized spatial component. The 2-D auditory cues lacked a spatial component (i.e., cues were non-spatialized).

Situation Awareness

This dissertation utilized a multi-faceted approach to assess the utility of auditory cues on the development of participants' situation awareness. Specifically, both query-based and event-based measures of situation awareness were administered during the experiment to assess both participants' knowledge and behaviors related to situation awareness, as described next.

Knowledge Related to Situation Awareness: SAGAT. Queries based on the SAGAT methodology were used to assess individual participants' current knowledge of the situation during task performance. These queries were administered at predetermined points during each scenario. The scenario was paused and the screen blanked during queries. To minimize the time required to respond as well as avoid any negative effects of pausing the scenario (such as in having to remove the HMD to respond manually), participants were asked to provide verbal (oral) responses to the queries. Specific sets of queries were created to assess distinct forms of situation awareness: Level 1 SA -- perception of elements in the environment; Level 2 SA -- comprehension of the meaning of these environmental cues; and Level 3 SA – prediction of their status in the near future (Endsley, 1995b). Level 1 SA queries assessed localization information for team members, combatants, noncombatants, and objects. Level 2 SA queries assessed participants' understanding of the threat posed to them or their team member by the presence of enemies. Level 3 SA asked participants to predict what would happen in the near future (e.g., who on the team would engage enemies in the next room first).

Appendix C contains the specific types of team knowledge being assessed by the queries. Responses to queries assessing localization information were assessed in terms of the precision of participants' judgments (i.e., numerical difference between reported and actual heading or distance). The remaining queries were scored as either correct or incorrect based on operationally relevant tolerance intervals.

Behaviors Related to Situation Awareness: SALIANT. The event-based SALIANT methodology was used to objectively collect data during scenarios to assess team behaviors related to SA. A performance measurement checklist, based on the SALIANT methodology, was developed to rate participants' use of behaviors in support of SA. The first step in the developing the checklist involved a detailed analysis of the MOUT team task to determine the types of observable behaviors that occur in this environment. Observations of actual MOUT teams were conducted to determine how SA behaviors are used during the room clearing task. From this, behaviors were operationalized in terms of the SA behaviors as defined by the SALIANT methodology. Finally, a checklist was developed comprised of a chronological listing of the SA behaviors and subcomponents of behaviors that were expected to occur throughout the participants' mission in the VE. This process will be described in more detail next.

The SALIANT indicators, as identified by Muniz et al. (1998) (for complete listing of these indicators, see Appendix D), can be further organized into five general categories based on how these behaviors are related: spatial orientation, cue sharing, problem solving, information management, and task management (for details on these categories, see Appendix E). This clustering process allows for a succinct analysis of the types of SA information used by team members (for a detailed description of this categorization process, see Fiore, Fowlkes, Martin-Milham, & Oser, 2000). *Spatial orientation* behaviors describe those related to communications regarding where the team is located. *Cue sharing* behaviors are those that have to do with communicating unfolding events and individual behaviors. *Problem solving* has to do with identifying and troubleshooting problem situations. *Information management* describes updating the team on current and completed task status. *Task management* concerns discussions regarding the team's task.

Guided by this SALIANT categorization scheme, the next step was to identify specific instances of these SA behaviors within the operational task environment. An analysis of the expected team communications and behaviors occurring during task performance was reviewed and each exchange was classified according to the appropriate SA category and indicator. Appendix F illustrates the resulting breakdown of SA behaviors for the MOUT scenarios. From this, a finalized checklist was developed from actual participant data to ensure that all behaviors were captured (see Appendix F). An overall score was calculated for each of the five SALIANT categories, summing the number of targeted SA behaviors exhibited by the teams.

Task Performance

Successful performance in the MOUT team task requires being able to quickly clear the room of enemy targets and maximize the number of targets (enemies) that are engaged while minimizing the number of non-targets (noncombatants) that are engaged (errors). Accordingly, participants' task performance was measured in terms of time-on-task (in milliseconds) in engaging enemies and clearing friendlies and target detection accuracy (number of correct engagements of enemies and clearing of friendlies). Scenarios contained 33 targets.

Workload Assessment: NASA-TLX and MARS SA Workload Subscale

Two measures were used to assess participants' perceived workload during task performance. First, the NASA-TLX (Hart & Staveland, 1988) was administered upon completion of each scenario. The paper-based NASA-TLX consists of a 6-item questionnaire that asks participants to rate their levels of perceived workload on a 20-point scale in terms of mental demand, physical demand, temporal demand, performance, effort, and frustration (see Appendix G). Perceived workload was assessed by examining participants' total score, summed across all of the components.

Upon completion of both VE scenarios, participants were asked to complete the SA Workload subscale of the Mission Awareness Rating Survey (MARS; Matthews, Beal, & Pleban, 2002). The Workload subscale consists of 4 items that asks participants to rate the mental effort exerted in identifying, understanding, and predicting situations that are occurring during a mission, as well as in deciding how to meet mission goals (see Appendix H). Each item is scored with an anchored scale from "easy to understand with little effort" to "very difficult and hard to understand the situation". Perceived SA workload was measured by summing scores for the four items.

Presence Questionnaire – Audio Presence Subscale

Perceived audio presence was evaluated with the 3-item audio presence subscale of the Presence Questionnaire (Witmer & Singer, 1998). These items asked participants to rate the degree to which the audio environment was related to their involvement in the VE on a 7 point scale (see Appendix I).

Simulation Sickness Questionnaire

Participants' potential experience of simulator sickness was assessed with the Simulator Sickness Questionnaire (SSQ) (Kennedy, Lane, Berbaum, & Lilienthal, 1993). The SSQ consists of 16 questions that targets specific symptoms of simulator sickness (see Appendix J). Participants are asked to rate the degree to which they are current experiencing each symptom on a 4-point scale, with responses consisting of *none*, *slight*, *moderate*, or *severe*. The SSQ produces four scores, an overall Total Severity Score, and three subscale scores: Nausea, Disorientation, and Occulomotor. The Total Severity Score was examined to assess participants' reported sickness after each scenario. If overall scores indicate any cause for concern, the subscales scores are examined to further define the problem.

Apparatus

The VE was run on two IBM compatible computers, with the auditory environment running from an additional IBM compatible computer. The auditory cue environment was developed with the ViBeStation system. The Virtual Research V6 and V8 Head Mounted Display (HMD) were selected to be used with this simulator, as they maintain a high standard in performance among professional HMDs. Headphones were used to present the participants with the auditory cues. Participants navigated through the environment with a joystick while sitting down in a swivel chair, allowing the ability to make complete turns.

Procedure

Upon arrival, each participant was asked to read and sign an informed consent form and an agreement not to operate motor vehicles, heavy machinery, or a bicycle for at least one hour following the experiment. Participants were also asked to complete a demographics form that requested information on previous experience with VEs, predisposition to motion sickness, level of gaming experience, level of computer experience, and handedness (see Appendix K). Participants then read the instructions for the experiment and given the opportunity to ask any questions they had about the procedure or the experiment in general. Participants were informed that they were free to terminate their participation at any time, at their discretion, without penalty. Participants were randomly assigned, in teams of two, to one of the three auditory cue conditions.

The VE phase included a training session and performance of two scenarios based on a MOUT team task. All participants used a head mounted display (HMD) to view the VE. First, participants went through a baseline task training session to familiarize themselves with the HMD and to ensure that they understood the mission and how to perform basic tasks within the testbed. Next, participants, in two-member teams, performed the first of the two VE scenarios created for this experiment. The two scenarios differed in the level of visual fidelity present, with one scenario consisting of dimly-lit visuals (low visual fidelity) and the other consisting of well-lit visuals (high visual fidelity). The order of presentation of the two scenarios was counter-balanced. During each scenario, participants' task performance and situation awareness *behaviors* (based on the SALIANT methodology) were recorded. At pre-determined points during the scenario, participants were queried (using the SAGAT methodology) as to their *knowledge* related to situation awareness (i.e., their awareness of the current situation). Upon completion of the first scenario, participants were asked to complete the workload and sickness measures. Healthy participants (as judged by self-report) performed the second scenario following this same procedure, followed by the workload and sickness measures. Altogether, participants interacted with the virtual environment between 20 to 45 minutes.

Upon completion of the VE phase, participants were given the MARS SA workload subscale questionnaire and the Audio Presence subscale questionnaire. Then, participants were debriefed regarding the purpose of the experiment and given a copy of the informed consent form to take with them. Participants were monitored for any lingering side effects from interacting with the VE by performing a past pointing task and were not be permitted to leave unescorted prior to one hour following exposure to the VE unless they demonstrated <u>complete</u> abatement of side effects. The entire duration of the experiment, including paperwork, training, performance, and debriefing, was approximately two hours.

RESULTS

Analyses

Due to unforeseen technical issues with HRTF selection (further explained in the Discussion section), data from participants in the 3-D best-fit spatialized audio condition could not be included in the analyses. Accordingly, results for the effect of auditory cues will focus on the analyses of the 2-D non-spatialized and 3-D generalized HRTF spatialized audio conditions. In addition, 16 teams were dropped from the analyses due to missing data and/or technical or procedural problems (e.g., missing videotape data or system log files): 7 teams from the 2-D audio condition and 9 teams from the 3-D audio condition, leaving 19 and 17 teams for analysis, respectively.

A 2 x 2 repeated measures analysis of variance (ANOVA) was conducted for all dependent measures, with level of visual fidelity (well lit or dimly lit) as the within-groups factor and type of auditory cues (2-D non-spatialized or 3-D generalized HRTF spatialized) as the between-groups factor, except where noted. Separate analyses were conducted for each of the dependent measures, including knowledge and behaviors related to situation awareness, task performance, perceived workload, and auditory presence. Multivariate test statistics are reported using Roy's Largest Root. For all analyses, an alpha level of .05 was used.

The presentation order of the within-groups factor (visual fidelity) was counterbalanced, as there was some concern with regard to potential order effects. To ensure the effectiveness of this procedure, analyses were conducted on all the dependent measures; results showed no significant main or interaction effects for presentation order. Further, participants' responses to the SSQ were examined to determine if there were any differential effects of audio condition on simulator sickness; no such effects were found. Finally, correlations were run between relevant individual difference variables (e.g., gender, spatial ability) and dependent measures to identify potential covariates or second factors. Gender emerged as a potential factor; these analyses will be discussed last.

Situation Awareness

Team Knowledge Related to Situation Awareness – SAGAT

Table 3 lists means and standard deviations of all relevant team level SAGAT measures. For team Level 1 SA, analyses were conducted on SAGAT queries assessing judgments of team member location (heading) and team member distance. Multivariate tests indicated significant main effects for audio condition, F (2, 69) = 4.62, $p < .05$, and visual fidelity condition, F (2, 69) = 4.14, $p < .05$, but no significant interaction effect. Univariate analyses were examined to further evaluate these findings.

For team member heading judgments, a significant main effect was found for audio condition, F (1, 70) = 7.02, $p = .01$, with teams in the 3-D audio condition providing more accurate heading judgments than those in the 2-D audio condition. Although the interaction effect was not significant, given the hypothesized visual dominance effect, an independent samples t test was conducted to determine if there were differences in accuracy of heading judgments depending upon the lighting condition (see Figure 1). Results showed that teams in the 3-D condition reported significantly more accurate judgments than those in the 2-D condition, but only in the dimly lit condition, t (70) = 2.79, $p < .01$ (two-tailed). Further, there was a significant main effect found for visual fidelity, F (1, 70) = 8.01, $p < .01$, with teams performing better in the dimly lit condition than in the well lit condition. Given the hypothesized differential effect of audio condition on team SA, separate independent samples *t* tests for each audio condition were conducted to further evaluate the effect of visual fidelity on judgments of team heading. Results indicated that only teams in the 3-D audio condition performed significantly better in the dimly lit condition than in the well lit condition, $t\ (70) = 2.79$, $p < .01$. No significant differences were found for the 2-D audio condition.

