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Proceedings for
The Third Annual Symposium and Exhibition on

Situational Awareness

in the Tactical Air Environment

June 2 & 3, 1998
Piney Point, Maryland

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INTRODUCTION TO THE PROCEEDINGS FOR THE THIRD ANNUAL SYMPOSIUM ON SITUATIONAL AWARENESS IN THE TACTICAL AIR ENVIRONMENT

Background

The 3rd Annual Symposium on Situational Awareness (SA) in the Tactical Air Environment was held on 2 and 3 June 1998 at the Paul Hall Center in Piney Point, Maryland. The symposium was sponsored by the Electronic Warfare Advanced Technology Program, Naval Air Systems Command (PMA-272). The symposium was coordinated and hosted by the SA Integrated Product Team (IPT) at Patuxent River; points of contact: LT Meghan Carmody-Bubb at 301-342-9265, Karen Garner at 301-342-2985, and Tom Assenmacher at 301-342-0026.

Purpose

The objective of the symposium was to provide program managers, system developers, and system users with a heightened appreciation for potential SA improvements in tactical aviation through the focus areas for the 1998 symposium: Cognitive / Intuitive Interfaces, Multi-modal Interfaces, Spatial Awareness Interface Considerations, and Validated Situational Awareness Performance Measures.

The symposium provided a unique opportunity to discuss how SA influences design; learn new ways to research SA in the tactical air environment; learn the latest developments in SA-related technologies; discuss SA with experts on panels and on a one-to-one basis; and network with a variety of SA researches from government, industry, and academia.

Description of Proceedings

Twenty-nine presentations were given during the symposium. This document contains formal papers based on those presentations. Where papers are not available, executive summaries previously printed in the symposium notebook are reprinted in the proccedings to provide comprehensive documentation of topics and authors for your reference.

Personal Note

Even with today's highly accurate and effective weapons, tactical airborne mission effectiveness depends on the aircrew achieving and maintaining a high level of situational awareness throughout the entire mission. This can be done first by recognizing the capabilities and limitations of the human operator and designing / upgrading systems based on these factors.

I hope that those who participated in the symposium left with ideas and insight for improving SA and new contacts to help in your work. I hope this proceedings document proves a useful reference for SA information and contacts.

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Cognitive/Intuitive Interfaces

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Haptics As The Most Intuitive Spatial Orientation System

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Background

Given the criticality of a high level of situation awareness (SA) for survival, the pressures of evolution have provided every successful species with multiple sensory systems to assure a keen sense of SA. All animals use a combination of exteroceptive sensors (e.g. visual, auditory, olfactory and somatosensory including tactile) to keep track of objects in the external environment and proprioceptive sensors (e.g. muscle and tendon stretch, vestibular linear and angular acceleration and touch receptors) to provide awareness of body orientation and dynamics within the environment. Touch spans both categories of sensors which together provide during our day-to day activities independent, complementary, concordant, redundant, reliable, and veridical sources of information that are assimilated and integrated in the central nervous system (CNS) to develop spatial orientation and SA. Obviously spatial orientation is a necessary prerequisite for SA. Over several million years, man and other terrestrial species have developed a refined set of sensors which are finely matched to the dynamics of our normal daily activities in the two dimensional environment for which they were "designed".

The sensory systems that serve so well on the ground fail when exposed to the acceleration dynamics of the high speed platforms in the aerospace environment. The frequent changes in acceleration and direction of aircraft motion subject aircrew to a resultant gravitoinertial force that is constantly changing in magnitude and direction. Under such circumstances, the somatosensory and vestibular sensors responding to this constantly varying apparent gravitational field provide concordant but false information concerning the direction of "down." Unfortunately, varying gravitoinertial force fields can also produce visual illusions of motion and position. Thus in unusual acceleration environments the CNS has the added responsibility of determining which sensory information is valid.

Understandably, the typical spatial disorientation mishap occurs when the visual orientation system is compromised (e.g. temporary distraction, increased workload, transitions between visual and meteorological conditions, or reduced visibility). The CNS must then compute orientation with the only information remaining – the frequently false vestibular and somatosensory information, which is however in agreement with each other and hence very compelling. It is for this reason that under these circumstances spatial disorientation is a physiologically **normal** response.

TECHNOLOGY Is The Situational Awareness Threat

1) Technology has provided platforms that expose our biological sensors to stimuli that exceed the limits of sensor design.
2) Technology now permits the presentation of so many sources and such large quantities of information that the cognitive integrative capacity of the CNS is overwhelmed.
3) The dynamics of the changing information and conditions provided by the new platform technologies far exceeds the processing limitations of biological systems.
4) Technology has increasingly provided aircrew with the opportunities to fly under conditions that are conducive to producing spatial disorientation and loss of SA.

The US Army has noted an increase in the number of spatial disorientation mishaps since 1985 coinciding with the introduction and widespread use of night vision goggles (NVGs) (1). This technology permitted new mission profiles including the introduction of night nap-of-the-earth flight, night formation flight, all weather flying and the carrying of external loads at night all of which subject the pilot to more opportunities to experience spatial disorientation. Furthermore new helicopters are more agile permitting more vigorous acceleration maneuvers – another factor responsible for the increasing incidence of spatial disorientation mishaps.

The Solution for Aerospace Spatial Disorientation: TECHNOLOGY

The solution to the biological problems posed above is technology.

To maintain spatial orientation in the three dimensional aviation environment, pilots must be provided with an intuitive, continuous, veridical source(s) of orientation information requiring minimal cognitive effort similar to the situation humans normally experience in the two dimensional terrestrial environment.

The Tactile Situation Awareness System (TSAS) is simply a matrix of tactile stimulators (tactors) incorporated into a flight suit (tactor locator system) that provides the pilot with critical flight parameters via the sense of touch. A variety of algorithms have been developed that apply information derived from the aircraft sensors via an intuitive haptic display to the aircrew so that they are continuously provided true orientation information. The success of TSAS as an orientation device is described in other papers in this symposium and elsewhere (2,3,4,5,6,7). What has made TSAS successful is the intuitive nature of the display.

The concept of using skin to receive information normally presented by the visual channel is not new. For example, the presentation of letters via Braille is used by thousands of visually challenged people. The disadvantage of Braille is the duration of the training period required to become proficient in its use. Like reading for children, the acquisition of Braille skills is non-intuitive and typically requires at least a year or two of intensive training. In the late 1960's and early 1970's there were several efforts (8,9) to provide visual information (pictures, movies, television etc.,) hapticly on the back or chest using large scale dense matrix arrays of tactors. In the early 1970's haptic aviation displays for navigation, airspeed control (10), or command direction to move controls were attempted without success. None of these attempts succeeded, in part due to the non-intuitive nature of the display and in part, due to presenting information that exceeded the physiological capabilities of the touch sensory system. Skin on the torso has a two-point discrimination of several centimeters, which prevents the presentation of information that does not match the bandwidth of the limited resolution available.

Intuition is the power of attaining direct knowledge or cognition without rational thought and inference. What makes a tool or system intuitive and how can you ascribe a value to the "intuitiveness" of a system? An interface or system is intuitive when the logical operation is consistent with the operator's life experience and mental model. Most pilot interfaces and avionics systems are designed by engineers and human factors engineers with the view of training the pilot/operator to think like the system they have designed. The recent trend in human-centered design is instead to develop a system that operates like the pilot thinks. However, despite marginal improvements, since these displays are visual they continue to require significant cognitive effort. TSAS as we shall see goes one step further in that it works like the pilot **reacts** by accessing the pilot at the level of "reaction" and "subconsciousness" behavior.

Spatial orientation in our daily activities is an automated process that does not normally require conscious effort. Nature has developed highly efficient automated "subroutines" that provide excellent spatial orientation to animals while permitting them to attend to other survival tasks such as hunting or evading predators. If it were necessary for prey animals to devote the same effort to orientation that pilots currently do they would not eat regularly and would themselves become hunted.

Reflexes, such as limb withdrawal in response to a painful stimulus, occur at the lowest level of the CNS organization -- at the segmental level of the spinal cord. Such reactions have limited, well defined, constrained neural elements that convey robust "hardwired" responses that posses limited ability to change with repeated experiences. By comparison high level cognitive tasks (e.g., instrument reading and subsequent decision making) are associated with cortical processes characterized as anatomicly diffuse, and subject to behavioral plasticity from many subtle spheres of influence. In terms of computer technology reflexes resemble hardware while cognition resembles software.

Between these two extremes is the organization of automated functions such as orientation. The lowest level at which we see a coordinated orienting reflex in response to local stimulation is at the level of the midbrain. Midbrain stimulation produces a patterned eye, head, neck, torso and limb movement to direct attention to a specific location in space. The organization and temporal development of the neural architecture responsible for these orientation reflexes reflects the primacy of touch for spatial orientation and situation awareness. In the ontogeny (i.e., developmental sequences in the life of the individual) of neural development, the first sensory system to which reactivity can be shown is the skin-muscle-joint proprioceptive system (11). As can be seen in Figure 1, the vestibular system follows and it is only much later that the auditory and visual orientation sensory systems are sequentially added to form the overall spatial orientation system. This is in keeping with the principle that "ontogeny recapitulates phylogeny" (i.e., individual development follows the temporal pattern that has occurred over the evolutionary time scale). It thus indicates that touch is the first orientation system from an evolutionary perspective.

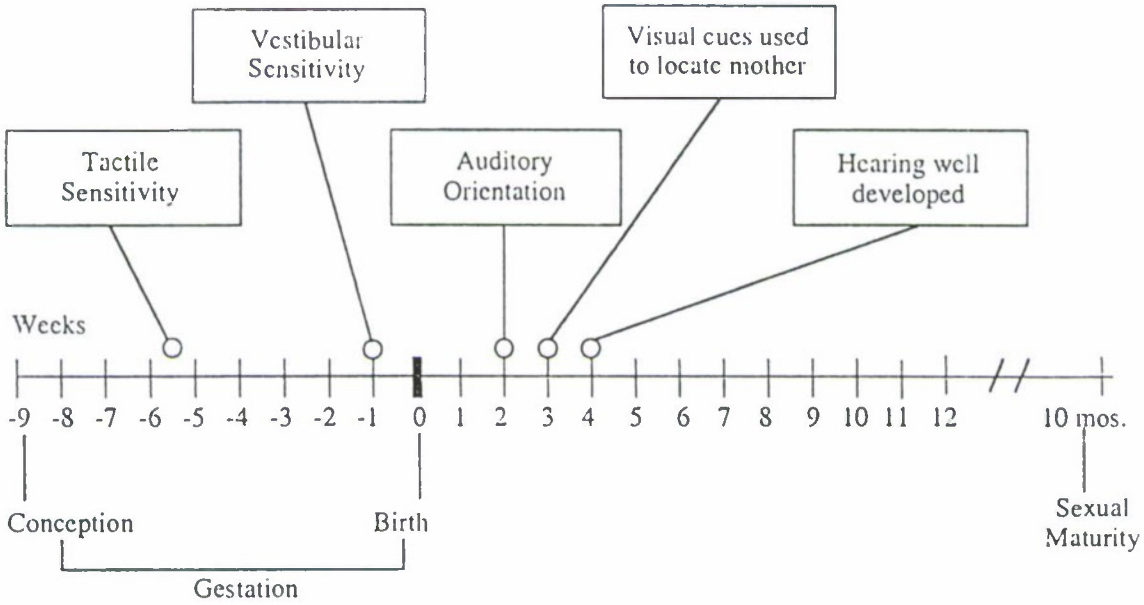

Figure 1. Timetable outlining sensory development of the domestic cat. (Turner and Bateson, 1988)

Within the midbrain the haptic system is topologically arranged to map to the external environment. It is the lowest layer and sequentially the auditory and visual representations of the world are overlaid during development with their connections and architecture built on the base architecture established by the sense of touch. For this reason touch is the primal orientation system. The other sensory systems depend on it for development. Although people are often born and survive without vision or without hearing, individuals born without proprioceptive touch do not survive. Indeed the very rare individual who loses the sense of proprioceptive touch later in life finds the simple task of reaching for objects or walking so cognitively demanding as to be totally exhausting to the point that remaining in a wheelchair may be the better choice. This should cause us to reevaluate the literature that so often claims vision is the most important orientation sense.

Proprioceptive touch like the vestibular system provides continuous information that does not reach our level of awareness or consciousness except under unusual circumstances (e.g., conflicting or confusing information). In summary, the automated function of haptic orientation has a well defined midbrain architecture (hardware), fast robust responses, and minimal demands on cognition which make it the best candidate to provide continuous, intuitive orientation information.

One measure of the "intuitiveness" of a tool or system is the time required to train an individual to use the system. A perfectly intuitive system requires no training. For example, a TSAS designed to tap the operator on the shoulder, or a location on the torso, to represent a threat towards which she/he is to direct attention is a system that the takes advantage of the cumulative life experience of the operator. In actuality, the operator has been "trained" from the point in development at which these reactions could be demonstrated in the womb. Consistent reinforcement of this reflex with day-to-day life experiences provides the training that TSAS takes advantage of through human-centered design of the TSAS interface. Another example is the TSAS orientation to the direction "down" – a prerequisite for both visual and instrument flight. The TSAS provides tactile stimuli to the area of the torso where the pilot would normally receive pressure cues on the ground if she/he were firmly attached to a chair with multiple straps. Such a presentation requires only minutes to train either an experienced pilot or novice since for both individuals the logical operation is consistent with their mental model based on cumulative life experience. The relation between intuitiveness and time required to train is obvious. Orientation displays that require little or no training take advantage of neural architecture developed over millions of years. When a designer can use the fast, robust reflexive tactile system in lieu of the slower, more plastic cognitive visual processes the resulting display will enhance pilot performance by increasing the cognitive reserve available for other cockpit tasks.

As pointed out earlier, some aspects of SA including spatial orientation are not normally cognitive tasks demanding attention. They occur at a lower level, sometimes reflexively, and operate on neural architecture reflecting the development of "subroutines" that permit the individual to allocate cognitive/attentional resources to other tasks. In the typical military cockpit there are many types of information that can only, or are best, presented visually. TSAS presentation of flight information will reduce "clutter" on visual displays thereby enhancing the presentation of visual data.

The TSAS is not limited to individual awareness but is easily applied collectively to the flight crew. Normally critical information is either duplicated as redundant instrumentation or alternatively, is located in the shared space between the pilots as an "open interface" whereby pilots monitor the action of the other without verbal communication. TSAS can provide simultaneously to all aircrew, the critical information (attitude, airspeed, ground proximity, target range and bearing, etc.) to enhance system robustness through multiple representation. It will also enhance detection of autopilot errors by providing all aircrew with attitude information to enable aircrew to detect uncommanded flight profiles.

Recommendations for Future Research Directions

1) Basic science research focused on a) optimizing the presentation of flow and dynamics of orientation, b) techniques to minimize the number of tactors using the illusions present in the system of touch, and c) mixtures of tactor clusters presenting vibratory, electrical, and tangential sweep stimuli.
2) Tactor development including reduction in size and power requirements.
3) Basic science research to determine the optimal mixture of sensory modalities to convey spatial orientation and situation awareness information in the aerospace environment.

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Evaluation of Prototype Display of Enemy Launch Acceptability Region (LAR) on the F/A-18 HUD

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This study began with an informal survey of tactical aircrew for suggestions on potential display modifications to improve situational awareness (SA) in the electronic air combat environment. One suggestion that was repeated among F/A-18 aircrew was to display an enemy's Launch Acceptability Region (LAR), in addition to ownship LAR, which is currently displayed. The current Launch Acceptability Region is displayed on the Normalized In-Range Display (NIRD) / Allowable Steering Error (ASE) circle on the head up display (HUD), as well as on the Radar Scope. It provides the pilot with information on his/her ability to destroy a threat. The LAR includes three parameters: Rmax (the pilot is within range to destroy the threat with the selected missile), Rno escape (if the pilot fires a missile, it will most likely destroy the threat), and Rmin (if the pilot shoots after Rmin, the missile will not arm fast enough to destroy the target). At the present time, there is no display telling the pilot when he/she is within lethal range of a threat aircraft; e.g., when he/she is in the threat's Rmin, Rmax and Rno escape. The pilot must calculate this information, considering prior information, training, intelligence regarding the threat, and it's probable missiles and their parameters. According to aircrew, this involves a good deal of "number crunching" headwork. While aviators are skilled at such tasks and often have the ability to learn weapon performance parameters rapidly, it takes experience and flight hours in a particular platform to develop what Schneider and Shiffrin (1977) describe as automatic processing of the information. According to Fisk and Scerbo (1987), there are several fundamental differences between automatic and controlled processing. Whereas controlled processing is serial in nature, requires effort, and requires little or no practice to achieve asymptotic performance, automatic processing is parallel in nature, requires little or no effort, but requires extensive, consistent training to develop. Perhaps most importantly, automatic processing, unlike controlled processing, is not limited by short-term memory (STM) capacity. Automatic processing of the information inherent in determining an enemy's LAR is critical to a pilot operating under the stress of combat conditions, particularly in a cockpit that is becoming increasingly complex, with multiple sources of data to be manipulated in STM. While automatic processing might be expected in the platform-seasoned aviator, many combat aviators, such as a pilot fresh out of the Fleet Replenishment Squadron (FRS), will not posses that level of familiarization with a particular platform.

The purpose of the present study was to examine whether the concept of displaying the enemy's LAR to the F/A-18 pilot would significantly enhance his/her SA of ownship vulnerability and improve performance by reducing number-crunching headwork and allowing for more timely and accurate decisions and tactical maneuvering. A prototype display of enemy LAR was presented on a simulated F/A-18 HUD, and compared with the current LAR display. Results indicated that pilots were more accurate in determining their own vulnerability with the prototype display, and that they did so more rapidly. Additionally, subjective data indicated that pilots perceived themselves as having better SA and lower workload with the prototype display.

Method

Eleven test pilots from Strike Aircraft Test Squadron at the Naval Air Warfare Center, Aircraft Division, Patuxent River participated as subjects. All had time piloting the F/A-18, including 6 qualified F/A-18 pilots. The study was conducted in the Crewstation Technology Laboratory (CTL) and utilized the behavioral and testing resources developed and operated by Dr. R. S. Dunn and his staff. Special contributions were made by Tom Moulds of the CTL, who spent many hours programming and reprogramming the various prototype displays and experimental scenarios.

The simulator used for the testing was a mid-fidelity F/A-18 mimic (did not utilize actual mission computer) developed by Sim Systems and maintained and modified, where applicable and allowable, in the CTL.

Prior to data collection, all subjects received a preflight brief. The brief included a "familiarization flight" in the simulator, the goals of the mission and the evaluation, and the parameters of the notional missiles carried by ownship and opponent aircraft, described below.

Each subject flew 5 scenarios that varied in altitude and airspeed. All scenarios began 40 miles out and ran until the clock on the ASE/NIRD circle reached just past Rmax. All scenarios were flown first with the current LAR display (Figure 1), and then with the prototype display of enemy LAR (Figure 2).

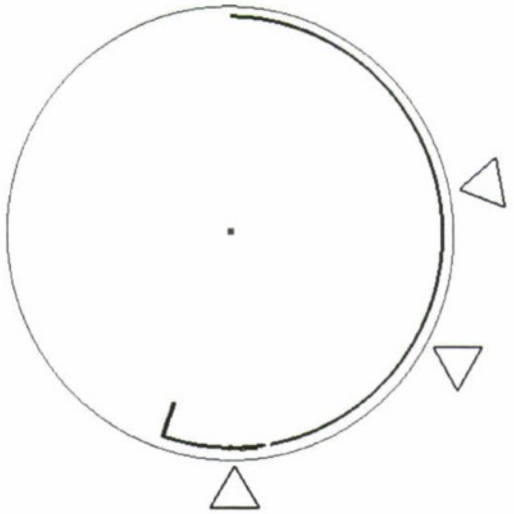


Figure 1: Current LAR Display
(Clock ticks down counterclockwise. In this instance, ownship is approaching Rmax.)

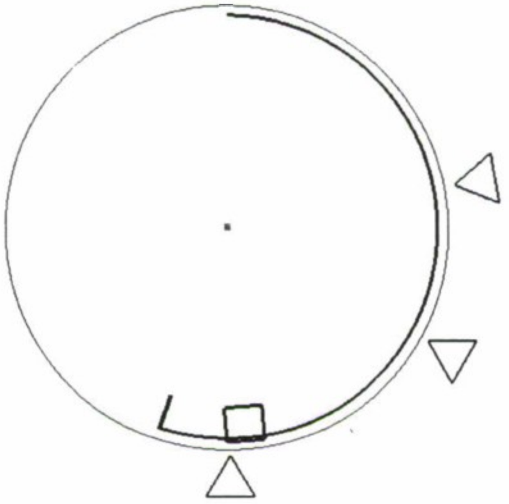


Figure 2: Prototype LAR Display
(Square box represents opponent's clock. In this case, the opponent is at Rmax before ownship; i.e., the opponent has "shoot first" advantage.)

This aspect of the design was not counterbalanced. As all subjects were familiar with the current display, it served essentially as a baseline and the experimenters did not expect its precedence to have an effect on data or ratings under the prototype display condition. On the other hand, it was expected that prior viewing of the prototype display might effect either performance, verbal reports, or subjective ratings of the current display.

Scenarios were designed to provide an equal number of engagements in which either the ownship or the opponent had the "shoot first" advantage. In all cases, the subjects were instructed to maintain altitude and airspeed (except the Combat Air Patrol scenario, in which they were directed to increase speed upon radar contact). Subjects were told to assume their opponent was co-altitude and co-airspeed, in a straight-on 1 v 1 engagement. Aircraft maneuvers had to be discouraged due to limitations of the simulator, but aircrew were instructed to verbally report any evasive or aggressive maneuvers they would pursue in any given scenario. Subjects were also instructed to verbally report whether they or their opponent had the "shoot first" advantage, both at initial contact and at Rmax.

The simulator was programmed with parameters for two different notional missiles: one for ownship and one for opponent aircraft. The concept of using a notional missile was applied in order to create a potential for memory load similar to what a novice (in platform) pilot might experience under combat conditions. Because we could not recreate this scenario in a simulation using highly experienced test pilots who have intimate knowledge of the F/A-18 weapons payload, we created notional missiles for both ownship and opponent. Each subject studied the performance parameters of both missiles prior to participation in the simulator runs.

During the simulator runs, video and audio data were recorded. The video recorded the information from the simulator screen (the HUD information), while audio recorded pilot comments and verbal data. Following each round of scenarios (without versus with the new prototype display), subjects were given the China Lake Situational Assessment (CLSA). This is a subjective situational awareness scale under development by Steven Adams at the

CHINA LAKE SITUATION ASSESSMENT (CLSA)

SA SCALE VALUE		**CONTENT**
VERY GOOD	**1**	o FULL KNOWLEDGE OF TACTICAL ENVIRONMENT / OWNSHIP LAR RELATIVE TO ENEMY LAR o FULL ABILITY TO ANTICIPATE/ ACCOMMODATE TRENDS
GOOD	**2**	o FULL KNOWLEDGE OF TACTICAL ENVIRONMENT/ OWNSHIP LAR RELATIVE TO ENEMY LAR o PARTIAL ABILITY TO ANTICIPATE/ACCOMMODATE TRENDS
ADEQUATE	**3**	o FULL KNOWLEDGE OF TACTICAL ENVIRONMENT/OWNSHIP LAR RELATIVE TO ENEMY LAR o SATURATED ABILITY TO ANTICIPATE/ ACCOMMODATE TRENDS
POOR	**4**	o FAIR KNOWLEDGE OF TACTICAL ENVIRONMENT / OWNSHIP LAR RELATIVE TO ENEMY LAR o SATURATED ABILITY TO ANTICIPATE/ ACCOMMODATE TRENDS
VERY POOR	**5**	o MINIMAL KNOWLEDGE OF TACTICAL ENVIRONMENT/OWNSHIP LAR RELATIVE TO ENEMY LAR o OVERSAT ABILITY TO ANTICIPATE/ ACCOMMODATE TRENDS

Figure 3: CLSA Scale Results

Naval Air Warfare Center Weapons Division (NAWCWD) China Lake. The descriptors on the scale were modified slightly to fit the present task. A sample of the scale is provided in Figure 3. Additionally, after all simulator runs were completed, each subject was given the Subjective Workload Dominance (SWORD) and SA-SWORD tests, a final questionnaire and a debrief. It should be noted that the SWORD and SA-SWORD were modified slightly. There were 9 response slots between the 2 displays being compared, as opposed to the typical 17 slots. According to Vidulich, Ward, and Schueren (1991), the number of slots was adapted directly from Saaty's (1980) Analytic Hierarchy Process (AHP) scale, in which 17 slots were selected to comply with Miller's (1956) seven plus or minus two capacity of working memory (1 slot for equal and 8 on each side). This was maintained in SWORD because the results of Budescu, Zwick, and Rapoport (1986) showed no reason to alter it. In other words, there's no evidence the absolute value of the slot number is a critical element.

Results

Video and audio data were post-processed to obtain accuracy and "decision time" data. Accuracy was determined by the subjects' verbal reports of whether they or their opponent had the "shoot first" advantage in a particular scenario. The percentage of correct reports across scenarios was recorded for both the initial report (initial radar contact / start of wind-down clock on ASE/NIRD circle) and the report at Rmax. Decision time data was somewhat less explicit. Because verbal data were used, there was not a specific subject-initiated event (like a button press) from which to time how long it took a subject to decide who had the advantage. Instead, the investigators used "length of report." Subjects either gave an immediate report, such as "I have the advantage," or they appeared to think aloud, giving reports such as "Now at this altitude and airspeed...... I should have the advantage." Length of the report or "decision time" was defined from the first verbalization to the point at which a distinction between ownship and opponent was made.

In analyzing the performance data, the scenarios were treated as separate trials across which the data were averaged. A t-test for dependent samples was performed on the current LAR display versus the prototype LAR display for both the accuracy and the decision time data. Results indicated significant improvements in accuracy ($p < .05$) both at initial and at Rmax, and significant decreases in decision time ($p < .05$) with the prototype LAR. The respective means are displayed in figures 4, 5 and 6 below.

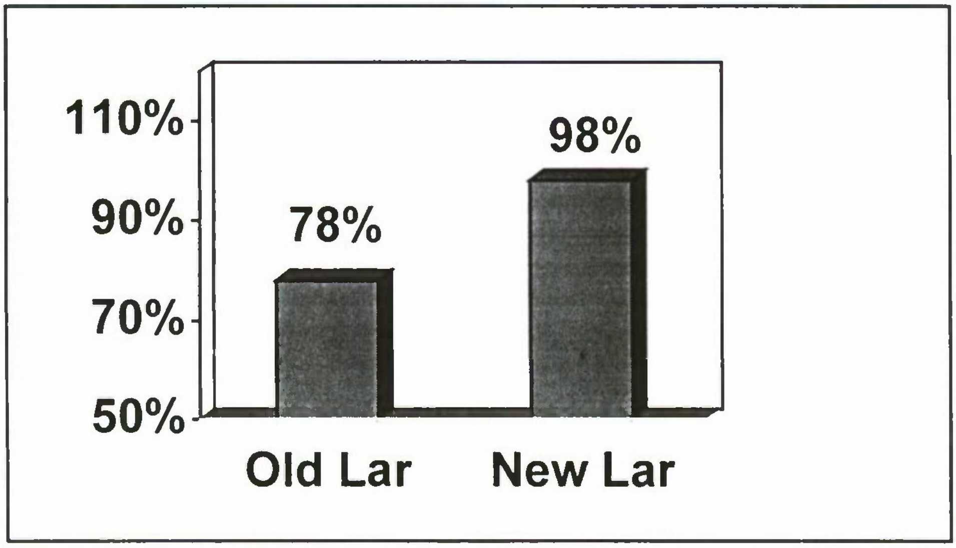


Figure 4: Mean % Correct at Initial

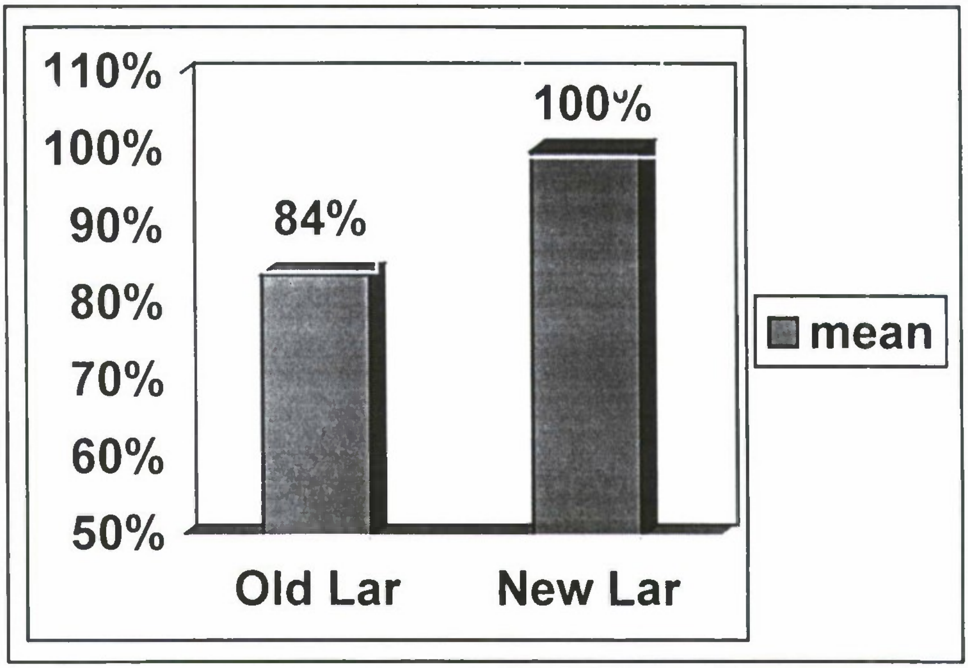


Figure 5: Mean % Correct at Rmax

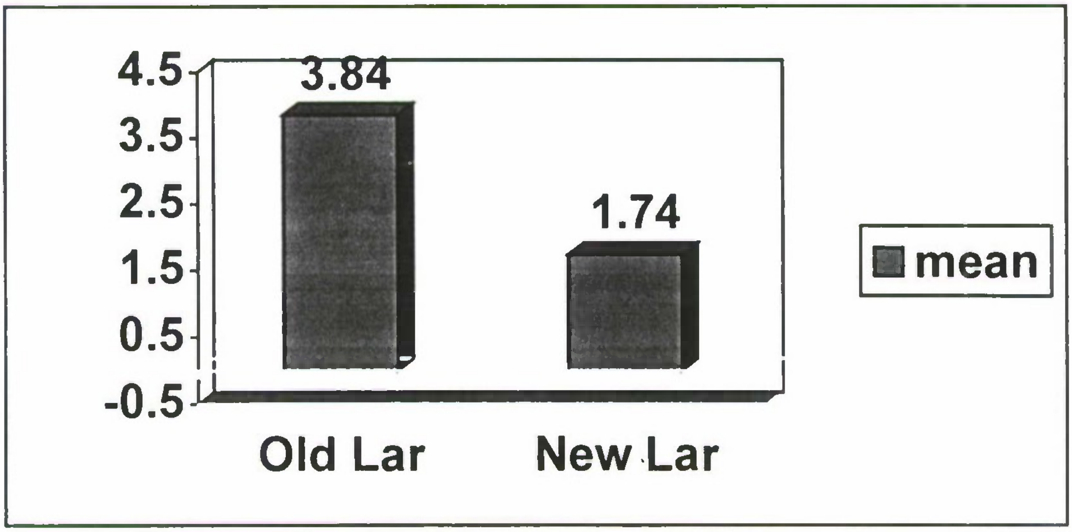
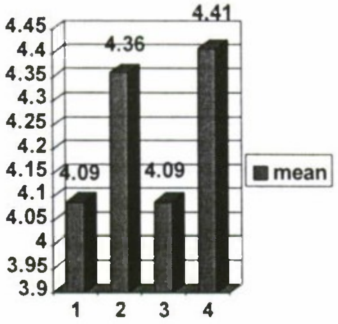


Figure 6: Answer Length/Decision Time (In seconds)

Regarding the subjective data, the Wilcoxon Matched Pairs test was performed on the CLSA data. It was significant at $p < .01$. For purposes of comparison, the mean CLSA rating for the current LAR display was 2.68, while that of the prototype LAR display was 1.45 (note that on the CLSA scale, the lower the rating, the higher the perceived SA).

A t-test for dependent samples was performed on both the SWORD and SA-SWORD data. As there is some controversy over whether SWORD data is truly ratio data, a Wilcoxon Matched Pairs test was performed, as well. Both tests were significant for both sets of data at $p < .01$. The workload rating means for SWORD were .744 and .256 for the current and the prototype display, respectively. Those for SA SWORD were .268 and .732 for the current and the prototype display, respectively.

Overall results for the questionnaire are reported on the chart below:



1 How much do you think the prototype display of enemy LAR would enhance your SA of your susceptibility to a threat??

2 How much do you think the concept of displaying enemy LAR would enhance your SA of your susceptibility to a threat?

3 How much do you think the concept of displaying enemy LAR would enhance your mission performance?

4 How much do you think the concept of diplaying enemy LAR would enhance your survivability?

In addition to the four rating-based questions, pilots were asked the open-ended question, "What changes, if any, would you like to see in the display?" The most frequent responses to this question included the following:

1) Answers related to the actual display, such as the desire for smoother transitioning of the tick-mark (less jumpiness), and the addition of aural cues (5 responses).