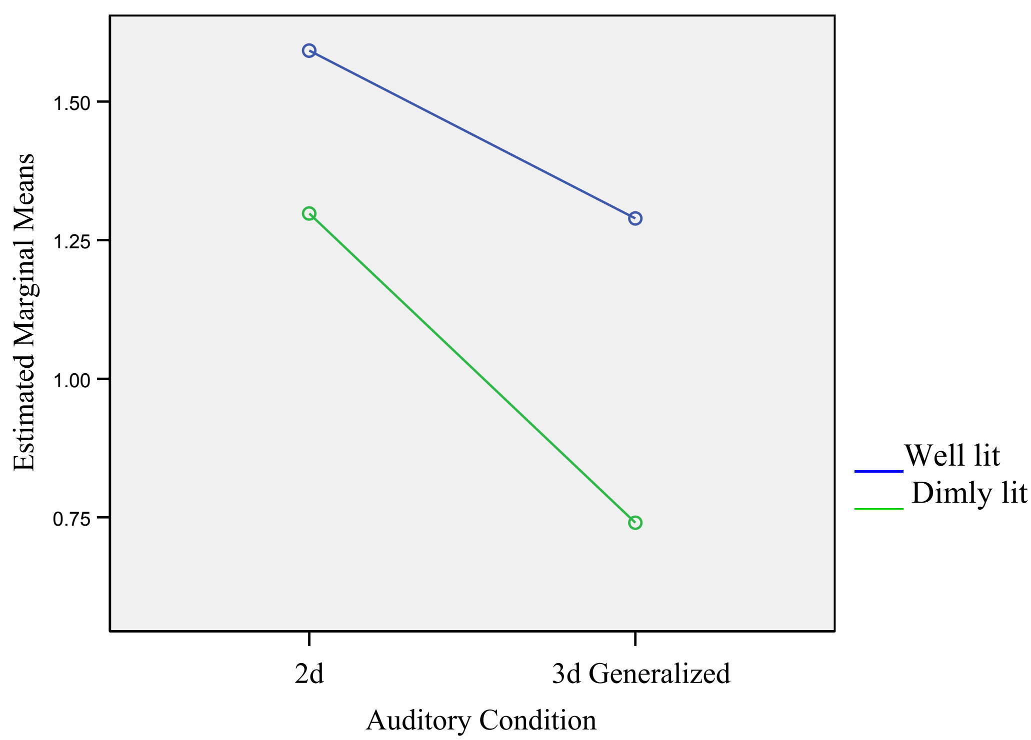


Figure 1. Team member heading judgment interaction.

For team member distance judgments, no significant main or interaction effects were found for the audio or visual fidelity conditions.

For team Level 2 SA, SAGAT queries assessing judgments of whether a team member was in danger were analyzed. No significant main or interaction effects were found. For team Level 3 SA, SAGAT queries assessing predictions of team member engagement of enemies were analyzed. No significant main or interaction effects were found.

Table 3.

Means and Standard Deviations for Relevant SAGAT Team Level Variables

Dependent Variable	**Auditory Cues**	**Visual Fidelity**	**Mean (Std Dev)**
SAGAT – Team Knowledge			
Level 1 – Perception Judgment of team member's heading[a]	2-D Non-Spatialized	Well Lit	1.59(1.13)
		Dimly Lit	1.29(0.87)
	Total		1.45(0.11)
	3-D Generalized	Well Lit	1.30(0.97)
		Dimly Lit	0.74(0.68)
	Total		1.02(0.10)
	Total	Well Lit	1.44(0.12)
		Dimly Lit	1.02(0.10)
Level 1 – Perception Judgment of team member's distance[a]	2-D Non-Spatialized	Well Lit	1.64(1.22)
		Dimly Lit	1.79(1.04)
	Total		1.72(0.13)

	3-D Generalized	Well Lit	2.24(1.08)
		Dimly Lit	1.71(1.05)
	Total		1.98(0.14)
	Total	Well Lit	1.94(0.14)
		Dimly Lit	1.75(0.12)
Level 2 – Comprehension	2-D Non-Spatialized	Well Lit	0.42(0.51)
Judgment of team member in		Dimly Lit	0.42(0.51)
danger	*Total*		0.42(0.09)
	3-D Generalized	Well Lit	0.41(0.51)
		Dimly Lit	0.29(0.47)
	Total		0.35(0.10)
	Total	Well Lit	0.42(0.09)
		Dimly Lit	0.36(0.08)
Level 3 – Prediction	2-D Non-Spatialized	Well Lit	0.89(0.57)
Team member		Dimly Lit	0.89(0.66)
engagement of enemy	*Total*		0.89(0.10)
	3-D Generalized	Well Lit	0.65(0.61)
		Dimly Lit	1.00(0.61)
	Total		0.82(0.11)
	Total	Well Lit	0.77(0.10)
		Dimly Lit	0.95(0.11)

[a]Lower scores indicate better performance.

Individual Knowledge Related to Situation Awareness – SAGAT

Table 4 lists means and standard deviations of all relevant individual level SAGAT measures. For individual Level 1 SA, SAGAT queries assessed the accuracy of distance and location (heading) judgments of combatants, noncombatants, and collective performance on queries related to the number and kind of entities in a room. Multivariate tests revealed a significant main effect for visual fidelity, F (5, 30) = 5.36, p = .001, but neither a significant main effect for audio condition nor a significant interaction effect. Univariate analyses were evaluated to further examine these results.

Univariate analyses showed a significant main effect for visual fidelity on the accuracy of judgments of combatant heading, with teams, overall, performing better in the well lit condition, F (1,34) = 10.44, p < .01. For noncombatants, there was also a significant main effect for visual fidelity, with teams, overall, reporting more accurate distance judgments in the well lit condition, F (1, 34) = 16.96, p < .001. With regard to the number and kind of objects in the room, univariate analysis also revealed a significant main effect for visual fidelity, with teams, overall, performing more accurately in the dimly-lit condition, F (1, 34) = 4.44, p < .05. No other significant effects were found.

Table 4.

Means and Standard Deviations for Relevant SAGAT Individual Level Variables

Dependent Variable	**Auditory Cues**	**Visual Fidelity**	**Mean (Std Dev)**
SAGAT – Individual Knowledge			

Level 1 – Perception Judgment of combatant heading[a]	2-D Non-Spatialized	Well Lit	0.50(0.41)
		Dimly Lit	1.16(0.97)
	Total		0.83(0.11)
	3-D Generalized	Well Lit	0.69(0.50)
		Dimly Lit	1.16(0.77)
	Total		0.92(0.12)
	Total	Well Lit	0.60(0.08)
		Dimly Lit	1.16(0.15)
Level 1 – Perception Judgment of noncombatant heading[a]	2-D Non-Spatialized	Well Lit	1.91(1.36)
		Dimly Lit	1.23(0.81)
	Total		1.57(0.20)
	3-D Generalized	Well Lit	1.73(0.97)
		Dimly Lit	1.74(1.21)
	Total		1.73(0.21)
	Total	Well Lit	1.82(0.20)
		Dimly Lit	1.48(0.17)
Level 1 – Perception Judgment of combatant distance[a]	2-D Non-Spatialized	Well Lit	3.93(1.64)
		Dimly Lit	3.80(2.00)
	Total		3.88(0.38)
	3-D Generalized	Well Lit	4.75(2.00)
		Dimly Lit	5.68(2.82)
	Total		5.22(0.41)

	Total	Well Lit	4.36(0.30)
		Dimly Lit	4.74(0.40)
Level 1 – Perception Judgment of noncombatant distance[a]	2-D Non-Spatialized	Well Lit	3.70(2.84)
		Dimly Lit	7.28(2.50)
	Total		5.49(0.43)
	3-D Generalized	Well Lit	4.22(2.73)
		Dimly Lit	5.94(2.67)
	Total		5.08(0.46)
	Total	Well Lit	3.96(0.47)
		Dimly Lit	6.61(0.43)
Level 1 – Perception Kind and number of entities in room	2-D Non-Spatialized	Well Lit	1.32(0.89)
		Dimly Lit	1.84(0.60)
	Total		1.58(0.13)
	3-D Generalized	Well Lit	1.53(0.62)
		Dimly Lit	1.65(0.79)
	Total		1.59(0.14)
	Total	Well Lit	1.42(0.13)
		Dimly Lit	1.75(0.17)
Level 2 – Comprehension Judgment of self in danger	2-D Non-Spatialized	Well Lit	0.32(0.48)
		Dimly Lit	0.63(0.50)
	Total		0.47(0.10)
	3-D Generalized	Well Lit	0.53(0.51)

		Dimly Lit	0.41(0.51)
	Total		0.47(0.10)
	Total	Well Lit	0.42(0.08)
		Dimly Lit	0.52(0.08)
Level 3 – Prediction	2-D Non-Spatialized	Well Lit	0.89(0.66)
Navigation, time to clear,		Dimly Lit	1.00(0.58)
number of enemies engaged	*Total*		0.95(0.11)
	3-D Generalized	Well Lit	1.24(0.75)
		Dimly Lit	0.76(0.75)
	Total		1.00(0.12)
	Total	Well Lit	1.07(0.12)
		Dimly Lit	0.88(0.11)

[a]Lower scores indicate better performance.

For individual Level 2 SA, SAGAT queries assessed the accuracy of an individual's judgment of whether they were in danger. Univariate analyses found no significant main effects, but did show a significant interaction effect, F (1, 34) = 5.81, p < .05. Separate repeated measures ANOVAs conducted on each audio condition found that teams in the 2-D audio condition had significantly more accurate judgments in the dimly lit condition than in the well lit condition, F (1, 18) = 5.59, $p < .05$. No significant differences were found for teams in the 3-D audio condition.

For individual Level 3 SA, SAGAT queries collectively assessed prediction accuracy for teams regarding navigation, time to clear the next room, and the percentage of enemies that the individual would engage. Univariate analyses revealed no significant main or interaction effects.

Behaviors Related to Situation Awareness – SALIANT

Table 5 lists means and standard deviations of all relevant SALIANT measures. Analyses of SALIANT categories were conducted to evaluate the degree that teams exhibited differences in the number of team behaviors related to Spatial Orientation, Cue Sharing, Problem Solving, Information Management, and Task Management. Contrary to hypotheses, multivariate tests revealed no significant main or interaction effects for any of the SALIANT categories.

Table 5.

Means and Standard Deviations for Relevant SALIANT Variables

Dependent Variable	**Auditory Cues**	**Visual Fidelity**	**Mean (Std Dev)**
SALIANT			
Spatial Orientation	2-D Non-Spatialized	Well Lit	42.16(10.82)
		Dimly Lit	43.95(11.43)
	Total		43.05(2.54)
	3-D Generalized	Well Lit	38.00(11.43)
		Dimly Lit	42.11(12.98)
	Total		40.06(2.69)
	Total	Well Lit	40.08(1.86)

		Dimly Lit	43.03(2.16)
Cue Sharing	2-D Non-Spatialized	Well Lit	8.21(8.53)
		Dimly Lit	8.16(8.74)
	Total		8.18(2.00)
	3-D Generalized	Well Lit	7.41(9.86)
		Dimly Lit	9.41(9.50)
	Total		8.41(2.11)
	Total	Well Lit	7.81(1.53)
		Dimly Lit	8.79(1.52)
Problem Solving	2-D Non-Spatialized	Well Lit	2.89(2.42)
		Dimly Lit	4.16(3.04)
	Total		3.53(0.60)
	3-D Generalized	Well Lit	3.00(2.57)
		Dimly Lit	3.47(3.97)
	Total		3.24(0.64)
	Total	Well Lit	2.95(0.42)
		Dimly Lit	3.81(0.59)
Information Management	2-D Non-Spatialized	Well Lit	15.58(7.99)
		Dimly Lit	13.74(7.70)
	Total		14.66(2.42)
	3-D Generalized	Well Lit	15.65(12.55)
		Dimly Lit	17.47(14.85)

	Total		16.56(2.55)
	Total	Well Lit	15.61(1.73)
		Dimly Lit	15.60(1.94)
Task Management	2-D Non-Spatialized	Well Lit	4.16(4.40)
		Dimly Lit	4.16(4.88)
	Total		4.16(1.07)
	3-D Generalized	Well Lit	3.59(4.95)
		Dimly Lit	3.65(5.74)
	Total		3.62(1.13)
	Total	Well Lit	3.87(0.78)
		Dimly Lit	3.90(0.89)

Task Performance

Task Accuracy

Table 6 lists means and standard deviations of all relevant task performance measures. Task accuracy was measured by examining the number of shots fired at enemy targets by individual team members in a room, friendly (non-enemy) entities cleared, and friendly entities shot (an error measure). Multivariate tests revealed neither a significant main effect for audio condition nor an interaction effect, but did show a marginally significant effect for visual fidelity, F (3, 68) = 2.32, p = .083. Univariate analyses on visual fidelity found a significant main effect on the number of shots fired, with more shots taken in the dimly lit condition, F (1,70) = 4.43, p < .05. Univariate analyses also revealed a significant main effect of visual fidelity on the number of friendly entities shot, with more errors made in the dimly lit condition, F (1,70) = 4.49, $p < .05$. No other significant effects were found.

Time on Task (Reaction Time)

Time on task (reaction time) was assessed by calculating the time that elapsed between when individuals entered a room and fired on an enemy target or cleared a friendly entity. Multivariate tests found neither a significant main effect for audio condition nor a significant interaction effect, but did reveal a significant main effect for visual fidelity, F (2, 65) = 4.33, p <.05). Univariate analyses revealed a significant main effect for visual fidelity on reaction time to clear friendly entities, with teams, overall, taking longer in the dimly lit condition, F (1,66) = 8.40, $p < .01$. No other significant effects were found.

Table 6.

Means and Standard Deviations for Relevant Task Performance Variables

Dependent Variable	**Auditory Cues**	**Visual Fidelity**	**Mean (Std Dev)**
Task Performance			
Accuracy – Shots fired at enemy targets[a]	2-D Non-Spatialized	Well Lit	20.58(11.66)
		Dimly Lit	23.76(13.38)
	Total		22.17(1.86)
	3-D Generalized	Well Lit	20.65(10.25)
		Dimly Lit	23.09(15.29)

	Total		21.87(1.96)
	Total	Well Lit	20.61(1.30)
		Dimly Lit	23.43(1.69)
Accuracy – Friendly entities cleared	2-D Non-Spatialized	Well Lit	6.03(2.88)
		Dimly Lit	5.95(3.60)
	Total		5.99(0.40)
	3-D Generalized	Well Lit	6.44(2.84)
		Dimly Lit	6.65(2.23)
	Total		6.54(0.42)
	Total	Well Lit	6.23(0.34)
		Dimly Lit	6.30(0.36)
Accuracy – Friendly entities shot[a]	2-D Non-Spatialized	Well Lit	0.84(1.57)
		Dimly Lit	1.63(2.83)
	Total		1.24(0.25)
	3-D Generalized	Well Lit	0.56(0.82)
		Dimly Lit	0.74(1.10)
	Total		0.65(0.26)
	Total	Well Lit	0.70(0.15)
		Dimly Lit	1.18(0.26)
Reaction time – Time to engage enemies[a]	2-D Non-Spatialized	Well Lit	7485.09(5421.02)
		Dimly Lit	6542.91(4613.13)
	Total		7047.14(544.27)

	3-D Generalized	Well Lit	5779.73(3327.72)
		Dimly Lit	6886.24(4918.20)
	Total		6252.61(560.52)
	Total	Well Lit	6563.02(552.26)
		Dimly Lit	6736.73(576.23)
Reaction time – Time to clear friendly entities[a]	2-D Non-Spatialized	Well Lit	4394.68(1906.89)
		Dimly Lit	6080.16(4658.95)
	Total		5237.42(391.95)
	3-D Generalized	Well Lit	4146.24(1698.06)
		Dimly Lit	5898.01(4376.22)
	Total		5022.37(403.65)
	Total	Well Lit	4270.45(219.43)
		Dimly Lit	5989.34(534.81)

[a]Lower scores indicate better performance.

Perceived Workload

Table 7 lists means and standard deviations of all relevant perceived workload measures. Perceived workload was assessed using participants' total score on the NASA TLX as well as participants' responses to the MARS SA workload subscale. Univariate analysis found no significant interaction or main effect of audio condition on the NASA TLX, but did reveal a significant main effect for visual fidelity, with teams, overall, reporting significantly lower workload in the well lit condition, $F\ (1, 70) = 5.09$, $p < .05$.

The MARS SA workload subscale was administered only once, at the end of the VE phase of the experiment. Thus, data were analyzed using an independent-samples *t* test, with audio condition as the grouping variable. Results showed that teams in the 3-D audio condition reported significantly lower workload than teams in the 2-D audio condition, $t\ (70) = 2.66$, $p = .01$ (two-tailed).

Table 7.

Means and Standard Deviations for Relevant Perceived Workload Variables

Dependent Variable	**Auditory Cues**	**Visual Fidelity**	**Mean (Std Dev)**
Workload			
NASA TLX	2-D Non-Spatialized	Well Lit	67.50(18.40)
Total Score[a]		Dimly Lit	68.29(15.96)
	Total		67.90(2.61)
	3-D Generalized	Well Lit	63.32(17.66)
		Dimly Lit	70.59(19.05)
	Total		66.96(2.76)
	Total	Well Lit	65.41(2.13)
		Dimly Lit	69.44(2.06)
MARS	2-D Non-Spatialized		8.42(2.27)
SA Workload Subscale[a]	3-D Generalized		7.09(1.94)

[a]Lower scores indicate better performance.

Presence

The degree to which differing audio cues may have impacted participants' experience of auditory presence in the VE scenarios was assessed using the 3-item Audio Presence subscale from the Presence Questionnaire. Data were analyzed using an independent-samples *t* test, with audio condition as the grouping variable. Results showed that teams in the 3-D audio condition (M = 14.65, SD = 2.87) reported a significantly higher experience of auditory presence than teams in the 2-D audio condition (M = 13.20, SD = 3.49), t (64) = 1.82, $p < .05$ (one-tailed).

Gender

To address possible concerns regarding the degree to which audio condition may have had a differential effect on performance outcomes depending upon participants' gender, repeated measures ANOVAs were conducted on the dependent measures, analyzing the data separately for male-male and female-female teams. As with the other analyses, audio condition served as the between-groups factors and visual fidelity served as the within-groups factor.

Multivariate analyses revealed no significant main or interaction effects for either gender on the SALIANT data or task performance. Univariate analysis for the Audio Presence subscale revealed no significant differences between audio conditions for either gender. However, analyses did reveal a differential effect on the SAGAT and perceived workload measures. These results will be presented next.

Situation Awareness

Team Knowledge Related to Situation Awareness – SAGAT. Means and standard deviations of all relevant team level SAGAT measures for the male and female teams are presented in Tables 8 and 9, respectively. For team Level 1 SA (i.e., judgment of team member heading and distance), multivariate analyses for the female teams revealed significant main effects for audio condition, F (2, 35) = 4.73, $p < .05$, and visual fidelity, F (2, 35) = 3.75, $p < .05$; however, the interaction was not significant. Univariate analyses indicated that female teams in the 3-D audio condition were significantly more accurate in judgments of team member heading than those in the 2-D audio condition, F (1, 36) = 6.36, $p < .05$. Univariate analyses also indicated that, overall, female teams were significantly more accurate in judgments of team member heading in the dimly lit condition than in the well lit condition, F (1, 36) = 6.44, $p < .05$. Multivariate analyses found no significant main or interaction effects for the male teams.

For team Level 2 SA, univariate analyses found no significant main or interaction effects for either gender. Univariate analyses of team Level 3 SA found no significant main effects for audio condition or visual fidelity, but did reveal a significant interaction effect for the male teams, F (1, 15) = 5.90, $p < .05$. Inspection of the means suggests that whereas male teams in the 2-D audio condition performed better in the well lit than in the dimly lit conditions, the reverse was true for male teams in the 3-D audio conditions, with performance better in the dimly lit than in the well lit conditions. However, further analyses found that these mean differences were not significant. No significant main or interaction effects were found for the female teams.

Table 8.

Means and Standard Deviations for Relevant SAGAT Team Level Variables for Male Teams

Dependent Variable	Auditory Cues	Visual Fidelity	Mean (Std Dev)
SAGAT – Team Knowledge			
Level 1 – Perception Judgment of team member's heading[a]	2-D Non-Spatialized	Well Lit	1.40(0.99)
		Dimly Lit	1.38(1.09)
	Total		1.39(0.16)
	3-D Generalized	Well Lit	1.33(0.82)
		Dimly Lit	0.85(0.63)
	Total		1.09(0.17)
	Total	Well Lit	1.37(0.18)
		Dimly Lit	1.12(0.15)
Level 1 – Perception Judgment of team member's distance[a]	2-D Non-Spatialized	Well Lit	1.32(0.85)
		Dimly Lit	1.72(0.92)
	Total		1.52(0.19)
	3-D Generalized	Well Lit	1.83(1.22)
		Dimly Lit	1.59(0.97)
	Total		1.17(0.20)
	Total	Well Lit	1.58(0.19)
		Dimly Lit	1.66(0.18)
Level 2 – Comprehension Judgment of team member in danger	2-D Non-Spatialized	Well Lit	0.33(0.50)
		Dimly Lit	0.33(0.50)
	Total		0.33(0.12)

	3-D Generalized	Well Lit	0.25(0.46)
		Dimly Lit	0.25(0.46)
	Total		0.25(0.13)
	Total	Well Lit	0.29(0.12)
		Dimly Lit	0.29(0.12)
Level 3 – Prediction	2-D Non-Spatialized	Well Lit	1.22(0.44)
Team member		Dimly Lit	0.89(0.60)
engagement of enemy	*Total*		1.06(0.13)
	3-D Generalized	Well Lit	0.50(0.53)
		Dimly Lit	1.13(0.64)
	Total		0.81(0.14)
	Total	Well Lit	0.86(0.12)
		Dimly Lit	1.00(0.15)

[a]Lower scores indicate better performance.

Table 9.

Means and Standard Deviations for Relevant SAGAT Team Level Variables for Female Teams

Dependent Variable	**Auditory Cues**	**Visual Fidelity**	**Mean (Std Dev)**
SAGAT – Team Knowledge			
Level 1 – Perception	2-D Non-Spatialized	Well Lit	1.76(1.24)

Judgment of team member's		Dimly Lit	1.22(0.87)
heading[a]	*Total*		1.49(0.16)
	3-D Generalized	Well Lit	1.26(0.93)
		Dimly Lit	0.64(0.72)
	Total		0.95(0.16)
	Total	Well Lit	1.51(0.17)
		Dimly Lit	0.93(0.14)
Level 1 – Perception	2-D Non-Spatialized	Well Lit	1.93(1.43)
Judgment of team member's		Dimly Lit	1.85(1.15)
distance[a]	*Total*		1.89(0.18)
	3-D Generalized	Well Lit	2.61(0.81)
		Dimly Lit	1.82(1.13)
	Total		2.21(0.19)
	Total	Well Lit	2.27(0.18)
		Dimly Lit	1.84(0.17)
Level 2 – Comprehension	2-D Non-Spatialized	Well Lit	0.50(0.53)
Judgment of team member in		Dimly Lit	0.50(0.53)
danger	*Total*		0.50(0.14)
	3-D Generalized	Well Lit	0.56(0.53)
		Dimly Lit	0.33(0.50)
	Total		0.44(0.15)
	Total	Well Lit	0.53(0.12)

		Dimly Lit	0.42(0.12)
Level 3 – Prediction	2-D Non-Spatialized	Well Lit	0.60(0.52)
Team member		Dimly Lit	0.90(0.74)
engagement of enemy	*Total*		0.75(0.16)
	3-D Generalized	Well Lit	0.78(0.67)
		Dimly Lit	0.89(0.66)
	Total		0.83(0.16)
	Total	Well Lit	0.69(0.14)
		Dimly Lit	0.89(0.16)

[a]Lower scores indicate better performance.

Individual Knowledge Related to Situation Awareness – SAGAT. Means and standard deviations of all relevant individual level SAGAT measures for the male and female teams are presented in Tables 10 and 11, respectively. For female teams, multivariate analysis on individual Level 1 SA queries showed a significant main effect for audio condition, F (5, 13) = 4.17, p < .05, but neither a significant main effect for visual fidelity nor a significant interaction effect. Univariate analyses indicated that female teams in the 2-D audio condition had significantly more accurate combatant distance and noncombatant heading noncombatant than those in the 3-D audio condition (F (1, 17) = 9.40, p < .05, and F (1, 17) = 7.41, p < .05, respectively).

For male teams, multivariate tests on individual Level 1 SA queries revealed a significant main effect for visual fidelity, F (5, 11) = 5.06, p < .05, and a significant interaction effect, F (5, 11) = 3.89, p < .05, but no significant main effect for audio condition. Univariate analyses showed that male teams had significantly more accurate judgments of combatant heading, noncombatant heading, and noncombatant distance in the well lit condition than in the dimly lit condition (F (1, 15) = 4.72, p <.05; F (1, 15) = 11.19, p <.01; and F (1, 15) = 15.66, p < .01, respectively). Univariate analyses also found a significant interaction effect for noncombatant heading, F (1, 15) = 10.54, p < .05, with males in the 2-D audio condition having more accurate heading judgments in the dimly lit condition than in the well lit condition.

For individual Level 2 SA, univariate analysis found no significant main or interaction effects for female teams. For male teams, univariate analyses found no significant main effects for audio condition or visual fidelity. However, results did reveal a significant interaction effect, F (1, 15) = 6.18, p < .05. Inspection of the means suggest that whereas in the 2-D audio condition male teams were more accurate in the dimly lit than in the well lit condition, in the 3-D audio condition, male teams were more accurate in the well lit than in the dimly lit condition. For individual Level 3 SA, univariate analyses found no significant main or interaction effects for either gender.

Table 10.