2) Desire to place the display heads-down in addition to the HUD, such as on the radar or SA page. Most of these respondents, however, stated that if they had to choose 1 position to display enemy LAR, it would be on the HUD (4 responses).

3) Display additional information, such as weapons type and multiple bogies (4 responses).

Discussion

Whenever a new concept of displaying information in the cockpit is introduced, it is often met with some resistance. This is with good reason. The modern cockpit is inundated with data from a variety of sources, and whether or not those data are transformed into usable information by the pilot depends on several factors inherent in human cognition, display design, and their interaction. This is particularly true of the F/A-18, with its single crewmember and its very utilized mission computer. In the case of displaying enemy LAR, for example, where it may seem obvious that such a concept should improve SA of ownship vulnerability, many would argue that any additions to the HUD would prove distracting to the pilot. The approach of this study, therefore, was to prove the utility of the concept of displaying enemy LAR through rapid and relatively inexpensive prototyping. Such prototyping can be a very useful and important method of obtaining initial data to examine whether or not a new concept is worth pursuing.

According to the findings, the concept of displaying enemy LAR on the HUD significantly improves the F/A-18 pilot's situational awareness of ownship vulnerability. This is evidenced by improved accuracy and reduced decision time in determining ownship versus opponent advantage, as well as subjective ratings of SA. Furthermore, the subjects indicated a strong belief that such information displayed on the HUD would enhance their mission performance and survivability.

From this point, it is now necessary to pursue more detailed areas of the research question, particularly related to displaying the information under the various operational conditions that are likely to be encountered. Future research needs to examine several display considerations in a high-fidelity simulation of realistic operational combat conditions. Display considerations should include those highlighted by the aircrew, including placement of the enemy LAR display (HUD versus radar screen versus SA page versus all three), optimal design of the display itself, and the optimal number of bogies that can be tracked. The research field is currently exploding with advanced display technologies, from 3-D audio to virtual reality displays, and such avenues should be considered for their potential to improve enemy LAR displays. Finally, there are several considerations regarding implementation of an enemy LAR display in the actual aircraft, and such practical matters as mission computer capacity must be taken into account when operating future evaluations under higher fidelity simulation, and well as in any fleet implementation planning.

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An Intuitive User Interface for the Virtual Reality Responsive Workbench

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1. INTRODUCTION

The Naval Research Laboratory (NRL) has been involved in research and development efforts in the areas of (1) automated routing of strike aircraft[1], (2) advanced 3D displays and interaction technologies, and (3) collaboration tools and protocols. This research has been conducted to advance the state of the art in each technology area, particularly for military command and control applications.

This paper will concentrate on the research conducted in item (2), the results of which are incorporated in the STrike Optimized Mission Planning Module (STOMPM). The STOMPM testbed allows the user to load various terrain data, create strike related routing scenarios consisting of threats and targets, test the various routing algorithms and assess their performance, and visualize this information and interact with it in a natural setting. Two versions of STOMPM currently exist, versions 1.0 (v1.0) and 2.0 (v2.0). The STOMPM v1.0 was primarily developed to test auto-routing technology, and does not include technology needed to run on advanced displays such as the Virtual Reality Responsive WorkBench, VRRWB (i.e., STOMPM v1.0 operates best on a computer monitor with a mouse/menu interface). The STOMPM v2.0 also includes autorouting technology (specifically autorouting algorithms which take into consideration fuel and turn constraints which are not included in STOMPM v1.0), but also includes a user interface that is well suited to running on more advanced displays such as the workbench.

This paper will provide a high level description of both versions of the STOMPM testbed. Following this discussion, we will describe state-of-the-art technologies in visualization, advanced displays and scene interaction capabilities that have been incorporated within STOMPM v2.0. We will conclude with a discussion of the advantages associated with the use of the workbench and also the interface that has been developed within STOMPM for the workbench. Lastly, we will discuss areas for future research.

2. STOMPM SYSTEM DESCRIPTION

The STOMPM system serves as a testbed for the research and development of strike asset routing algorithms, 3D displays and interaction techniques, and research in collaborative tools and protocols. Version 1.0 of STOMPM was built mainly to support research conducted in strike asset routing algorithms, while version 2.0 of STOMPM was built primarily to support advanced 3D displays and interaction techniques (both versions have similar models, e.g., Radar Terrain Masking (RTM)[2]. The following sections provide details associated with each version of STOMPM.

2.1 THE STOMPM v1.0

The original STOMPM testbed (V1.0)[3] was developed in C using the FORMS[4] software library for the user interface and the native SGI graphics library for rendering the scene. The main emphasis of STOMPM V1.0 is to allow the developer to easily incorporate auto-routing technology and be able to test the algorithms via a simple mouse/menu user interface. Many autorouting algorithms were implemented ranging from simple least cost path to jointly optimal routing[1]. A screenshot of the STOMPM system is shown in Figure 1. This version of STOMPM allows the user to load terrain maps (i.e., Digital Terrain Elevation Data or DTED), place assets, radar types, and targets on the terrain, specify routing parameters, and eventually choose a particular routing routine to find route(s) from the assets to the targets. The user has the ability to save/load scene files, view the environment from various locations, get/change information about entities in the scene, and modify certain attributes associated with the visualization of this information.

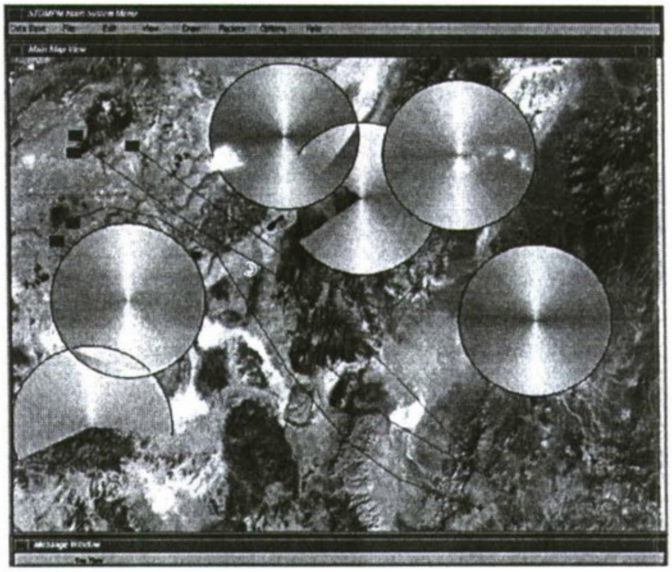

Figure 1: Screenshot of STOMPM V1.0 User interface. Shown are the RTM cones and a set of suppression and attack routes. The suppression routes open a corridor for the attack routes.

Although version 1.0 of STOMPM was specifically designed to test autorouting technology, near the latter part of it's development cycle stereographics[5,6] were incorporated into the interface. Since this version of STOMPM was still based on the mouse/menu style interface, it did not work well with stereographics because the menus were not drawn as a part of the environment being modeled, and only the environment and the objects contained in it were in stereo. This was part of the reason that STOMPM was eventually reimplemented. A second reason for reimplementation was due to the fact that version 1.0 was not easily extendable. Creating new objects meant defining new data structures for objects. An object oriented paradigm was investigated and eventually accepted as part of the design in order to provide a more flexible system in which new objects could be created with little effort, making use of already existing object classes.

2.2 THE STOMPM v2.0

The STOMPM V2.0 is a set of object-oriented C++ toolkits that facilitate the development of virtual environment simulation & planning environments. The STOMPM toolkits as they exist now provide a means to access and use routing algorithms, visualize and interact with a scene, and collaborate with other distributed STOMPM modules. A primary goal of STOMPM was that it be useful and easily transferable to other uses or designs. Towards this end, each of the STOMPM toolkits is specific in purpose, either extending existing functionality or adding to it. Through the combined use of some or all of the toolkits, it is possible to easily build new applications and/or interfaces by adding to the existing foundation of components and coding practices. In the discussion that follows, all italicized words can be interpreted as base classes or objects derived from those base classes. In either case, the meaning of these italicized words are the same in the context in which they are used, the difference is important only in the design and implementation phase (i.e., they can be used interchangeably for the purpose of the discussion).

The purpose of STOMPM is to support the capability to generate an automated set of routes from a set of starting points (sources) to a set of targets (sinks) contained in a defined scene with obstacles. A primary goal of STOMPM V2.0 is that it continues to be an extensible application, ready for use or as the basis of new or old applications. In achieving these two goals, as with all programming, it is important to define the constraints, key dependencies, and post-conditions that define how to implement the goals more concretely. Therefore, the design of STOMPM started with the desired capabilities, which were mainly set at the beginning, but also evolved over the course of the project. Below we discuss the capabilities developed as a result of our goals.

The routing algorithms in STOMPM, given a correctly specified scene and set of routing constraints, calculate an optimal route from a source to a target. Currently there are three algorithms in V2.0, but this number will be extended in the future. There is an unconstrained router, a router that is restrained by turn-angles but trades speed for a possibly non-optimal route, and an optimal turn-angle constrained router. The algorithms are interested in those objects in the scene that represent a threat to an asset attempting to get from the source to the sink. An example of such a threat is a radar, which interacts in complex ways with the surrounding terrain. Thus the router is dependent upon a certain scenario or scene the user has created, and the underlying objects that make up this scene.

STOMPM provides several different utilities that may be used to create a versatile, alterable, and extendable user interface to interact with the objects in a scene or other components of STOMPM. The first point regarding the STOMPM interface is it's ability to provide a representation of the scene which the router will use, implying both a user viewpoint, and graphic representations for all objects that make up the scene. Visualization is crucial for concepts like RTM that are most intuitively understood and correctable when visualized. Secondly, the ability to alter the user viewpoint and the objects in the scene (hereafter referred to as *SceneObjects*) is present in the form of a user *HotSpot*. The *HotSpot* is a 3D version of a mouse pointer and can be driven by a variety of input devices (mouse, 6 degree of freedom tracker, keyboard, etc.) and is used to select, move objects, alter the user's view, etc. STOMPM also is able to store and retrieve scenes for use at a later time.

Though the interactions with the *HotSpot* can be varied in several ways, there is still a need for other forms of input. STOMPM also provides both keyboard support and 3D menus (which interact with the *HotSpot*). All of this assumes that the user wishes to interact directly with the scene. However, another means of changing the scene the router uses is also available within STOMPM. There exists support for distributed communication, currently limiting the users to one concurrent shared scene. Thus, it is possible to alter the layout of the scene by reading from a STOMPM feed coming from another computer over a network. The interactions with the scene are merely support to supply the router with the necessary information to do its work.

The STOMPM system is composed of a complex set of components. It is able to provide scene management, viewing, support for various input devices, a 3D menuing system (Figure 2), peer-to-peer networking support, object interaction through the *HotSpot*, provide information feedback, archivability, as well as providing hooks for other useful operations. The next section will describe the visualization, advanced display, and scene interaction capabilities that have been implemented within STOMPM v2.0.

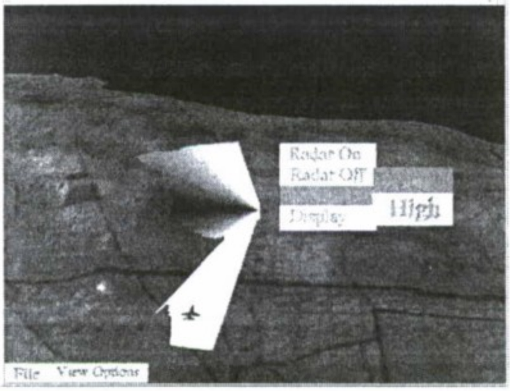

Figure 2: The STOMPM v2.0 user interface showing the *HotSpo*t (seen as circle in ``Low" per object submenu), 3D System Menu, and 3D Per/Object menus for manipulating object specific information

3. VISUALIZATION, ADVANCED DISPLAYS AND INTERACTION IN STOMPM

The next section will discuss a visualization technology that has been investigated and implemented within STOMPM, namely the use of stereographics for the inspection of the 3D strike information. The following section will discuss an advanced display technology being utilized for the 3D visualization of STOMPM scenarios, namely the virtual reality responsive workbench. The advantages of using the workbench will be presented. Lastly, we will discuss novel interaction technologies that have been developed within STOMPM for the workbench.

3.1 VISUALIZATION TECHNIQUES

Stereographics[5,6] provides a true 3D representation of an environment by providing two images to the eyes in sequential order, one for the left and one for the right. This allows the user to perceive depth on a two-dimensional monitor. Implementing the stereo effect in software is not very difficult and works as follows: produce two images of the scene and double the monitor's refresh rate. One of these images is for the right eye while the other is for the left eye. The user can then wear Liquid Crystal Display (LCD) shutter glasses to view the image in stereo. The shutter glasses work by showing the left eye the image intended for the left eye and the right eye the image intended for the right eye, in alternating sequence (i.e., the shutters in the glasses open and close in synchronization with the monitors refresh rate - the synchronization signal is sent to the glasses from an emitter). The overall effect to the user is a view which more closely resembles 3D - the stereo image can be either projected in front of, or behind, the computer screen, by adjusting a parameter in the software that controls the distance from the eyes to the image convergence point.

There are several items worth mentioning about the use of stereo. As was already mentioned, the stereo image can be projected in front of, or behind, the computer screen by adjusting a certain parameter in the software. When one sets the parameter such that the image is projected in front of the screen, the eyes can get confused by a floating image in front of the screen, which when seen in comparison to the edges of the window/display, appear underneath the window/display (edge effects). Zooming or panning effects can further magnify the "edge effect" phenomenon. Therefore, it is important to have the entire scene visible when one wishes to project the image in front of the computer screen. However, by having the entire scene visible on the screen, it may be impossible to view the important details associated with the scenario. In many instances, it is desirable to project the image behind the screen. What we have noticed is that in our particular application, when the maximum height of the viewable terrain is projected behind the screen, even after panning or zooming, edge effects are removed. In this regard, it may be easier to zoom or pan, thus enabling more details associated with the scenario to be seen.

3.2 ADVANCED DISPLAYS

The NRL has investigated the use of advanced displays for Command and Control applications, particularly the use of a virtual reality responsive workbench, (Figures 3a and 3b). The workbench was originally developed and built at the GMD National Research Center for Information Technology, and a copy was built at NRL for initial research. Currently, NRL is using a commercially available workbench developed by Fakespace Corporation. Whereas the original workbench top was not adjustable, the one developed by Fakespace has an adjustable table top which can tilt to approximately 45 degrees for easier viewing.

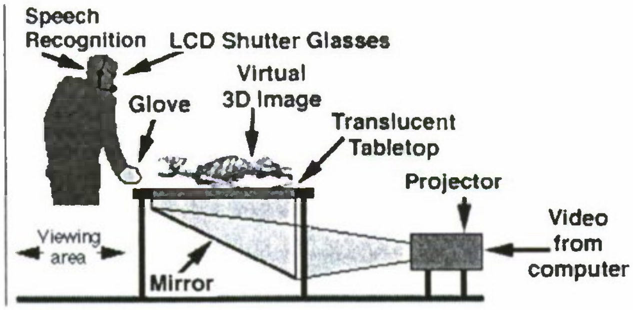

Figure 3a: A schematic of the virtual reality responsive workbench (printed from the NRL's VR Laboratory homepage).

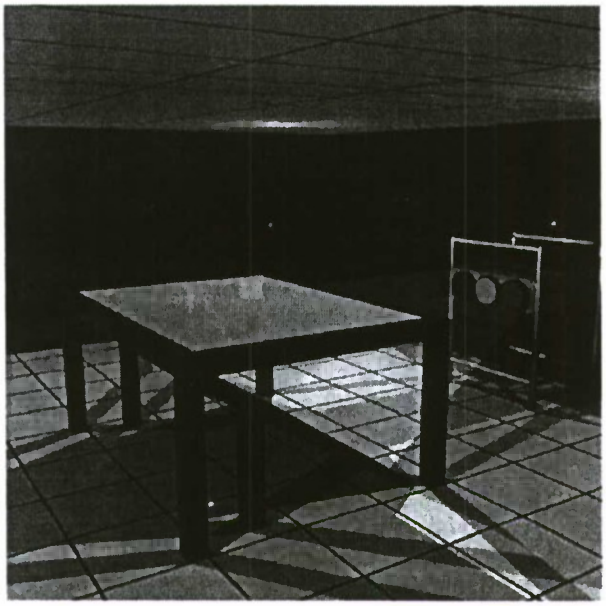

Figure 3b: A computer generated image of the virtual reality responsive workbench.

Video from the computer is sent to the projector, which projects the stereo image onto a mirror. The mirror reflects this image onto a translucent table top. Two pairs of emitters are mounted at the back two corners of the table top. The use of two pairs of emitters provides a stronger synchronization signal for the shutter glasses, however, a single emitter could be configured for use. When displaying an image on the workbench, the user can control whether the image appears to float above, or just below, the table top by adjusting the same parameter which controls where the image converges (e.g., with respect to the far/near clipping planes).

The advantage of the use of stereo on the virtual workbench arises from observing that users naturally perceive altitude in the same direction as a vector which is perpendicular to the earth. The workbench provides an environment in which users can naturally interact with objects on terrain in a natural table top environment. On a computer monitor, altitude would be in the same direction as a vector perpendicular to the computer screen. This is a little awkward to work with, especially when trying to adjust the routes in the z direction. The viewing area is also greater as compared to the standard computer monitor. This larger viewing area provides a more comfortable environment for multiple user to interact with the workbench application.

3.3 INTERACTION IN STOMPM v2.0

STOMPM is made up of several components and toolkits. Each toolkit/component provides an independent functionality that is intrinsically different from the others. The primary toolkits that STOMPM provides are the Application Tool Kit (ATK), the Routing Tool Kit (RTK), the Graphic ATK (GATK), and the Networking TK. Within each of these toolkits are components and/or extensions to objects in other toolkits. Another crucial component is the *SceneObject* that the other toolkits either manage or use to accomplish their task.

The ATK provides a framework basis for the other toolkits. The GATK adds graphic capabilities to the existing system. The RTK uses the ATK and *SceneObjects* to perform its routing tasks. The Networking TK extends network functionality to the ATK & GATK, but could also be considered more an extension of the existing framework than a part of the framework. The GATK will now be described in greater detail.

The purpose of the GATK is to provide a base set of tools that are extendable for developing the GUI that will meet the end-users' needs. The GATK, as its name implies, inherits from the ATK, mainly because all of the components it uses must also be changed to be graphic in nature but are the same in functionality. A platform limitation of the current implementation is that the GATK uses Performer, an SGI rendering system, to do its rendering and much of its interfacing. Beyond these factors, the GATK extends the ATK to include input devices, viewing paradigms, interface mechanisms, and other IO components which are usable in part, whole, or not at all, based on user requirements.

The key extension of the GATK is the introduction of the *HotSpot*. The *HotSpot* corresponds to a 3D mouse pointer in concept. With the *HotSpot*, you can select, pop menus up, move objects, etc. It is the graphical means by which input is specified. Visually it is represented as a spot on the screen, which is simple enough to understand. The more difficult part, is how to move and position it with 6 degrees of freedom, and how it communicates with the objects it interacts with.

The *HotSpot* currently is driven by one of two input devices. The first input device is a 3-Button mouse, and the second input device is a 6 degree of freedom tracker. The tracker is currently used as a virtual pointing stick to obtain the point of interest on the screen. The point of interest for a mouse is likewise an x-y coordinate pair. The point of interest is used to project a ray from the users viewpoint to the viewing screen's position in world-space, and the first object of intersection (assuming intersection) becomes the location of the *HotSpot*. So in a very real sense, the *HotSpot* is its own device that is driven by the tracker or the mouse. Using the buttons, the tracker or mouse handler can move the *HotSpot* in or out. As the *HotSpot* is considered native to the GATK, whereas the tracker/mouse devices are not, the *HotSpot* has communication protocols established with the objects it interacts with.

Every object of significance on the display is given the ability to handle events. By this mechanism, all *GSceneObjects* (and *InterfaceObjects* such as menus) are given the ability to respond to events that relate to them. This is set up primarily for interactions with the *HotSpot*, though the developer has the option of extending this. The *HotSpot* thus at agreed times sends informational messages to the objects it interacts with. In particular, when the object is selected, unselected, hit, or unhit, the object in question is notified that the event took place. Thus, each object chooses how it will respond to particular events. Most objects will probably respond in the same way, and thus are given a default handler. For instance, when most *SceneObjects* receive a move event, they move themselves in space. However, when the *TerrainObject* receives a move event, its behavior is overridden to move the viewer of the scene thereby accomplishing the desired interaction. Thus every object has the chance to easily override behavior.

By using the *HotSpot* and its communication protocol, several features of interest have been added to STOMPM. The user can now add 3D menus that when selected will perform developer specified callbacks. These menus are also operable on a per-object basis, radars can have one type of menu, each tank can have its own specialized menu, etc. Since these menus are just like any other 3D object in the scene, the stereo effect is preserved. Objects can have designated common handlers, e.g. all objects that must be placed on the ground can use one common handler that drops the object back to the ground when left in the air, while objects that can be left in the air use a different handler. An important aspect of a good user interface is the ability to move through the displayed scene quickly and easily.

STOMPM currently has two chief modes of viewing the scene. These modes are tethered viewing and egocentric viewing, which are entered into by selecting the menu items under the viewing menu. In tethered viewing mode, the user is virtually tethered to the 3D point of interest in world space, which is where the *HotSpot* was before entering viewing mode. In this case, moving to the left entails rotating about the 3D point of interest at a fixed radius in the XY plane that corresponds to the viewer's left. Viewing in egocentric mode is simpler. When the camera “moves” to the left, the viewer rotates their view and does not translate at all. Tethered viewing mode is of primary use when examining an object from several angles, but always looking towards the same area. Egocentric viewing mode is always looking from the same area. A third useful application of egocentric viewing is the ability to jump to any object the *HotSpot* points to, and then view from that point. Thus, it is possible to jump to a pilot's view or a view from a certain hilltop.

By using these two interface mechanisms, and other aspects of the GATK and *GSceneObject* interface it is possible to quickly maneuver through a scene and view its objects, as well as relocate them. Currently missing from the framework is an informational feedback of where the objects are as they are being moved, though this could be implemented quickly enough. Other features, such as drop-lines from the objects to give the user positioning information when they float above the terrain, bins to temporarily place objects in, means of removing all objects of a given type, etc. are all possibilities with the current STOMPM. However, as may have been apparent from the discussion there are some features that are more a part of the toolkit than others, and it is questionable where to draw the line between the toolkit components and objects proper, and those specific to the application. The end choice is always up to the developer.

4. CONCLUSION

The visualization of strike related information such as aircraft routes, terrain and radar envelopes has been enhanced by the use of stereographics, which has made it easier to view depth. Furthermore, coupling stereographics with an advanced display technology such as the workbench allow the users to work with a true 3D representation of the world on a table top environment, which appears to be most natural for planners as many of the planning activities with maps, etc are done on table tops. The workbench also provides a greater viewing area, allowing multiple participants to view and potentially interact with the environment being modeled. The interface that we’ve developed within STOMPM works well with the virtual workbench in many respects. Because the menu system is 3D, it does not interfere with the stereoscopic workbench application as would the traditional menus. Secondly, the object reachability constraints make it more convenient to drive the *HotSpot* via a joystick as opposed to driving it via other devices on the workbench such as data gloves. Due to the large display area associated with the workbench, a person wearing a data glove may find it difficult to interact with objects placed over such a wide display area. Using the joystick and associated buttons, the user is able to rapidly point and click with the *HotSpot* anywhere on the display area.

5. FUTURE DIRECTION

The GATK has a wealth of opportunities for expansion. It currently stores none of its parameters to file, so it is not customizable at all. There are many concerns regarding the display of other information, and options that are possible in the VR world that go beyond the components common to the X environment and personal computer operating environments. It would also be interesting to provide X widgets and menus, and/or porting to non-SGI systems, which would require a hefty rewrite of all the graphical elements. A potential area for investigation is the use of web technologies such as Java/ Virtual Reality Markup Language (VRML) as a graphical front end for STOMPM. This would allow planners to interactively plan and collaborate with workbench planners. We have replicated a module within STOMPM using Java and plan to continue research in the use of this emerging technology for real applications. Another area that we’re investigating is the potential for the use of immersive environments in conjunction with the workbench. A hypothesis is that planning functions would work best in an environment which allows “Gods Eye” viewing such as that provided by the workbench. Also, once generated, these plans would best be simulated in immersive environments. We are actively looking into issues pertaining to the interface between these two different display platforms. We are also investigating multi-modal interfaces to replace or complement the already existing interface within STOMPM. A multimodal interface will be of particular importance in immersive environments in which there may be a varied and large amount of data to navigate through.

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Pilot-Vehicle Interface Adaptation Based on Situation and Workload

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We describe a pilot/vehicle interface (PVI) adaptation system that uses a computational situation assessment (SA) model and pilot workload metrics to drive the content, format, and modality of military cockpit displays, as well as modulate the degree of automaticity of various vehicle functions. Our conceptual design integrates two key information streams: 1) a "content" path, driven by a tactical situation assessment module that uses avionics system outputs to determine the aircraft's current condition and the pilot's information needs based on the assessed situation; and 2) a "format" path, which uses an estimate of the pilot's state (workload level, attentional focus, etc.) to determine the most appropriate format/modality for presenting the needed information to the pilot. Both streams are also used to control the degree of automation of vehicle functions, e.g., defensive countermeasures, communication tasks, etc. The resulting PVI maximizes the pilot's situation awareness by filtering out situationally irrelevant information, makes optimal use of the pilot's parallel channels of information processing by using his multiple sensory modalities to transfer information between pilot and vehicle, and reduces the pilot's workload by automating less critical tasks during dangerous and demanding periods.

The system is designed modularly to facilitate testing of various computational formalisms for the individual components. The system currently uses Bayesian belief networks for the situation assessment and mental workload estimation subsystems and a rule-based system for the PVI adaptation subsystem. The mental workload model incorporates several physiological variables, including heart rate and heart rate-derived measures, EEG-derived measures and eyeblink measures. The belief network's quantitative relations were derived using results from correlation studies in the mental workload literature. While narrow in scope, the network produces intuitively sensible results for a range of simulated physiological input signals, and motivates refinement of the existing model and extension to include performance-based mental workload measures, e.g., task response time and error data, as well. Operational evaluation in which the network will be driven by a physiological measurement system is planned for the immediate future.

We provide an analysis that rank orders the importance of the various pieces of information available in the cockpit (e.g., threat geometry, type, and kinematics, and ownship kinematics and weapons) as a function of pilot task, situational state and mission phase. For example, one important high-level measure of situational state is the pilot's overall offensive/defensive posture, expressible as various "defcon" levels. We then describe a candidate PVI adaptation strategy, developed in collaboration with domain experts, which maps task/state/phase configurations to optimal PVI configurations.

(Reprint of executive summary; formal paper not available.)

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Sensor-to-Shooter Rapid Targeting Projects Overview

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Acknowledgments

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Major Jeff Johnson	Avionics Directorate, Wright Laboratory
Jim Artz	Space & Naval Warfare Systems Command
Major Alan Tucker	SAF/SP Intelligence Support

The United States Air Force and United States Navy are maturing advaneed Real-Time Information Into / Out-of the Cockpit (RTIC/RTOC) technologies to enhance aircrew situation awareness, increase operational flexibility and increase mission effectiveness against time critical fixed and mobile targets.

Under an umbrella of Sensor-To-Shooter (STS) Systems/Software Engineering and Integration activities, GDE Systems, Inc. is supporting the development and integration of onboard/offboard core technologies as well as new Concepts for Rapid Targeting operations. The fiscal year 1997 STS efforts comprise a series of advanced technology prototype development and demonstration projects focused on new offboard and onboard data processing capabilities. Initial proof-of-concept demonstrations have established feasibility of key components with technology transition initiatives underway.

Although STS objectives are oriented toward conventional Global Reach, TACAIR and Standoff Weapon precision strike mission applications in support of Joint Vision 2010, the underlying technology is applicable to multiple mission areas, such as Army Deep Strike, Naval Surface Fire Support, Strategic Nuclear, Combat Search and Rescue, Special Operations and Non-Traditional Warfare (e.g., crisis management).

(Reprint of executive summary; formal paper not available.)

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Cue-Recognition Training for Enhancing Team Situational Awareness

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With the importance of situational awareness and team situational awareness to tactical performance well established, it is critical that viable solutions are identified to enhance their development (Salas, Prince, Baker, & Shrestha, 1995; Stout, Cannon-Bowers & Salas, 1996). The key to designing instructional strategies to promote and maintain situational awareness and team situational awareness relies upon understanding the process of situation assessment. Fortunately, the literature has provided some insight into this process. That is, the nature of expertise relies upon the rapid and accurate assessment of cues and patterns of cues to build high levels of situational awareness (e.g., Cannon-Bowers, Salas, & Grossman, 1991; Klein, 1989). Likewise, the nature of team expertise embodies the ability to pass and obtain relevant information among the team that contributes to high levels of team situational awareness. In team settings, both of these are required to enable the taking of appropriate task actions. Therefore, to expedite the development of expertise and team expertise and thus situational awareness and team situational awareness, it is crucial to help trainees to identify and comprehend relevant features, cues, and patterns in the task environment that are often quite subtle.

Through a thorough review of the literature across several areas and interviews with operational military pilots, the instructional strategy of *cue-recognition training* has been identified as a potentially effective means of increasing situational awareness and team situational awareness. *Cue-recognition training* is referred to here as the process of making relevant cues and patterns of cues more salient, thereby increasing the probability for which they will be attended. Given the potential importance of this instructional strategy, the purpose of this paper is threefold: 1) to explicate the theoretical foundation of this instructional strategy; 2) to describe through example what this instructional strategy might look like; and 3) to provide anecdotal data obtained from interviews with pilots regarding the potential utility of this training approach.

We start by briefly summarizing recent conceptual work that has been done on team situational awareness from which the idea of cue-recognition training was initially derived. We turn next to briefly describing other related literature that supports the potential importance of this instructional strategy. Following this we provide a more detailed discussion of cue-recognition training specifically. Finally, we give examples from pilots regarding their reactions to cue-recognition training.

Brief Summary of Team Situational Awareness Literature

Recent theoretical treatments provided by Shrestha, Prince, Baker, and Salas (1995), Salas et al. (1995), and Stout et al. (1996) have all discussed the criticality of team situational awareness and have attempted to delineate a conceptual understanding of this construct. For example, both Shrestha et al. and Salas et al. offered the notion that team situational awareness is greater than the sum of the situational awareness of individual team members, as well as stressed the importance of shared mental models to the development of team situational awareness. Stout et al. extended these works by providing a model of team situational awareness. In essence, their work suggests that team situational awareness is a dynamically changing cognitive state, which is influenced by the process of situation assessment. This process of situation assessment is in turn influenced by: 1) mental models and shared mental models that team members bring to bear to the task situation; 2) cues/patterns of cues that occur in the dynamic task situation, which come from a variety of sources; and 3) team process behaviors, which influence both individual models of the situation, or individual situational awareness, and team level situational awareness. According to these authors, team situational awareness is high when the situation has been assessed compatibly by the team members, enabling them to work in concert.

The Stout et al. framework yields implications for training team situational awareness. That is, given that it is a dynamically changing cognitive state, we cannot actually train team situational awareness per se, but we *can* train the process of situation assessment, one critical component of which is making trainees aware of the relevant cue/patterns in their specific task situation. Given the potential positive impact that accurate and appropriate cue/pattern assessments can have on developing high levels of team situational awareness, we focus here on a strategy that may improve cue/pattern assessments - cue-recognition training – prompting the trainees' attention to relevant cues/patterns of cues.

A vast body of literature across several domains, such as cognitive and educational psychology also supports the potential effectiveness of this strategy. While a review of this literature is beyond the scope of this paper, we briefly review some particularly relevant research in the next section.

Support for the Link Between Cue/Pattern Assessments and Human Performance

Relevant features, cues, and patterns of cues in a particular task context are often quite subtle. Recognizing and assessing more quickly and completely these aspects of the task have often been cited as a key to developing domain expertise (e.g., Druckman & Bjork, 1994; Means, Salas, Crandall, & Jacobs, 1993). A set of studies conducted by Bransford and colleagues and summarized by Bransford, Franks, Vye and Sherwood (1989) serves as an excellent example of bodies of research that have concentrated on determining how individuals come to discriminate one case from another. In this work on cue learning, Bransford et al. explained that individuals must learn the process rather than the outcome of cue assessments. For example, pointing out to the trainee that "the territory ahead is hostile" is the output of an expert's assessment and does not allow the trainee to learn the underlying cues that led to this determination. According to these authors, it is far more important to specify what the relevant cues are that allow one to conclude that a territory is hostile and to compare and contrast these cues under differing conditions. For example, indicating that an aircraft is an enemy because of critical features "1, 2, and 3," when it is in close proximity to another aircraft with both similar and different features, provides relevant contrasts and allows cues to take on meaning.

In addition to more basic research on cue learning, a body of applied work has amassed which advocates the importance of rapid and accurate cue/pattern assessments to effective decision making and performance (Adams, Tenney, & Pew, 1995; Cannon-Bowers & Bell, 1997; Endsley, 1995a, 1995b; Gaba, Howard, & Small, 1995; Kaempf & Klein, 1994; Kaempf, Wolf, Thordsen, & Klein, 1992; Klein, 1989; Orasanu, 1990; Salas et al., 1995; Sarter & Woods, 1991; Stout et al., 1996). Indeed, in Klein's well-known model of recognition primed decision making (1989), perhaps the most important factor in effective decision making among experts is to correctly assess the situation. According to Klein, experts often make correct choices and take appropriate action in complex, cue-rich contexts by using their experience to draw accurate inferences from available cues and patterns.