Means and Standard Deviations for Relevant SAGAT Individual Level Variables for Male Teams

Dependent Variable	**Auditory Cues**	**Visual Fidelity**	**Mean (Std Dev)**
SAGAT – Individual			

Knowledge			
Level 1 – Perception Judgment of combatant heading[a]	2-D Non-Spatialized	Well Lit	0.59(0.43)
		Dimly Lit	1.21(1.02)
	Total		0.90(0.16)
	3-D Generalized	Well Lit	0.69(0.57)
		Dimly Lit	0.96(0.50)
	Total		0.82(0.17)
	Total	Well Lit	0.64(0.11)
		Dimly Lit	1.08(0.22)
Level 1 – Perception Judgment of noncombatant heading[a]	2-D Non-Spatialized	Well Lit	2.70(1.25)
		Dimly Lit	1.30(0.89)
	Total		2.00(0.26)
	3-D Generalized	Well Lit	1.29(0.65)
		Dimly Lit	1.27(0.82)
	Total		1.28(0.28)
	Total	Well Lit	2.00(0.25)
		Dimly Lit	1.28(0.24)
Level 1 – Perception Judgment of combatant distance[a]	2-D Non-Spatialized	Well Lit	3.79(1.08)
		Dimly Lit	3.94(1.94)
	Total		3.87(0.51)
	3-D Generalized	Well Lit	4.22(1.99)
		Dimly Lit	3.94(1.94)

	Total		4.08(0.55)
	Total	Well Lit	4.01(0.45)
		Dimly Lit	3.94(0.53)
Level 1 – Perception Judgment of noncombatant distance[a]	2-D Non-Spatialized	Well Lit	3.52(2.28)
		Dimly Lit	6.65(1.96)
	Total		5.09(0.63)
	3-D Generalized	Well Lit	2.90(2.55)
		Dimly Lit	6.22(3.35)
	Total		4.56(0.66)
	Total	Well Lit	3.21(0.66)
		Dimly Lit	6.44(0.63)
Level 1 – Perception Kind and number of entities in room	2-D Non-Spatialized	Well Lit	1.67(0.71)
		Dimly Lit	1.89(0.60)
	Total		1.78(0.19)
	3-D Generalized	Well Lit	1.63(0.74)
		Dimly Lit	1.75(0.89)
	Total		1.69(0.20)
	Total	Well Lit	1.65(0.18)
		Dimly Lit	1.82(0.17)
Level 2 – Comprehension Judgment of self in danger	2-D Non-Spatialized	Well Lit	0.00(0.00)
		Dimly Lit	0.33(0.50)
	Total		0.17(0.11)

	3-D Generalized	Well Lit	0.38(0.52)
		Dimly Lit	0.13(0.35)
	Total		0.25(0.11)
	Total	Well Lit	0.19(0.09)
		Dimly Lit	0.23(0.11)
Level 3 – Prediction Navigation, time to clear, number of enemies engaged	2-D Non-Spatialized	Well Lit	1.00(0.87)
		Dimly Lit	1.11(0.60)
	Total		1.06(0.19)
	3-D Generalized	Well Lit	1.25(0.71)
		Dimly Lit	0.88(0.83)
	Total		1.06(0.20)
	Total	Well Lit	1.13(0.19)
		Dimly Lit	0.99(0.18)

[a]Lower scores indicate better performance.

Table 11.

Means and Standard Deviations for Relevant SAGAT Individual Level Variables for Female Teams

Dependent Variable	**Auditory Cues**	**Visual Fidelity**	**Mean (Std Dev)**
SAGAT – Individual Knowledge			

Level 1 – Perception Judgment of combatant heading[a]	2-D Non-Spatialized	Well Lit	0.42(0.38)
		Dimly Lit	1.11(0.99)
	Total		0.77(0.15)
	3-D Generalized	Well Lit	0.70(0.47)
		Dimly Lit	1.33(0.94)
	Total		1.02(0.16)
	Total	Well Lit	0.56(0.11)
		Dimly Lit	1.08(0.22)
Level 1 – Perception Judgment of noncombatant heading[a]	2-D Non-Spatialized	Well Lit	1.20(1.07)
		Dimly Lit	1.17(0.79)
	Total		1.18(0.25)
	3-D Generalized	Well Lit	2.11(1.07)
		Dimly Lit	2.15(1.40)
	Total		2.13(0.26)
	Total	Well Lit	1.66(0.24)
		Dimly Lit	1.66(0.23)
Level 1 – Perception Judgment of combatant distance[a]	2-D Non-Spatialized	Well Lit	4.11(2.07)
		Dimly Lit	3.68(2.14)
	Total		3.90(0.49)
	3-D Generalized	Well Lit	5.22(2.00)
		Dimly Lit	7.22(2.63)
	Total		6.22(0.51)

	Total	Well Lit	4.67(0.42)
		Dimly Lit	5.45(0.50)
Level 1 – Perception Judgment of noncombatant distance[a]	2-D Non-Spatialized	Well Lit	3.87(3.39)
		Dimly Lit	7.84(2.89)
	Total		5.85(0.59)
	3-D Generalized	Well Lit	5.40(2.44)
		Dimly Lit	5.69(2.06)
	Total		5.55(0.63)
	Total	Well Lit	4.63(0.63)
		Dimly Lit	6.77(0.60)
Level 1 – Perception Kind and number of entities in room	2-D Non-Spatialized	Well Lit	1.00(0.94)
		Dimly Lit	1.80(0.63)
	Total		1.40(0.18)
	3-D Generalized	Well Lit	1.44(0.53)
		Dimly Lit	1.56(0.73)
	Total		1.50(0.19)
	Total	Well Lit	1.22(0.17)
		Dimly Lit	1.68(0.16)
Level 2 – Comprehension Judgment of self in danger	2-D Non-Spatialized	Well Lit	0.60(0.52)
		Dimly Lit	0.90(0.32)
	Total		0.75(0.11)
	3-D Generalized	Well Lit	0.67(0.50)

		Dimly Lit	0.67(0.50)
	Total		0.67(0.12)
	Total	Well Lit	0.63(0.12)
		Dimly Lit	0.78(0.10)
Level 3 – Prediction	2-D Non-Spatialized	Well Lit	0.80(0.42)
Navigation, time to clear,		Dimly Lit	0.90(0.57)
number of enemies engaged	*Total*		0.85(0.14)
	3-D Generalized	Well Lit	1.22(0.83)
		Dimly Lit	0.67(0.71)
	Total		0.94(0.15)
	Total	Well Lit	1.01(0.15)
		Dimly Lit	0.78(0.15)

[a]Lower scores indicate better performance.

Perceived Workload

Univariate analyses on the NASA TLX data found no significant main or interaction effects for either gender. However, with regard to responses on the MARS SA Workload subscale, an independent samples *t* test revealed a significant difference between the two audio conditions for the female teams, t (36) = 2.15, $p < .05$. Specifically, female teams in the 3-D audio condition (M = 6.83, SD = 1.76) reported significantly lower workload than female teams in the 2-D audio condition (M = 8.35, SD = 2.48). No significant differences were found for the male teams.

DISCUSSION

This dissertation investigated the effects of different types of auditory cues on the development of situation awareness for teams performing a MOUT team task embedded within a virtual environment. Based on extant research, presentation of 3-D spatialized auditory cues was hypothesized to enhance a team's ability to develop knowledge about team member location and support the usage of team behaviors for developing and maintaining situation awareness, thereby leading to better task performance and decreased workload. In general, the results of this study provided partial support for the beneficial effects of 3-D audio cues in facilitating the development of situation awareness and reducing workload. Findings will be discussed next in greater detail.

Situation Awareness

Hypotheses regarding the effect of 3-D audio cues on the development of team knowledge related to situation awareness were partially supported. Specifically, teams provided with 3-D audio cues were significantly more accurate in monitoring the location of their team members than those presented with 2-D audio cues. This result extends previous findings in the literature (Nelson, 2001) which suggests that, in simple environments, 3-D audio cues facilitates better spatial localization; however, this dissertation demonstrates this beneficial effect for 3-D audio cues in a more complex environment, namely a MOUT task requiring physical coordination among team members. For successful performance in this complex team task, there is a clear advantage to team members who know where their team members are in relation to themselves.

In addition, results showed that the beneficial effect of 3-D cues in facilitating localization performance was most salient under conditions of low visual fidelity (i.e., dimly lit environments). Teams provided with 3-D audio cues were able to ascertain where team members were when they were out of their visual range and when visual conditions were poor. In these situations, the audio cues may have provided critical information for judging where team members were located. Thus, in dimly lit environments, teams presented with the 3-D audio cues had a clear advantage with regard to localization. In well lit environments, however, it appears that teams were able to rely more on visual cues to judge team member location, which is reflected in the lack of significant differences in performance under these conditions.

Contrary to hypotheses, the benefits of 3-D audio did not lead to overall improvements in judgments of team member distance, when team members were in danger, or predictions of team member's future performance. It may be that auditory cues provided some benefit to perceiving and comprehending this information (e.g., distance and future performance); however, the added spatialization of this information did not supplement the fact that the cue was perceived. For example, distance information is primarily provided to participants via changes in *intensity* (i.e., loudness) of cues. This information was provided equally to participants in the 2-D and 3-D audio conditions, as 2-D cues used intensity to provide information regarding the nearness of different objects. This may explain why there were no benefits for judgments of team member and combatant distance. With respect to Level 3 SA (prediction), team members may have utilized either information regarding their own performance (i.e., the number of enemies they shot) or general auditory information (i.e., the number of gun shots they heard coming from their team member) to build knowledge regarding their team member's success in performing the task.

With individual level SA, it was expected that 3-D audio cues would support visual search performance (Bolia, D'Angelo, & McKinley, 1999), and lead to greater detection of relevant objects in the environment. Although the environment was populated with combatants (enemies), noncombatants, and room objects, it was hypothesized that individuals presented with 3-D audio cues would have better location judgments of combatants only, as these targets were co-located with audio cues (noncombatants and room objects had no associated audio cues). However, this hypothesis was not supported by the results. One possible explanation may be that teams were not aware of how many enemies were in the room. Specifically, when entering a room, enemies' audio cues emerged as the sound of gunshots from their respective location. The audio cues were identical in terms of signature and loudness, which may have led to possible confusion with regard to the number of enemies present in the room. With a misjudgment of the number of combatants, it would then be impossible to have accurate location judgments when participants did not even realize that enemies were present. In a dimly lit environment, this effect would be even more pronounced, as participants could not use visual cues to validate the number or location of entities.

Moreover, Level 2 and 3 SA queries were not directly related to audio cues, in that comprehension of the situation and prediction of future events may not be directly linked to the location of objects, one of spatialized sounds greatest benefits. Level 2 queries were related to judgments of the degree to which participants felt they were in danger, given the potential presence of enemies in the room. The information needed to respond to this query could conceivably have been provided by any type of audio cue (either 2-D or 3-D); thus, this may explain the lack of specific benefit for participants presented with 3-D audio cues. Similarly, Level 3 SA queries involved predictions regarding navigation through the environment and time and accuracy of performance. The 3-D audio cues may not have provided any additional information over and above that provided by 2-D audio cues that would facilitate better performance.

A major hypothesis that was not supported was the degree to which 3-D audio cues would elicit explicit demonstration of team behaviors related to situation awareness, including spatial orientation, cue sharing, problem solving, information management, and task management. The level of monitoring of team members' location was expected to extend to other monitoring behaviors and communications to that effect. One possible explanation for these null results may be that the presence of additional audio cues may have led to a greater shared understanding of the situation, leading to less of a requirement to verbalize information (i.e., less need to share cues verbally).

In addition, several of the targeted team behaviors focused on assessing what individuals said and what they were looking at, such as, for example, spatial orientation team behaviors involving use of information sources, cross checking information, and scanning the environment. As currently examined, these behaviors were primarily visual, in that to demonstrate or enact these behaviors, observers focused on where the team was looking and what the team was saying, rather than on what the team was hearing. As the experimental manipulation was auditory, it was expected that differences in spatial orientation team behaviors would be related to the audio channel. Specifically, individuals would be using their sense of hearing to gather and cross check information, and scan the environment. As such perceptual acts are not overtly observable, it may be that these behaviors did occur but were not detected given current observation methods.

Finally, in the MOUT environment, teams work together to clear rooms, but there is considerable overlap in terms of team member roles and responsibilities. That is, every team member can conduct every task independently and there is 100% overlap of capabilities and limitations. No team member provides unique contributions that require exchange of information. Further, the simulated room clearing task is relatively straightforward. In terms of problem solving, most problems (e.g., enemies shooting at you) are dealt with in a relatively straightforward manner, and decision making is limited to determining who to actually shoot. Individuals do not need to collaborate with others to make these discriminations nor is it time effective to do so. Given these factors, it may be that the MOUT task may not have elicited the targeted team behaviors related to situation awareness.

Moreover, operational task analyses for MOUT operations suggest that situation awareness is more nebulous in this environment, as awareness is related to knowing where the gun is pointed at all times, monitoring team members actions, and adjusting self methods correspondingly, 'reading' a room and adapting entry technique, among others. Each of these behaviors requires an expert-level skill in the team. Even with such teams, however, and in environments where teams are not able to use visual cues, auditory cues may provide the data to know where your team members are, but this added team knowledge may not articulate itself except via subtle implicit behaviors (e.g., less head turning to see where team members are, or knowing from experience with a team member that they are located where expected).

Task Performance

Task accuracy and time on task metrics were both hypothesized to benefit from 3-D audio cues; however, no differences were found. For task accuracy, it was expected that improved localization would decrease the number of shots required to kill the enemy. However, as participants, in fact, did not exhibit improved localization of the enemies, as assessed by queries listed above, it is, therefore, not surprising that they were not more accurate at shooting them. Further, participants were instructed to not start shooting until they had positively identified an entity as an enemy. With this, it would be expected that benefits from localization would impact the time to identify the location of the enemy, rather than the number of shots taken. With regard to clearing or shooting noncombatants, as there were no audio cues associated with these entities, any benefits from 3-D audio cues would be indirect; that is, if enemy detection is quicker and more accurate, then such teams would be expected to make less errors in locating, discriminating, and clearing noncombatants.

For time on task, the results neither supported the hypotheses nor the extant literature on visual search (Bolia, D'Angelo, & McKinley, 1999). Previous studies on visual search performance suggest that targets co-located with spatialized auditory signals will be detected quicker than when 2-D audio cues are presented (Bolia, D'Angelo, & McKinley, 1999). However, some studies also suggest that an exception to this finding is expected in target-poor environments (i.e., when very few targets are present; Fudmann & Strybel, 1999). This research suggests that, in cases where there are few targets in an environment, precision may not be critical, as general auditory cueing provides all the information that is required. As such, simple cueing (present in both the 2-D and 3-D audio conditions) may have provided the level of precision needed for quick target detection. Given the task environment used in this study (between 0 – 3 targets per room, dispersed evenly through the room), it appears that benefits for audio cues, if any, would be similar for both the 2-D and 3-D conditions.

Perceived Workload

Hypotheses regarding perceived workload were partially supported. Although the NASA TLX failed to reveal any significant differences in perceived workload between audio conditions, the MARS SA workload subscale found that, overall, teams presented with 3-D audio cues reported significantly lower perceived workload than those presented with 2-D audio cues. Items in this measure focus on assessing participants' perceived difficulty in gathering data to identify cues, understand situations, and predict events during a mission. As such, the MARS SA workload subscale may have been more sensitive than the NASA TLX in detecting workload related to perception of cues.

Presence

Audio presence was evaluated to examine if 3-D audio provided participants with an increased feeling of being in the environment developed by the audio cues. Findings support those of Vastfjall (2003), suggesting that a 3-D sound environment leads individuals to experience a greater sense of involvement and presence than 2-D audio.

Gender

Although not specifically hypothesized in this study, results did reveal a differential effect of audio cues on performance outcomes depending upon participants' gender, particularly with regard to measures assessing knowledge related to situation awareness and perceived workload. For judgments of team member heading, female teams in the 3-D audio conditions had significantly more accurate performance in dimly lit conditions than female teams in 2-D conditions. Research suggests that males have an overall advantage with respect to spatial ability (cf. Kramer & Smith, 2001). Research suggests that females may use strategies to support tasks which require spatial skills (Kingsberg, LaBarba, & Bowers, 1986). Given this, these findings suggest that female teams may have been able to use audio cues as supplemental data in order to make better spatial localization judgments.

However, it appears that the 3-D audio may have hampered performance in judging distance of combatants and localization on noncombatants, as female teams in the 2-D condition had significantly more accurate judgments than female teams in the 3-D audio condition. One interpretation of this finding is that 3-D audio facilitates performance only when it provides meaningful information; when 3-D audio provides perceived non-relevant information (as discussed above, individuals did not benefit from audio cues from combatants or non combatants), these cues may be ignored or treated as noise, and possibly distracts teams from tasks that are deemed less relevant. These findings suggest that, for some facets of SA (i.e., team member localization), 3-D audio cues benefited performance for female teams, but for other forms of SA, performance was hindered.

Finally, female teams in the 3-D audio condition reported less SA-related workload than female teams in the 2-D audio condition. These findings suggest that female teams may have experienced lower workload related to perceiving and interpreting what they judged to be mission critical cues.

Best-Fit HRTF Technical Issues

This dissertation utilized a validated method of HRTF selection to evaluate the effect of 3-D best-fit spatialized audio cues on performance outcomes. However, recent findings from studies utilizing the same best fit library and selection methodology (Jones, Fouad, Cummings, & Stanney, 2005) and preliminary examination of the data clearly indicated that participants in the 3-D best-fit audio condition were performing poorly across the range of metrics. The use of best-fit HRTFs is a relatively new technology, which is directed at providing a solution to the time and expense of developing completely customized HRTFs for an individual. Methodologies for developing and selecting HRTFs are in their infancy, with only some published validation (Seeber & Fastl, 2003). Preliminary research into this matter suggests that there are a number of serious selection and HRTF development issues that result in the selection of poorly fit HRTFs. With a poorly fit HRTF, performance decrements are commonly found (Begault, Wenzel, Shrum, & Miller, 1996). In an attempt to understand the unforeseen technical problems encountered during this study, this section will discuss four main issues with the best fit HRTF development and selection: construction of the HRTF, reliability of selection of HRTF, use of a low number of static sound cues, and user error in selection.

The library of HRTFs used for this dissertation has been used in both research and applied domains (Fouad, personal communication). Each of the HRTFs in the library is made from actual measurements of human participants, as opposed to measurements from a static dummy body used to develop generalized HRTFs. The dummy head supports the precise nature of developing the HRTF. With the introduction of human participants, slight movement and positioning errors can lead to errors in the resultant HRTF (Miller, personal communication). In addition to HRTF development errors, there currently exists no research to support the reliability of HRTF selection. That is, it has not been established if an individual would select the same HRTF if they repeated the procedure.

Furthermore, the current methodology has been validated only on a group of participants performing a simple task involving the identification of a sound source while stationary. With the MOUT task, both the sound sources and the individuals are moving. If the selection methodology provides a set of target locations that match the locations in the test task, then the HRTF selected in one instance may generalize. However, if the test task provides sound sources at more complex locations, then the HRTF may not generalize. In this case, even a well fitting HRTF may not work in a dynamic environment (Miller, personal communication).

Finally, it is possible that untrained listeners use different (and inappropriate) criteria to determine their best fit rather than those that are spatially accurate. For example, listeners may judge a loud sound as ‘better’. In the methodology utilized, it appears that some of the tones had slightly different timbres. Given that certain timbres may have been more pleasing to hear, listeners may have based their selections on sounds that were pleasing rather than spatially accurate. Given these unanticipated issues, data from the 3-D best-fit audio condition were not included in the analyses of the results, as findings cannot be unequivocally explained as resulting from the intended manipulation.

IMPLICATIONS FOR THE DESIGN OF VE TRAINING SYSTEMS

Although only partial support was found for this dissertation's hypotheses, nevertheless, these findings suggest a number of important implications for the design of VE training systems. First, the design of virtual environments often focuses only on the fidelity of the visual cues present in the environment, ignoring the importance of the multimodal cues that are essential for developing situation awareness in many real world settings. Furthermore, in training situations, the focus on visual fidelity may be detracting from the full benefits of an operationally rich sensory environment, which can be used to support novice development of perception of complex cue patterns. Indeed, recent studies have shown that multisensory cues are used to detect cue patterns (Apostolos, Zak, Das, & Schenker, 1992). In some operational environments, smell, sound, and touch are key to quick detection and understanding of a situation. Yet training in less ecologically-valid environments (i.e., relying only on a single modality) does not allow trainees to develop search and detection patterns that rely on other senses, such as auditory cues. Practicing and using alternate sensory cues to develop situation awareness may provide trainees with the necessary competencies to achieve successful task performance.

Second, although experts may unquestionably argue that multimodal cues are critical to situation awareness, the degree to which such cues lead to specific, measurable outcomes is still unclear. Current metrics may not be sufficiently sensitive to reliably detect the value of multisensory cues. Future research is clearly warranted to develop and validate performance assessment methodologies that can facilitate the detection and appropriate use of auditory, olfactory, and haptic cues to begin to determine the ways that these cues are combined to define complex cue patterns.

Third, current research has focused on the effects of 3-D audio cues in very simple environments, limiting the generalizability of these findings to VE training systems, where the benefits of these cues may have implications for training complex skills. In addition, much of the extant research examines the impact of non-authentic (i.e. low informational content) auditory cues on performance (Ho & Spence, 2005). This dissertation takes a first step at addressing this issue by assessing how operationally authentic 3-D spatialized audio cues can be used by trainees in a MOUT environment to develop knowledge regarding the location of team members in support of situation awareness, especially for teams performing in impoverished visual conditions (e.g., dimly-lit rooms). Such conditions are operationally valid, representative of performing in fog, smoke, night operations, or when there is a loss of power. These findings may have even more practical application in teams where formation is key to successful task performance. For these teams, 3-D spatialized audio cues may supplement their sense of awareness of team member location, especially in limited field of view VEs. In addition, it should also be noted that the results of this study provided some evidence for the effect of 3-D spatialized audio cues on reductions in perceived workload. Paired with the benefits of localization, these findings suggest that 3-D audio may be particularly beneficial in high workload, operational training environments.

With respect to gender, it appears that females receive more benefit from spatialized audio than males. If audio information provides critical localization information that extends females' ability to build situation awareness, then the inclusion of such cues in VEs used by females would be recommended. Further, additional research should examine the degree that multisensory information is used differentially by males and females. Resulting design guidance could used to support the notion of whether adaptive training systems are necessary based on a person's gender.

Finally, it is important to note that, in this study, 3-D spatialized audio cues did not have an overall global effect on situation awareness; rather, audio cues provided specific localization information regarding targeted cues only (e.g., team member location). Given that these beneficial effects did not generalize to localization of other entities (e.g, combatants, noncombatants, etc.), it is critical to carefully determine *what* needs to be coincident with auditory cues to facilitate perception of key cues. Alternatively, it may be that other auditory information (e.g. loudness of audio) or visual information is used by individuals to make judgments and build situation awareness. In either case, multisensory task analysis methodologies could be developed to determine relevant operational cues, categorize them into those that are meaningful and critical to situation awareness, and then empirically examine the degree to which benefits are realized.

CONCLUSIONS

When done well, incorporating multimodal cues into VE training systems can provide trainees with the rich environmental stimuli typically present in the real world. Yet, the integration of environmental cues into the design of virtual environments is often haphazard, with little research-based guidance informing developers. To address this issue, this dissertation endeavored to identify the conditions under which presenting 3-D spatialized auditory cues would optimize team performance in a complex operational environment. This line of research can lead to the development of a theoretical framework for garnering a better understanding of the unique and overlapping impact that multimodal cues may have on desired team performance outcomes, such as situation awareness, adaptability, and decision making. In turn, research findings based upon this theoretical framework can be used to generate practical yet empirically-validated guidelines that would allow designers of VE training systems to select those technologies that can best support the training objectives necessary for effective performance in the domain of interest.

APPENDIX A: INSTITUTIONAL REVIEW BOARD (IRB) COMMITTEE APPROVAL LETTER AND APPROVED STUDENT INFORMED CONSENT FORM

University of
Central
Florida

Office of Research and Commercialization

December 13, 2004

Laura Milham
c/o David Jones
1700 Woodbury Road, Apt. 2806
Orlando, FL 32828

Dear Ms. Milham and Mr. Jones:

With reference to your protocol entitled, "Assessing the Effects of 3-D Spatialized Audio on Individual and Team Performance" I am enclosing for your records the approved, expedited document of the UCFIRB Form you had submitted to our office.

Please be advised that this approval is given for one year. Should there be any addendums or administrative changes to the already approved protocol, they must also be submitted to the Board. Changes should not be initiated until written IRJ3 approval is received. Adverse events should be reported to the IRB as they occur. Further, should there be a need to extend this protocol, a renewal form must be submitted for approval at least one month prior to the anniversary date of the most recent approval and is the responsibility of the investigator (UCF).

Should you have any questions, please do not hesitate to call me at 407-823-2901.

Please accept our best wishes for the success of your endeavors.

Cordially,

Barbara Ward
CIM IRB Coordinator

Copies: IRB File

12443 Research Parkway • Suite 3O2 • Orlando, FL 32826-3252 • 4O7-823-3778 • Fax 4O7-823-3299

THE UNIVERSITY OF CENTRAL FLORIDA INSTITUTIONAL REVIEW BOARD (IRB)

IRB Committee Approval Form

IRB #: 04-2186

PRINCIPAL INVESTIGATOR(S): Laura Milham & David Jones

PROJECT TITLE: Assessing the Effects of 3-D Spatialized Audio on Individual and Team Performance

Committee Members:

Full Board
[ ] Contingent Approval Dated:

[ ] Final Approval Dated:

[ ] Expiration Date:

Dr. Theodore Angelopoulos:
Dr. Ratna Chakrabarti: __
Dr. Karen Dennis: _____
Ms. Patricia Kent: _____
Dr. Robert Kennedy: ___
Dr. Valerie Sims: _____
Dr. David Boote: ______
Dr. Debra Reinhart: ___
Dr. Tracy Dietz (alt): ___
Dr. Janet Whiteside (alt) : _
Dr. Barbara Fritzsche (alt):
ke (alt): _

Chair
[X] Expedited Approval Dated: 30 Oct 2004

Cite how qualifies for expedited review: Minimal Risk, no more than many usual activities for recreation

IRB Co-Chairs:

Signed: _,
Chair. Sophia Dziegielewski

[ ] Exempt Dated:

Cite how qualifies for

Signed: Dr. Jacqueline Byers

Date: 29 Oct 2005

NOTES FROM IRB CHAIR (IF APPLICABLE):
Change contact information on consents prior to implementing, or distributing consent forms

STUDENT INFORMED CONSENT FORM

Name: ________
Identification Number:

Introduction to Study:

This research, "Assessing the Effects of 3-D Spatialized Audio on Team Performance" is being conducted by principal investigators Laura Milham and David Jones.