Studies that have directly examined how experts and novices use cues also provide insight into the importance of assessing cues and patterns in task accomplishment (e.g., Myles-Worsley, Johnston, & Simons, 1988; Kaempf & Klein, 1994). In general, these studies lend support that experts are often unable to articulate the specific cues that they attended to and/or how they used these cues to make their assessments. Also, surprisingly, experts often use unexpected strategies in assessing cues and patterns.

In summary, the efforts focused on team situational awareness and those described in this section are important, because they theoretically support the potential application of a strategy aimed at improving cue/pattern assessments. The latter research on expert and novice differences is also particularly important, because to use strategy to improve team situational awareness that enhances cue/pattern assessment, it is obviously crucial to determine which cues to point out to the trainee. Because it is difficult to gather this information from experts (given conscious unawareness), a paradox arises. Fortunately, the area of cognitive engineering has yielded techniques that can be used to identify training content by "teasing out" this information (see Cooke, 1994, for a review of these techniques). Clearly, it would be important to utilize these techniques when developing the content of cue-recognition training. Given a better understanding of *what to cue*, we now turn to how cue-recognition training should take place.

How Might We Cue?

Attaining and sustaining a high level of situational awareness is primarily based upon the accurate assessment of relevant cues/patterns of cues in any given situation (Adams et al., 1995; Endsley, 1995a; Salas et al., 1995; Stout et al., 1996). Actively prompting individuals or teams to take note of cues that are pertinent to successfully completing their tasks is one possible training strategy for elevating the level of situational awareness attained. As mentioned, we term this training process of guiding individuals to attend to relevant task parameters as cue-recognition training. Taking into consideration each of the research examples outlined in the prior section, we now endeavor to explain how cue-recognition training could be made possible. We suggest that in each specific case, cue-recognition training would be both appropriate and potentially beneficial.

First, Bransford et al. (1989) contended that it is imperative to guide trainees, from the beginning, to take notice of crucial features as they are learning new information. They also offered that experts have a wealth of diverse experiences to draw upon when presented with a set of stimuli. This provides them with internal contexts and alternatives, which may not be readily apparent to the novice. Mann and Decker (1984) supported this notion in that they described a cue's distinctiveness (i.e., how it contrasts with other cues) and meaningfulness as critical to the learning process. Therefore, it may be suggested that presenting novices with relevant contrasts in respective environments causes germane cues to become more apparent and thus better learned.

Based upon the above assumption, scenarios could be designed with a myriad of system malfunctions, for example, in which cues may or may not be relevant to the malfunction. An instructor could then point out the cues that are relevant to the malfunction. This would aid the trainee in developing an accurate mental model of the pertinent cues to look for when a part of the system is malfunctioning. Additionally, the trainee would become aware of which cues/patterns of cues were not predictive of system performance and thus not important to attend to. Distinctiveness is the key to making cues relevant to the novice (Bransford et al., 1989; Mann & Decker, 1984). This can be accomplished by displaying the cue/behavior out of context, exaggerating the behavior, repeating the behavior frequently and by using learning points to identify the crucial determinants of the behavior. Several methods may attain the goal of creating contrastive learning effects; Bransford et al. suggested the use of random access videotape to show the trainee contrasting segments.

To date, studies on situation assessment, that have investigated the cues that experts attend to, posit that it is critical that trainees have awareness of cues that are pertinent to their task performance. Specifically, trainees could potentially learn an inaccurate set of cues which would result in a flawed mental model. In a time compressed situation, this could be fatal. Accurate mental models/shared mental models are imperative to high levels of team situational awareness (Stout et al., 1996) therefore. we suggest that cue-recognition training can foster the development of team situational awareness. In the next section, we delineate a strategy for implementing cue-recognition training. Additionally, we describe in greater depth how this particular strategy could increase team situational awareness thereby enhancing performance.

How Might We Implement Cue-Recognition Training

First, there are a number of ways that cue-recognition training can be delivered. Cue-recognition training can take place through passive demonstrations or while the trainee is practicing his/her tasks. It can also occur through instructor input or it can be delivered by the system itself (such as through highlighting relevant gauge cues). Additionally, information can be presented directly or through questioning the trainees about what cues are relevant given the situation. The cues presented would come from a variety of operational sources, such as the external/internal environment, the mission, the cockpit instrumentation, and teammates. In addition to prompting the trainees' attention to relevant cues and patterns of cues, instruction could be provided regarding what the trainee should "say" and "do" based upon the situation at hand.

Four subsets of cue-recognition training are proposed, based upon a review of the literature which has described strategies related to some type of guidance or prompting (summarized in Figure 1):

CUE-RECOGNITION TRAINING

	Passive	**Active**
System	Passive System Prompting	Active System Prompting
Instructor	Behavioral Coaching	Instructor-Guided Practice

Figure 1. Categorization of cue-recognition training methods.

Note. From "A team perspective on situational awareness (SA): Cueing training" by Stout, R. J., Cannon-Bowers, J. A., & Salas, E. (1997). [CD-ROM]. *Proceedings of the 19th annual Interservice/Industry Training, Simulation and Education Conference, Orlando, FL,* 174-182. Reprinted by permission.

Passive System Prompting: cue-recognition training which occurs through a passive demonstration, such as a videotape or a static system demonstration, which shows the system prompting the relevant information as in active system prompting.

Active System Prompting: cue-recognition training which occurs on-line, or as the individual/team is practicing their tasks and which is provided by the system (e.g., via highlighting or fading).

Behavioral Coaching: cue-recognition training which occurs through a passive demonstration, such as a videotape or a real time demonstration by an instructor in which the instructor verbalizes the cues he/she *is* attending to in accomplishing the tasks, the relevant processes, and the necessary steps being taken

Instructor-Guided Practice: cue-recognition training which occurs on-line, or as the individual/team is practicing their tasks and which is provided via instructor comments, where the instructor points out the cues to attend to, the processes to attend to, and the necessary steps to take to accomplish the tasks.

In each of these cases, the information can be either directly presented as statements of fact, can be presented by questioning the trainee, or can use a combination of the methods.

These four teaching methods can all be used to improve the level of team situational awareness achieved. In all four methods, this can be accomplished when the relevant cues/patterns of cues are pointed out so that an accurate system assessment can be made. In addition to pointing out the relevant cues to attend to, emphasis would be placed on appropriate team processes to engage in based upon the particular situation assessment. All four of these strategies can aid in the understanding of specific situations resulting in compatible mental models among teammates. These strategies can supply trainees with information relevant to evolving task conditions in order to provide contrasts. As a result of these contrasts, trainees will know which information to share, will interpret cues consistently and will share all of this information in an expected manner with fellow teammates. While the passive strategies also impart strategic knowledge to the trainees, the training, in these two cases, is not as complete due to the passive nature inherent in these two techniques. The active training strategies that provide a more "hands-on" approach are better suited for increasing strategic knowledge and hence effect team situational awareness. The choice of one method over another, however, is probably best made on practical grounds based upon available resources.

Research is needed to test each of these training strategies to determine their impact on team situational awareness. With the active cue-recognition training strategies (i.e., instructor-guided practice and active system prompting), we hypothesize that individual team members will: a) form expected and appropriate task strategies; b) be able to accurately predict a team member's behavior; c) develop common expectations of additional task and information requirements; d) form common explanations of the meaning of task cues; and e) form compatible situation assessments. Research is also needed to determine the sequencing that these strategies should follow. For example, the passive strategies may need to precede the active strategies to maximize the effect on team situational awareness. Additionally, it is crucial that research be directed at determining the pertinent cues that should be emphasized during the course of training. This can only be accomplished successfully by employing a systematic framework to guide the research and by using emerging techniques, such as knowledge elicitation approaches. We suggest that the Stout et al. model can be used as the cadre to guide this research. Next, an example is provided to illustrate what a cue-recognition training method might look like and how it could potentially aid in enhancing team situational awareness.

What Might a Cue-recognition Training Approach Look Like?

We provide a military transport helicopter Search and Rescue (SAR) mission example to illustrate what a cue-recognition training approach might look like. The crew complement in this aircraft is that of a pilot, a copilot, and crew chiefs who operate in the rear of the aircraft. Let us assume that the downed aircraft is in the water, so the SAR helicopter is in a high hover sending the swimmer down to retrieve survivors. When the swimmer has been lifted half way back up the hoist with one survivor, suddenly the aircraft experiences an engine malfunction. Let us also assume that knowledge elicitation techniques from cognitive engineering were employed to determine from subject matter experts the relevant cues in this situation. In this case, let us say that experts tended to agree that the most important cues related to correctly diagnosing the engine problem, maintaining safety of flight, and correctly deciding whether to put the helicopter in the water and when and where to do so. Assume that the experts agreed that engine diagnostic cues are from engine gauges (e.g., torque, rpm, NF relative to NR, temperature, and whether or not an engine chip light was illuminated). Assume also that safety of flight cues are from both cockpit instrumentation (e.g., airspeed and altitude) and from the environment (e.g., visual cues from the water indicating the helicopter's position in space). Finally, assume that cues related to taking action involve knowing where the swimmer is. At times this information can only be obtained via crew chief communications.

Given all of this information as a baseline, a cue-recognition training approach should be geared toward imparting to the trainee that each of these cues is relevant, as well as toward making the trainee aware of when these cues are important. We would also want them to understand the relative significance of each of the cues. In addition, it would be important for trainees to know what cue information must be communicated to other team members to build a compatible understanding of the situation and to thereby allow appropriate coordinated action to be taken. Using our notion of behavioral coaching as an example, an instructor could prompt the trainee's attention to each of these issues, either while performing in the simulator or by using a videotape of the simulation from which to discuss the situation. That is, the instructor could explain to the trainee what it is that he/she would be thinking about and saying as each member of the crew. This could include detailing what information should be passed to other crewmembers and stating the problem in a manner that allows all crewmembers to understand what is happening. The instructor would be guided in his/her behavioral coaching technique to utilize the information gathered through the knowledge elicitation methods. The following example shows what an instructor may, therefore, say.

> "As a pilot or copilot, given that we are in a high hover over water, I might expect salt from the ocean to cause some type of problem with the engine, so I would be scanning my engine gauges. As a pilot, I would also continue to scan altitude and airspeed to maintain a safe hover, and I would keep an eye on the water to see if the waves look larger or smaller, and to see if I am level. As a copilot, I would back the flying pilot up by looking at the same cues. The first indication of an engine problem would probably be a change in torque or rpm. Either the pilot or copilot might notice it, and then each of us would look for secondaries, expecting either NF to go below NR (or for NF to split off from NR) or a change in engine temperature. If either or both of these occur we might ask the crew chief to look for any other secondaries in the back, but I would assume that we have an engine problem and would ask my copilot to execute engine shut down procedures while I watch for safety of flight items (altitude, airspeed, and visual water cues). Given that we are over water with an engine problem and are not single-engine capable, we may need to land it in the water as soon as possible, so I would have stated the symptoms that I had seen originally to all crew and stated that there was a possible engine problem, and once confirmed by the secondaries, I would tell the crew that we need to land it in the water as soon as possible. The crew chief would then look for the swimmer, if he/she was still on the hoist, and make a determination of whether or not to cut the swimmer or bring him/her on board based upon his/her distance from the water, which would be communicated to me. Once safe, I would tell the crew that we are putting it in the water. The crew chief would let me know that the passengers are strapped in and I would land it in the water."

The key distinction, between the approach that we offer and traditional behavioral coaching approaches is that the instructor is emphasizing critical cues, and what he/she is thinking and communicating to develop and maintain team situational awareness rather than simply stating what he/she is doing. Keeping in line with what was suggested by Bransford et al. (1989), the output of the expert's judgment is not what is presented – rather, the processes used to make that judgment are presented.

This section has simply served as one example of the myriad of specific instruction that could be provided via cue-recognition training. Again, research is greatly needed to empirically determine how best to implement this instruction.

Given a better understanding of what we mean by cue-recognition training and that the literature reviewed in this paper supplied hypothetical evidence of the potential usefulness of this training approach, we next sought reactions about this technique from operational personnel. We describe some of these reactions next.

Fleet Reactions to Cue-Recognition Training

Our approach to determining what aviators think about the potential effectiveness of a cue-recognition training scheme was to first discuss with them our notion of team situational awareness and to then provide examples of what this training might look like in a manner consistent with that presented in this paper. We interviewed 47 aviators from 5 different operational communities. A very typical response obtained from the aviators was that they did not feel that team situational awareness could be trained. That is, they felt that "experience" is what is needed. After careful explanation of our ideas, however, many aviators commented that, while they had not received a formal systematic cue-recognition training during their careers, "good instructors informally provide some form of cue-recognition training ... such as saying, hey get your head inside the cockpit now and look at this gauge because..." A typical response was also to the effect that "while good instructors do this kind of thing, I have often wondered if what they are saying is correct, because it is just one instructor's opinion, and a technique that makes this more systematic and pools opinions would give me greater confidence in the product." In addition, almost universally, pilots commented that this approach would be particularly valuable for student pilots. Finally, pilots noted the importance of providing active practice opportunities with cue-rich scenarios. Thus, initial reactions of pilots toward cue-recognition training were favorable.

CONCLUSIONS

The purpose of this paper was to extend our understanding of how team situational awareness can be improved through training. It did so by elaborating upon one potential training strategy derived from the literature and positively reacted to by aviators – cue-recognition training. This is important because it is a first step in linking theory to practice in this area. Obviously, research must be conducted to empirically validate cue-recognition training. We hope that our paper stimulates interest and research in this important arena.

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AUTHOR NOTES

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Application of the Virtual Retinal Display™ (VRD™) to the Virtual Cockpit Optimization Program (VCOP)

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In the last decade, the Army has successfully developed technologies designed to improve the rotary-wing cockpit environment and individual aircrew equipment for tactical flight operations. Since many of these technologies have now matured, the Army has recognized the need to pool various research and development results to determine which technologies should be further explored to optimize pilot performance in current and future aircraft cockpits. The Army's VCOP initiative will analyze the Pilot Vehicle Interface (PVI) and recommend insertion of the best technologies into the existing helicopter fleet.

There is a rapidly accelerating need to control and manage information currently provided to the Army Aviator in order to optimize his ability to perform effectively in the cockpit and on the digitized battlefield. To date, the Army has amassed an arsenal of tools to assist the pilot functioning in the cockpit. VCOP has been formalized to identify and select optimal cockpit technologies for actual integration in today's aircraft. This program will evaluate off-the-shelf and emerging technologies from all military departments which could best apply to the unique demand of the highly complex helicopter cockpit and pilot situational awareness environment. At the conclusion, the best of the Army's recent R&D initiatives can be properly identified and applied to the current helicopter inventory.

Current plans call for the Virtual Cockpit Optimization Program to evaluate a full-color, high resolution, high brightness helmet-mounted display, three-dimensional audio, tactile display, voice recognition, and voice synthesis. The resultant all-electronic crew station will enable the evaluation of a simulated, reconfigurable cockpit in which the pilots' abilities to interface with both aircraft and environment can be optimized independent of external conditions such as degraded visibility. Such an evaluation capability can also be viewed as an important step toward remote pilotage of high performance aircraft. Simulation capabilities will be specifically employed to validate selected technologies and their potential for integration with existing systems. VCOP success could readily enhance improvement in similar cockpit environments in armor and self-propelled artillery systems.

Because pilot situational awareness is key to mission success, the majority of imagery and information needs to be presented in an out-the-window format, and in a manner that the pilot will readily comprehend. VRD provides the necessary brightness, contrast, and resolution for both day and night operations for VCOP mission requirements. Unlike other display technologies such as flat panel displays, the VRD is an integrated display system with modular components, which can be developed in parallel instead of sequentially. This modularity permits rapid advancement of and improvements to system performance, while at the same time continuing to decrease overall VRD system size.

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Flight Simulator Comparison of Two Tactical Cockpit Configurations Under Static and High-G Conditions

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A two-phase flight simulation research program was conducted to compare two tactical cockpit configurations in relation to tactical mission performance. One of the configurations, defined as the advanced configuration, incorporated advanced control and display concepts and weapon capabilities. The other, called the standard configuration, employed conventional cockpit and weapon technologies. These cockpit configurations were compared under static conditions in the first phase of the research program and under high vertical gravitational (Gz) conditions in the second phase.

The reconfigurable cockpit developed by the Boeing Company as an advanced concept demonstrator was used to provide the two cockpit configurations. The cockpit is installed in the gondola of the centrifuge located at the Veda, Inc., facility in Warminster, PA. It is equipped with a forward instrument panel that contains four multifunction displays (MFDs), three cathode ray tube (CRT) monitors for displaying the computer-generated outside visual scenes and head-up display (HUD) symbology, and a variety of operational controls. The cockpit controls include a side-arm control stick, a throttle, a master mode switch, and a master arm switch. Various switches are integrated into both the control stick and throttle to provide hands-on-stick-and-throttle (HOTAS) switch functionality.

In the advanced cockpit configuration, the simulated aircraft is loaded with two Joint Direct Attack Munitions (JDAMs) and four AIM-120 missiles. The JDAM is a global positioning system (GPS)-guided, "smart" bomb that autonomously steers to the target designated by the pilot, and is released at high altitude to reduce aircraft exposure to enemy defenses. The JDAMs are delivered using the target attack MFD, which displays ground target and JDAM impact envelope symbology. Deployment of the missiles is accomplished using air-to-air weapon symbology displayed on the HUD. In the standard configuration, the aircraft has two conventional Mk-82 bombs and also four AIM-120 missiles. Continuously computed impact point (CCIP) symbology displayed on the HUD is used to deliver the Mk-82 bombs. The bombs are delivered at low altitude, and the CCIP symbology must be precisely positioned over the target in the visual scene for the weapon to hit the target. As with the advanced cockpit configuration, the missiles are fired using the air-to-air weapon symbology displayed on the HUD.

The simulated tactical mission consisted of three segments: terrain following, air-to-ground weapon deliveries, and air-to-air combat. The terrain-following segment involved flight over mountinous terrain and required sharp and left and right turns to induce high G forces. There were two ground targets and four air targets. The ground targets were a large canister, representing an oil storage tank, and a bridge; the air targets were four moving MiG-29 models. The performance measures used in both study phases were (1) time between mission start and cockpit air-to-ground mode switch activation, (2) time between cockpit air-to-ground mode switch activation and first bomb release, (3) time between bomb releases, (4) time between cockpit air-to-air mode switch activation and first missile release, (5) time between first and last missile releases, (6) number of ground targets destroyed, (7) number of air targets destroyed, and (8) NASA-TLX workload ratings.

There were four participants in the first phase. Each performed the mission twice in both cockpit configurations under static, no-motion conditions. Analysis of variance (ANOVA) statistical tests showed that there were no significant differences in performance between cockpit configurations and repetitions, and that there were no significant interactions between cockpits and repetitions for any of the performance measures.

Six participants were used in the second phase, and each also performed the mission twice in the two cockpit configurations. The centrifuge was operational during the flights, and the participants were subjected to a maximum of 7.0Gz. ANOVA results indicated that there were significant differences between the two cockpit configurations for (1) time between cockpit air-to-ground mode switch activation and first bomb release, (2) time between bomb releases, (3) number of ground targets destroyed, and (4) four of the six workload scales. In these analyses, performance was better and workload was less in the advanced cockpit than in the standard cockpit configuration. Only the "effort" workload ratings were significantly different between repetitions, and none of the cockpits by repetitions interactions were significant. In conclusion, this research demonstrated that the advanced cockpit technologies facilitated tactical mission performance, but the performance benefits were not evident until the participants were subjected to realistic Gz conditions.

(Reprint of executive summary; formal paper not available.)

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Multi-modal Interfaces

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The Effects of 3D Audio on Tactical Situation Awareness

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Introduction

Three-dimensional (3D) audio uses the cues enabling humans to localize sounds in their natural environments to create the perception of a sound in space. Theses cues are described in greater detail below.

Binaural Cues

Position of a sound can be determined using binaural cues, specifically sound reaching the ears at different times (as much at 700 µsec) and intensities (as much as 40 dB). Localization of sounds below 2000 Hz is based primarily on time differences, above 4000 Hz on intensity differences. Localization is poorest between 2000 and 4000 Hz (Figure 1).

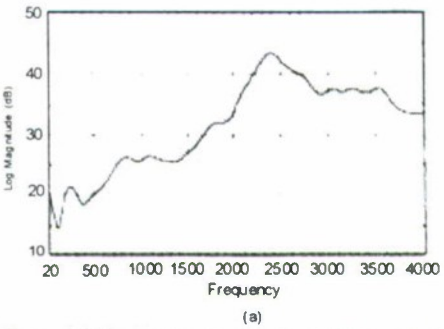

Figure 1. 20-Hz to 4-kHz frequency response (Begault, 1991, p. 869).

Sounds 20 or 120 degrees straight ahead have the greatest intensity difference (Figure 2).

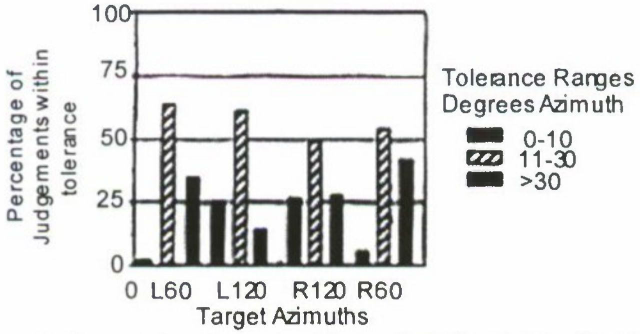

Figure 2. Errors in headphone localization for left and right 60 and 120° target azimuths at 0° elevation (Begault, 1991, p. 867).

Sound intensity is the primary cue for distance to a sound source.

Phase Cues

Phase cues are also used for localization of periodic sounds but only if successive cycles are at least 1600 Hz apart. Rise times of 100 msec or greater also aid in sound localization. Distance and elevation also have effects (Figures 3a and b, respectively).

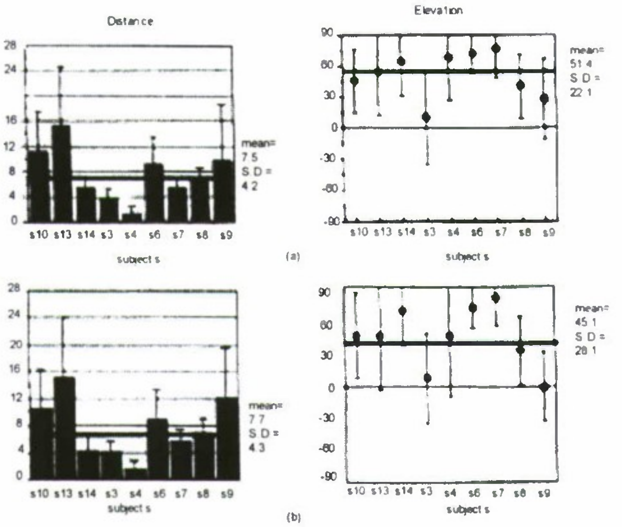

Figure 3. Summary of distance and elevation judgments.
(a) Targets at 0° azimuth, 0° elevation.
(b) Targets at 180° azimuth, 0° elevation (Begault, 1991, p. 868)

Additional Cues

Head movements provide cues but only for sounds with durations greater the 250 msec. Monaural cues (sound shadowing by the head and loudness changes of moving sounds) are also used in sound localization. Localization can also be affected by memory (where your phone is) and cognitive cues (where speech emanates from a speaker). "Environmental cues include the effects that the listening environment imposes on distant sources, early reflections from the ground, walls and ceilings, and reverberation, or late reflections." (Scarborough, 1992, p. 2).

3D Technology

3D systems are being produced by many companies (Table 1). With competition has come improvements in the technology. These improvements include binaural recording, "a method of making recordings that capture the temporal and spectral cues that exist in binaural sound" (Scarborough, 1992, p. 3) and the use of head-related transfer function (HRTF). "The HRTF imposes a unique frequency response for a given sound-source position outside of the head, which can be measured by recording the impulse response in or at the ear canal and then examining its frequency response using fast Fourier Transform techniques. The binaural impulse response can also be directly implemented into a pair of digital filters for use in a 3D audio system, using convolution techniques" (Begault, 1991, p. 864).

Table 1. Companies Selling 3D Audio Products (Wright, 1996, p. 94)

Analog Devices
Aureal Semiconductor Inc.
Binaura Corp.
Creative Labs Inc.
Crystal River Engineering
Crystal Semiconductor Corp
DSP Group Inc.
E-mu Systems Inc.
ESS Technology Inc.
Harman Interactive Group
Motorola
NEC Electronics
OnChip Systems Inc.
Panasonic Industrial Corp.
Qsound Labs Inc.
Seponix Corp
Spatializer Audio Laboratories Inc.
SRS Labs Inc.
Yamaha Systems Technology Inc.

There are individual differences in HRTF (Figure 4) and localization performance is poorer when using someone else's HRTF. There are two approaches to minimizing this error: 1) mathematical manipulation such as averaging, structural modeling, or principal components analysis or 2) use the HRTF of a "good localizer" (Begault, 1991).

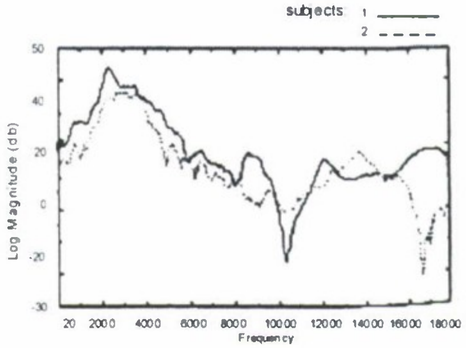

Figure 4. HRTF spectra for two different persons:
left ear, source at 0° azimuth, 0° elevation (Begault, 1991, p.864).

Uses of 3D Audio

3D audio has been used to: 1) improve intelligibility, 2) provide navigation cues, 3) warn of threats, 4) support targeting, 5) indicate location of wingman, and 6) fly an aircraft. Evaluation of each of these uses is described in the following sections.

Improve Intelligibility

Begault (1993) reported a 6 to 7 dB intelligibility improvement using 3D audio over monaural listening. The call signs were presented at 60 and 90 degree light and right positions. The task was identifying the call signs of 130 aircraft. This finding is not unique. NASA (Begault, 1995) has consistently shown about a 6 dB improvement in intelligibility through the use of 3D audio communications.

The US Army (Haas, Gainer, Wightman, Couch, and Shilling, 1997) compared the number of correct pilot responses (i.e., pilot replied on the target radio channel when a target message was present) in three radio signal presentation modes: diotic, dichotic, and 3D audio. In the diotic mode, speech messages from three simulated radios were routed to both ears equally; in the dichotic mode, speech messages from two simulated radios were routed to one ear and the third radio to the other ear; and in the 3D mode, the three radios were presented one each at 90°, 270 °, and 315 ° azimuth. Data were collected in the Army Research Institute Simulation Training Research Advanced Testbed for Aviation (STRATA) simulator. The subjects were 11 US Army helicopter pilots certified in the AH-64 helicopter. The subjects performed the radio identification task while performing target acquisition and responding to aircraft malfunctions. The results showed significantly better performance using the 3D audio (5.0) than diotic displays (2.0) currently used in helicopters. Performance for dichotic displays (3.9) was between the other two displays.

Ericson, McKinley, Kibbe, and Francis (1993) reported a 25% enhancement in intelligibility of spatially separating competing speech messages in high ambient noise environments (115 dB). Also in flight, separating the source of multiple radio signals enhanced intelligibility in an AV-8B (Jane's Information Group, 1991).

Provide Spatial Orientation and/or Navigation Cues

Pilot critiques indicate that a 3D audio signal of taxiway location may enhance terminal area productivity by decreasing time to taxi from runway to gate.

Threat Warning

The US Marines flight tested 3D audio displays in an AV-8B in the Fall of 1991. The displays were those developed by the US Air Force's Armstrong Laboratory. The test evaluated the utility of these displays for warning of missile approach. Results indicated that missiles could be located within 10 degrees (Jane's Information Group, 1991).

US Air Force researchers (McKinley, et al., 1995) reported that subjects could detect a monochrome silhouette of an SU-27 aircraft with the naked eye as well as with a Helmet Mounted Display if 3D audio cueing was used. Rated workload (NASA Task Load Index) was lowest in the 3D audio condition as compared to no sound or non-localized sound conditions.

NASA has shown a 500 ms improvement in acquiring targets using a 3D audio version of the Traffic Alert and Collision Avoidance System.

Targeting

Pilots participating in the 3D audio AV-8B display flight tests reported targeting accuracy within 15 degrees azimuth which they felt was adequate to orient toward a target (Kibbe and Francis, 1994). However, elevation cues were less accurate and enabled only rough judgments of low or high. Ericson, McKinley, Kibbe, and Francis (1993) reported that in-flight, 3D audio reduced target acquisition times.

The US Air Force (Perrott, Cisneros, McKinley, and D'Angelo, 1995) in a series of laboratory experiments reported significantly shorter search times for targets using 3D audio cues. The worst performance occurred at +/- 150 degrees azimuth but even that performance was better with than without 3D audio. Perrot, et al. (1991) had reported a similar enhancement with 3D audio in a two-alternative visual search task (Figure 5).

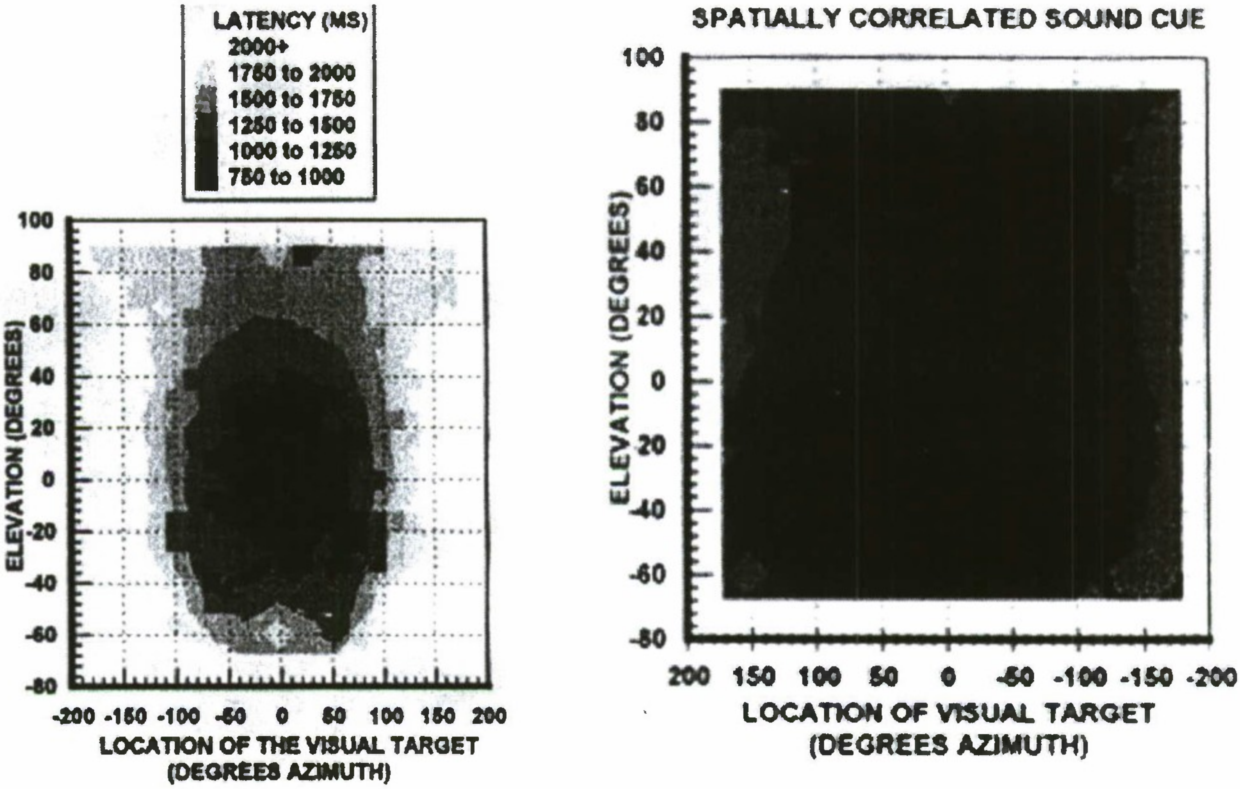

Figure 5. Target search latency with and without 3D audio cueing.
(Perrott, et al., 1995, pp. 105 and 106)

NASA (Begault and Pittman, 1995, 1996) compared the acquisition time of targets using the standard head-down Traffic Alert and Collision Avoidance System (TCAS) and a 3D audio presentation of the same information. The subjects were ten two-person crews composed of airline pilots rated in Boeing 757, 767, 737-300/400, or 747-400 aircraft. Data were collected in the NASA-Ames Crew-Vehicle Systems Research Facility Advanced Concepts Flight Simulator. The results indicate a 500 ms improvement in acquiring targets using a 3D audio version of the TCAS (2.13 s) rather than the standard TCAS (2.63 s).