This research is investigating how we can best use the sense of hearing for training in virtual reality (VR) environments. You will participate in task using a VR system in which you will wear a helmet mounted display which will be used to present visual images. Your task is to search a room with a simulated team member and identify enemy soldiers encountered.

We will be collecting performance data during the simulation and knowledge, attitude, workload, and satisfaction data after the simulation. The time required for this research is approximately 3 hours. All data collected will remain confidential (see below).

Risks and Benefits:

A possible risk of this study will be the development "simulator sickness." Simulator sickness includes symptoms that may result from exposure to simulators and virtual training environments. Symptoms include nausea, stomach awareness, sweating, disorientation, eye strain, headaches, and dizziness. To minimize risk, we are taking the following precautions.

- You will be asked if for any reason, medical or otherwise, you have difficulty with video/computer games, and if so, you will be excused from the experiment (and earn extra credit for the time you have spent in the experiment).
- You will be asked to complete the simulator sickness questionnaire (SSQ). You will be excused if you report symptoms and if you are not in your usual state of fitness (and receive any extra credit owed to you for the time you have spent in the experiment).
- Finally, you will be asked to remain on site until any symptoms you may have experienced subside.

There are no anticipated benefits from participating in this study.
If you believe you have been injured during participation in this research project, you may file a claim against the State of Florida by filing a claim with the University of Central Florida's Insurance Coordinator, Purchasing Department, 4000 Central Florida Boulevard, Suite 360, Orlando, FL 32816, (407) 823-2661. University of Central Florida is an agency of the State of Florida and that the university's and the state's liability for personal injury or property damage is extremely limited under Florida law. Accordingly, the university's and the state's ability to compensate you for any personal injury or property damage suffered during this research project is very limited. Information regarding your rights as a research volunteer may be obtained from:

Barbara Ward
Institutional Review Board (IRB) Coordinator
University of Central Florida (UCF)
12443 Research Parkway, Suite 207 Orlando, FL 32826-3252 Telephone: (407) 823-2901.

APPROVED BY
University of Central Florida
Institutional Review Board

CHAIRMAN

Confidentiality of Personal Data:
All data you contribute to this study will be held in strict confidentiality by the researchers and your individual data will not be revealed to anyone other than the researchers and their immediate assistants.

To insure confidentiality, the following steps will be taken: (a) only researchers will have access to the data; (b) data will be stored in locked facilities; (c) the actual forms will not contain names or other personal information. Instead, the forms will be matched to each participant by a number assigned by and only known to the experimenters; and (d) only group means scores and standard deviations, but not individual scores, will be published or reported.

YOUR PARTICIPATION IN *THIS* RESEARCH IS COMPLETELY VOLUNTARY. YOU MAY WITHDRAW FROM PARTICIPATION *AT* ANY TIME WITHOUT PENALTY - THIS INCLUDES REMOVAL/DELETION OF ANY DATA YOU MAY HAVE CONTRIBUTED. SHOULD YOU DECIDE NOT TO COMPLETE THE TRAINING STUDY, YOU WILL RECEIVE RENUMERATION FOR THE PART OF THE STUDY YOU HAVE COMPLETED.

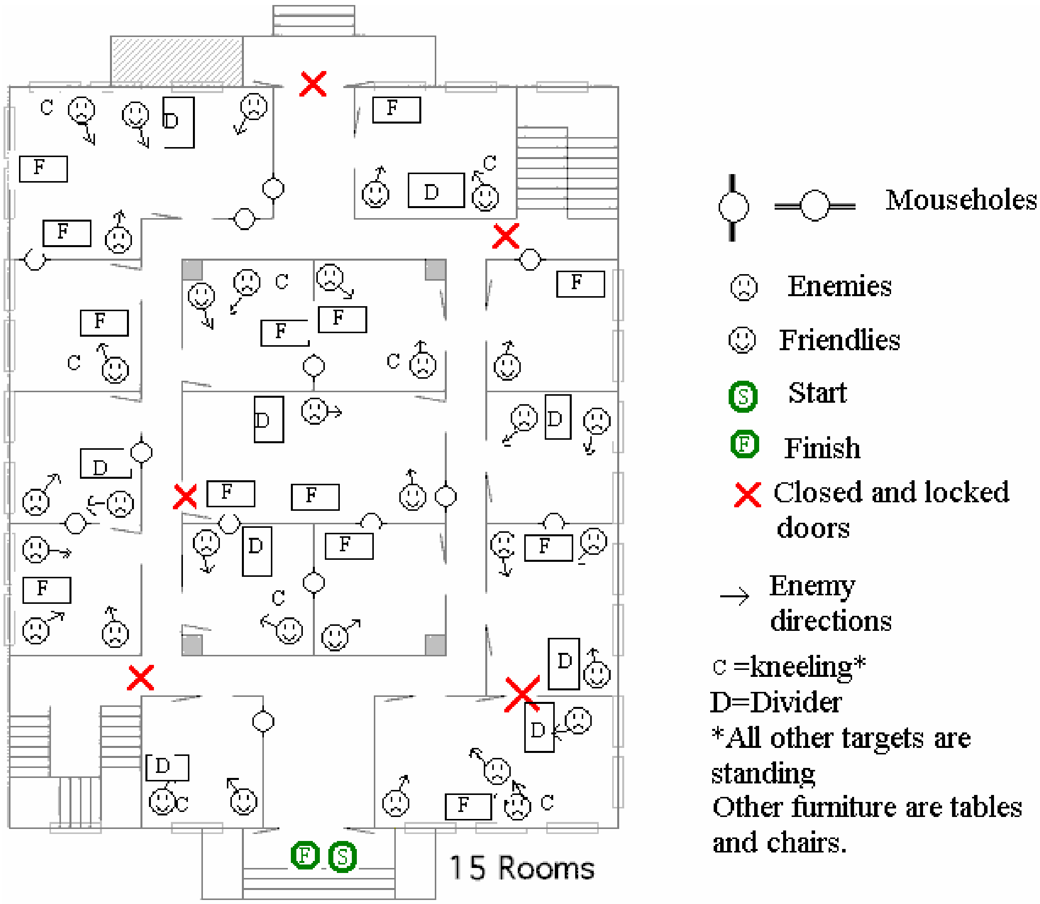
You will be given a copy of the informed consent form to take with you.

Experimenter Date Participant Date

APPROVED BY
University of Central Florida
Institutional Review Board

CHAIRMAN

APPENDIX B: ILLUSTRATIVE LAYOUT OF VE SCENARIO FACILITY



Mouseholes
Enemies
Friendlies
Start
Finish
Closed and locked doors
Enemy directions
c =kneeling*
D=Divider
*All other targets are standing
Other furniture are tables and chairs.
15 Rooms

1st Floor

APPENDIX C: SAGAT QUERIES

SAGAT Queries for MOUT Team Task

Level 1 SA: Perception of Cue Patterns

1. Using a ‘clock position’, such as 12 o’clock or 9 o’clock, where is _____(see below)
2. How far away, in feet, is __________ from you at this time?
   (a) Your team member?
   (b) Combatants?
   (c) Non combatants?

2) What kind of objects are in the room?
3) What is the number of combatants and non combatants in this room?

Level 2 SA: Comprehension of Situation:

1. Are you in danger of being shot right now?
2. Is your team member in danger of being shot right now?

Level 3 SA: Prediction of Situation Future Status:

1. When you exit this room, in which direction will you turn?
2. How long will it take for the team to clear the next room? (in seconds)
3. What percentage of the total number of enemies will you engage in the next room?
4. What percentage of the total number of enemies will your team member engage in the next room?
5. Who on the team will identify enemies quicker in the next room?

APPENDIX D: SALIANT INDICATORS

Sixteen SALIANT behavioral indicators as originally identified by Muniz et al. (1998)

1. Demonstrates awareness of location in space
2. Uses available information sources
3. Briefs status
4. Provides information in advance
5. Informs others of actions taken
6. Cross checks information
7. Demonstrates knowledge of tasks
8. Provides and requests backup
9. Exhibits skilled time sharing among tasks
10. Scans internal and external environment for abnormal conditions, changes, landmarks
11. Anticipates consequences of actions, decisions, and potential problem situations
12. Takes action at the appropriate time
13. Reports problems
14. Locates potential source of problem
15. Resolves discrepancies

APPENDIX E: CATEGORIZATION OF SALIANT INDICATORS

Categorization of SALIANT Indicators (adapted from Fiore et al., 2000)

SA Category	SALIANT Indicator
1. Spatial Orientation (SO)	1.1 Demonstrates awareness of location in space
	1.2 Uses available information sources
	1.3 Cross checks information
	1.4 Scans internal and external environment for abnormal conditions, changes, landmarks
2. Cue Sharing (CS)	2.1 Provides and requests backup
	2.2 Reports problems
	2.3 Informs others of actions taken
3. Problem Solving (PS)	3.1 Locates potential source of problem
	3.2 Resolves discrepancies
	3.3 Anticipates consequences of actions, decisions, and potential problem situations
4. Information Management (IM)	4.1 Provides information in advance
	4.2 Adheres to standard communication format
	4.3 Briefs status
5. Task Management (TM)	5.1 Takes action at the appropriate time
	5.2 Demonstrates knowledge of tasks
	5.3 Exhibits skilled time sharing among tasks

APPENDIX F: SALIANT CHECKLIST

SALIANT Checklist for MOUT Team Task

Scenario 1: Well Lit																			Team # ________
Task	**Communications**	**Positive/ Negative**	**MOUT Room (1-15)**															SALIANT Category	SA Indicator
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		
Orienting to next room																			
	Let's go to the room on the left / We go to the left/right room	p																1.1	Demonstrates awareness of location in space
	Let's go to the next room	p																1.2	Uses available information resources
	Where do we go next?	p																1.2	Uses available information resources
	We just came from that way	p																1.1	Demonstrates awareness of location in space
	Did we skip a room?	p																2.2	Reports problems
Avoiding danger areas																			
	Are there any mouseholes?	p																1.2	Uses available information resources
	Yes, on your left/right	p																1.4	Scans internal and external environment for abnormal conditions, changes, and landmark

				s
	Watch out for the mousehole/doorway	p	3.3	Anticipates consequences of actions, decisions, and potential problem situations
	*[Scans for mousehole/doorway]**	*p*	1.4	Scans internal and external environment for abnormal conditions, changes, and landmarks
	The enemy may be able to see you from where you are	p	3.3	Anticipates consequences of actions, decisions, and potential problem situations
	[Scans for enemy]	*p*	1.4	Scans internal and external environment for abnormal conditions, changes, and landmarks
Strategizing room entry approach/Task assignment				
	Correct door	p	1.1	Yes: Demonstrates awareness of location in space; No: Indicator

				of low SA
	Incorrect door	n	low SA	indicator of low SA
	I see an enemy/friendly on the right/left/ it looks clear	p	4.1	Provide information in advance
	[Scans for enemies/friendlies]	*p*	1.4	Scans internal and external environment for abnormal conditions, changes, and landmarks
	I see a mousehole/ divider/danger area	p	4.1	Provide information in advance
	[Scans for mouseholes etc.]	*p*	1.4	Scans internal and external environment for abnormal conditions, changes, and landmarks
	I'll take the right	p	2.3	Informs others of actions taken
	You take the left	p	2.3	Informs others of actions taken
	Let's eliminate enemies before clearing friendlies	p	5.3	Exhibits skilled time-sharing among tasks
	Do you want to take the right/left?	p	1.2	Uses available information sources
	What do	p	1.2	Uses

	you want to do?			available information sources
Stacking /team member location				
	Where are you?	p	1.2	Uses available information sources
	[is he looking for his team member?]	*p*	1.4	Scans internal and external environment for abnormal conditions, changes, and landmarks
	You need to stay closer/tell me when you are getting behind, etc.	p	3.3	Anticipates consequences of actions, decisions, and potential problem situations
	Are you ready?	p	1.2	Uses available information sources
	Yes, I am/No/wait	p	4.3	Briefs status
	[is he scanning for enemies?]	*p*	1.4	Scans internal and external environment for abnormal conditions, changes, and landmarks
Entering the Room				