The 500 ms improvement has also been reported in simple laboratory search tasks (Strybel, Boucher, Fujawa, and Volp, 1995). This improvement occurred 24 degrees from the fixation point of five subjects in an audiometric chamber for a 70 dB audio cue. The improvement was slightly less (300 ms) for a 40 dB audio cue.

Endsley, Rosiles, Zhang, and Macedo (1996) examined the effects of tone type (pure, oscillating, variable), tone number (single, with reference tone, graduated), frequency type (high, low), and subject type (fighter, transport pilot). The dependent variables were time and accuracy of identifying the location of an auditory signal. The smallest elevation error occurred with the variable, graduated, high frequency tone. There was no effect of type of subject. Accuracy was poorest at elevations below zero or at azimuths above 70 degrees. The smallest azimuth error occurred with the oscillating, reference, high frequency tone. In addition, fighter pilots had smaller azimuth errors than transport pilots. Response times were longest when a reference tone was present and in high frequencies. There were no significant effects for elevation but for azimuth, response time decreased from the subject's far left to directly in front of him. Ironically, subjects performed better with the high frequency tone but preferred the low frequency tone.

Wightman (1995) reported that auditory cues did not enhance the localization of moving targets. However, giving the subjects control of the target movement decreased the number of front/back reversals. He also reported that there were no differences in localization performance between using HRTF measurements made with open-canal probe microphones or closed-canal insert microphones.

Julig and Kaiwai (1995) are evaluating the use of 3D auditory displays to enhance sonar operator performance.

Locate Wingman

A method has been developed of indicating location of wingman to a lead pilot using outputs from the aircraft's GPS receivers to establish their relative location.

Fly Aircraft

Forbes (1946) modified an auditory display called the Flybar. The Flybar presented a single tone that changed in intensity between the pilot's two ears to indicate turn rate and bank angle. The presentation rate of the tone indicated the airspeed. Similar displays have been developed more recently, for example the Acoustic Orientation Instrument (AOI) developed by Lyons, Gillingham, Teas, Ercoline, and Oakley (1990). Endsley, Rosiles, Zhang, and Macedo (1996) tested an auditory Head Up Display (HUD) in which pitch was presented as the vertical location of the tone and bank as the horizontal location of the tone. The subjects were instructed to maintain their flight path and to search for visual targets. Graduate variable broadband tone or the single tone was associated with smaller RMS altitude error. There were also significant subject differences. But there were not any significant differences in auditory tone or subject for Root Mean Square (RMS) heading error. The same results occurred for the visual search task. However, there were again significant subject differences. Neither task was associated with significant differences in the Situational Awareness Global Assessment Technique (SAGAT) scores. The Auditory HUD was then tested in an unusual attitude recovery task. There was no significant effect of tone on response time or response accuracy.

Implementation Problems with 3D Audio

Problems of implementation include:

1. Dual-channel equalization - for the human to detect direction, it is critical that the sound in each ear is equalized prior to the delivery of the 3D signal; this requires cross-talk cancellation in the ear phones;
2. Vibration - reduces hearing perception especially at high vibrations (100,000 Hz);
3. Noise - for signal-to-noise ratios less than about 15 dB, noise can make localization more difficult, this is especially true of pure tones;
4. Communication - the same earphones used for the 3D signal are used for communication and there have been some problems of acceptance by transport pilots;
5. Postural adaptation - after head rotation, the perception of center is displaced in the direction of the original rotation;
6. Cones of confusion - 3D audio requires temporal disparity between signals to the left and right ear. Small or no disparities indicate that the sound is emanating from the vertical plane between the two ears, anywhere in this plane. The greatest confusion is up/down and front/back. Front/back reversals are common, back/front less so. For example, Begault and Wenzel (1993) reported 11% back/front reversals compared to 47% front/back. The task was an auditory target localization task in a sound isolation chamber.

7. Intracranially heated sound - "inability to hear sound outside of the head" (Begault, 1992, p. 895). This can be minimized using spatial reverberation," HRTF processing is applied not only to the direct sound, but to the indirect sound field as well . "The purpose for doing so is to allow modification of the original recording so that it seems to have been recorded within an arbitrary environmental context" (Begault, 1992, p. 896). A sample of reflection intensities is given in Figure 6. Spatial reverberation decreases intracranially heard sound but increases the magnitude of azimuth and elevation localization errors (Figure 7).

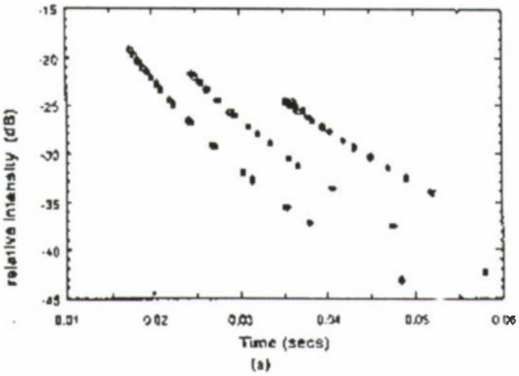

Figure 6. Reflection Intensities Over Time (Begault, 1992, p.897)

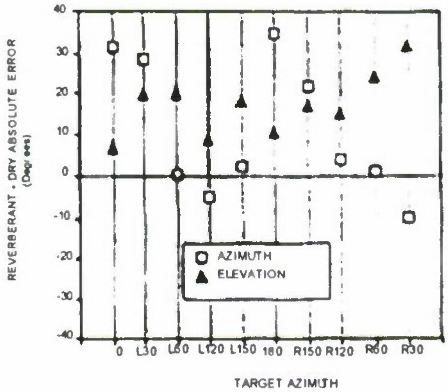

Figure 7. Difference in absolute errors for azimuth and elevation (Begault, 1992, p. 901)

8. Nonlinearities in amplification - these can change the time and intensity differences that provide binaural cues; and

9. Inconsistent donning of headphones - this may result in a mismatch with the HRTF.

For systems using loudspeakers rather than earphones, another set of problems arise. The first is crosstalk, i.e., interference between signals from the two loud speakers. Transaural stereophony has been used to cancel or eliminate crosstalk by precisely controlling the acoustic signals at the listeners' ears. Bauck and Cooper (1996) identify several advantages of transaural stereo: 1) accurate images i.e., the primary sources of sound "may be heard anywhere around the listener if they were present during the performance" (p. 683) and 2) accurate spaciousness, i.e., "accurate placement of secondary, or reflected, sounds is tantamount to proper spatial rendering" (p. 683).

To simulate binaural images, binaural image synthesis can be done from multitrack recordings combined with crosstalk cancellation. Shuffler filters are the most economical way to perform binaural image synthesis (Bauck and Cooper, 1996).

Test Vehicle

Problems of implementation are being addressed in the installation of 3D audio in the Variable Stability In Flight Simulator (VISTA). The VISTA (Figure 8) is the newest concept in the development and use of in-flight simulation. VISTA has independent control of five degrees of freedom of motion by directly commanding surface deflections and engine thrust through the F-16 fly-by-wire control systems. The airframe front cockpit has been modified to be the evaluation cockpit with a variable-feel centerstick and with simulation controls and displays. The safety pilot's cockpit (rear) has been modified to permit control and alteration of the simulation in flight and to also be the primary command and flight control station for the basic F-16 host airplane.

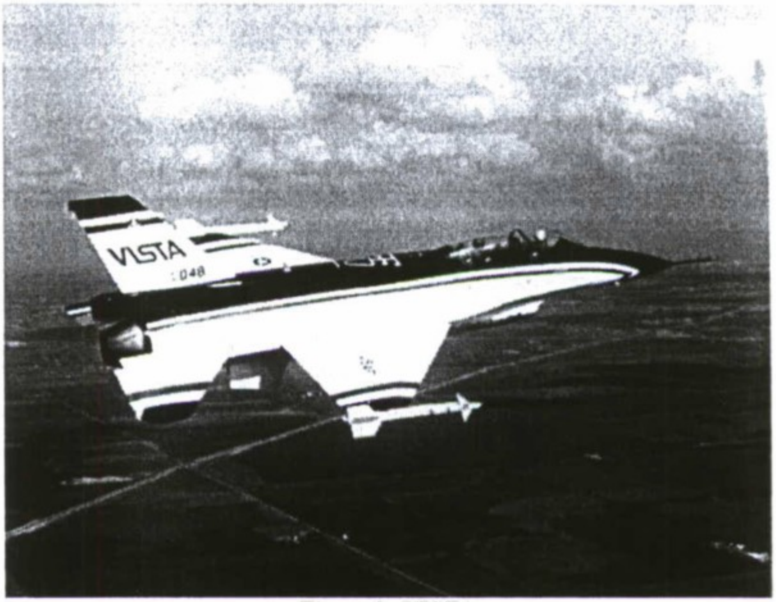

Figure 8. VISTA

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Preliminary Results of the Effective Information Fusion for the Helmet Mounted Display Technologies Program

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INTRODUCTION

Background

In recent years information in the cockpit has proliferated and become more sophisticated. The integration of weapon, navigation and communication systems has resulted in information management issues of interpretation, dissemination, and utilization. It is nearly impossible for the aircrew to utilize all of the information provided by advanced technology capabilities due to the current inability to effectively synthesize and present information to the aircrew. This lack of information management not only impacts safety of flight and aircrew survivability but reduces the operational envelope of the aircraft. These factors and issues must be addressed to properly configure advanced cockpit systems for enhanced mission effectiveness and increased aircraft/aircrew survivability. Future tactical aircraft cockpits must provide the aircrew with the information and interfaces necessary to maximize aircraft performance and fully utilize advanced weapons and the myriad of information available from on-board and off-board sensors.

There is significant research and development currently being performed on various types of cockpit display hardware (e.g., HUD's, MFD's, HMD's), however, little work has been performed in the area of information fusion and information management. Helmet mounted displays in future aircraft will not only save weight and reduce costs but can also potentially increase the operational capability of the aircraft by improving the information management capabilities of the pilot. To date, research focused on determining what information should be presented on the HMD, when that information should be presented, and formats for information presentation has been limited. During the Effective Information Fusion for HMD Technologies program, empirical data has been collected on the performance benefits of various types of information presented in an HMD. This data will aid in an objective selection of effective HMD information content for operational implementation.

Purpose

The Effective Information Fusion for Helmet Mounted Display Technologies program has four major objectives:

(1) Develop and demonstrate integrated HMD information concepts.
(2) Empirically demonstrate performance benefits of HMD information display concepts using pilot-in-the-loop simulation.
(3) Identify technology gaps and avionics requirements that need addressed to achieve proposed HMD formats.
(4) Develop an HMD image base for effective information management. To this end, a multi-media CD-ROM will be used to present dynamic HMD images that demonstrate effective information fusion, avionics requirements to produce those images, identification of HMD/information management technology gaps, and quantitative performance benefits of the HMD images.

Expected payoffs are directly related to the Navy's needs for technical solutions to operational requirements. The specific payoffs listed below are consistent with those identified in the Human Systems Interface Defense Technology Area Plan[1].

- Higher accuracy off-boresight targeting resulting in a 10:1 improvement in exchange ratio/lethality and survivability. Provide real-time re-targeting capability in-flight.

- Lower latency sighting/lock-on capability resulting in a doubling of first pass target acquisition and kill capability.

- Improved accuracy of visually coupled systems resulting in decreased reliance on the head-up display (with associated cockpit design advantages), improved targeting and navigation update performance.

- Advanced control/display crewstation integration and flexible "open" avionics architecture designs characterized by increased throughput and reduced latency.

- Improved aircrew safety and survivability through a control/display system configuration compatible with advanced crew systems life support and escape technologies. Higher "G" tolerance and integrated loss-of-consciousness detection capability, coupled with an optimized visual interface which contribute to expanded flight performance envelopes.

Test Equipment

Helmet Mounted Display

The helmet-mounted display used during this evaluation was a Hughes Training ClearVue system (Figure 1). The system consisted of a helmet shell, display unit, and a separate electronics rack. The ClearVue display provided full color, high-resolution display of symbology and video in a "see-through" mode which allowed the user to also view the out-the-window scene of the simulation. The ClearVue system has an advertised resolution of 1280x1024 pixels for each eye and a total field-of-view of 80 degrees horizontal by 60 degrees vertical.

Figure 1: ClearVue Helmet Mounted Display

Flight Simulator

The flight simulations and empirical evaluations were performed in an advanced technology cockpit simulator at the Boeing Integrated Technology Demonstration Laboratory. This facility contained a 30-

foot-diameter dome display with an advanced fighter cockpit mounted in its center point. The Evans & Sutherland ESIG 4500 projection system consisted of three background projectors which provided a high-resolution forward inset and a lower resolution full-dome out-the-window scene for air-to-air use. A single 8x8 color cathode ray tube (CRT) monitor flanked by two 6x6 color CRT monitors graphically presented the head-down, dynamic, interactive PVI display formats. The entire simulation was generated using a Silicon Graphics Onyx 2 with 16 processors and 3 graphics pipes. A viewing and simulation control room was on an elevated, enclosed platform behind the dome cockpit. Visitors and engineering personnel viewed the cockpit activity in this area while monitoring and examining the entire spectrum of technical and mission aspects of the simulation in progress.

SYMBOLOGY DESCRIPTIONS

Baseline Symbology

Virtual HUD - The Virtual HUD provided a baseline HUD configuration which approximated a MIL-STD 1787B configuration for basic flight symbology. The virtual HUD symbology was presented directly on the helmet mounted display in the aircraft-stabilized position normally occupied by a physical HUD combiner. A depiction of the Virtual HUD symbology is provided in Figure 2.

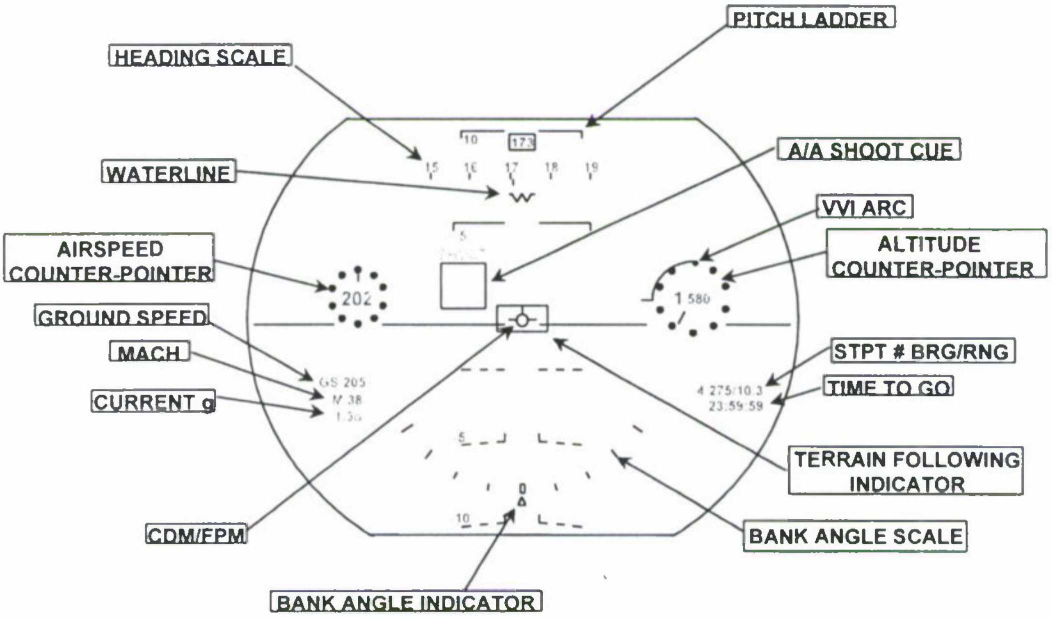

Figure 2: Virtual HUD Symbology

Additional air-to-air weapon symbology, common to the F/A-18 aircraft, was also displayed. This symbology consisted of a Normalized In-Range Display/Allowable Steering Error circle, Steering Dot, and Target Designator Box with SHOOT Cue[2]. The baseline air-to-air symbology is depicted in Figure 3.

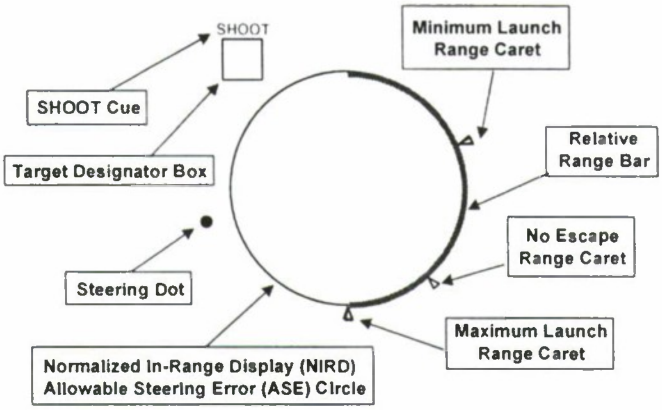

Figure 3: Baseline A/A Symbology

Advanced Symbology

Several concepts were integrated to form an advanced symbol set for the air-to-air, air-to-ground and navigation master modes. These concepts were designed to utilize the unique characteristics of helmet mounted displays including the large display field of regard and egocentric display presentation.

Air-to-Air Symbology

The air-to-air (A/A) symbology consisted of four major components which combined to present an intuitive, egocentric representation of the air battle picture. These components included the 3D Target Icon, Locator line/Reflected Cue, Weapon Field of Regard Boundary, and Caged Display.

The 3D Target Icon (depicted in Figure 4) identified the line of sight to a target as well as information on target range, altitude, aspect and relative weapon range.

Figure 4: 3D Target Icon Symbology
Note: Target range for relative range bar was calculated using a generic unclassified missile model.

The center 3D aircraft icon showed target attitude by movement about its 3 rotational axes. The icon appeared as the actual target would have if it were visible. Threat or friendly aircraft were indicated by icon color (red=threat, blue=friendly) and by shape.

The miniature Normalized In-Range Display (NIRD) circle around the aircraft icon indicated target range relative to the range of the selected missile. The heavy portion of the circle, or relative range bar, rotated clockwise around the circle as target range increased. This range was computed relative to the fixed locations of max and min missile range. The bottom caret represented max missile range (Rmax), the center caret was no escape range (Rne), and the top caret was minimum missile range (Rmin). The color of the NIRD circle was red for highest priority target (next-to-shoot) and green for all other targets in the shoot list.

A "SHOOT" cue and alphanumerics indicating target altitude and range were also associated with the 3D Target Icon Symbology.

The entire symbol set (target icon, NIRD circle, alphanumerics, etc.) was visible for the highest priority target anytime that target was within the HMD field of view. For other targets, symbol sets appeared only when that target was within a 10 degree radius of HMD boresight and the target ID hands on throttle and stick (HOTAS) switch was depressed. In the case of secondary targets, the NIRD circle was displayed in green to distinguish them from the primary target.

The locator line (Figure 5) was designed to give an observer quick and accurate line-of-sight or "look-to" oriented guidance toward a selected point of interest[3]. In the air-to-air targeting application, the locator line indicated the continuously computed azimuth and elevation vector to the highest priority target in the shoot list. The main purpose of the locator line was to indicate the relative position of a target being tracked within the sensor field-of-regard (FOR) when the actual target location was beyond the display field-of-view (FOV). The line was anchored at the center of the display, at the aimsight reticle, and radiated outward toward the edge of the display drawing surface. The locator line and the associated designator symbology superimposed over a target did not coexist. The locator line was replaced by the designator symbology whenever the real world target location was within the display FOV. Likewise, the designator symbology was replaced by a locator line as it crossed outside the display FOV. Additional locator line features indicated the continuously computed angular distance between the target and the aimsight reticle (observer LOS) as well as relative target aspect, range, and weapon firing solution status.

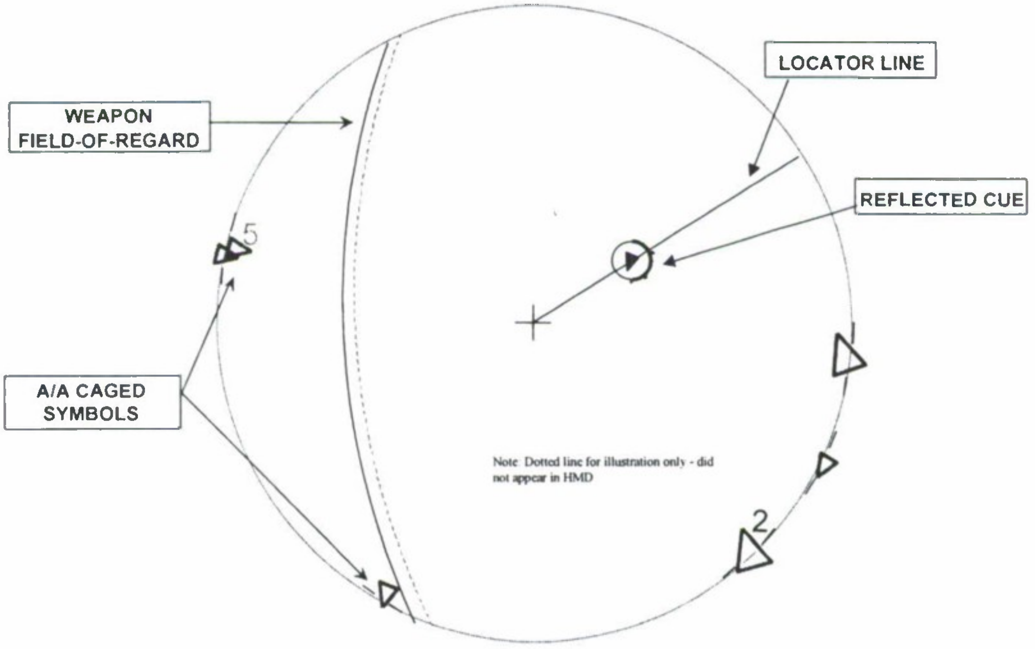

Figure 5: Advanced A/A Symbology

Changes in angular distance (degrees of arc) between the target and the aimsight reticle were represented by a dynamic reflected cue symbol that moved along the locator line in proportion to the rate and magnitude of angular distance change. The length of the visible drawn line represented a compression of the maximum angular distance the target can be tracked beyond the HMD FOV. The position of the reflected cue on the drawn line represented the instantaneous angular distance of the target within the maximum available distance. The compression mechanized into the symbology results in a natural slowing of the apparent motion of the cue along the line. This was important to reduce ballistic head movement overshoots due to the high rates of closure resulting at typical head movement velocities. The cue moved out toward the edge of the display FOV as the angular distance between the aimsight reticle and the target location was decreased. In this way, the cue appeared to be a "reflection" of the converging target location. The observer's visual attention was intuitively led with the cue along the locator line to the point where the designator symbology crossed into the HMD FOV.

Because the observer's attention would be most likely concentrated on the reflected cue symbology, additional features were included to add target/weapon status information to the tracking task. The primary component of the reflected cue was formed of a filled shape and color-coded symbol consistent with the coding strategies employed in the head-down tactical situation displays. In the case of an airborne target, the symbol represented the aspect of the target relative to ownship flight path. A miniature NIRD circle surrounded the reflected cue. The symbol and line color were consistent with the identification convention used throughout the cockpit.

The Weapon FOR Boundary symbology was designed to map the weapon launch volume in an egocentric manner onto the outside scene to afford quick comparison of airborne target position to the limitations of the selected weapon. The symbology viewed in its entirety would appear as a large double ring drawn in space. Viewed through the more limited FOV of the HMD, the symbology appeared as a portion of an arc (Figure 5). The inner circle was formed of a segmented line to indicate "inside" the launch parameter volume. A solid line outside ring indicated the launch volume boundary. Using this concept, a target symbol superimposed over its position in the real world can be naturally related to the selected weapon launch limitations. For this evaluation the Weapon FOR Boundary was designed to behave as an Allowable Steering Error circle, dynamically changing in size according to changes in weapon limitations due to ownship maneuvering, target range changes, target maneuvering, etc. The symbology could also be mechanized to represent only the missile seeker field of regard. This mechanization would be useful when incorporated with future high off-boresight short-range missiles.

The A/A Caged Display (Figure 5) represented priority air-to-air targets within the HMD FOV using symbology conventions consistent with those applied within the head-down displays.[4] Triangle shape codes were employed to indicate air-to-air target location and relative aspect angle. The target symbology was superimposed directly over the real world target location whenever the location was within the HMD FOV. Targets being tracked within the sensor FOR but beyond the display FOV were drawn caged along the edge of the display FOV at the proper azimuth and elevation extrapolation. To keep caged symbols from being confused with superimposed symbols, a small conformal line was drawn through the caged symbol to represent the appropriate portion of the FOV edge against which the symbol was caged. Additional symbology features were employed to convey basic identification information and changes in target state. For example, color-coding was used to indicate team membership. A numeral associated with an air-to-air symbol indicated the target's order in the shoot list. A flashing target accompanied by an auditory warning indicated that target was located within ownship's rear quadrant, providing a "check six" alert. Symbol size was increased for any target sensed to be in a track or firing mode.

Air-to-Ground Symbology

The air-to-ground (A/G) HMD concepts consisted of Locator Lines and a Caged Display similar to those used in the air-to-air mode along with head steered targeting and navigation Forward Looking Infrared (FLIR) sensors. The Locator Lines and Caged display differed from the air-to-air equivalents only in the symbology used to represent the targets.

The Integrated Targeting FLIR concept (Figure 6) integrated targeting pod forward-looking infra-red (T-FLIR) imagery with the out-the-window (OTW) scene, represented by either natural terrain or, in a night/all weather condition, by head-steered navigation FLIR (Nav-FLIR) imagery.

Figure 6: Head-Steered TFLIR Presented in the HMD

The pilot was presented with a head-stabilized aiming reticle and T-FLIR field-of-view (FOV) indicators in the center of the HMD. Once the pilot visually acquired a target, he would center it within the aiming reticle and command a "magnification" by a HOTAS switch. As the pilot looked at the target, the T-FLIR system correlated head-position and moved its line-of-sight to the proper location, using its narrow FOV capability to provide the pilot with a magnified image in the center of the HMD. A second HOTAS switch activation moved the T-FLIR image inset window to an off-set position in the HMD and commanded the T-FLIR sensor to a ground track stabilized mode. This allowed the pilot to resume normal head movement while the target FLIR image remained available in the HMD for further evaluation or target designation purposes.[5]

Missile Evasion Symbology

Missile evasion symbology was available in both the A/A and A/G modes to help the pilot plan and execute missile defense maneuvers. This symbology consisted of a locator line, which directed the pilot's line of sight to the missile, integrated with a missile type symbol, which identified the inbound missile as either IR guided or radar guided. An alphanumeric that displayed the missile time-to-impact was also associated with the missile symbol.

Navigation Symbology

In addition to the Virtual HUD symbology, which was used in conjunction with all the other symbology (except pathway-in-the-sky), three other concepts were evaluated which were designed to aid the pilot in performing the basic flight task.

Synthetic terrain was used to aid the pilot during a low-level terrain following mission segment. This concept displayed a grid pattern which overlaid the terrain to provide an artificial representation of the earth's surface. The grid pattern contour was based on digital terrain elevation data and displayed 50 feet above the actual database terrain. The synthetic terrain was designed to reduce the pilot's dependence on the traditional primary flight reference instruments, such as the attitude indicator, altimeter, and airspeed indicator, by allowing him to use the simulated terrain as he would the actual visual scene for attitude reference and spatial awareness.

An off-boresight 3D Attitude Reference (Figure 7) displayed aircraft attitude to the pilot while he was looking to either side of the aircraft. It was designed to provide attitude maintenance information only, and was not intended as a reference for unusual attitude recovery. The display consisted of a 3D aircraft icon which repeated ownship attitude (pitch and roll only). The aircraft icon was read against a horizon ring, which was displayed around the animated aircraft and referenced to actual horizon. Airspeed (left), altitude (right) and heading (top) were presented as standard alphanumeric indications. The 3D icon/horizon ring symbology changed perspective with pilot head movement such that the attitude symbology appeared as another aircraft "in formation" with ownship. This was an "outside-in" display, with the horizon ring always remaining congruent with the actual horizon.

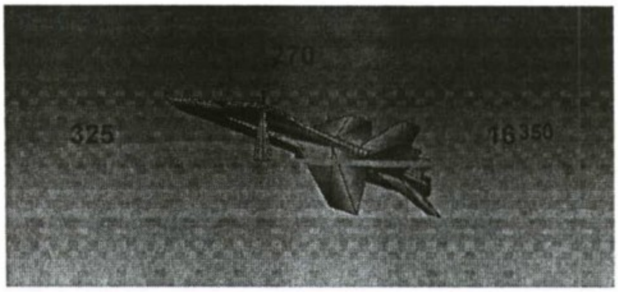

Figure 7: Off-boresight 3D Attitude Indicator

A Navigation FLIR gave the pilot a wide field-of-view, head-steered, FLIR image for pilotage in conditions of reduced visibility, or for wide area target search. The Nav-FLIR image was presented at one-to-one magnification and geospatially referenced to the outside scene. Flight and targeting symbology were overlaid on the Nav-FLIR image providing the pilot with visibility and situation awareness nearly equal to that of day-VFR conditions.

Approach Symbology

Two concepts for carrier approach to landing guidance were compared to the basic glide path deviation needles contained in the Virtual HUD.

The Pathway-in-the-Sky concept used the familiar method of displaying pathway blocks to indicate the intended route of flight (Figure 8). Two vertical scales near the top of the display indicated angle of attack (left) and optimum altitude above the pathway (right). A large "return to path" arrow was

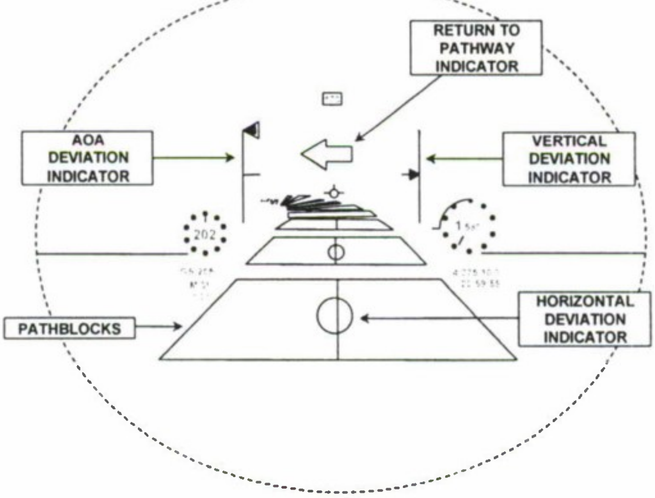

Figure 8: HMD Pathway-In-The-Sky

presented in the top-center of the display if ownship strayed more that five hundred feet off course.

The Approach Path Command Guidance concept was modeled after the flight director guidance cues found on many civil aircraft (Figure 9).

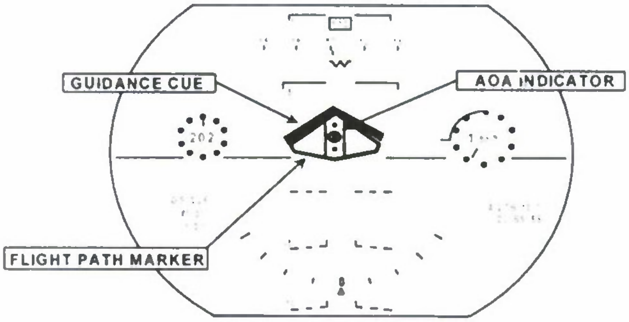

Figure 9: HMD Approach-Path Command Guidance

This concept utilized a red chevron symbol to display commanded roll and pitch angle. The chevron was read against a wedge symbol which was mechanized as an aircraft climb/dive marker. The pilot flew the aircraft to match the top of the wedge symbol with the notch of the chevron.

Symbology in center of the wedge presented angle of attack (AOA) information using a circle moved vertically on dotted scale - up to indicate higher angles of attack and down to indicate lower AOA. The aircraft was "on-speed" when the circle was over the center dot.

METHOD

Mission Scenario

An air-interdiction mission scenario was developed containing segments which were representative of missions that current and future tactical aircraft might support. The major mission elements included an air-to-ground Joint Direct Attack Munition (JDAM) delivery, a reconnaissance segment (Recee)/low-level target-of-opportunity (TOO), an A/A battle, and carrier recovery.

Participants

Six pilots from Naval Air Station Lemoore CA participated in the study. All were qualified F/A-18 pilots with three having additional experience in A-6E aircraft. Total flight hours of the participants ranged from 1300-3300 hours. None of the participants had any significant prior experience with helmet mounted displays. The subjects participated on a voluntary basis and were paid travel and per diem expenses. Two participants per week traveled to the Seattle test facility and each was in the simulator for five to six hours per day for the entire week.

Training

During the week-long test period for each subject, Mondays were fully devoted to training. Each participant spent approximately five hours in the simulator cab learning the HMD symbology and mission tasks. During the Monday training period the participant not flying the simulator was encouraged to watch from the simulation control room where he could monitor the display repeaters and discuss the HMD display concepts with project personnel. Each participant received approximately 30-45 minutes of refresher training before beginning the day's evaluations during the remainder of the week. Participants were not allowed to observe each other during actual data collection.

Test Matrix

Overall, the evaluation was divided into part task evaluations and a full mission evaluation. Due to the limited time available to perform this evaluation, a building-block approach was chosen to compare the part task conditions. The part task evaluations began with a baseline condition which was representative of current tactical aircraft capability. Additional display concepts were added to the baseline, each building on the previous, until all the selected advanced concepts were incorporated. The full mission evaluations consisted of a baseline condition and an advanced condition which contained all of the advanced display concepts. The part task evaluations were performed on Tuesday – Thursday of the test week and the full mission evaluation was performed on Friday.

The carrier approach display concepts were evaluated at the end of the full mission conditions. Since there were three carrier approach concepts and only two full mission conditions, an additional carrier approach was flown after every other full mission condition.

The order of the part task mission segment presentations was randomized across subjects. The order of presentation of the conditions within the mission segments, both part task and full mission, was also randomized. The conditions for the part task and full mission evaluations are listed in Tables 1-4.

Table 1: Air-to-Ground Part Task Test Conditions

Condition	*Display Concepts*
A/G Baseline (HUD)	Virtual HUD symbology Heads-down T-FLIR
A/G HMD 1	Virtual HUD symbology Head steered T-FLIR
A/G HMD 2	Virtual HUD symbology Head steered T-FLIR A/G Look-to Line

Table 2: Recee/TOO Part Task Test Conditions

Condition	*Display Concepts*
Recee Baseline (HUD)	Virtual HUD symbology w/ HUD FLIR display T.F. Box Head-down T-FLIR video
Recee HMD 1	Virtual HUD symbology T.F. Box Head Steered Nav FLIR and T-FLIR
Recee HMD 2	Virtual HUD Symbology Synthetic Terrain Head Steered Nav FLIR and T-FLIR
Recee HMD 3	Virtual HUD Symbology TF Box 3D Attitude Indicator (Nav mode only) Head Steered Nav FLIR and T-FLIR
Recee HMD 4	Virtual HUD Symbology/3D Attitude Head Steered Nav FLIR and T-FLIR Synthetic Terrain
Recee HMD 5	Virtual HUD Symbology /3D Attitude Head Steered Nav FLIR and T-FLIR Synthetic Terrain Caged Ground Threat Symbols, Pop-up Labels and Threat Symbols

Table 3: Air-to-Air Part Task Test Conditions

Condition	*Display Concepts*
A/A Baseline (HUD)	Virtual HUD symbology with traditional A/A symbology
A/A HMD 1	Virtual HUD symbology Locator Line Simple Target Icon/ASE/Shoot Cue
A/A HMD 2	Virtual HUD symbology Locator Line 3D Target Icon/ASE/Shoot Cue
A/A HMD 3	Virtual HUD symbology Locator Line 3D Target Icon/ASE/Shoot Cue A/A Caged Symbols/Check Six display
A/A HMD 4	Virtual HUD symbology Locator Line 3D Target Icon/ASE/Shoot Cue A/A Caged Symbols/Check Six display Weapon Field-of-Regard display
A/A HMD 5	Virtual HUD symbology Locator Line 3D Target Icon/ASE/Shoot Cue A/A Caged Symbols/Check Six display Weapon Field-of-Regard display Missile evasion symbology (highest priority locator line)

Table 4: Full Mission Test Conditions

Condition	*Display Concepts*
Full Mission 1 Baseline **Carrier Approach 1**	**All Modes** Virtual HUD symbology **A/G Mode** HUD FLIR display T.F. Box Head-down T-FLIR video **A/A Mode** ASC & Steering Dot/TD Box/Shoot Cue
Full Mission 2 Advanced **Carrier Approach 2**	**All Modes** Virtual HUD symbology **Nav/ILS Modes** 3D Attitude/Pathway-in-the-Sky **A/G Mode** Head Steered Nav FLIR/T-FLIR Synthetic Terrain Caged Ground Threat Symbols, Pop-up Labels and Threat Symbols A/G Look to Line **A/A Mode** Locator Line /ASE/Shoot Cue 3D Target Icon A/A Caged Symbols/Check Six display Weapon Field-of-Regard display Missile evasion symbology (highest priority locator line)
Carrier Approach 3	**Nav/ILS Modes** Virtual HUD with Approach Path Command Guidance

Measures of Merit

The measures of merit recorded during the simulations are listed in Table 5. Pilots also completed the NASA Task Load Index (TLX) questionnaire after every run.

Table 5 – Measures of Merit

Mission Phase	*Measures*
Recce/TOO	Altitude Deviation (WP5 to 6 only)
	Course Deviation (WP5 to 6 only)
	Airspeed Deviation (WP5 to 6 only)
	Acquisition Time for Each TOO
	Designation Time for Each TOO
	Overall Time for Acquisition/Designation
	Designation Accuracy for Each TOO
	Number of TOO's Acquired
	SAM Exposure Time
	Number of SAM Tracks
	Number of SAM Launches
	Number of SAM Hits
	Number of Ground Strikes
	Fuel Consumed
	Pilot Workload - NASA TLX
Air-to-Ground	Fuel Consumed
	SCUD Acquisition Time
	SCUD Designation Time
	Overall Time for Acquisition/Designation
	SCUD Designation Accuracy
	SCUD Acquisition Success (yes/no)
	Stand-Off Range at Designation
	Pilot Workload - NASA TLX
Air-to-Air	Exchange Ratio
	Number of Threat Radar Tracks
	Threat Exposure Time
	Length of time threats in 6 o'clock position
	Fuel Consumed
	Pilot Workload - NASA TLX
Full Mission	All Part-Task Measures (above)
	Time-On-Waypoint
	Glideslope Deviation (Landing only)
	Total Fuel Remaining
	Pilot Workload - NASA TLX

Data Analysis

The analysis was conducted by assessing pilot performance data, subjective workload ratings, and interview responses. Prior to conducting the formal objective data analysis, frequency distributions of all the measures of merit were reviewed in search of outliers. Data points greater than two standard deviations away from the distribution mean were corrected using the same mean value. This procedure was conducted only once and no outlier patterns were detected.

Upon completion of the descriptive analysis, statistical comparisons of the performance levels and workload ratings, using MANOVA techniques, were performed across the different PVI Configuration and Replication conditions. Because the Off-Boresight 3D Attitude Indicator was limited to Navigation Mode and the Target

Locator Line/Pop-Up Labeling was presented after target designation, data associated with TOO and SCUD acquisition/ designation were collapsed across HMD conditions based on FLIR mechanization (head-down vs. head-up).

Post-hoc Analysis of Variance (ANOVA) and Tukey-HSD tests were performed on the significant effects to identify the nature of the statistical differences. Subjective data collected during the post-mission and exit interviews were reviewed and summarized. The following sections provide the relevant results of the evaluation.

RESULTS AND DISCUSSION

General

Results will be discussed by mission segment. A short description of each task is provided. Data from the part task conditions and the associated full mission segments will be covered together in order to more easily associate data with a specific display concept. Significant or trend data given will be denoted as either from the part task or full mission runs.

Across all concepts, the use of color in the HMD was considered highly desirable. Color facilitates the quick determination of friendly from foe and provides an intuitive relationship between heads up and heads down display symbology. It was noted by most pilots however, that the number of colors used in the HMD should be kept to a minimum.

Recce/TOO

Task

The Recce/TOO task contained a low-level (200 ft.), terrain following flight task in conditions of poor visibility. During this segment pilots were comparing the functionality of the terrain following (TF) box with synthetic terrain. During this low-level segment, pilots came under fire from several surface-to-air (SAM) missile sights located along the route. They were to attempt to avoid being hit by the SAMs, using missile evasion symbology in the HMD in one condition and using heads down missile defense symbology in the other conditions.

After completing the low level run, the pilots climbed to 1000 feet AGL and commenced a search for pre-briefed targets of opportunity. Using a targeting FLIR, either manually steered (via the throttle designator control) or head steered, the pilots located, identified and designated various targets. During the pre-brief they were shown screen shot "photos" of the intended targets which they were to pick out. Distracter targets were also present in the visual database.

Results and Discussion

Pilots generally preferred the synthetic terrain to the terrain following HUD cue. They found it more intuitive to fly although nearly all of them noted that the terrain grid tended to interfere with the HUD symbology, especially at lower altitudes where the terrain lines tend to be very close together. The most prevalent complaint about the TF box was that it did not provide a good predictive capability of the upcoming terrain.

Objectively, the synthetic terrain showed one key advantage over the TF box. SAM exposure time and number of SAM tracks were lower during the full mission scenario which contained the synthetic terrain (Figure 9). This indicates that pilots were able to use the predictive nature of the synthetic terrain to alter the route of flight slightly in order to obtain terrain masking from the SAM threats.

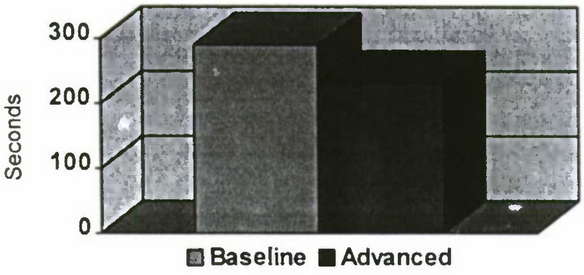

Figure 9: SAM Exposure Time

Pilots overwhelmingly preferred the head steered T-FLIR to the manually steered system. The ability to quickly designate targets while staying heads out of the cockpit allowed them to maintain greater situational awareness. The only negative comments associated with the head steered T-FLIR were simulator related. The resolution of the T-FLIR image in the HMD was lower than on the heads down T-FLIR display, making identification of the pre-briefed targets more difficult in the HMD. This complaint was validated by the fact that the target designation accuracy was much worse during the advanced full mission scenario using the head steered FLIR.

Objective results of the part-task evaluation indicated that pilots deviated significantly less from commanded altitude (1000 ft. AGL) with the advanced condition consisting of the head-steered T-FLIR presented in the HMD than with the baseline condition consisting of the head-down T-FLIR (Figure 10). This would indicate that providing the T-FLIR image in the HMD allowed the pilots to cross-check flight information more efficiently.

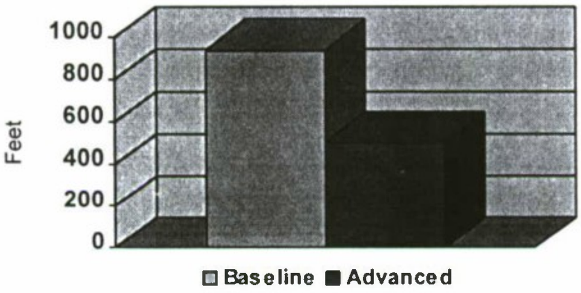

Figure 10: Altitude Deviation During TOO Acquisition

Although not significant, pilots tended to take less time to designate a TOO using the head-steered T-FLIR (advanced condition) than with the head-down T-FLIR (baseline condition) (Figure 11). The head-steered cueing capability provided by the HMD enabled the pilot to slew the T-FLIR over a target and designate much quicker than with the traditional HOTAS mechanization. Further evidence of this is provided by the significant results found in the Air-to-Ground task.

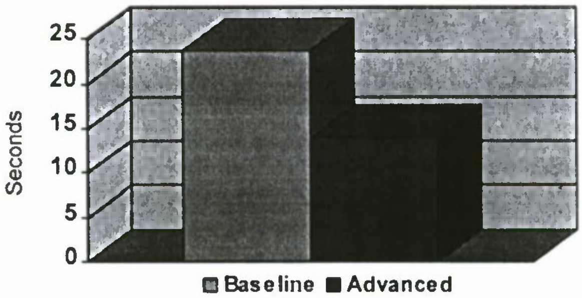

Figure 11: TOO Designation Time

Air-to-Ground

Task

The A/G part task evaluations consisted of a target acquisition task during which the pilot searched for a SCUD target. Though the target position was pre-briefed, the actual target position in the database differed from the pre-briefed position to simulate a mobile target. After locating and designating the target with the T-FLIR, the pilot delivered a JDAM weapon on the target. As in the Recce/TOO conditions, a manually steered T-FLIR was used for the baseline configuration and a head steered T-FLIR for the advanced conditions.

Results and Discussion

Pilot opinion concerning the head steered T-FLIR was even more positive during the A/G phase of the evaluation. The capability to look at a target and accept or reject it, and designate when appropriate, was unanimously well received. As in the Recee/TOO phase, the only negative comments had to do with the poor T-FLIR display resolution in the HMD. Target designation accuracies were again better using the head down display.

The objective data for the A/G evaluations indicated that target acquisition times and target designation times were significantly better with the head-steered T-FLIR (advanced) than with the head-down T-FLIR (baseline) (Figure 12).

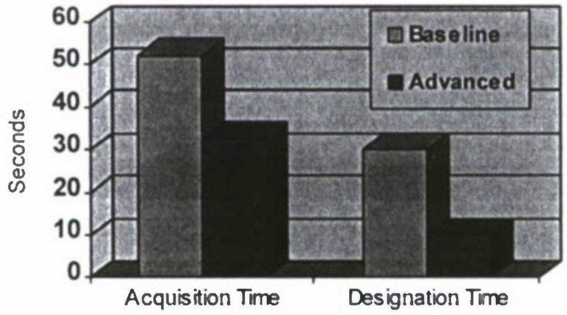

Figure 12: A/G Acquisition and Designation Time

Using the pilots subjective comments as a guide for interpretation, the head-steered cueing capability provided by the HMD allowed the pilots to quickly slew the T-FLIR over possible targets and evaluate using its magnification capability. By enabling the pilot to locate/evaluate targets more rapidly, acquisition time and thus designation time for the actual target was reduced.

Overall subjective workload ratings (mental demand and performance estimation specifically) were significantly lower for the advanced condition with head-steered T-FLIR and target locator line than for the baseline condition with head-down T-FLIR. This indicates that the advanced condition reduced workload by allowing the pilot to more easily return to and attack the target once it was designated.

Air-to-Air

Task

The A/A task consisted of a 3 friendly vs. 5 hostile engagement. The other two friendly aircraft were controlled by the simulation and always engaged the same two hostile aircraft. The subject pilots were responsible for the remaining three bogeys and were briefed on which aircraft to engage. As they entered the A/A engagement zone they saw only four of the five hostile aircraft – the fifth was a pop-up threat that was programmed to appear at the subject pilot's six-o'clock position after a certain time had elapsed. The pop-up threat was designed to evaluate the functionality of the "check six" portion of the A/A caged display.

Results and Discussion

Pilot comments regarding information presented by the advanced concept A/A symbology were generally favorable. All subjects seemed to like the locator line symbol for look-to guidance to the target and the use of the NIRD circle as the target designator "box," All but one also favored the 3D target icon over the basic triangle icon as the target designation symbol, and that subject showed signs of changing his mind as the week progressed. All of the subject pilots noted a requirement that the 3D target icon become transparent or even be removed as the actual target comes into visual range.

Comments on the caged display were mostly favorable but less numerous. Due to problems in accurately fitting the HMD to all subjects, the periphery of the display was sometimes difficult to see. Since the caged display was, by design, always near the display edge, it was often difficult to see.

During the full mission evaluations, the number of threat radar tracks and the number of ownship deaths were both significantly less in the advanced condition (Figure 13). This could indicate that pilots had greater situation awareness when using the advanced A/A HMD concepts. Pilots often noted the SA improvement of being able to look at a target and get range information from the NIRD circle and being able to anticipate target movements from the 3D target icon. The mean time a threat was in ownship's six o'clock position was also significantly less when the advance HMD concepts were available. This would indicate that the pilots were able to achieve some benefit from this display despite it being difficult to see.

Figure 13: Number of A/A Threat Tracks and Ownship Deaths

Though not statistically significant, an interesting trend was shown in the pilot workload ratings for the air-to-air part task evaluations (Figure 14).

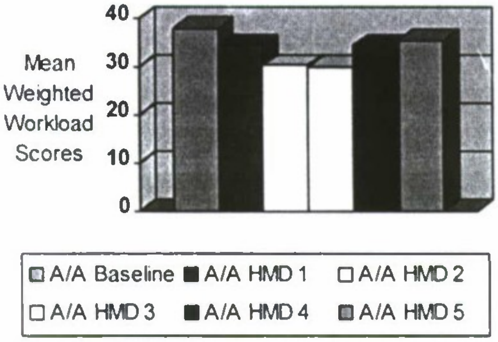

Figure 14: A/A Workload Scores

Workload showed signs of decreasing as some of the advanced symbology was added, but as more symbology was added workload began to increase again. This trend would indicate that in some conditions the symbology became cluttered and more difficult to use.

Carrier Approach

Task

The carrier approach evaluations were performed in conjunction with the full mission simulations. At the end of the baseline full mission condition, the pilots performed a carrier landing using the standard glideslope deviation needles. At the end of the advanced full mission condition they performed a carrier approach using the pathway-in-the-sky. A third approach symbology condition was given after every other full mission condition.

The carrier approach phase seems to be the one mission aspect upon which pilot's felt there was really no improvement to be gained with any of the advanced symbology evaluated. There were some positive comments regarding the ease of flying the pathway once established on it. Several of the pilots felt that the mechanization of the pathway in this evaluation could have been improved upon. In this evaluation, pilots obtained all attitude information from the orientation of the pathway, there was no back-up attitude symbology available. If the pilot strayed too far from the pathway, there was no attitude information available. Most pilots also commented that the pathway would have been easier to fly if the altitude and angle-of-attack scales had been further down toward the middle of the display near the end of the path blocks, rather than near the top of the display. There were no differences in airspeed or glideslope deviation between the standard approach symbology and the pathway.

There were no positive comments whatsoever regarding the approach path command guidance. It was by far the most maligned and disliked concept presented during this evaluation. The primary complaint was that it was too large and blocked the view of the carrier. Another complaint was that it only provided command guidance to the glidepath and did not provide information on the magnitude of the glidepath error. Glideslope deviation was not significantly worse with this concept than the other two approach symbologies, however airspeed deviation was.

SUMMARY

Helmet mounted displays will undoubtedly become a major element of the of the cockpit display suite in future tactical aircraft. In fact, basic HMD systems are already being incorporated into many aircraft. The need for extensive research in helmet display formats is ongoing.

The primary goals for this project were to evaluate the basic requirements for helmet mounted display *information content* and identify the technological shortfalls which must be addressed to meet the information requirements. To this end, the Effective Information Fusion for Helmet Mounted Displays Technologies program has demonstrated that the HMD can be used to provide an intuitive, *egocentric* display medium which can greatly increase the situation awareness of the tactical aircraft pilot.

The authors believe there are two issues of paramount importance when considering the design of future helmet display formats. First, developers of display formats must not lose sight of the unique nature of the helmet display and its capability to present information in an egocentric format. *The HMD should always remain first and foremost a weapons cueing and sensor display device.* The display of basic primary flight information can be accomplished as well by traditional or modified *aircraft referenced* HUD formats (whether displayed on a traditional HUD combiner or in an HMD). Big picture, "God's eye" situation awareness formats are better presented on heads down display.

Second, the temptation to put too much information in the HMD must be resisted to an even greater extent than in HUD symbology design. A pilot can look around or away from the HUD if it becomes too cluttered. A helmet display is extremely compelling and will always be directly in the pilot's line of sight. Too much information or symbology in the HMD could distract the pilot from his primary task, or even worse, obscure important information or visual cues available in the real world.

Though not discussed in this paper, the technological requirements which must be addressed in order to meet the information display requirements set forth during this evaluation will be covered in the CD-ROM desktop demonstration. The CD-ROM will also contain interactive multimedia demonstrations of the concepts evaluated during this project as well as animations of many concepts which we were unable to incorporate into the flight simulation due to time and budgetary constraints.

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Force Feedback Interface to Reduce Pilot's Spatial Disorientation

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Summary

The objective of the present research is to enhance pilot performance and reduce *spatial disorientation* which was identified as the major cause of aircrew/aircraft losses. Spatial disorientation tends to occur when a pilot's gaze is temporarily directed away from the aircraft feedback instruments.

Our approach is to use a haptic interface to provide continuous and non-visual feedback of the aircraft attitude and orientation to the pilot. This can be done by using an elbow force feedback system being developed at Rutgers University for human biomechanical rehabilitation.

The sensation of attitude is provided by applying a torque on the elbow joint to resist the flexion/extension movement. The sensation of orientation is provided by applying a torque to resist the rotation of the forearm. The intensity of the torque is proportional to the deviation from the optimal attitude and orientation. Zero torque signals to the pilot that the attitude and orientation are correct while high torque signals that the aircraft is in a dangerous attitude or orientation. It is clear that high torque should not exceed 25% of the maximum human capability to move the elbow in order to let the pilot override if needed.

The elbow force feedback unit is made of pneumatic structural fabric located around the elbow joint. The system is adapted to the morphology of the human elbow and doesn't reduce its motion range. The pneumatic actuator designed for rehabilitation is light and capable of producing a torque up to 35Nm at 30psi which is enough to resist the forearm flexion and rotation of most men.

This newly designed haptic system can easily be adapted to the anti-G suit and aircraft cockpit conditions. Initial experimental tests were done to evaluate the improvement of the situation awareness when information of attitude and orientation of the aircraft are provided hapticly to the pilot.

1 Introduction

The aircraft cockpit is designed so that all the instrument information is displayed to the pilot visually. In a normal situation, the amount of significant instrument data are small and the pilot has enough time to perceive and interpret everything before making a decision and taking action. Unfortunately, in situation awareness, the significant sensor information increases and the pilot has to frequently switch attention between different visual displays, which is demanding and can cause a dangerous delay in reaction.

Also, in certain situations, the pilot can be temporarily disoriented and his gaze can be directed away from the altitude and the orientation display. Without this critical information, the risk of crash is higher. This temporary disorientation was identified as the major cause of aircrew/aircraft losses [1][2]. In these cases, the presence of a second source of information concerning aircraft attitude can be very helpful for pilots. One of these sensorial channels uses the haptic perception.

Our interest in developing haptic interfaces for pilots was motivated by two factors. Firstly, the haptic perception of the pilot is underutilized, while the visual perception is overloaded. Secondly, humans perceive haptic information at much higher bandwidth than visual information, and the pilot can make use of it particularly in situation awareness.

There is not much research being done in this area. One project is the tactile suit developed at the Spatial Orientation Systems Department (NAMRL) [3]. The system uses vibrotactile stimulators to apply attitude and motion information taken from the aircraft's instruments to the pilot's body torso (Figure 1). This torso suit system provides continuous non-visual information to the pilot.

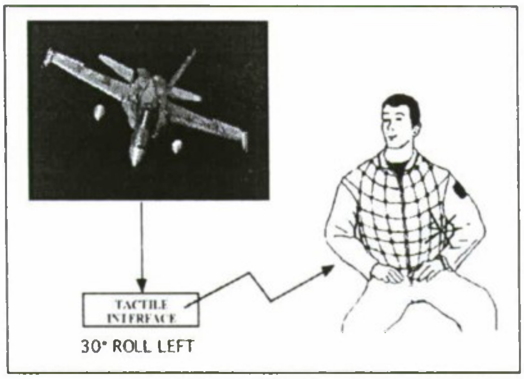


Figure 1: The vibrotactile body torso suit [3]

Haptic feedback was also provided by handling the aircraft control in a fighter simulator [4]. The force feedback simulates the centrifugal forces when the aircraft is rolling and by wind forces during turbulent weather. Experimental results showed increased landing accuracy compared to simulation using a control stick with no force feedback [5].

Most of the haptic feedback interfaces were developed for virtual reality applications like tele-surgery and tele-rehabilitation applications [6]. The research of our laboratory focuses on developing a force feedback interface for hand tele-rehabilitaion and recently for elbow and knee tele-rehabilitation [7]. The force feedback interface proposed in this paper is based on our research on the elbow tele-rehabilitation system. Our goal is to use the elbow interface unit to increase the perceptual understanding of the spatial orientation of the aircraft. The paper presents in sections 2 and 3 the concept and design of the elbow interface. Section 4 describes the structure of the pneumatic actuator used to build the interface. Initial experimental results evaluating the interface for spatial orientation are presented in section 5. Conclusions are given is section 6.

2 Spatial orientation using an elbow haptic interface

The concept of the elbow interface is based on the application of torque to the elbow joint in order to inform the pilot about the deviation of the aircraft from its optimal orientation and attitude. The applied torque intensity is proportional to the amplitude of the deviation. The elbow interface can apply two torques at elbow joint axes (Figure 2).

The first torque opposes the flexion and the extension of the forearm which is interpreted by the pilot as a deviation of aircraft pitch orientation from horizontal reference (or other optimal reference). When the interface torque is directed to open his elbow joint, the pilot should react naturally to this force by extending his forearm until the torque becomes zero. In this case, the pilot arm motion pushes the aircraft stick in the forward direction, which corresponds to a pitch down orientation and to a reduction of the aircraft altitude. In the other case, when the torque tends to close his elbow joint, the pilot reaction should be natural and rotate his elbow joint in order to reduce the torque. This elbow rotation corresponds to a backward stick motion, which increases the aircraft altitude.

The second interface torque is perpendicular to the flexion-extension torque and is directed in order to turn the pilot forearm to the left or to the right. When the torque bends the pilot forearm to the left, the pilot should react in the same direction and rotate his forearm to the left until the torque becomes zero. This forearm motion corresponds to a left turn of the aircraft stick or a left roll of the aircraft with value equal to his deviation from optimal orientation. In a similar way, when the interface actuator produces a torque to bend the pilot's arm to the right, the pilot should then rotate the stick to the right which corresponds to a rotation of the aircraft to the right.

Note that this left/right motion doesn't correspond to a natural degree of freedom at the human elbow joint, but it corresponds to the aircraft stick motion for varying the aircraft roll orientation. In the next section, we will describe the interface design and we will see that the user feels very comfortable with this torque.

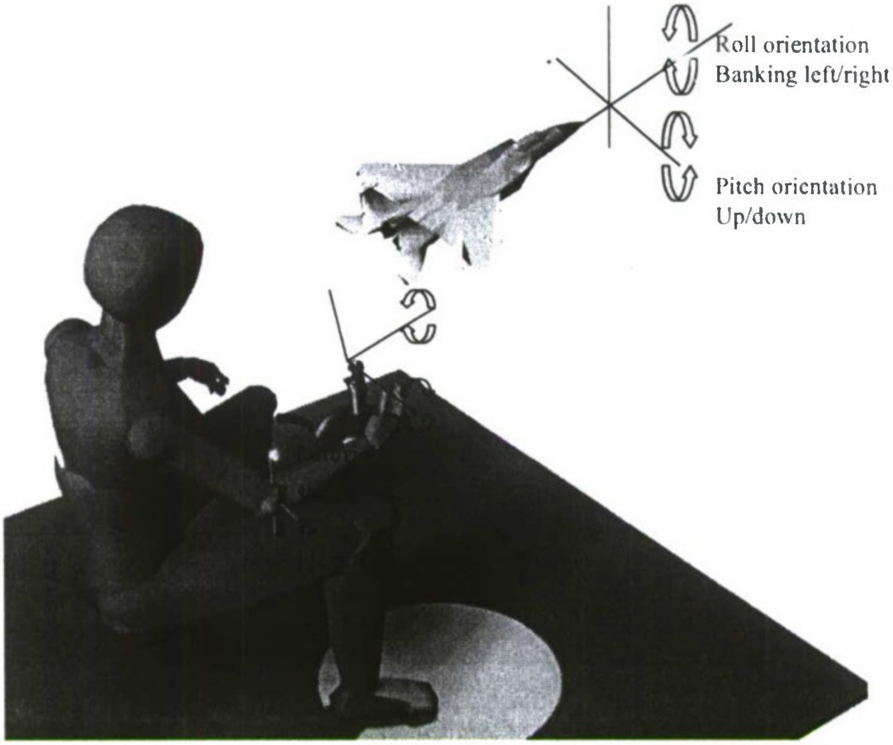


Figure 2: Correspondence between the aircraft attitude and the elbow torque: the elbow flexion/extension torque corresponds to the aircraft nose up/down (pitch angle) and the elbow left/right torque corresponds to the aircraft banking (roll angle).

3 Design of the elbow force feedback interface

Physical interface for pilots should assure: 1) comfort and safety, and 2) unconstrained natural motion. The first design goal is accomplished by developing an interface without using mechanical joints nor mechanical links. The unique components are small pressurized bladders which make the interface easy to be integrated as part of the anti-G suit. Note that the anti-G suit already contains a pressure system to prevent pooling of blood during high accelerations. The pressure system is built with several air bladders and can apply positive pressure to lower body extremities of pilots [8].

The second design goal is accomplished by developing an interface made of two separate parts fixed at the forearm and arm links. Thus, the area near the center of elbow joint is always free to allow a complete and natural motion of the pilot's arm. With such design, the interface simulates the elbow torque instead of applying a real torque as was previously designed for the tele-rehabilitation application. Therefore the pilot always has control of his arm motion and aircraft stick even in the presence the feedback torque. Thus the interface informs the pilot about the aircraft attitude but does not control the aircraft by constraining his arm motion.

The elbow haptic interface is made with eight pneumatic bladders grouped in two sets of four, an arm set and a forearm set (Figure 3). The bladders of each set are fixed around the pilot arm link at 90° intervals. Each bladder of the arm set is coupled to a bladder of the forearm set located on the opposite side at 180°. When the bladder is pressurized, it expands in balloon-like fashion against the pilot's arm and maintains a directed force. Therefore, exerting a variable pressure (force) among the bottom bladder of the arm set and the top bladder of the forearm set (Figure 3-a), creates a pair of forces which mechanically correspond to the elbow extension torque. On the other hand, pressurizing the top bladder of the arm and the bottom bladder of the forearm (Figure 3-b) creates a pair of forces which mechanically correspond to the elbow flexion torque. In a similar way the left/right direction of the elbow torque is created with the left and right bladders (Figure 3-c and 3-d).

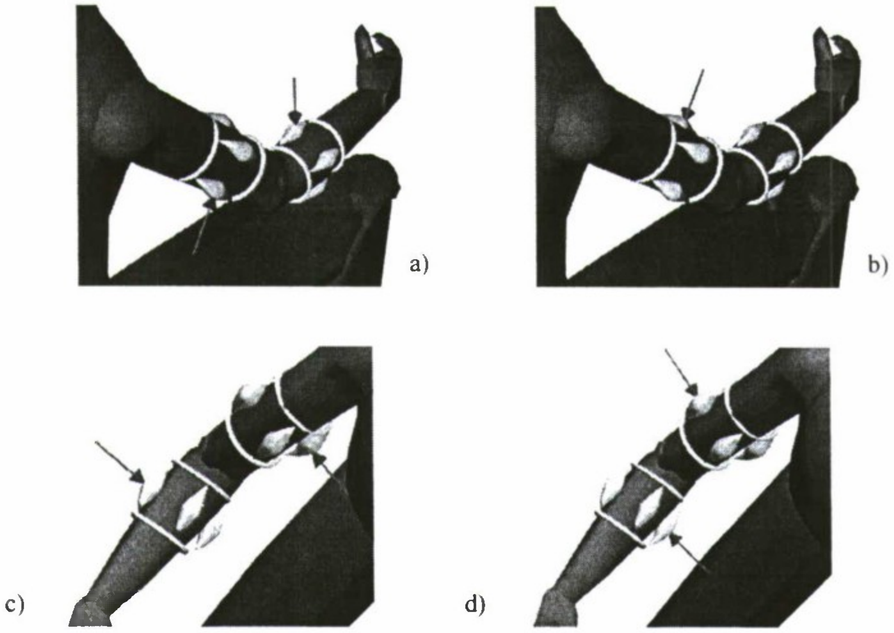


Figure 3: Distribution of the pneumatic bladders near the elbow joint:
a) extension torque, b) flexion torque, c) left torque, d) right torque.

4 Structure of the pneumatic actuator

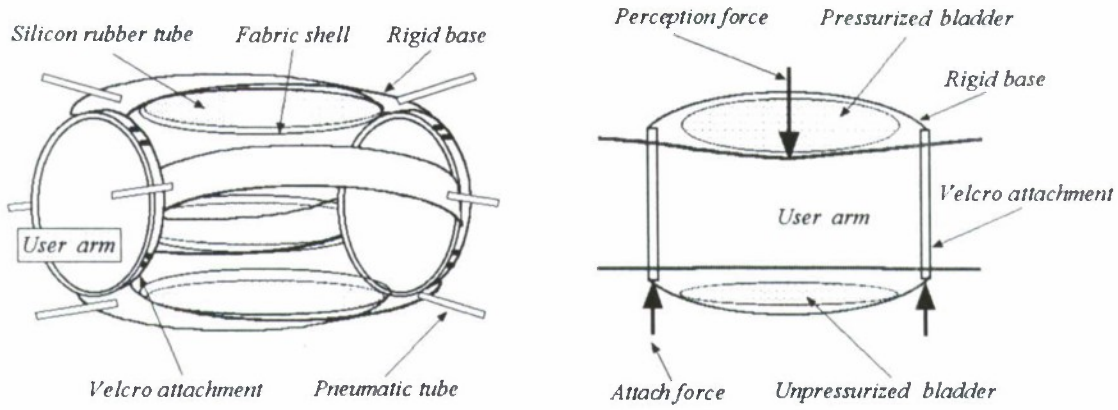
The interface bladder consists of an expandable internal tube surrounded by a fabric shell. The inner elastic tube is made of silicon rubber material, which has the capability to sustain repeated strains of over 300%. The fabric shell acts to constrain the expansion in order to prevent the tube from blowing out under high pressure.

Each bladder is attached to its own thin and rigid base made of carbon composite material (Figure 4-a and 5-b). The base's rigidity keeps the force direction toward the pilot's skin when the bladder inflates. Note that the base has a small bent shape in order to avoid a permanent contact of the bladder with the pilot's skin when no pressure is present.