	I'm going in now	p	4.3	Briefs status
	Are you going to go?	p	1.2	Uses available information sources
	Go!	p	5.1	Takes action at appropriate time
	[Executed efficiently?]	*p*	5.1	Takes action at appropriate time
Clearing the room				
	I'm going to get this guy	p	2.3	Informs others of actions taken
	I shot that guy.	p	2.3	Informs others of actions taken
	I see a mousehole/ divider/danger area	p	4.1	Provide information in advance
	[Scans for danger areas]	*p*	1.4	Scans internal and external environment for abnormal conditions, changes, and landmarks
	My side is clear	p	4.3	Briefs status
	There's someone behind you	p	2.2	Reports problems
	[Scans for enemies/friendlies in team member's assigned area]	*p*	2.1	Provides and requests backup
	What is that?	p	1.2	Uses available information sources
	Is that a friendly/enemy?	p	1.3	Cross-checks informati

			on
Did you shoot a friendly?	p	2.2	Reports problems
Yes, I did	p	3.2	Resolves discrepancies
I shot a friendly.?	p	2.2	Reports problems
Did you check behind the furniture?	p	1.2	Uses available information sources
I checked behind the furniture/Yes/No	p	2.3	Informs others of actions taken
Do you see (some environmental cue)		1.3	Cross-checks information
Acknowledgment (Yes/No)		1.3	Cross-checks information
Teammate clears own side, then the other	p	2.1	Provides and requests backup
[did one of the team members make an error? If so, what?	n		
• shot a friendly	n	low SA	indicator of low SA
• missed a friendly	n	low SA	indicator of low SA
• cleared an enemy	n	low SA	indicator of low SA
• missed an enemy	n	low SA	indicator of low SA
• didn't clear a room	n	low SA	indicator of low SA
• shooting from outside room	n	low SA	indicator of low SA
Did they catch/correct	p	3.2	Resolves discrepancies

themselves verbally?			
Did they catch/correct themselves behaviorally?	p	3.2	Resolves discrepancies
Did the other team member correct the error verbally?	p	3.2	Resolves discrepancies
Did the other team member correct the error behaviorally?	p	3.2	Resolves discrepancies
Teammate does not say anything regarding error	n	low SA	indicator of low SA
Other errors [list]		low SA	indicator of low SA
Did you already shoot/clear that guy?	p	1.3	Cross-checks information
I already shot/cleared that guy	p	2.3	Informs others of actions taken
I'm not sure if I hit /cleared him	p	2.2	Reports problems
I don't think you got/cleared him	p	3.2	Resolves discrepancies
Watch out	p	3.3	Anticipates consequences of actions, decisions, and potential problem situations
[is he scanning for	*p*	1.4	Scans internal and

	enemies?]				external environment for abnormal conditions, changes, and landmarks
	All Clear.	p		4.3	Briefs status
	All clear??	p		1.2	Uses available information sources
	Are we all done?	p		1.2	Uses available information sources
	[answer] All clear / all right [acknowledge/repeat]	p		4.3	Briefs status
	Enemies were engaged in a timely manner			5.1	Takes action at appropriate time
	Friendlies were cleared in a timely manner			5.1	Takes action at appropriate time
	Time in danger areas was minimized			5.1	Takes action at appropriate time
*italics denote physical behaviors; other text reflect communications					

APPENDIX G: NASA-TLX

Workload Survey

Here we are interested in examining the experiences that you think that you will have during the mission. In the most general sense, we are examining the sense of "workload" experienced during the mission(s).

Workload is a difficult concept to define precisely. The factors that influence your experience of workload may come from several factors.

Instructions: Place an X on each scale at the point that best represents your experience of workload during the mission. Marks must be placed inside the box, not on the lines.

1. Mental Demand:
How much mental and perceptual activity did the mission require of you (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)?

Low Medium High

2. Physical Demand:
How much physical activity did the mission require of you (e.g., pushing, pulling, turning, controlling, activating, etc.)? This refers to you not your soldier.

Low Medium High

3. Temporal Demand:
How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred?

Low Medium High

4. Performance:
How successful do you think you were in accomplishing the goals of the task? How satisfied were you with your performance in accomplishing these goals?

Bad Average Good

5. Effort:
How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low Medium High

6. Frustration:
How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Low Medium High

APPENDIX H: MARS SA WORKLOAD SUBSCALE

Instructions. Please answer the following questions about a typical mission. Your answers to these questions are important in helping us evaluate situational awareness. Check the response that best applies to your experience.

The questions ask how difficult it was for you to detect and understand important cues present during the mission.

1. How difficult – in terms of mental effort required - is it for you to ***identify*** or detect mission-critical cues in the mission?

___ very easy – can identify relevant cues with little effort
___ fairly easy – can identify relevant cues, but some effort required
___ somewhat difficult - some effort required to identify most cues
___ very difficult – substantial effort required to identify relevant cues

2. How difficult – in terms of mental effort – is it to ***understand*** what is going on during the mission?

___ very easy – understand what was going on with little effort
___ fairly easy – understand events with only moderate effort
___ somewhat difficult – hard to comprehend some aspects of situation
___ very difficult – hard to understand most or all aspects of situation

3. How difficult – in terms of mental effort – is it to ***predict*** what is about to happen during the mission?

___ very easy – little or no effort needed
___ fairly easy – moderate effort required
___ somewhat difficult – many projections require substantial effort
___ very difficult – substantial effort required on most or all projections

4. How difficult – in terms of mental effort – is it to decide on ***how to best achieve*** mission goals during a mission?

___ very easy – little or no effort needed
___ fairly easy – moderate effort required
___ somewhat difficult – substantial effort needed on some decisions
___ very difficult – most or all decisions required substantial effort

APPENDIX I: AUDIO PRESENCE SUBSCALE

Characterize your experience in the environment, by marking an "X" in the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as the intermediate levels may apply. Answer the questions independently in the order that they appear. Do not skip questions or return to a previous question to change your answer.

WITH REGARD TO THE EXPERIENCED ENVIRONMENT

1. How much did the auditory aspects of the environment involve you?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

2. How well could you identify sounds?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

3. How well could you localize sounds?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

APPENDIX J: SIMULATOR SICKNESS QUESTIONNAIRE (SSQ)

Simulator Sickness Questionnaire (Kennedy, Lane, Berbaum, & Lilienthal, 1993).

Instructions: Please indicate how you feel **right now** in the following areas, by **circling** the word that applies.

1.	General Discomfort	None	Slight	Moderate	Severe
2.	Fatigue	None	Slight	Moderate	Severe
3.	Headache	None	Slight	Moderate	Severe
4.	Eye Strain	None	Slight	Moderate	Severe
5.	Difficulty Focusing	None	Slight	Moderate	Severe
6.	Increased Salivation	None	Slight	Moderate	Severe
7.	Sweating	None	Slight	Moderate	Severe
8.	Nausea	None	Slight	Moderate	Severe
9.	Difficulty Concentrating	None	Slight	Moderate	Severe
10.	Fullness of Head	None	Slight	Moderate	Severe
11.	Blurred vision	None	Slight	Moderate	Severe
12.	Dizzy (Eyes Open)	None	Slight	Moderate	Severe
13.	Dizzy (Eyes Closed)	None	Slight	Moderate	Severe
14.	Vertigo*	None	Slight	Moderate	Severe
15.	Stomach Awareness**	None	Slight	Moderate	Severe
16.	Burping	None	Slight	Moderate	Severe

*Vertigo is a disordered state in which the person or his/her surroundings seem to whirl dizzily: giddiness

**Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Are there any other symptoms you are experiencing right now? If so, please describe the symptom(s) and rate its/their severity below. Use the other side if necessary.

APPENDIX K: DEMOGRAPHICS QUESTIONNAIRE

Identification Number: __________

DEMOGRAPHIC DATA FORM

Please complete the following questions. Any information you provide is voluntary and will be kept strictly confidential. A participant number will be assigned to your responses and in no way will your name be associated with this data. The information you provide will be used only for the purposes of this study.

1. Gender: _______ Male _______ Female

2. Age: _______

3. Handedness (check one)? _____Left-handed _____Right-handed

4. Year in school: ___Freshman ___Sophomore ___Junior ___Senior

5. Major: _________________________

6. In how many teams (including sports teams) have you participated in the last five years?

   _____0
   _____1-2
   _____3-4
   _____5-6
   _____More than 6

7. Give an estimate of the percentage of time spent on teamwork activities as opposed to individual activities in the last week

   _____0%
   _____Between 0% and 20%
   _____Between 20% and 40%
   _____Between 40% and 60%
   _____Between 60% and 80%
   _____More than 80%

8. Do you have a history of experiencing Motion Sickness (including car sickness, air sickness, etc.)? Please check the appropriate response from the list below:

   ____No history of motion sickness at all

   ____Occasional symptoms of motion sickness

   ____Motion sickness is a fairly normal occurrence

____Always get motion sickness

9. In general how do you feel about working with computers?

________ I don’t like working with computers.
________ I have no strong like or dislike for working with computers.
________ I like working with computers.
________ Other (please explain)
____

10. How would you describe your general level of computer experience?

________ ***None*** (I have never used any computer applications).
________ ***Low*** (I have used only 1 or 2 computer applications).
________ ***Moderately Low*** (I have learned and used between 3 and 10 different computer applications).
________ ***Moderately High*** (I have learned and used more than 10 different computer applications but have no programming skills).
________ ***High*** (I have used many different computer applications and have some programming skills).
________ ***Other*** (please explain)
____

11. Have you ever been in a virtual environment (VE)? YES_____ NO____

If **YES**, how many times have you been in a VE? _________________

12. How would you describe your general level of gaming experience (i.e., playing video games)?

________ ***None*** (I have never played a video game).
________ ***Low*** (I have played a video game a few times in the past).
________ ***Moderately Low*** (I have played a video game a regularly in the past).
________ ***Moderately High*** (I currently play video games weekly).
________ ***High*** (I currently play video games daily).
________ ***Other*** (please explain)
____

REFERENCES

Abouchacra, K., Tran, T, Besing, J., & Koehnke, J. (1997). Performance on a selective listening task as a function of stimuli presentation mode. *Association for Research in Otolaryngology Abstracts, 210*, 53.

Abouchacra, K., Breitenbach, J., Mermagen, T., & Letowski, T. (2001). Binaural helmet: improving speech recognition in noise with spatialized sound. Human Factors, 43, 4, 584-594.

Apostolos, M., Zak, H., Das, H., & Schenker, P. S. (1992). Multisensory Feedback in Advanced Teleoperations: Benefits of Auditory Cues. In *Proceedings of the Sensor Fusion V, (pp. 98-105*). : SPIE.

Baddeley, A. (1990). *Human Memory: Theory and Practice*. Boston: Allyn & Bacon.

Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Science, 4*, 417-423.

Badiqué, E., Cavazza, M., Klinker, G., Mair, G., Sweeney, T., Thalmann, D., & Thalmann, N.M. (2002). Entertainment applications of virtual environments. In K.M. Stanney (Ed.), *Handbook of Virtual Environments: Design, Implementation, and Applications* (pp. 1143-1166). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Begault, D., Wenzel, E., Shrum, R., Miller, J. (1996). A virtual audio guidance and alert system for commercial aircraft operations. *Proceedings of the International Conference on Auditory Display (ICAD),* Palo Alto, CA, Nov. 4-6, 117-122

Begault, D. (1995) Head-up auditory display research at NASA Ames Research Center. *Proceedings of the 39th Annual Human Factors and Ergonomics Society Meeting, San Diego, CA*

Begault, D. (1993). Head-up auditory displays for traffic collision avoidance system advisories: a preliminary investigation. *Human Factors 35*, 707-717.

Bolia, R., D'Angelo, W., McKinley, R. (1999). Aurally aided visual search in three-dimensional space. *Human Factors, 41*, 4, 664-669.

Bronkhorst, A., & Plomp, R. (1992). Effect of multiple speech-like maskers on binaural speech recognition in normal and impaired hearing. *Journal of the Acoustical Society of America, 25,* 3132-3139.

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

Cannon-Bowers, J., & Salas, E. (1998). Individual and team decision making under stress: theoretical underpinnings. In J. Cannon-Bowers and E. Salas, (Eds.), *Making Decisions Under Stress: Implications for Individual and Team Training* (pp. 17-38). Washington, DC: American Psychological Association.

Cannon-Bowers, J., Tannenbaum, S., Salas, E., & Volpe, C . (1995). Defining competencies and establishing team training requirements. In R. Guzzo and E. Salas (Eds.), *Team Effectiveness and Decision Making in Organizations* (pp. 333-380). San Francisco, CA: Jossey-Bass.

Cohn, J., Schaffer, R., Milham, L., & Stanney, K. (2004). A virtual environment for urban combat training. *Proceedings of the 2004 ASC meeting*.

Colavita, F. (1974). Human sensory dominance. *Perception & Psychophysics, 16(2),* 409-412.