The four bases and the bladders are attached together with four thin velcro straps to form a cylindrical shape. The velcro attachments allow the adjustment of the 90° interval position of each bladder considering the different sizes of the pilot's arm. Also, the ring shape of the velcro attachment allows the pilot to feel each bladder separately and locate the direction of the bladder's forces. Figure 4-b shows the force distribution around the arm when only one bladder is pressurized.

The maximum pressure that can be sustained by the bladders is 50psi. To increase comfort, we limit this pressure to 30psi. A high-pressure range increases the sensitivity of the interface to small variations of the aircraft attitude. The pneumatic bladders are driven by proportional pressure regulators that operate in a closed loop. The bandwidth of the output pressure was experimentally measured at 5 Hz. These units are controlled with an embedded 486 PC which can communicate with any host computer through a RS232 line (Figure 5-a). This control unit is part of the interface normally controlling the Rutgers Master hand interface [7].

The pressure regulator bandwidth of the above controller may be insufficient for perception of spatial orientation through the elbow interface at the maximum pitch and roll speed motion (10 rpm speed of the spatial disorientation trainer). A new pressure regulator which increases this bandwidth is currently being developed in our laboratory. This new regulator uses fast, high airflow, solenoid valves controlled by software. The bandwidth of the output pressure is estimated at 20Hz when the maximum controlled pressure is 30psi and the input pressure is 100psi.



a) b)

Figure 4: Illustration of the pneumatic actuator:
a) set of 4 bladders, b) forces distribution.

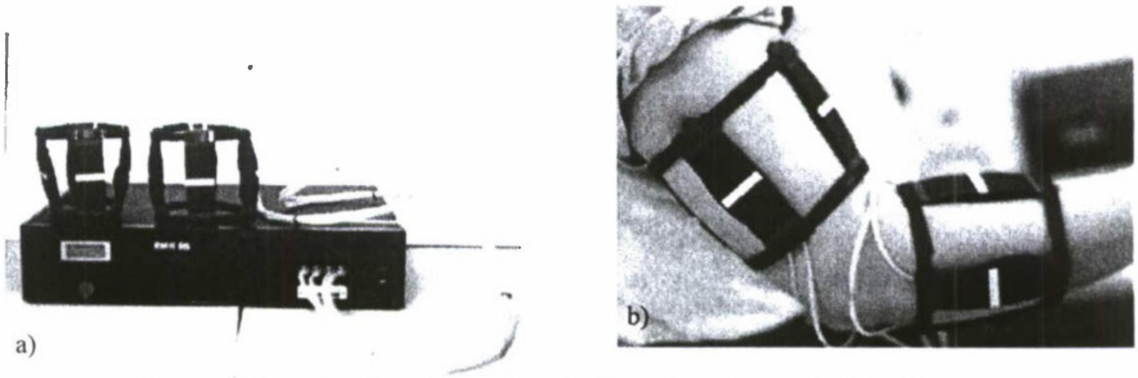


Figure 5: Elbow interface: a) controller unit, b) user's arm wearing the interface unit.

5 Initial experimental study

The experiment reported here, studies the effect of force feedback at the elbow joint on controlling the aircraft attitude when visual information is either poor or absent. To achieve this, we built a dedicated experimental flight system. It consists of a graphics station (Pentium 300 with Fire-GL graphics accelerator), a 2D joystick (a replica of the F15E flight stick) and the elbow interface described above. The joystick and the elbow interface communicate with the graphics station through a serial line, and receive new commands at 60 Hz.

The graphics station displays an animated virtual aircraft attitude indicator implemented using Sense8 WTK software library [9] at 60 fps. The virtual attitude indicator displays a reference line, a horizon line, and a virtual line (Figure 6). The horizon line represents the aircraft attitude (aircraft nose down/up and banking right/left) controlled by the user through the stick. The virtual line represents the target or the desired aircraft attitude generated randomly by computer.

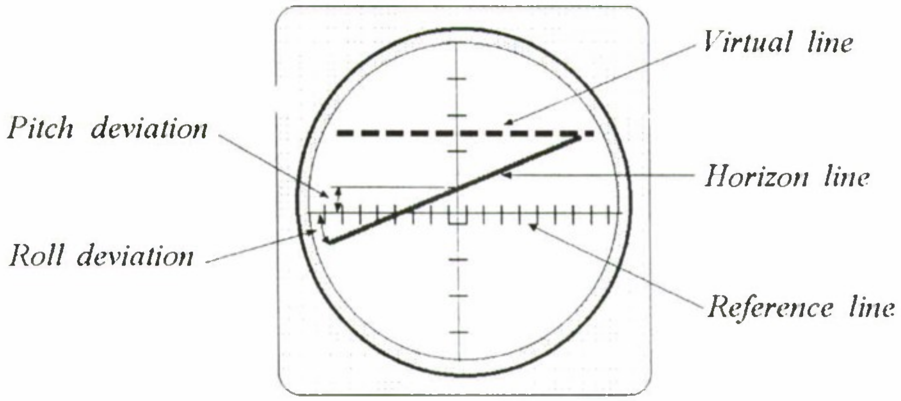


Figure 6: Illustration of the Virtual Attitude indicator displayed on the PC

The maximum deviation of the target line (virtual line) from the reference line is set to 90° (from 0° to -90° or from 0° to 90° according to the direction) for the roll and pitch orientation. The rate of change in orientation is set at 10°/sec, which is close to the real attitude rate of change.

When the deviation of the horizon line (controlled by user) from the target line (controlled by computer) is less than 30°, the bladder pressure of the elbow interface is proportional to the attitude deviation. Thus an attitude deviation of 20° roll left will correspond to pressure of 20psi on the corresponding bladders. When the attitude deviation is greater than 30°, the corresponding bladder pressure is constant and equal to 30psi. With this approach, we increase the resolution at small attitude deviations and expect that an attitude deviation greater than 30° will be an infrequent event. When the target line is aligned with the virtual line, the bladder pressure is equal to zero.

During the experiment, the user is seated in the front of the PC screen, while wearing the elbow interface and grasping the joystick (Figure 7). The user is then instructed to track the virtual line with visual feedback and haptic feedback. The user performs a few minutes of trials to become familiar with the interface (recognition of the bladder pressure and torque distribution). The experimental measurements were recorded from several trials done by one user.

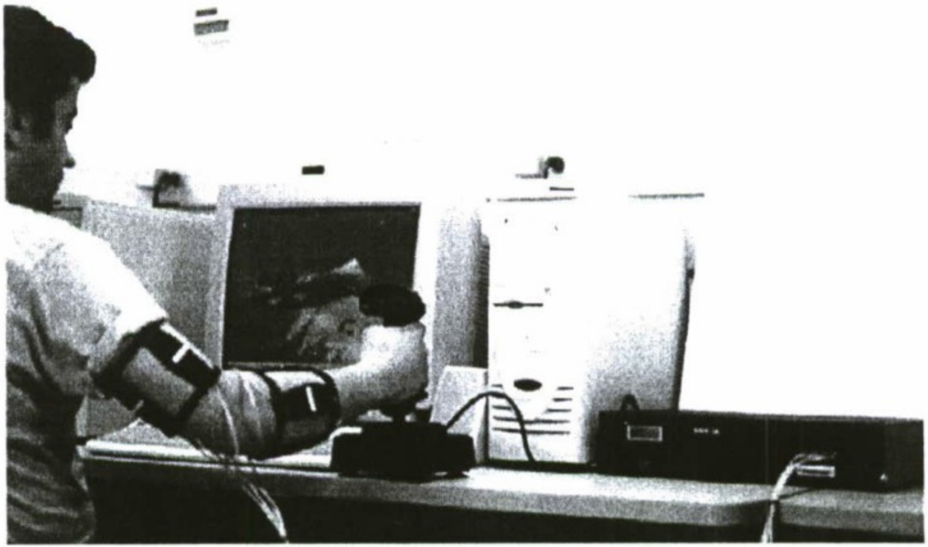
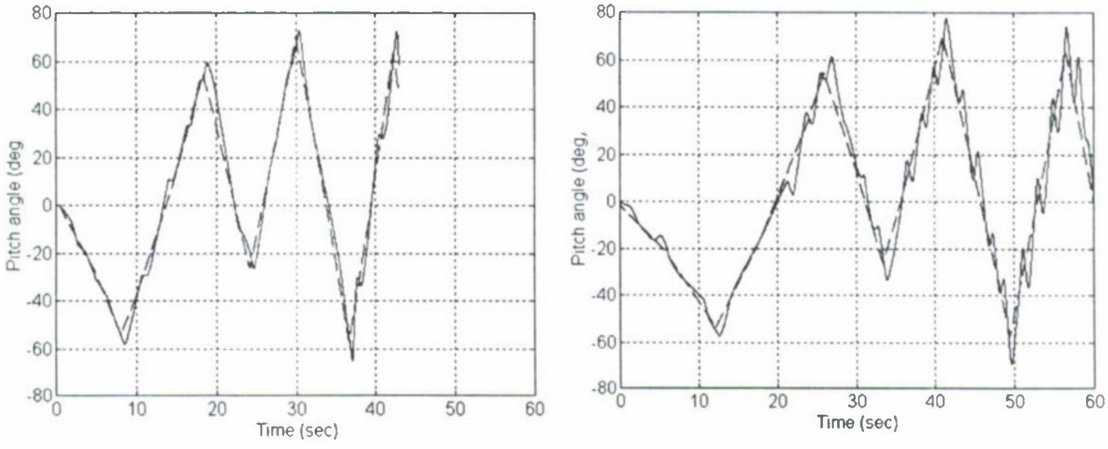


Figure 7: Overview of the experimental site

The first experiment compares the performance of the haptic display with the visual display in presenting attitude information to the pilot. The experiment consists of tracking a random attitude trajectory with visual feedback alone and then with haptic feedback alone. Figures 8-a and 8-b plot the target and user's trajectory for pitch deviation. The average tracking error was about 4.2° for the visual feedback and 6.4° for the haptic feedback. The average tracking error with only haptic feedback is close to the error measured when using visual feedback, which means that the information sent by the interface is correctly understood by the user.

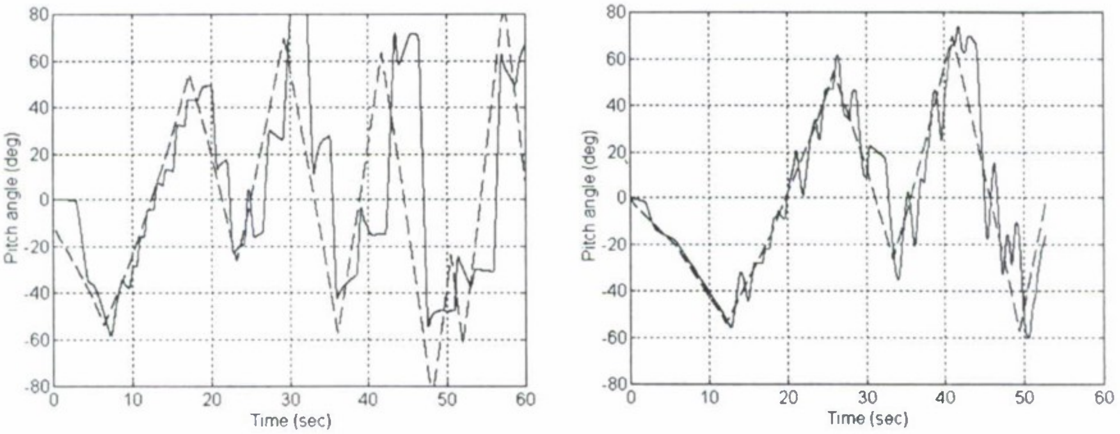


a) b)

Figure 8: Pitch orientation tracking:
a) with visual feedback only, b) with haptic feedback only

The second experiment simulates the situation awareness when pilot gaze is temporarily directed away from the visual display. The experiment consists of tracking a random attitude trajectory with an altered visual feedback, with and without haptic feedback. The altered visual feedback is simulated by switching on/off the display of the attitude indicator at different times. The switch-off times change continually from 0 (attitude indicator is permanently displayed) to 5 sec after 60 sec of tracking, while the switch-on time is constant and equal to 0.2sec. For example, at 30 sec into the experiment the attitude indicator is switched off for 2.5sec. and switched on for 0.2sec.

Figures 9-a and 9-b show an example of the tracking results for one user. The average tracking error decreases from 27.4° without haptic feedback to 8.9° when haptic feedback supplements the poor visual feedback. The improvement is significant when the haptic feedback is present.



a) b)

Figure 9: Roll orientation tracking:
a) altered visual feedback, b) altered visual supplemented by haptic feedback

6 Conclusions

A simple and ergonomic elbow force feedback interface designed to improve the spatial orientation of the pilot was developed. The interface has the advantage that it allows the full and natural motion of the arm and can be easily integrated with the pressurized anti-G suit. The interface is made with four pairs of pneumatic bladders surrounding the arm and the forearm near the elbow area. When the bladders are pressurized, a simulated torque is created at the elbow joint which informs the pilot about the aircraft attitude deviation from an optimal or a reference attitude.

A simple evaluation experiment using a graphics station as an attitude indicator display and a 2D joystick as an aircraft stick was performed. The experiment compared the performance of tracking a virtual attitude randomly generated by computer using visual display, with and without haptic feedback. The results show a real improvement in the understanding of the attitude information when the haptic feedback was present.

More experiments should be performed in future, using a more sophisticated flight simulator, to evaluate precisely the improvement in reducing the pilot's spatial disorientation in situation awareness. Further experiments should measure the benefit of using a faster pneumatic controller currently under development at Rutgers University

Acknowledgments

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The Application of Tactile Cues to Enhance Situation Displays

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Abstract: The Tactile Situation Awareness System (TSAS) consists of an array of tactors applied, in columns and rows, to the torso, that provide intuitive three dimensional (3D) information to aircrew, astronauts and operators of remote operated vehicles. Intuitive delivery of orientation, velocity and range has been proven in actual flight tests with TSAS. Due to the integrative nature of central nervous system design, haptic interfaces enhance and supplement audio and visual displays. Tactile displays have already demonstrated synergistic effects with standard flight instruments, improving precision in areas such as hovering and transitioning to and from forward flight both with and without degraded external visual conditions. TSAS, like 3D sound, provides 360 degree coverage in an easy-to-interpret format. Furthermore, it can resolve some of the illusions and ambiguities that occur when using 3D sound displays in dynamic environments. Applications to enhance head up displays (HUD) and helmet mounted displays (HMD) include drawing attention to and targeting of objects outside the field of view tactilely and haptic presentation of spatial orientation flight parameters. Such a system would increase situation awareness (SA) while allowing reduced clutter in a visual display. Utilization of the presently unused haptic sensory channel permits reduced visual distraction and improved resolution of audio cues. A multi-modal system promises reduced spatial disorientation and pilot workload.

A number of tests in fixed and motion based simulators have demonstrated decreased reaction time, increased precision of maneuvers and decreased perceived workload when tactile cues are provided in addition to the normal visual, audio and motion (on motion platforms) information. Flight tests in fixed and rotary wing aircraft have proven that haptic displays can supplement cockpit displays and external cues to improve SA in flight. Furthermore, in test situations, TSAS has supplanted pilot visual systems, when visual information was excluded. In flight, relying on tactile information, pilots have reported decreased workload, increased SA, and improved maneuver accuracy.

Simulations of helicopter, fixed wing aircraft, astronaut extravehicular activity, space shuttle landing, parachute navigation, high speed boat and undersea diving scenarios have been developed. Deployed systems have been tested in a Navy T-34 turboprop, an Army UH-60 and by special forces divers, with positive results. TSAS development continues, as more platforms and applications are identified and systems are deployed into real world situations.

Keywords: Situation Awareness, Spatial Disorientation, Tactile Situation Awareness System, Extra Vehicular Activity, Three Dimensional Audio, Workload.

Introduction: In the course of human evolution, the sense of touch has developed to be preeminent in providing immediate and intuitive awareness of the location of things that are so near that they come in contact with the body. The adaptive advantage of this development is self-evident. Tactile interfaces that exploit the unambiguous and vivid awareness of location on the body's surface have been shown to improve the SA of pilots of fixed and rotary wing aircraft and of divers in undersea environments. The tactile situation awareness system (TSAS) consists of an array of tactile transducers (tactors), held in contact with the torso of a human operator, that delivers spatial orientation intuitively. With the inherent and intuitive body-referenced organization of the somatic tactile sense, the brain readily assimilates position and attitude relative to other significant objects in the environment. Providing orientation information in this manner reduces perceived workload in real world operations. This reduction results from the continuous nature of the TSAS provided data, which is maintained even while the operator focuses on a specific instrument or changes radio frequencies. By exploiting this relatively "unused" sensory pathway, TSAS allows an operator to concentrate on those mission tasks requiring the higher resolution senses of sight and sound more effectively.

In the aviation context, tactile interfaces for military fixed-wing and rotary-wing aircraft have been developed to improve the spatial orientation and SA of pilots. These tactile interfaces have been shown effective and intuitive (i.e., minimal training required) in three flight test programs. An underwater diving TSAS application has been field tested, as well as fixed base simulations of extravehicular activity (EVA), space shuttle landing, parachute navigation, high speed watercraft TSAS applications. While TSAS was developed primarily in response to the number of military aircraft mishaps related to loss of SA, work continues on tactile interfaces for special forces missions such as undersea mine countermeasures, parachuting, and overland navigation. The sense of touch has proven to be a flexible conduit for a human-machine interface for SA.

Background: The first and most reliable inflight SA display used by pilots is the visual world outside the cockpit. When these outside cues are ambiguous (e.g., fog or brown out/white out conditions), the pilot transitions to visual flight instruments which accurately display the aircraft spatial orientation (SO). TSAS was developed in response to an alarming number of SA related military aviation mishaps. Even conservative estimates of loss of materiel and human resources are alarming [Collins, 1995]. It was noted that spatial disorientation (SD) resulting from loss of SA often occurs in concert with an element of visual distraction [Murdock, 1998]. Since present SA displays in military aircraft are visual, pilots can not receive critical SA information when not looking at the display. Existing audio warnings, such as ground proximity, may give coarse SA information but do not relay an accurate portrait of the aircraft SO. Proposed solutions have included wide field visual displays (such as the Malcolm horizon) or three-dimensional (3D) audio [Doll, *et. al.*,1986]. While much effort has been directed toward these venues, no system has yet been successful in operational deployment. Both systems have demonstrated deficiencies in the evolving operational envelope of the modern air warfighter. Elements such as night vision goggles (NVG's) limit field of view, constraining presentation of any SA information to the same narrow visual angle (Figure 1). One problem of 3D audio results from what Doll, *et. al.* (1986) refer to as a zone of confusion that exists for a subject responding to synthetic 3D audio cues. Estimations of elevation and azimuth in this conical region, extending out in front of a subject, show significant error across a wide range of frequencies. For most aviation situations, this area is likely to be of greatest interest for maintaining SA. Tactile cueing could be integrated with visual and audio situation displays in a complementary fashion, possibly improving SA synergistically. Previous tactile displays that have attempted to present images to the skin [Bach-y-Rita, 1970, White, 1970] failed due to the relatively low bandwidth of the human torso's touch sense. Others have tried to map instrument displays on the torso

Figure 1: Head up display symbology superimposed on night vision goggles (ANVIS).

[Sanneman, 1975] without much success. The TSAS approach has been to exploit three dimensional distribution of the tactile sensory system for three dimensional orientation information.

Because the sense of touch conveys location on the body of a tactile stimulus intuitively [White, 1970], an operator utilizing an appropriately designed tactile interface immediately knows the location of the tactile transducer (tactor) as it fires. As such, SA is maintained at a low cognitive cost as compared to interpreting a two dimensional visual display. Tactors may be placed anywhere on the body of the pilot, and objects and motion in the surrounding three-dimensional space intuitively maps to specific tactor locations. Figure 2 shows a conceptual mapping of 3D space to tactor locations on the torso. With such a system, pilots can rapidly interpret three-dimensional information such as orientation, obstacle position, object location, track, etc. While TSAS strives primarily to improve SA, additional benefits include decreased perceived pilot workload and increased accuracy, evidenced during the flight test evaluated maneuvers.

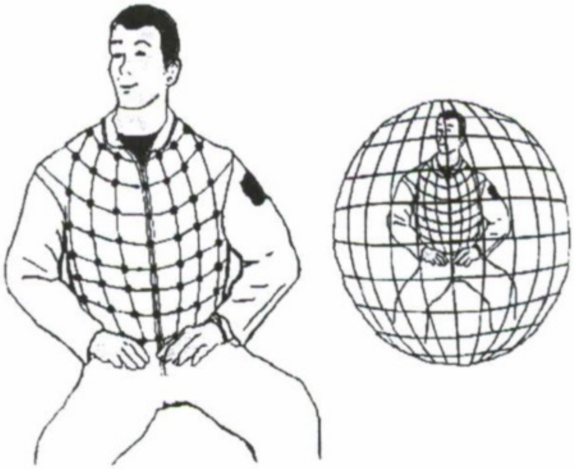

Figure 2: Three dimensional space mapped to the body.

Methods: The TSAS program has completed three flights tests (and one underwater field test) for proof of concept. In the first test, conducted in 1995, a Navy test pilot-flight surgeon flew a series of maneuvers in a Navy T-34C Mentor (fixed wing, two seat, tandem, single engine turboprop trainer).

These maneuvers included straight and level flight, standard rate turns, unusual attitude (UA) recoveries and ground controlled approaches (GCA). In addition, two aerobatic maneuvers were performed, aileron rolls and inside loops. Throughout all these maneuvers the test pilot was controlling the aircraft from the rear cockpit. All instruments were removed from this cockpit (Figure 3) and the instrument flight rules (IFR) training hood prevented use of external visual cues.

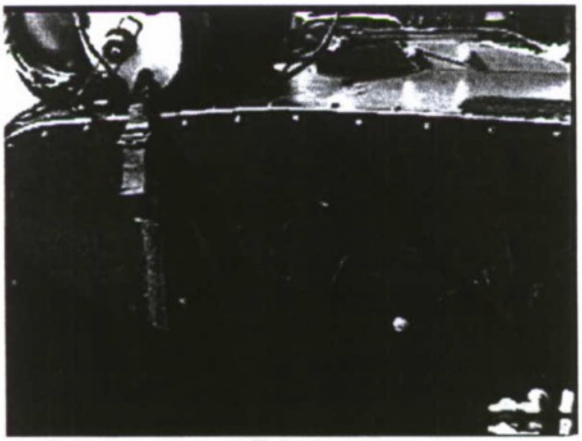

Figure 3: Rear cockpit of T-34C with instruments removed.

The TSAS apparatus provided aircraft pitch and roll angles to tactors on the test pilot's torso. As the pitch angle increased, the tactor stimulus frequency would increase in three discrete steps. Each step indicated transition from one preset angle range to the next (e.g., 2.0° to 3°, then 3.0° to 5°). When the angle exceeded that defined for the highest frequency on a given tactor location, the next tactor in sequence fired instead at its lowest frequency. Each of 16 tactors were encoded this way for both pitch and roll. With this system, the pilot could determine the direction to the earth's surface. When the aircraft was in straight and level flight, the null condition, no tactors were active. The pilot performed all the required maneuvers with the addition of auditory cues for altitude, airspeed and g-force, as needed, from the safety pilot.

In the second flight test, a UH-60A (twin turbine, 14 passenger, multirole helicopter) provided the rotary wing TSAS proof of concept for non-hovering flight. The same set of maneuvers were performed by U.S. Army research pilots, less the aerobatics. The pilots wore a blackout helmet visor to exclude internal and external visual information (Figure 4).

Figure 4: Blackout helmet visor used in UH-60 flight test.

Pilots in this test program received pitch, roll, airspeed error and heading error tactually (a total of 20 tactors used), with additional required information (such as altitude) provided via audio. Again, each tactor encoded three frequencies corresponding to set intervals of deviation from straight and level flight (for airspeed/heading error, deviation from desired airspeed/heading was presented in three interval steps). Two research pilots performed the described maneuvers in the blind.

A third flight test, utilizing the same UH-60 platform, consisted of a TSAS proof of concept for hovering with transitions to and from forward flight for the Joint Strike Fighter program. Four research pilots hovered in and out of ground effect, translated fore-aft and side to side, and transitioned successfully to and from forward flight in simulated shipboard maneuvers. Tactile information delivered to the pilots consisted of drift velocity (direction and speed) in the horizontal plane. Tactors were arrayed about the torso in a ring of eight (45° apart). The position of the tactor indicated the direction of the aircraft motion (nose of the aircraft relative to the earth's surface). A differential global positioning system (GPS) provided groundspeed information which TSAS delivered in three steps, 0.2 to 1, 1.0 to 2 and 2.0 or greater meters/second. The pilots integrated TSAS data with either full internal and external visual cues as in normal flight or with full internal visuals (instruments) and degraded external visual cues (using semi-fogged spectacles, "foggles," equivalent to 20/200 vision). In addition, audio cues were provided by the safety pilot as needed.

An underwater diving field test consisted of a simulated mine countermeasure triangular search pattern. Special forces divers utilized a two tactor system (one on each side of the torso) that provided course deviation and end of search pattern leg information. They were permitted normal vision (murky water with low visibility) and utilized a digital readout of compass heading and X-Y position relative to the starting point of the search.

In addition to the functional tests, numerous ground based simulations have been developed. In support of the Joint Strike Fighter hover flight test, a UH-60 motion model running on a desktop simulator (Silicon Graphics) provides a visual scene along with driving a multifunction display patterned after that from the MH-60K helicopter. Subjects may pilot the simulation using these visual displays or integrate them with a TSAS display. Similar simulations have been used to develop TSAS displays for underwater diver, surface craft, parachutist and astronaut.

The astronaut EVA simulation consisted of a simplified space station model. The subject was tasked, as a suitably equipped astronaut, with three dimensional navigation toward a target astronaut (Figure 5).

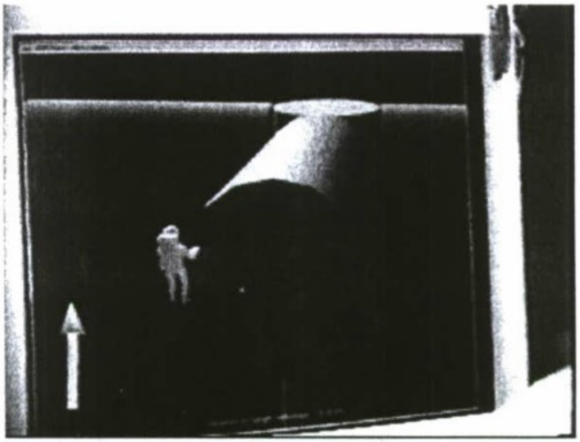

Figure 5: EVA simulation display with target astronaut and space station in view.

The target astronaut was placed in one of four locations and was either on a straight line path from the subject, on a straight line path but not in view, on an indirect path with part of the space station preventing a straight path, or on an indirect path with only a small portion of the space station in view. These four tasks are listed in increasing difficult, but were presented in a balanced manner to 12 subjects to control for order effects. Since a limited set of tactors was available for this experiment, only 6 tactors were used. As such, one to three were fired in order to represent 3D space (e.g., one tactor "front," three tactors "front, up, left"). The control task without TSAS consisted of the same sets of maneuvers, but with voice commands directing the subject toward the target (as presently practiced by NASA [Rochlis, 1998]).

Discussion: In the first two flight tests, the blindfolded pilots safely completed each maneuver with greater accuracy than with full instruments and external visuals [Rupert, *et. al.*, 1996]. The pilots often reported SD symptoms such as "the leans" while in the blind, but could easily and reliably determine the SO of the aircraft via the tactile cues. In addition, the TSAS equipped pilot did not lose SA when performing unusual attitude recoveries, unless the system was deactivated during set-up maneuvering and not reactivated until the moment the subject pilot took over control [Raj, 1996]. Combining audio and tactile data presented adequate information to the blindfolded pilot to perform GCA's down to minimum altitude or complete a 3 G inside loop with no more than one degree oscillation in roll.

The third (hover) flight test demonstrated integration of normal visual flight information with audio cueing and TSAS. Pilots in this test flight series initially commented that TSAS appeared to increase their workload as the tactors seemed to fire in constantly changing directions. However, once the pilots saw how much more accurate their hover station keeping was, they began to trust the system and respond quickly to the cues. Rapid response to the cues reduced oscillation around a given hover point and reduced the number of times the tactors actually fired during a given maneuver or time interval. When the pilots were utilizing the increased precision of the system this way, they reported that their perceived workload decreased, at the same time their maneuver accuracy increased. This training was rapid since this change in workload and accuracy typically occurred by the third attempt at a particular maneuver. Figure 6 depicts a typical simulated shipboard landing from the TSAS hover flight test. The pilot is wearing the foggles and performs the task of decelerating to an out of ground effect (OGE) hover to the left of the desired landing zone (LZ). Once stabilized, the pilot descends to in ground effect (IGE) hover, then translates to the right until over the LZ, and then descends to land. The histogram shows how often each tactor fired during the maneuver (for the TSAS active case). Little tactor activity is seen aside from the left and right tactors. This manifests also in the velocity plot as there is very little drift (graph centered about zero velocity), except to the right when translating over to the LZ. Without TSAS, the velocity plot shows a much more erratic pattern and the position plots demonstrate decreased precision. These pilots were successfully able to integrate visual instruments, audio cues and the tactile display to expand their mission capabilities.

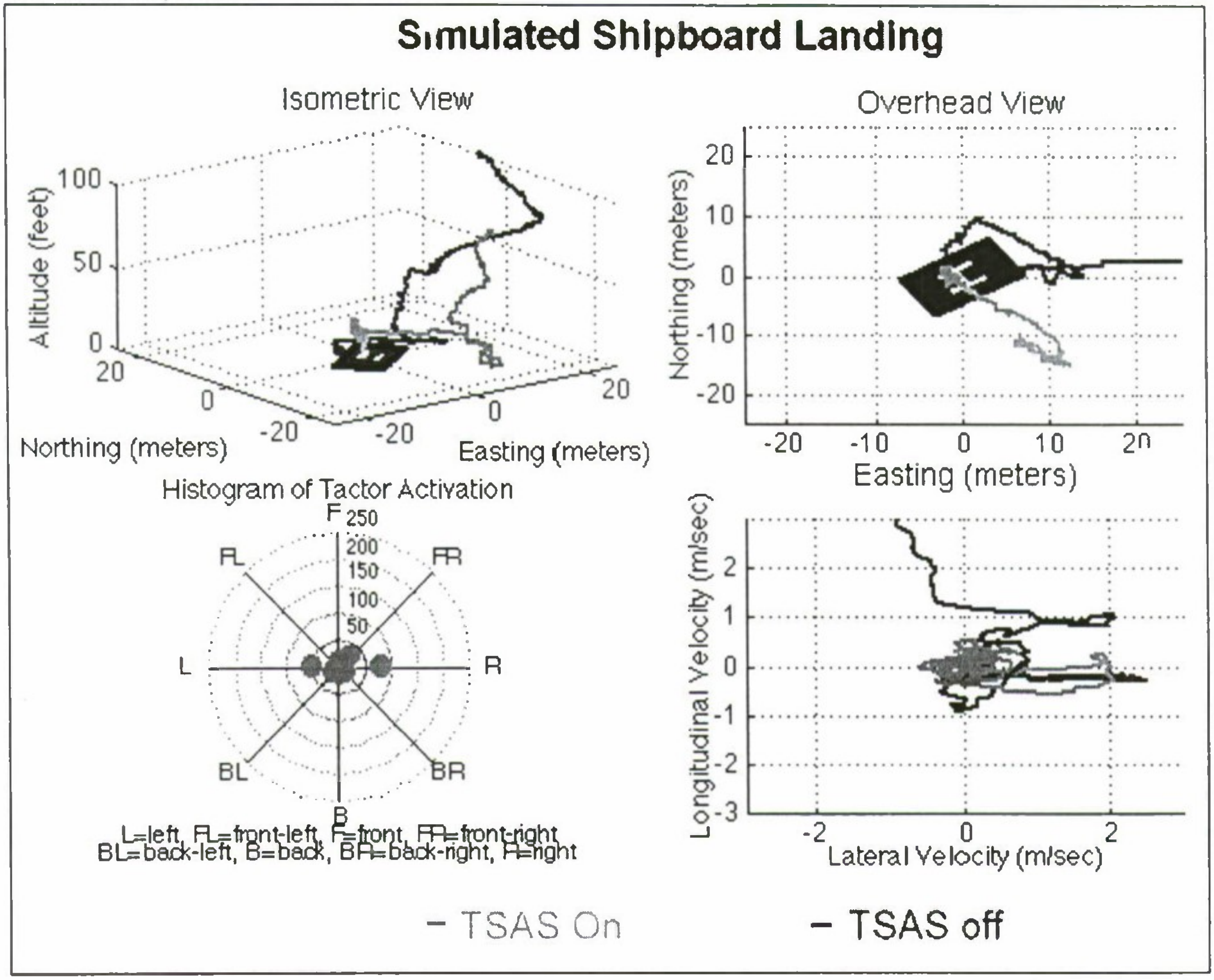

Figure 6: Simulated shipboard landing with foggles, with and without TSAS.

The underwater field test successfully demonstrated improved navigational ability in poor visibility conditions. One diver commented that the system allowed the diver "use of his eyes so he can avoid running into mines or obstacles." Most commented that the system was intuitive ("easy to learn") and that it would easily integrate into their operations [Coastal Systems Station, 1997].

Lastly, the simulation of an EVA astronaut rendezvous showed significant improvement in ability to perform the task (both in reaction time and time to complete the task). Controlling a six degree of freedom EVA astronaut model with a six degree of freedom force sensing hand controller proved difficult, but not impossible. Subjects often lost control of the model during maneuvering due to this novel input device; such runs were recorded as a failure. Figure 7 depicts the number of failures encountered for each of the four scenarios, and demonstrates the decrease in failures seen when TSAS is integrated with the visual simulation. This graph also shows that while the task difficulty increases the number of failures decrease. Since the harder scenarios require a maneuver to initially find the target, subjects may be more cautious with their inputs. The first (easiest) scenario, however, has the target in sight at the onset, which may encourage a more heavy handed approach. These results demonstrate that tactile cues can help maintain SA and control of a maneuvering platform despite the use of difficult and fatiguing control systems

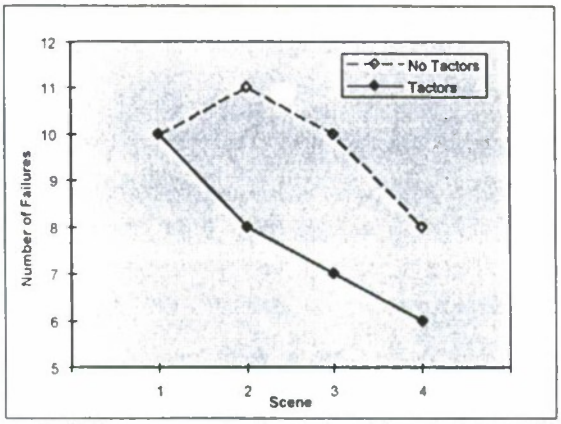

Figure 7: Failures vs. navigation task, with and without TSAS.

Conclusions: The TSAS program has shown that tactile cues can integrate into existing situation displays and can function even in the absence of other SO information. Future cockpit and other platform control systems will no doubt include more elaborate SA displays [Joint Advanced Strike Technologies, 1996] that would benefit from tactile interfaces to provide a true multimodal display. In such a system, the effects of the zone of confusion associated with 3D audio could be mitigated by providing additional tactile data to aid in localization in this zone. Tactile cues may be used to direct an operator toward an area of interest outside the field of view of head mounted displays or NVG's. Likewise, other visually demanding displays could utilize tactual signals to steer attention toward critical sections of the display. In the most intuitive form, as a spatial orientation instrument, TSAS displays will allow a pilot to focus more attention on other mission critical tasks, such as navigation control (as seen in the EVA simulation), or concentrating on a map or approach plate, without losing SA. In multiship operations, TSAS could be used to provide spacing information to each element of the formation with proximity warning to prevent collisions. These and other future applications would improve operational capability by allowing safe flight into more hazardous locations with fewer meteorological restrictions.

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Computational Modeling of Multi-Modal I/O in Simulated Cockpits

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The purpose of this research is to investigate the use of computational models of human performance to design and evaluate information displays in military cockpits. The focus of the current work is using computational modeling to evaluate auditory interfaces. The approach includes four steps: 1) develop auditory interface designs; 2) augment a computational model called Executive-Process/Interactive Control (EPIC) to incorporate the human performance effects of these interface designs; 3) collect human performance data; and 4) evaluate the accuracy of the model against the empirical data. Work at the Naval Research Laboratory (NRL) includes the development of interface designs and the collection of human performance data. David Kieras and David Meyer are doing the EPIC modeling at the University of Michigan. This paper reports some of the results of the empirical studies at NRL.

Computational modeling is emerging as a potential method to do early system design. Initial work in this area focused on single-task, office workstation domains, but recently Kieras and Meyer (1995) have been successful in modeling dual task performance in a low fidelity cockpit domain. Their work has shown that control of peripheral resources, particularly eye movement, is the dominant factor in mediating performance. This focus on eye movement as a mediator of performance is consistent with the perspective of the aviation community, which has long recognized the importance of eye movement. Basic Instrument Flight training manuals include sections on visual scanning, emphasizing the importance of efficient scan patterns. For example, the Navy's flight training instruction manual for basic instruments includes the following paragraph:

> "In order to determine the aircraft's attitude quickly and effectively, you must know what instruments to scan for a particular maneuver. The following section lists the correct instruments or scan "pattern" for every situation. It is mandatory that the student commit these patterns to memory." (Naval Air Training Command, 1989, p. 16)

The research reported here is based upon previous work at NRL (hereafter referred to as the '92 study) on the design of adaptive automation interfaces. Ballas, Heitmeyer and Perez (1992) found that certain interface features mitigated a transient automation deficit. This effect is seen in longer reaction times on the first few responses upon resuming a task that has been previously automated. The effect is short-lived, and has not been found in studies that examine average performance over several minutes. For example, Parasuraman, Hilburn, Molloy and Singh (1991) reported that there was no evidence of automation cost in their studies of adaptive automation. However, their dependent variable was average performance over a 10-minute block of trials. In addition, the task demand was low in the phase after automation, under the assumption that a task would be returned to the person only under conditions of low performance demand. The '92 study found the automation deficit effect on responses in the first few seconds, under conditions of heavy demand.

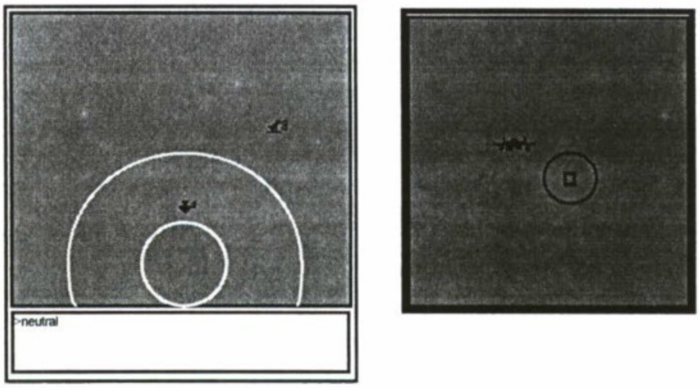
The '92 study used a low fidelity cockpit simulation in which the subject performed two tasks, tracking and tactical assessment. Kieras and Meyer have modeled the human performance of both tasks in that study, including the automation deficit effects. Empirical predictions can be made from their model, and this paper is a report about two of these predictions. The first prediction is about automation deficit. Their detailed model generated an explanation for this effect: upon resuming the task, the subjects randomly scan the tactical assessment window and handle the objects in a random order. This produces longer reaction times on the events that should be handled first. If the subjects have been performing the task, they know about the developing pattern and handle the objects in the proper order, producing shorter reaction times. Based on this explanation, it was predicted that the effect would not occur if the subjects began the task with a low level of demand. To test this prediction, the '92 study was repeated with two scenarios: one similar to what was used before (i.e., with the heavy demand when the task is resumed), and a scenario with a moderate task demand.

The second prediction is about performance in the tracking task when keypresses are made in the tactical assessment task. The EPIC model assumes that the tracking task is momentarily suspended when the eyes move into the tactical assessment task window, as well as when the response on the tactical task is executed. To evaluate this assumption, the software was modified to record more details of tracking performance, and an analysis was conducted of the joystick holds that occur when keypresses are made.

Method

Experimental Tasks

Subjects performed two tasks, a pursuit tracking task and a tactical assessment task. A summary of the tasks is shown in Figure 1. To establish a setting for adaptive automation, the difficulty of the tracking task was modified in phases throughout the experiment. During moderate difficulty phases, the subject performed both the tracking task and the tactical assessment task. When the tracking difficulty was increased, the tactical assessment task was automated, and the subject performed the tracking task only. The display screen used in the experiment was partitioned into two windows, one for the tracking task, the other for the tactical assessment task. Changes in the automation of the tactical assessment task were signaled in two modalities. A beep occurred at each change and a border was placed around the window when the task was performed manually. The color of this border matched the border of the tracking window so that the tasks would be integrated while both were in the manual mode.



Tactical assessment
Display: Graphical
Input: Keypad
User involvment: Intermittent

Tracking
Difficulty: Two levels
Input: Joystick
User Involvment: Continuous

Automation Logic

L H L H L H L ...
L = moderate; H = high
Tactical Mode: M A M A M A M ...
M = manual; A = automatic

Figure 1. Interfaces for the tactical assessment task and the tracking task and a summary of the interface properties and automation logic.

The tracking task simulated air-to-air targeting of an enemy aircraft using a gun sight similar to the piper and reticle on a typical head-up display. The target on the display was a graphical representation of an enemy aircraft. The target's driving function was the sum of nine nonharmonic sinusoids (.02, .03, .07, .13, .23, .41, .83, 1.51, and 3.07 Hz) with randomly determined starting phases. The amplitudes of these components were varied to produce two levels of tracking difficulty. The amplitudes for the "less difficult" tracking were flat up to a cutoff frequency of .07 Hz and reduced in amplitude 3 dB/octave above this frequency. The "difficult" function was flat up to a cutoff frequency of .23 Hz and reduced in amplitude 3 dB/octave above this frequency. The target position was updated every 83 ms and the joystick position was sampled at the same rate. The tracking device was a self-centering, displacement joystick. The control dynamics were a 25%/75% mixture of rate and acceleration. A continuous record of the joystick, target and piper position was recorded.

For the tactical task, the subjects assessed three types of simulated tracks—fighters, aircraft, and ground-based missiles. The tracks appeared on the screen as possible threats using black color coding, and as they got closer to the *ownship* (the symbol for the aircraft the pilot was in), they were designated as neutral, hostile, or unknown, using blue, red, and amber color coding, respectively. The subjects were told that simulated sensor systems were assigning these designations. The subjects were required to make one of two decisions, confirm or classify, on each track. If the system designated a track as neutral or hostile (i.e., the track was colored blue or red), the subject had to *confirm* the designation by picking the track and then indicating the proper designation, i.e., neutral for blue tracks and hostile for red tracks. Thus, confirm decisions only required the subject to discriminate colors. If the system designated the track as unknown (i.e., the track was colored amber), the subject had to *classify* the track as hostile or neutral based on its behavior. Table 1 shows the rules for making this decision.

Table 1. Rules for Tactical Assessment of Tracks

Track Class	Hostile	Neutral
Fighter	On approach bearing	Bearing away
Airplane	Air speed ~ 800	Air speed ~ 300
Missile site	Within threat range	Outside threat range

To classify the amber tracks, the subject needed to monitor bearing for fighters, speed for aircraft, and projected lateral distance for ground missile threats. The responses were timed and analyzed to produce measures of accuracy and response time. The subject had a response interval of 10 seconds to make the assessment response.

The tactical interface (Figure 1) simulated a radar display with continuously moving symbols representing the tracks. The bottom portion echoed the subject's keypresses. The subject used a keypad to insert a confirm or classify decision. For each decision, two keypresses were required, one designating hostile or neutral, the second indicating the track number.

Training and Scenarios

The subjects were tested in three 1-hour sessions. The first two sessions were used for training and collection of single and dual task performance data. Training time was doubled over the '92 study. In the third session, they were tested in two 25 minute sessions with intermittent automation of the tactical task. Two scenarios with different task demand were used in these sessions. In each of these sessions, they started with a dual-task phase, performing both tasks. They then went through 6 automation-manual cycles as illustrated in Figure 1. The duration of the automation and manual phases varied between 105 and 135 seconds. When the tactical task was automated, the tracking task increased in difficulty. During the intermittent automation sessions, the scenarios produced 138 tracks that had to be confirmed or classified, for an average event rate of one per 12 seconds. About 75 of these tracks were presented for manual assessment. Two scenarios were used: one in which the tracks occurred at a relatively steady pace (Level scenario) and one in which the tracks occurred at a variable rate (Wax & Wane). The latter scenario was used in the '92 study and demanded several decisions at the beginning of each manual phase. This meant that the transition from automated to manual operation occurred at a period of high task demand. This demand was repeated later in the manual period to obtain comparison data. Specifically, the properties of stimulus seven matched the first stimulus in the manual phase, and the inter-stimulus intervals between stimuli seven, eight and nine matched the intervals between stimuli one, two and three. The evaluation of an automation deficit has been comparing performances on stimuli one and seven.

Results and Discussion

The average time to assess the tactical tracks in the manual phases are shown in Figure 2, for each of the scenarios. For comparison purposes, the average times from the '92 study for the same type of tactical interface are also shown. The '92 study evaluated four interfaces for the tactical assessment task. Only the graphical-keypad interface was used in this research. The '92 study only used a wax and wane scenario.

The automation deficit effect was computed by taking the difference between the first and seventh responses. In the '92 study, this difference was about 1500 ms; in the current study this difference was about 900 ms. The Wax & Wane results in the current study also show longer times for events following stimulus seven. These results are consistent with a Psychological Refractory Period (PRP) since stimuli eight and nine are presented with short inter-stimulus intervals. But the increased response times for these stimuli over the '92 study is confusing. Recent modeling (Kieras, 1997) of these data suggests that the current subjects were performing nearly as well as they could on the first two stimuli, but performing at an average level on the eighth stimulus. If this is the case, it would explain why the automation deficit effect is less in the current study (because of better than expected performance on the first stimulus) and why the PRP effect is greater on event eight in the current study (average performance on stimulus eight).

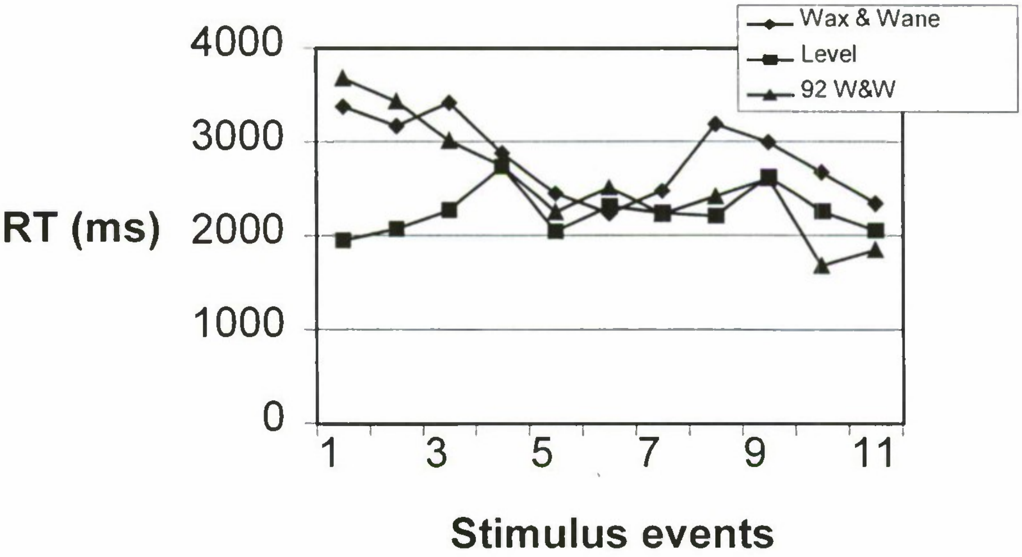


Figure 2. Response times to classify stimuli during the manual phase of the tactical assessment task. Data are for two scenarios in a '97 study, and one scenario in '92.

As predicted by the EPIC computational modeling, the deficit did not occur with a level scenario, which eliminated the heavy demand at the onset of the manual phase. The level scenario also did not present a stimulus to be classified simultaneous with the end of automation (and onset of manual tactical assessment). These results imply that the deficit effect will occur when either one or both of two conditions are present: 1) the first event occurs at or shortly after the beginning of the manual phase; 2) a heavy task demand is present at the beginning of the manual phase. Further studies could investigate these two possibilities in detail.

The second prediction being addressed is that the tracking task is suspended while a person scans the tactical assessment display and while keypresses are made for the tactical assessment. These predictions follow from the task switching logic in the EPIC model for this dual task. To investigate this prediction, successive positions of the joystick were compared to locate stick holds. The length of these holds was tallied and plotted in a frequency distribution. The result is an example of Zipf's law (Figure 3). With the distribution of holds known for the tracking record as a whole, a second distribution was tallied which includes only holds that began when keypresses were made. To derive this distribution, the keypress times were used as array pointers into the tracking record. This focused the comparison of successive joystick positions onto times when keypresses were initiated. If a hold did not occur at a particular keypress time, then the comparison was stopped for that location in the record, and resumed at the next keypress time. The analysis was designed so that a long joystick hold that spanned more than one keypress would only be tallied once.

The two distributions are shown in Figure 3 for three scenarios: continuous dual task with no intermittent automation, and the two scenarios with intermittent automation. For all three scenarios, the proportion of holds is greater at keypresses. By implication, the proportion of no holds, which is not plotted in these figures because it is in the range of .6-.8, is greater for the overall distribution. The difference in the distributions occurs for holds up to a second in length.

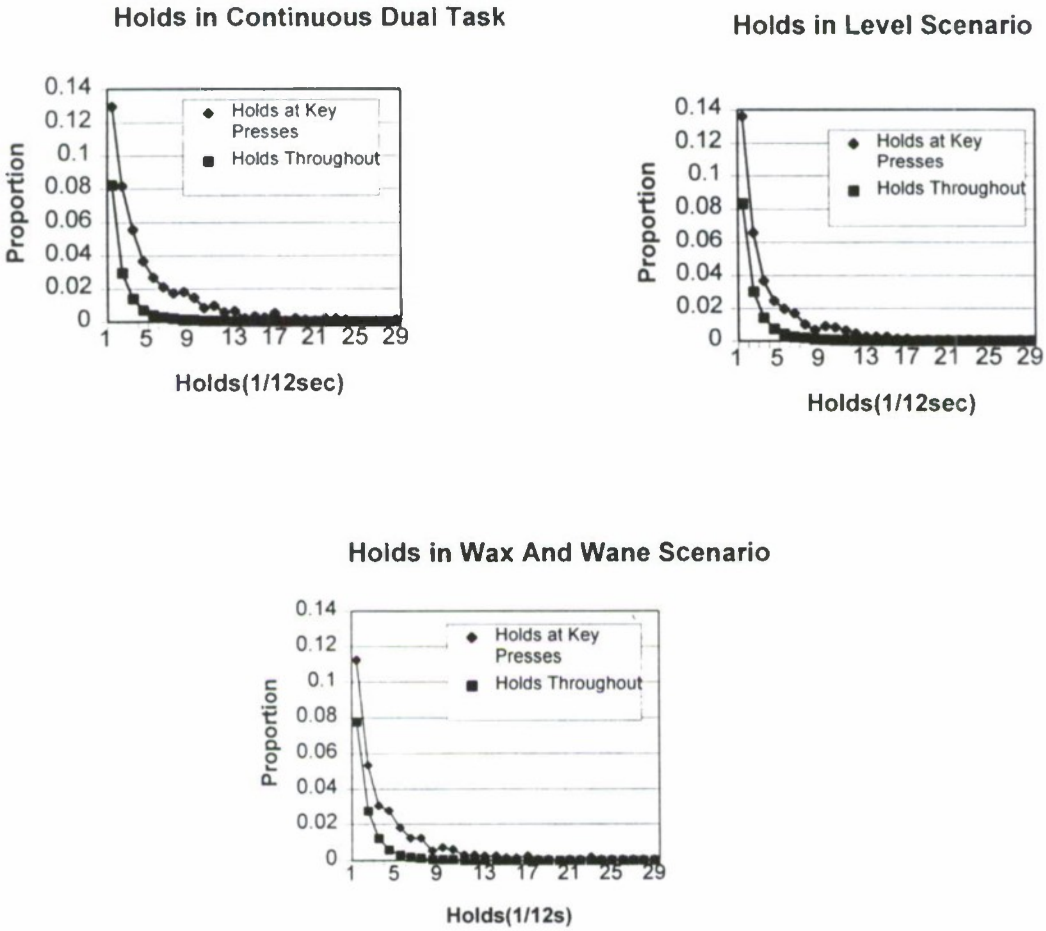


Figure 3. Tracking holds throughout the tracking record and at keypresses in three scenarios.

These results support the assumption made in the EPIC model. However, they do not tell how often tracking is suspended at keypresses, and do not address the suspension of tracking when eye movement is out of the tracking window and into the tactical window. Further analyses of the tracking data will investigate the first issue.

These results generally support the predictions from computational. Two predictions that came from the modeling were generally supported in subsequent empirical studies. Of course, these predictions might have been made in the absence of the modeling effort, which is difficult and expensive. Certainly tracking holds have been a topic in the manual control literature. However, the computational modeling can focus the predictions and have both a strategic (suggest general issues) and a tactical (suggest specific experimental design modifications) on empirical research. These benefits are in addition to the early impacts on system design impacts of a computational model.

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Spatial Awareness Interface Considerations

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Applications of 3-D Auditory Displays in Threat Avoidance, Collision Avoidance, and Target Cueing

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Almost everyone uses spatial (3-D) auditory information in everyday life. When a person is standing on a street corner, they know the direction and approximate distance of an approaching car or bicycle, which is outside their current field of view by using their auditory localization capabilities. The goal of the Air Force Research Laboratory's 3-D audio display program is to provide this type of sensory information over headphones in the cockpit for threat avoidance, collision avoidance, and target cueing.

The in-house experiments in aurally guided visual search have demonstrated an approximate 2X improvement in target acquisition times, 2X improvement in target detection range, and 2X to 10X improvement in locating targets in clutter or decoys.

Most of these laboratory findings have been verified in flight tests on NASA Lewis Research Center's OV-10 flight test aircraft and Naval Air Warfare Center's AV-8B Harrier flight test aircraft. The aircraft objective results mirrored the laboratory results and the subjective comments from the flight test pilots described significant improvements in situational awareness and attack capability with reductions in workload.

These findings have direct application to USAF and Navy combat aircraft operations as well as applications to civilian aircraft operations.

(Reprint of executive summary; formal paper not available.)

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Naval Situational Awareness Enhancements within the Maritime Avionics Subsystems and Technologies (MAST): Advanced Graphics and Data Fusion

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Summary: Various levels of the military command infrastructure require visualization of data and fusion of tactical and strategic information. Specifically, visually oriented displays can provide intuitive, readily understandable information which is easily interpreted and acted upon. Visual systems provide a variety of data and information which include key elements such as maps, terrain elevation, imagery, iconic, symbology, and/or text. Use of these information forms must be specific to individual missions yet consistent to all. Consistency among and between command levels is critical to support coordinated planning, execution, and after-action activities.

Information forms and presentation to a user are constrained by system and cost considerations. This presentation and associated manuscript provide a discussion of application of virtual, visualization environments within a hierarchical requirements structure based on warfighting functional requirements. Additionally, functional requirements are related to system characteristics and utility to airborne applications are also discussed.

Introduction: The ability to convey information and to exploit it is an age old issue. Plato referred to the purist of information as a "form"[1]. He also discussed mental processes which are appropriate to military visualization within a continuum of mental processes which include understanding, reasoning, opinion, and imagination. The philosopher discussed his notion of forms as the highest level of knowledge. In the present as well as the past, the ability to impart the highest level of knowledge is critical to the human endeavor whether in war or peace. Thus, the objective of providing the perfect information should strive to provide understanding by intuitive means at the form level of the knowledge continuum.

Today's visualization of military forms presents unique challenges and perplexing technological tradeoffs. Achieving the right look or feel for combat data is difficult. A gap in communication/ interpretation exists between users and developers. Decision makers, who are of the slide rule generation, are often determining system needs for operators who grew up using video games and personal computers.

Discussion: Visualization requirements span a continuum from simple line depiction to fusion of multiple sources of data and rendering of high fidelity, geo-specific perspective scenes in real-time. This range of capabilities has been employed to support mission planning, rehearsal, execution, debrief; intelligence efforts; and modeling/simulation efforts.

As provided within US Defense Science and Technology Guidance for Joint DOD applications, several areas are impacted by visualization enhancements. Specifically, Command, Control, Communications, and Computers (C^4) (Provide common, accurate, mission-tailored picture to all warfighters; Develop ability to "learn" from users, and improve visualization); Intelligence, Surveillance, Reconnaissance (ISR) (Improve situational awareness, manage information and decision aids); Manpower / Personnel: (Determine optimum human/computer tasking, improve decision-making, reduce user workload, and reduce crew / manning requirements). These capabilities will foster performance improvements and manpower reduction by improving warfighter performance, and reduce workload by tailoring displays to user requirements.

Consistent and repeatable visualization capability are critical throughout and among the command levels. Example of advanced applications for concurrent visualization at multiple levels include recent activities for Bosnian Operations: planning and rehearsal during Deliberate Force Operations, use of virtual environments for the Bosnian peace talks, Exploitation within Joint Strike Fighter (JSF) development program, Investigation of US

Secretary of Commerce Brown's Crash, and Convey data to US National Command Authority. Simulated environments offer the opportunity to "see into the future" and allow operators to expand their understanding of future events while expanding situational awareness. These virtual environments also provide user augmented reality with actual situations which may have limited information resources. An example is evident in airborne applications to enable flexible targeting and retasking as well as a context for off-board information fusion.

The Tactical Moving Map Capability (TAMMAC) is planned for F-18, AV-8B, and AH-1W with potential applications to the V-22, UH-1N, F-14, P-3C, and H-60. 2D map requirements are included in Table 1.

Table 1. 2D Requirements Based on the US Navy Tactical Air Moving Map Capability.[2]

Change of map scales and features in real-time	Mag/Zoom from 1 to 1 up
Coverage area in standard scales (ex. 1 inch to 5 million meters)	Programmable color palettes
Variable map scales between 2.5 and 250 nm	Standard symbol generation
Map orientation north-up or heading-up	Dynamic overlays
Center/de-center	Dataframe rates
Sun/moon shading	Slewing

3D perspective, scene generation requirements can be found in Table 2. Figure 1 provides examples of desire 2D rendering capabilities for the TAMMAC. Planned TAMMAC improvement included implementation of 3D functions. 3D perspective scene generation needs were assessed in terms of user suggested enhancements to Bosnian prototype systems and desire JSF capabilities.

Table 2 provides a list of 3D, scene perspective capabilities based on situational awareness needs related to the JSF STT framework. Users have also asked that future visualization to incorporate other sensor imagery, Provide simulations of sensor and performance predictions, Extrude objects and buildings, Provide aircraft appropriate flight dynamics, Add weapon simulations, Display threats dynamic/accurately, Provide interface to mission planning systems, and Permit user to retrieve coordinates from scene.

Table 2. 3D Requirements Based on the JSF Virtual Ground Map Functionality.

Multi-source/spectral data	Threat overlays
Mutli-source/resolution elevation	Updated and real-time threat overlays
Geo-located/specific imagery and elevation	Multiple fields of view
Display of vector products/data	Degrees of freedom view angle control
Annotations and pointers	Remote and slewable eye point.

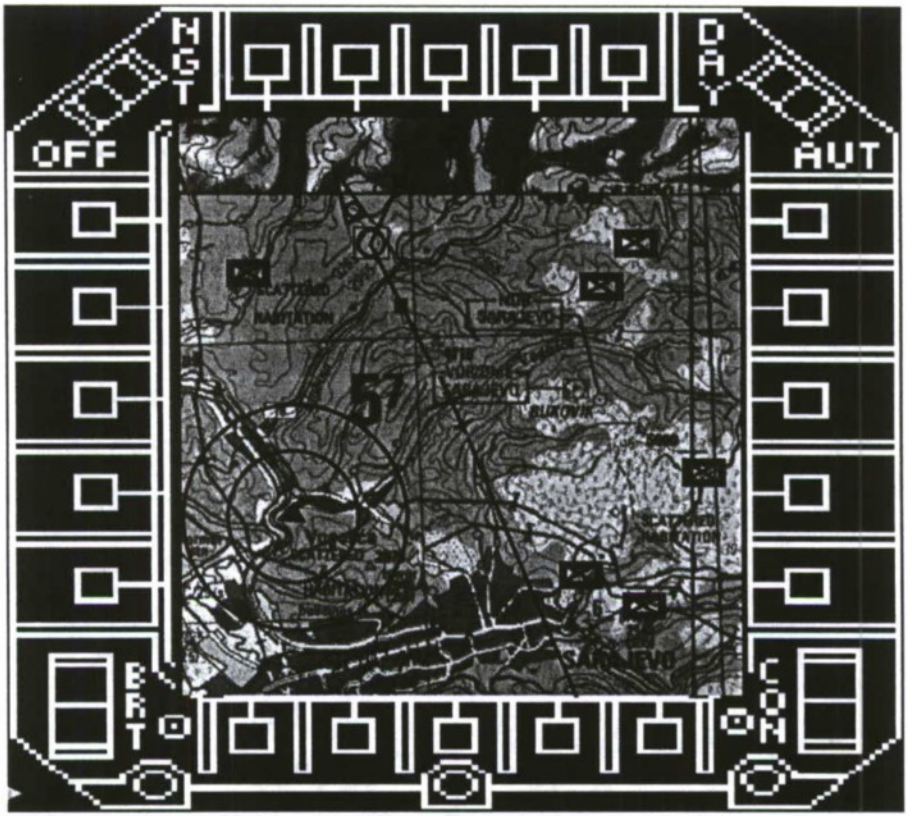

Figure 1. Current 2D Map Capabilities. Example illustrates map data over Sarajevo and includes tactical overlays.

Figure 2 provides a notional view of a perspective scene capability using photo-based imagery and elevation data and appropriate strike symbology. This includes threat domes, target locations, collateral damage warning, approach restrictions, sensor updates and weapons effects. The 2D information portrayed in Figure 1 is an example of a display which requires interpretation by the user.

The information in Figure 2 provides intuitive graphics in mission context for a strike platform.

Figure 2. Futuristic 3D Perspective Capabilities. Example shows unclassified US Geological Survey imagery & elevation data over the Naval Air Station China Lake, CA.

Additionally, the growth of communications and display techniques provides an opportunity to update this information within the mission timeline providing expanded sensor data to the warrior. The intent is to provide Common Battlefield Awareness which provides command, control, and operational data to user within his/her mission context.

As depicted in Figure 3, the utility of this data can be seen at various levels of the command infrastructure. At the command center levels mission preview and rehearsal, fusion of intelligence and threat data can be performed providing enhanced command and control using intuitive display.

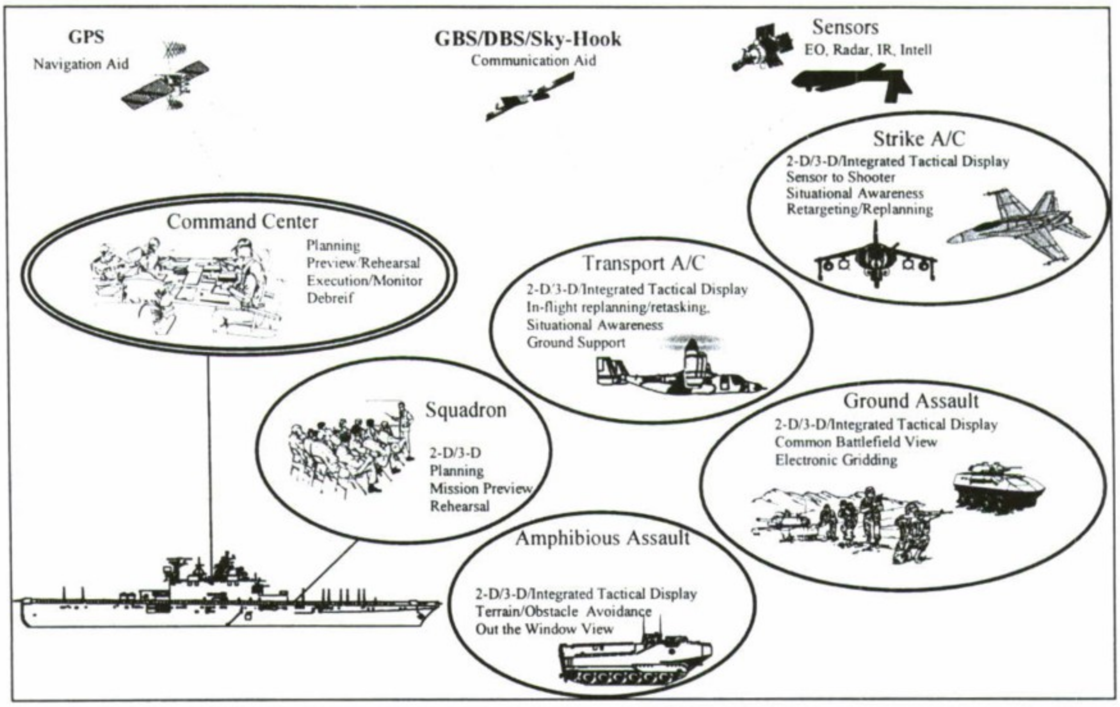

Figure 3. Warfighting Visualization Tasks at Various Levels of the Command Infrastructure.

Additionally, what if scenarios can be played using advanced modeling, simulation, and analysis tools which can provide campaign level analysis? Tactical information could be fused into such pictures for real-time operational use of data from global positioning, imagery, and Direct Broadcast Systems. Data can also overlay and update via Intel sources. These command level activities can be used to provide more specific strategic direction to operational levels for squadron level planning. Future techniques would exploit "smart" applications to parse data appropriate to operational levels from the strategic command levels. Additionally, reach back capabilities for lower command levels could provide greater insight into great campaign level goals.

Operational level data could be passed further to individual mission areas and exploited at lower levels by individual operators within a specific mission context. Integrated tactical displays linked to information resources at unit and command levels could provide current operational information beyond that available today. Such capabilities could enable flexible retargeting and/or replanning; in-flight updates with data and imagery; and remote, future views within virtual reality concepts. Operational concepts might include modes which include video teleconferencing.