Cook, G. (2002). *Company Builds Game Plan to Help the Blind*. www.digitalmass.com

Cooke, N., Kiekel, P., & Helm, E. (2001). Measuring team knowledge during skill acquisition of a complex task. *International Journal of Cognitive Ergonomics, 5(3),* 295-315.

Cooke, N. J., Stout, R., & Salas, E. (1997). Expanding the measurement of situation awareness through cognitive engineering methods. In *Proceedings of the Human Factors and Ergonomics Society 41st annual meeting* (pp.215–219). Santa Monica, CA: Human Factors and Ergonomics Society.

Cooper, R. (1998). Visual dominance and the control of action. In Gernsbacher, M.A. & Derry, S.J. *Proceedings of the 20th Annual Conference on the Cognitive Science Society*.

Driskell, J. & Johnston, J. (1998). Stress exposure training. In J. Cannon-Bowers & E. Salas, (Eds.), *Making Decisions Under Stress: Implications for Individual and Team Training* (pp191-218). Washington, DC: American Psychological Association.

Endsley, M. (1988). Design and evaluation for situation awareness enhancement. *Proceedings of the Human Factors Society, 32nd Annual Meeting,* 97-101.

Endsley, M. R. (1995a). Measurement of situation awareness in dynamic systems. *Human Factors, 37*, 65-84 (Special Issue: Situation awareness).

Endsley, M. R. (1995b). Toward a theory of situation awareness in dynamic systems. *Human Factors, 37*, 32-64 (Special Issue: Situation awareness).

Endsley, M. R. (1997). The role of situation awareness in naturalistic decision making. In Zsambok, C. E. & G. Klein (Eds.), *Naturalistic decision making* (pp. 269-283). Mahwah, NJ: LEA.

Endsley, M. R. (2000). Direct measurement of situation awareness: Validity and use of SAGAT. In M. R. Endsley & D. J. Garland (Eds.), *Situation awareness analysis and measurement* (pp. 147-173). Mahwah, NJ: Lawrence Erlbaum Associates.

Endsley, M., & Rosiles, S. (1995). Auditory localization for spatial orientation. *Journal of Vestibular Research, 5, 6*, 473-485.

Ericson, M., & McKinley, R. (1997). The intelligibility of multiple talkers separated spatially in noise. In R.H. Gilkey & R.R. Anderson (Eds.*), Binaural and spatial hearing in real and virtual environments* (pp. 701-724). Mahwah, NJ: Erlbaum.

Fiore, S. M., Fowlkes, J., Martin-Milham, L., & Oser, R. L. (2000). Convergence or divergence of expert models: On the utility of knowledge structure assessment in training research. *Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomic Society*, 2, 427 – 430. Santa Monica, CA: HFES.

Fisher, H., &Freedman, S. (1968). The role of the pinna in auditory localization. *Journal of Auditory Research, 8,* 15-26.

Flanagan, P., McAnally, K., Martin, R., Meehan, J., & Oldfield, S. (1998). Aurally and visually guided visual search in a virtual environment. *Human Factors, 40*, 461-468.

Foyle, D., Andre, A., McCann, R., Wenzel, E., Begault, D., & Battiste, V. (1996). Taxiway navigation and situation awareness (T-NASA) system: problem, design philosophy and description of an integrated display suite for low-visibility airport surface operations. *Proceedings of the SAE/AIAA World Aviation Congress*.

Garinther, G., Whitaker, L., & Peters, L. (1995). The effects of speech intelligibility on military performance. *In Proceedings of the Symposium on Speech Communication Metrics and Human Performance* (Technical Report AL/CF-SR-1995-0023, pp. 72-82). Wright-Patterson Air Force Base. OH: Armstrong Laboratory.

Hart, S. G. & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock & N. Meshkati (Eds.), *Human mental workload* (pp. 139-183). North-Holland: Elsevier Science.

Hawley, M., Litovsky, R., & Colburn, H. (1999). Speech intelligibility and localization in a multi-source environment. *Journal of the Acoustical Society of America, 105*, 3436-3448.

Hendrix, C., & Barfield, W. (1996). The sense of presence within auditory virtual environments. *Presence: Teleoperators and Virtual Environments, 3*, 290-301.

Ho, C., & Spence, C. (2005). Assessing the effectiveness of various auditory cues in capturing a driver's visual attention. *Journal of Experimental Psychology: Applied, 11, 3,* 157-174.

Kaber, K., Draper, D., & Usher, J. (1999). Speculations on the value of telepresence. *CyberPsychology and Behavior, 2(4),* 349-362.

Kazem, M., Noyes, J., & Lieven, N. (2003). Design considerations for a background auditory display to aid pilot situation awareness. *Proceedings of the 2003 International Conference of Auditory Displays*, Boston, MA.

Kennedy, R., Lane, N., Berbaum, K., & Lilienthal, M. (1993). Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology*, 3 (3), 203-220),

Kingsberg, S., LaBarba, R., & Bowers, C. (1986). Sex differences in the lateralization of spatial abilities. *Paper presented at the convention of the Southeastern Psychological Association, Orlando, FL.*

Kraiger, K., Ford, K., & Salas, E. (1993). Application of cognitive, skill-based, and affective theories of learning outcomes to new methods of training evaluation. *Journal of Applied Psychology 78(2),* 311-328.

Liang, D., Moreland, R., & Argote, L. (1995). Group versus individual training and group performance: the mediating role of transactive memory. *PSPB, 21(4),* 384-393.

Martin-Milham, L. & Fiore, S. M. (2004). Team situation assessment training for adaptive coordination. To appear in N. Stanton, H. Hendrick, S. Konz, K. Parsons, and E. Salas (Eds.), *Handbook of Human Factors and Ergonomics Methods*. London: Taylor & Francis.

Matthews, M. D., Beal, S. A, & Pleban, R. J. (2002). *Situation Awareness in a Virtual Environment: Description of a Subjective Measure.* (Research Report 1786). Alexandria, VA: U.S. Army Research Institute for the Behavioral and Social Sciences.

Milham, L. M., Barnett, J. S., & Oser, R. L. (2000). Application of an event-based situation awareness methodology: Measuring situation awareness in an operational context. *Proceedings of the XIVth Triennial Congress of the*

International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Society, 2, 423-426. Santa Monica, CA: HFES.

Milham, L., Cuevas, H.., Stanney, K., Clark, B., & Compton, D. (2004). *Human Performance Measurement Thresholds, Phase I Final Report*. Technical Report submitted to Naval Surface Warfare Center, Dahlgren VA.

Milham, L., Stanney, K., Gledhill-Holmes, R., Jones, D. (in preparation). Task Analysis of Military Operations over Urban Terrain (MOUT) Teams. VIRTE Program Report, Contract No. N0001402C0138, Arlington, VA: Office of Naval Research.

Miller, M. (1982). Divided attention: evidence for coactivation with redundant signals. *Cognitive Psychology, 14,* 247-279.

Miyake, A., & Shah, P. (Eds.). *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control*. New York: Cambridge University Press.

Moreland, R., & Myaskovsky, L. (2000). Exploring the performance benefits of group training: transactive memory or improved communication? *Organizational Behavior and Human Decision Processes, 82, 1,* 117-133.

Mulgund, S., Stokes, J., Turieo, M., & Devine, M. (2002). *Human/machine interface modalities for soldier systems technologies.* Final Technical Report, Natick, Massachusetts.

Muniz, E., Stout, R., Bowers, C., & Salas, E. (1998, April). A methodology for measuring team situation awareness: situational awareness linked indicators adapted toward novel tasks (SALIANT). *The 1st Annual Symposium/Business*

Meeting of the Human Factors & Medicine Panel on Collaborative Crew Performance in Complex Systems, Edinburgh, United Kingdom.

Nelson, W., Bolia, R., & Tripp, L. (2001). Auditory localization under sustained +G acceleration. *Human Factors 43(2),* 299-309.

Nelson, W., Hettinger, L., Cunningham, J., Brickman, B., Haas, M., & McKinley, R. (1998). Effects of localized auditory information on visual target detection performance using a helmet-mounted display. *Human Factors, 40,* 452-460.

Peissig, J., & Kollmeier, B. (1997). Directivity of binaural noise reduction in spatial multiple noise-source arrangements for normal and impaired listeners. *Journal of the Acoustical Society of America, 101,* 1660-1670.

Perrott, D., Cisneros, J., McKinley, R., & D'Angelo, W. (1996). Aurally aided visual search under virtual and free-field listening conditions. *Human Factors, 38*, 702-715.

Ren, Y., Carley, K., & Argote, L. (2001). Simulating the role of transactive memory in group training and performance. *CASOS Conference 2001*.

Rudmann, D. & Strybel, T. (1999). Auditory spatial facilitation of visual search performance: effect on cue precision and distracter density. *Human Factors, 41(1),* 146-160.

Salas, E., Cannon-Bowers, J. A., Fiore, S. M., & Stout, R. J. (2001). Cue-recognition training to enhance team situation awareness. In M. McNeese, E. Salas, & M. Endsley, (Eds.), *New trends in collaborative activities: Understanding system* *dynamics in complex environments* (pp. 169-190). Santa Monica, CA: Human Factors and Ergonomics Society.

Schneider, W. (1999). Working memory in a multilevel hybrid connectionist control architecture (CAP2). In A. Miyake & P. Shah (Eds.). *Models of Working Memory* (pp. 340-374). New York: Cambridge University Press.

Smith-Jentsch, K. A., Zeisig, R. L., Acton, B., & McPherson, J. A. (1998). A strategy for guided team self-correction. In J. A. Cannon-Bowers & E. Salas (Eds.), *Making decisions under stress: Implications for individual and team training* (pp. 271-297). Washington, DC: American Psychological Association.

Stanney, K., Graeber, D., & Milham, L. (2002). *Virtual Environment Landing Craft Air Cushion (VELCAC): Knowledge Acquisition / Knowledge Engineering*. Report submitted to Naval Air Warfare Center. Orlando, Florida.

Stanney, K., Hale, K., Nahmens, I., & Kennedy, R. (2003). What to expect from immersive virtual environment exposure: influences of gender, body mass index, and past experience. *Human Factors, 45(3),* 504-520.

Stanney, K., Samman, S., Reeves, L., Hale, K., Buff, W., Bowers, C., Goldiez, B., Nicholson, D., & Lackey, S. (2003). A paradigm shift in interactive computing: deriving multimodal design principles from behavioral and neurological foundations. Submitted to the *International Journal of Human-Computer Interaction, Special Issue on Augmented Cognition*, Eds. D. Schmorrow and D. McBride.

Strybel, T., Boucher, J., Fujawa, G., & Volpe, C. (1995). Auditory spatial cueing in visual search tasks: Effects of amplitude, contrast and duration. In *Proceedings of* *the Human Factors and Ergonomics Society 39th Annual Meeting* (pp. 109-113). Santa Monica, CA: Human Factors and Ergonomics Society.

Stein, B., & Meredith, M. (1993). *The Merging of the Senses*. Cambridge, Massachusetts: The MIT Press.

Stout, R., Cannon-Bowers, J. A., & Salas, E. (1996). The role of shared mental models in developing team situation awareness: Implications for training. *Training Research Journal, 2,* 85–116.

Swezey, R., & Llaneras, R. (1997). Models in training and instruction. In G. Salvendy (Ed.), *Handbook of Human Factors and Ergonomics*, 514-577. New York: John Wiley and Sons.

Vastfjall, D. (2003). The subjective sense of presence, emotion recognition, and experienced emotions in auditory virtual environments. *CyberPsychology & Behavior, 69(2),* 181-188.

Webster, J., & Solomon, L. (1955). Effects of response complexity upon listening to competing messages. *Journal of the Acoustical Society of America, 27,* 1199-1203.

Wegner, D., Erber, R., & Raymond, P. (1991). Transactive memory in close relationships. *Journal of Personality and Social Psychology, 61*, 6, 923-929.

Wenzel, E. (1993) Research in virtual acoustic displays at NASA, *[Invited paper] Proceedings of SimTecT 96, The Simulation Technology and Training Conference, March 25-27, 1996, Melbourne, Victoria, AUSTRALIA, pp. 85-90.*

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

Wenzel, E., Wightman, F., & Foster, S., (1988). A virtual display system for conveying three-dimensional acoustic information. In *Proceedings of the Human Factors Society 32nd Annual Meeting* (pp. 86-90). Santa Monica CA: Human Factors and Ergonomics Society.

Wickens, C. (1992). *Engineering Psychology and Human Performance* (2nd ed.). New York: Harper Collins Publishers.

Wightman, F. & Kistler, D. (1989). Headphone simulation of free-field listening. II: Psychophysical validation. Journal *of the Acoustical Society of America, 85(2*) 868-878.

Witmer, B., & Singer, M. (1998). Measuring presence in virtual environments: a presence questionnaire. *Presence, 7, 3*, 225-240.