At the operational level, virtual walk-/fly-through capabilities would allow users to see through the next hill or discuss safe transit routes. Interfaces to mission planning resources could provide the view ahead and support positional and maneuver control or electronic gridding. Visually augmented identification of friend or foe as well as obstacle identification within tactical situation displays could be provided. Opening the operators line of sight by projecting an outside view through the wall of an amphibious tank or submarine could provide a better understanding of the world around and object. Underwater Threats Structure, Obstructions, and Mines, Beach Assault Routes could be displayed to support these users needs.

Two important principles which should guided future visualization developments are: (1) an emphasis on using real-world photo-imagery and (2) the use of portable, standardized software tools that do not require non-standard hardware. Additionally, military and commercial systems which support visualization should: use/display real world data, from any perspective, and in any desired level of detail; exploit imagery of varying source, scale, breadth, or resolution from satellites, aerial photographs, and other sources and combine into a seamless visual scene; and correlate to real-world coordinates, other data (such as maps and cultural features) and combine with the imagery and display together.

Military visualization should also consider the opportunity provided by commercial imagery sources. Present capabilities include use of defense, Government, and commercial providers. However, emerging sources of this data in high resolution formats should be seriously considered. These resources will make data a commodity rather than a luxury.

Summary: Future visualization techniques for military users include requirements to provide intuitive two dimensional and three dimensional data within a mission context. Graphics techniques presently provide area expanding to provide consistency within military command levels and provide greater opportunity within the C4I context. The user of these integrated techniques will foster the development of enhanced operational concepts and future operations which improve the militaries abilities to reach strategic and operational goals.

1. Plato translated by G.M. Grube, Plato's the Republic, (Hackett Pub. Co.; Indianapolis, ID; 400 BC (1974)); Pg. 164.
2. M. Lohrenz, et. al., TAMMAC Digital Map Requirement Study in support of Advanced Cockpit Moving Map Display, NRL Formal Report No. 7441-96-9652, (Stennis Space Center; Stennis MS); Pub. Date TBD; Pg. 5.

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Physiological Implications for a Helmet-Mounted Display Spatial Awareness Interface

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Advanced display concepts and rapidly evolving interface technology have brought to the forefront the possibility of a helmet mounted display (HMD) becoming an integral part of the tactical aircraft cockpit by providing primary flight information in addition to mission specific capabilities. This represents a radical change in pilot-cockpit interface. If we are to successfully pursue this goal, the physiological implications of employing a HMD as a primary spatial awareness interface must be addressed.

Life Support Equipment: The first major consideration addresses the complications encountered when an aircraft cockpit display is located not on the cockpit structure, but instead attached to the pilot's head. To be an effective "primary flight reference," a HMD would need to be securely in place for the duration of the mission. The HMD would not only need to accommodate a wide variety of face structures, but also it must integrate with life support and protective equipment, e.g., Combat Edge and Laser Eye Protection. Because of the criticality of a primary flight reference, the issues of comfort, stability, helmet mass, neck strain, thermal strain, and visual problems take on increased meaning.

Workload: Generally speaking, spatial disorientation mishaps result from inattention, distraction, or just plain excessive mental workload. The increasingly complex cockpit environment continues to be a challenge. HMDs will exasperate the current flight duties. An effective spatial awareness interface must provide continuous intuitive spatial orientation information aimed at minimizing workload. However, it is necessary to thoroughly understand system limitations and flight task requirements to develop flight symbology that will reduce the causes of increased workload.

Human Sensory Systems: Especially in the tactical air environment, perceived spatial awareness develops from both visual and vestibular stimuli as well as preconscious orientation percepts. The flyer's mental model, whether correct or incorrect, is an integration of continuous multisensory inputs to the brain. The phenomena of visual dominance, vestibular suppression, and vestibular opportunism are central to an accurate mental model.

Issues: Traditional laboratory studies have primarily focused on the visual aspects without incorporating simultaneous vestibular or tactile sensory inputs. With the increased interest in expanding mission effectiveness with helmet-mounted displays, the dynamics of head movements in conjunction with aircraft movements may increase the impact of these multisensory signals. A major task of the Spatial Disorientation Countermeasures Task Group is to quantify the physiological significance of these human sensory inputs as they pertain to operationally relevant metrics. Issues that will be addressed with our facilities, such as the Advanced Spatial Disorientation Demonstrator, include visual conflicts between flight symbology and external scenes; increased vestibular components and erroneous perceptions resulting from the combined head and aircraft motion; simulated flight motion with and without conflicting visuals, head position, and collimation; and effects on flight performance when transitioning between HMD symbology and either head-up display or head-down display symbology. The current study quantifies the effects of helmet-mounted display attitude symbology motion cues on basic flight tasks, e.g., unusual attitude recoveries or precision instrument control tasks. Significant findings from the completed series of studies will form the basis for future inflight validation.

(Reprint of executive summary; formal paper not available.)

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The Physiological Aspects of Mishaps in the Tactical Environment

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The operational capability of current high performance tactical aircraft is pushing the physical and cognitive limits of the aircrew. The demanding flight envelope of future aircraft will only further jeopardize the aircrew's ability to effectively operate the aircraft and complete the mission with increases in altitude, speed, load factors and high acceleration (G) maneuvers with rapid onset rates.

The forces the pilot experiences stress the cardiovascular system resulting in pooling of blood away from the head towards the extremities and eventually leads to loss of vision and acceleration-induced loss of consciousness (G-LOC). In addition, current research has identified G-related altered states of awareness (ASA), where the pilot is awake, but exhibits amnesia, facial tremors, hand/arm flailing, spatial disorientation (SD), and may not perform instructions critical to mission completion. ASA not only occurs at high G, but is related to the level and duration of the G exposures throughout the mission and may even occur after the G exposure. Furthermore, as G-related ASA episodes are not identified as loss of consciousness, these episodes may be misclassified as "loss of situational awareness" or pilot error, especially if the incident under investigation involved low G level excursions.

The current methods used to combat such physiologic events include anti-G suits and valves, physically demanding straining maneuvers, elegant displays, intelligent software, and pilot training. However, Class A Mishaps are still occurring at an alarming rate. Analysis of official Navy/Marine and Air Force data will demonstrate G-LOC and other altered states of awareness remain a problem.

(Reprint of executive summary; formal paper not available.)

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THE TACTICAL AIRCRAFT MOVING MAP CAPABILITY (TAMMAC) DIGITAL MAP SYSTEM

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The US Navy is currently sponsoring the Tactical Aircraft Moving Map Capability (TAMMAC) program to develop a standard Digital Map System (DMS) to be used in a variety of Navy and Marine Corps aircraft. Digital Map requirements from both fixed and rotary wing platforms were combined with the results from Human Factors studies[1, 2] to arrive at the desired capabilities that shaped the requirements for the TAMMAC DMS. The resultant system offers a significant improvement in aircrew situational awareness, particularly during low level and nap of the earth (NOE) flight.

The TAMMAC system consists of a Digital Map System (DMS) and an associated Advanced Memory Unit (AMU) for loading of mission planning data and logging of maintenance data. This paper describes the baseline and growth capabilities of the TAMMAC DMS as they pertain to enhancing situational awareness.

The first platform to receive the new TAMMAC DMS will be the F/A-18 for the C, D, E, and F versions. Other aircraft planning to utilize the TAMMAC DMS include the AV-8B, AH-1Z, UH-1Y, MV-22, and some versions of the CH-60. Undoubtedly, once the DMS has been proven, other platforms will be included as well. In addition, since the TAMMAC system has received a Joint designation, it is also being considered for use on Air Force C-130s and Army CH-47Ds. For many of these aircraft, the addition of a color moving digital map display will in itself be a significant improvement in situational awareness since the flight crews currently use paper maps. Other aircraft have been flying with a moving map capability for some time and for them, the TAMMAC DMS offers improved image quality and many new operating modes.

At the simplest level, the DMS provides the aircrew with a display of standard paper aeronautical charts that have been digitized and stored inside the DMS, as seen in Figure 1. The aircrew can select from several scales of aeronautical charts and, since the DMS receives information from the aircraft navigation equipment, it can move the map along with the aircraft to always show the area around the aircraft's location. The map can be displayed north up or track up or heading up. Utilizing terrain elevation data, the DMS can also display terrain relief maps with contour lines at user specified intervals, as seen in Figure 2. The DMS can also create moving displays of satellite photo data, as seen in Figure 3. This data is currently available in 5 and 10 meter resolution.

Figure 1
Example Aeronautical Chart

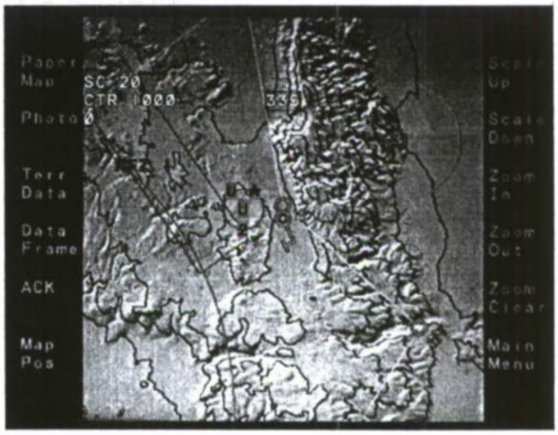


Figure 2
Example Terrain Elevation Display

All three of these DMS modes are created from standard database products provided by the National Imagery and Mapping Agency (NIMA). Aeronautical charts are created from Compressed Arc Digitized Raster Graphics (CADRG), terrain relief is created from Digital Terrain Elevation Data (DTED) and satellite photo maps are generated from Controlled Image Base (CIB). These standard database products are the same ones used on aircraft mission planning systems, which ensures that the maps displayed in the cockpit are identical to those seen during mission planning. Also, since the DMS reads database files exactly as they come from NIMA, database management is simplified and load times are significantly improved when compared with earlier digital map products.

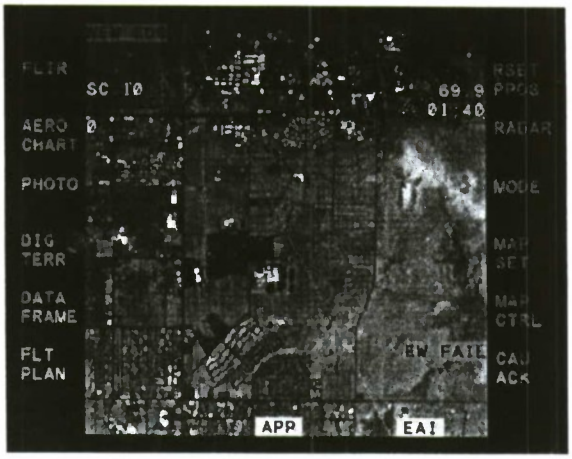


Figure 3
Example Satellite Photo Display

The DMS provides several scales of map imagery as shown in the table below:

Scale Set 1	**Scale Set 2**	**Aeronautical Chart (CADRG)**	**Satellite Photo (CIB)**	**Terrain Elevation (DTED)**
160 nmi		GNC (1:5 M)		
80 nmi	104.22 nmi	JNC (1:2 M)		Level 1
40 nmi	52.11 nmi	ONC (1:1 M)		Level 1
20 nmi	26.05 nmi	TPC (1:500 K)		Level 1
10 nmi	13.03 nmi	JOG (1:250 K)		Level 1
10 nmi	5.21 nmi	TLM (1:100 K)		Level 1
2 nmi	2.61 nmi	TLM (1:50 K)	10 meter	
1 nmi	1.305 nmi		5 meter	
0.5 nmi		City Graphics (1:12.5 K)		

The three modes discussed so far are all geographically referenced, that is, they represent specific areas of the earth and the DMS knows the exact latitude and longitude of every point in the image. The DMS can also display non- geographically referenced Data Frames, as shown in Figure 4. Data Frames are created by scanning any type of hard copy information and storing it digitally. This would include check lists, diagrams, approach plates, reconnaissance images, or anything else that can be carried to the scanner at a mission planning station. Data Frames can be rotated, panned, and zoomed.

Figure 4
Example Data Frame

Overlays

Once the background layer of the digital map has been established, several types of overlay graphics can be applied that are pertinent to situational awareness. Figure 5 shows several types of overlay information applied to a Terrain Elevation Display. Letter designations in the figure pertain to the references in the following text. For purposes of brevity, not all overlays are depicted in this paper. In general, overlays can be segregated into two classes, geographic oriented and screen oriented.

The table below indicates several types of screen oriented overlays that the baseline TAMMAC DMS supports.

Example Screen Oriented Overlays

General

- ✧ MFD Soft Key Legends (A)
- ✧ Caution and Alert Messages
- ✧ Stores Status

Map Control/Status

- ✧ For Chart, Photo, & Elevation:
  - Scale Displayed (B)
  - Zoom Factor Applied
- ✧ For Elevation:
  - Contour Line Interval (C)
- ✧ For Data Frames:
  - Data Frame Number

Navigational

- ✧ Aircraft or Cursor Position
  - In Latitude/Longitude
  - In MGRS
  - In UTM
- ✧ Air or Ground Speed (D)
- ✧ Heading Angle (E)
- ✧ Elevation
- ✧ Distance and Time to Go to Next Waypoint (F)
- ✧ Range and Bearing to Cursor (G)
- ✧ Time on Target
- ✧ Compass Rose/Arrow
- ✧ HSI

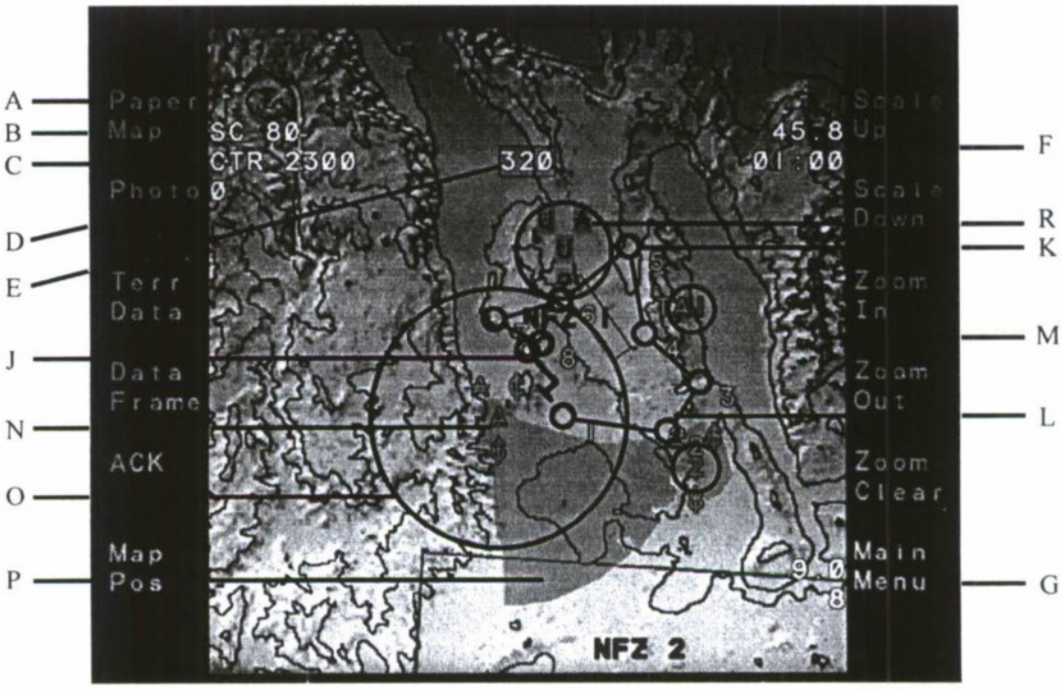
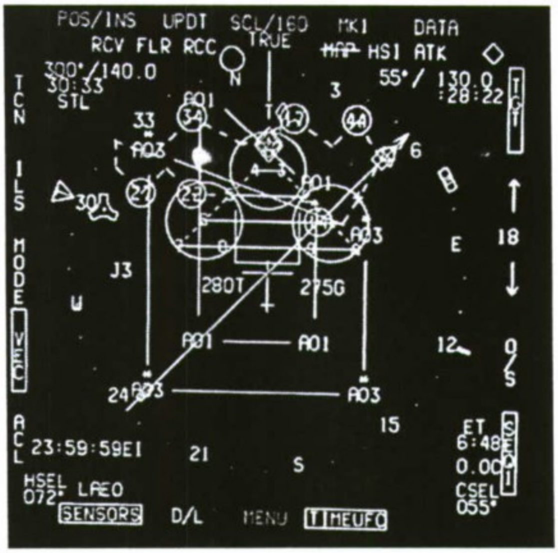
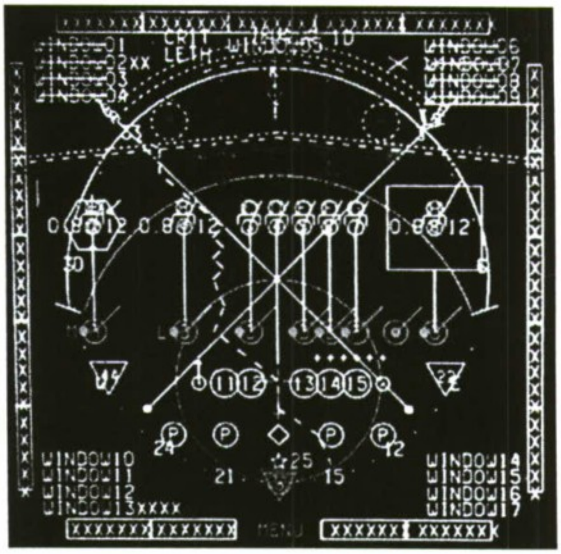


Figure 5
Overlay Information Applied to a Terrain Elevation Map

Complex screen oriented graphics can be created on the TAMMAC DMS by employing its high order macro language. Examples of F/A-18 nominal and worst case overlay graphics are shown below.





The DMS can create these screens either overlaid onto a digital map background or with the map blanked as shown here.

The second type of overlays generated by the DMS, geographic oriented, are features associated with the terrain. Geographic overlays can be applied to aeronautical charts, terrain elevation, and satellite photo displays. Perhaps the most common examples of geographic overlays are the aircraft symbol (J), waypoints (K), and flight plans (L). The DMS can display primary and alternate flight plans generated during mission planning and fully supports in flight route replanning. A Hook Cursor is provided to allow lift, drag, and drop of individual waypoints. Any number of flight plans can be managed by the mission computer and displayed on the DMS. Closely associated with the flight plan are Trend Dots. Trend Dots are three dots that appear in front of the aircraft symbol that indicate the predicted location in 10, 20, and 30 seconds respectively[1]. They respond to changes in velocity and turn rate and move on screen as the aircraft maneuvers. An example can be seen in Figure 5. Pilot feedback regarding Trend Dots from MH-53J flight testing has been very favorable. One case cited was that when flying a blind turn through a valley, the pilot could adjust the aircraft turn to place the Trend Dots in the center of the valley and the aircraft responded exactly as the Trend Dots predicted.

There are actually two types of geographic overlays provided by the DMS, symbology and tints. Symbology overlays include lines, circles, polygons, symbols, and text. Tints apply a translucent color over the background. A tinted overlay is used to indicate areas on the map where the terrain is above the aircraft altitude (M). This capability is sometimes referred to as Height Above Terrain (HAT) and sometimes Elevation Color Banding although neither term is particularly accurate and the latter has another meaning also. For the purposes of this paper, the capability will be referred to as Terrain Above Aircraft or TAA. The DMS constantly processes the terrain elevation database in its mass memory in order to determine the areas to tint. One color is used to indicate the areas that are above the current aircraft altitude and a second tint color is used to show the areas that are below the aircraft altitude but above the set clearance altitude. The tinted areas change size as the aircraft changes altitude to always convey to the flight crew an indication of safe flying areas. Since the tint applied over the map is translucent, all details from the background map always remain readable through the tint.

The DMS also provides a Clear Line of Sight (CLOS) indication either from the aircraft location to a point or between any two points. A line is shown on the display to show CLOS with the line being broken by any intervening terrain. The location of the obstruction is provided by the DMS for use by other systems.

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[1] The Trend Dot intervals are actually programmable values that can be configured uniquely by the user for different types of aircraft. Any practical time interval can be specified.

Threat Processing

The TAMMAC DMS also provides a new level of capability to display details of the threat environment surrounding the aircraft. First, threat locations are denoted by the presence of threat symbols on the map. Each unique threat type is represented by a particular threat symbol (N). The list of threat symbols is loaded onto the DMS along with the map database information and can be unique for each platform type. Each threat can have an associated legend displayed. Threats can also have an associated threat ring shown that identifies the range of its lethality (O). Like waypoints, threats can be lifted, dragged, and dropped by the Hook Cursor.

A new dimension to situational awareness is provided by the threat intervisibility overlay. Threat intervisibility is another tinted overlay that shows the areas where the aircraft can be seen from a threat, given its altitude above ground level relative to the surrounding terrain (P). The DMS continually processes the terrain elevation database to calculate line of sight visibility between the threat site and the aircraft, with antenna height of the threat taken into account. The threat intervisibility overlay is continuously updated as the aircraft changes altitude so that tinted areas always show where the aircraft would be detected. Conversely, untinted areas depict areas where the aircraft would remain hidden. Like TAA, the tint applied is translucent so that the nothing on the background map is obscured. The range to display threat intervisibility can be different for each threat type in order to accurately reflect its detection range. Also, a threat penetration indication can be enabled to alert the flight crew when the aircraft has entered a threat's range.

Threats are organized into several categories with each category occupying a separate layer. The flight crew can choose to display all threat categories or can declutter the display by only choosing certain categories for display. It is expected that initially most of the threats depicted on the map will be preplanned, that is, threats that were known at the time of mission planning and transferred to the aircraft along with other mission data. However, the DMS also supports the display of pop up threats, which are any new threats that are identified during flight. Pop up threats can be identified by either on-board or off-board sensors. Pop up threats can be configured to appear different from preplanned threats. Typically, pop up threats would have the same symbol shapes as they would if they had been preplanned but would have different symbol colors or attributes (R).

In addition to the specific types of geographic overlay features described above, the DMS provides a generic interface to allow any type of geographically referenced information to be displayed. Several independent geographic layers are provided that can each contain symbols, lines, circles, polygons, and text strings. These layers can be managed to show information such as targets, ground force locations, restricted airspace, downed airman indications, CHUM data, or any other type of entry. Each layer can be selectively enabled to allow the flight crew to declutter the display.

Image Positioning

The TAMMAC DMS provides considerable flexibility in controlling the map image. When displaying aeronautical charts, satellite photo, or terrain elevation displays, the image can be oriented north up or alternatively in a track up or heading up orientation. For helicopter applications the map can be controlled to automatically orient heading up when hovering and at low speed and then switch to a track up orientation as speed increases. Aircraft position on screen can be in the center of the display or offset to show more area ahead of the aircraft. This decenter position can be defined differently for each platform. When desired, the map can be commanded to display a location other than at the aircraft location, such as a target area, landing zone, or future waypoint. When the map is displaying imagery that is not centered on the aircraft, an alternate center of interest symbol can be enabled to denote the focal point selected. All display modes of the DMS can be rotated, panned, and zoomed. Zooming can either be in discrete steps, or be smooth and continuous. Displays can be zoomed out as far as 0.5:1 and zoomed in as far as 8:1.

All of the capabilities of the DMS are available on two completely independent channels. As an example, one channel can be viewed by the pilot at the aircraft location in track up orientation with a set of overlays he has selected while the other channel can support a weapons officer who is viewing the target area in north up orientation with a different set of overlays applied. Each channel provides both a color and a monochrome output to facilitate the displays particular to any aircraft.

Because the aircraft slated to use the TAMMAC DMS vary so much in aircraft performance, the DMS was designed to support a particularly wide range of aircraft dynamics. It provides smooth image motion, regardless of scale, at any speed or turn rate. It can change scale or jump to any position in the world in less than one second.

Flexibility

The TAMMAC DMS was designed from the start to support a wide variety of aircraft. Platforms ranging from utility and attack helicopters to fighter and attack jets provided the initial requirements that shaped the DMS specification. This direct involvement from so many types of aircraft has ensured that the DMS will provide the capabilities needed to execute a diverse range of missions. Although providing these capabilities goes a long way toward supporting numerous kinds of aircraft, there will always be individual platform preferences about the exact appearance of the digital map backgrounds and overlays.

In order to allow the appearance of the digital map displays to be tailored to satisfy these preferences, the TAMMAC DMS utilizes a Configurable Parameters Table. The table controls the colors and attributes associated with features such as waypoints, flight plans, threats, pop up threats, cursor, threat intervisibility tint and TAA tint. The table also contains timing and voltage level definitions for the video outputs. Color remapping tables are provided to allow special color palettes and NVIS compatible colors to be used. Each platform can have its own symbol set. Symbol shapes can be created by the user with standard PC tools. Once created, these symbols are combined into a symbol table that is downloaded to the DMS. The symbol set, color tables, and configurable parameters table can all be loaded into the DMS without removing it from the aircraft.

Despite the high degree of flexibility provided by the TAMMAC DMS, it is expected that as additional platforms consider it for use, new modes and capabilities will be identified. Also, evolution in the baseline aircraft will drive the need to expand the DMS's capabilities. For these reasons the TAMMAC DMS was designed to change and evolve without becoming obsolete. The initial set of capabilities of the DMS utilizes less than half of its available capacity. In addition, not only can its software be reprogrammed but, through the use of Field Programmable Gate Array integrated circuits, the DMS can actually change its circuit design. All of the DMS software, circuit configuration, and configurable parameters can be changed in the field through simple operations.

Data Loading

Data is loaded into the DMS via the TAMMAC AMU and is performed in two steps. First, when the unit is deployed to a new area, a theatre load is performed. The theatre load would normally be accomplished by the maintenance crew chief and would consist of all the paper chart, terrain elevation, and satellite photo data available for the region along with any general Data Frames that would be utilized repeatedly during missions. Sufficient mass storage is provided by the DMS to guarantee full area coverage over entire mission areas. Map database files are loaded onto Type 3 PCMCIA[2] cards at the mission planning station, transported to the aircraft, and inserted into the AMU from which the data is downloaded to the DMS. A full theatre download of 3 Gbytes of database files can be accomplished in approximately 30 minutes. Since loading is performed through the AMU, the DMS can be located deep within the aircraft in order to avoid use of precious cockpit space. Once the theatre area is loaded, the DMS is ready to fly and the theatre load cards are no longer needed.

The second step in loading data into the DMS is to install mission specific data. Mission data would include information such as flight plans, the threat environment, any restricted airspace, reconnaissance photos, CHUM, and any updates to theatre data files - in short, any data available on the mission planning station. Mission data is loaded onto flightworthy Type 2 PCMCIA cards by the flight crew at the mission planning station, transported to the aircraft, and inserted into the AMU.

Growth

Although the digital map capabilities described so far provide a significant improvement in situational awareness for today's flight crews, many more enhancements will be added shortly that will continue to improve the TAMMAC DMS for the flight crews of tomorrow. The DMS provides its current capabilities while only using half of its available resources. That leaves a considerable capacity to support the addition of new features.

Databases

Some of the initial enhancement that will occur will be in the type of the database products that the DMS can display. More scales of City Graphics paper chart data, along with higher resolution CIB and DTED will be available shortly. Also, NIMA is developing a new type of database known as Vector Product Format (VPF). This type of data keeps track of all of the cultural feature information that is contained on a map. Use of VPF data will allow text labels and legends to always appear upright on the map display regardless of how the map is rotated. Also, cultural features will be able to be decluttered by category so that only the desired information is displayed.

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[2] PCMCIA stands for Personal Computer Memory Card and Industry Association. The cards are used widely in laptop PCs for a variety of functions such as modems, special interfaces, and memory. PCMCIA cards are available in Type 1, 2, & 3 with each type having a different thickness. Flash EEPROM is typically available in Type 2 cards with densities ranging from 85 Mbytes, now, up to 350 Mbytes in the next few years. Type 3 cards can contain a miniature hard disk drive which allows significantly higher memory capacity.

Other database types under consideration for use by the DMS include digital FLIP charts (DFLIP), Digital Bathymetric Database (DBDB), Controlled Multispectral Image Base (CMIB), Digital Topographic Data (DTOP), Digital Nautical Chart (DNC), and Digital Point Position Database (DPPDB). Of course the addition of all these new database types, along with DTED and CIB data down to 2 and 1 meter resolutions greatly increases the amount of mass memory needed in the DMS to store it all. That is why the DMS mass storage is implemented in a ruggedized hard disk drive. As the laptop personal computer market continues to push hard drive capacities higher and their costs lower, these newer hard drives can be dropped into the ruggedized disk housing inside the DMS to increase its storage capacity.

Ground Collision Avoidance Warning

Just as the stored terrain elevation data is used to determine what terrain is above the aircraft, it can also be used to predict when the aircraft is headed for a collision with the ground. Techniques of this sort, for preventing Controlled Flight into Terrain (CFIT), are becoming known as Predictive Ground Proximity Warning Systems (PGPWS). Existing GPWS equipment considers only the terrain directly under the aircraft for predicting CFIT situations. The performance of these systems has been acceptable over flat terrain but has not been particularly effective in mountainous areas[3]. As a result, the Navy has begun an effort to enhance the performance of existing GPWS algorithms by using stored terrain data. It is envisioned to have the new PGPWS algorithms operate in the TAMMAC DMS. Using the stored terrain database in this fashion is considered by many to be the first step toward employing the terrain data for passive TF/TA.

Figure 6
PGPWS Display

Enhanced Threat/Target Processing

Another growth area for the TAMMAC DMS is in the processing and display of the threat environment. The existing capability allows the display of a static threat ring indicating the lethality range for threats. This capability can be enhanced to utilize aircraft Radar Cross Section (RCS) along with its orientation and velocity relative to the threat to provide a dynamic threat ring that changes shape and dimension as the aircraft maneuvers.

A capability that is already in use on a digital map in the MH-53J helicopter is integration of the DMS with off-board sensors to provide a near real time update of the Electronic Order of Battle (EOB). In that system the DMS receives new pop-up threat information from a secure satcom radio. Transfer of offboard sensor data to an aircraft for display on the digital map is now being referred to as Real Time Information in the Cockpit or RTIC. RTIC data transfers are not limited to new threat information. Flight demonstrations have been conducted, using a digital map that preceded TAMMAC, where near real time imagery was been sent to the aircraft for display on the digital map as an inset "picture-in-picture" window. A follow on demonstration will expand the capability by passing new target information to the DMS.

Operation with Other New Aircraft Equipment

Much of the growth areas expected for the TAMMAC DMS are in the area of staying up to date as other new equipment are added to the aircraft. New displays will have larger screens and call for higher resolution imagery. Many of these displays will no longer accept the traditional analog video interface used today. Digital video outputs will be required. Also, some users will have a need for a third independent video output. Also, new interfaces, such as Fibre Channel, are being considered to replace MIL-STD-1553. All of these areas are included in the TAMMAC DMS specification as growth areas that the equipment must be able to support.

Perspective View

Another enhancement that is included in the TAMMAC DMS road map is the addition of a 3-D "out the window" perspective view. Processing of the map database would be performed to render an image that would approximate the view seen from the aircraft window. A display of this type could be used for correlation with onboard FLIR sensors as the aircraft flies or, alternatively, could provide an in cockpit mission rehearsal capability.

Conclusion

The TAMMAC DMS will provide an unprecedented array of new capabilities for aircrews to enhance situational awareness and improve mission effectiveness. The baseline capabilities of the system will, in themselves, allow platforms to tailor the DMS operation to suit the needs of their particular missions. Considerable thought has already been given to identifying and shaping the growth capabilities described for the TAMMAC DMS. However, a methodical study, including flight crew interaction and human factors activities, should be undertaken to guide the platforms in deciding how to manage the considerable growth capabilities offered by the system.

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Promoting Situational Awareness with the Tammac Digital Map System: Human Factors Research and Design Issues

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Abstract

The US Navy's Tactical Aircraft Moving Map Capability (TAMMAC) program will provide the standard cockpit digital moving map system for Naval aviation. The TAMMAC system will be used by a variety of Navy aircraft with differing operational needs and resources and can be tailored to meet each aircraft's operational requirements. A major design goal of the TAMMAC program is to enhance situational awareness (SA) and aircrew mission effectiveness without further burdening pilot workload. The TAMMAC system has been designed to give pilots a great deal of flexibility to tailor the map capabilities to meet platform-specific needs. There is a need to structure the TAMMAC user interface to take maximum advantage of these capabilities to promote SA without contributing to pilot workload. The existing TAMMAC requirements and capabilities are largely based on user preferences from limited demonstrations of preliminary moving-map capabilities. Therefore, there is a need to test the applicability of these capabilities for promoting SA using part-task trainers or simulators. The paper summarizes human factors research relevant to SA with digital moving map systems and identifies research and design needs for promoting SA with the TAMMAC system.

Introduction

Background

The US Navy is currently sponsoring a Tactical Aircraft Moving Map Capability (TAMMAC) program that will provide the standard cockpit digital moving map system for Naval Aviation. The TAMMAC system consists of a Digital Map System (DMS), an Advanced Memory Unit (AMU) for loading mission planning data and logging maintenance data, and a High Speed Interface Bus. TAMMAC will be used by a variety of Navy aircraft with different operational needs. It can be tailored to meet each aircraft's operational requirements by selecting from several capabilities. Many of these capabilities are discussed in a separate paper presented at this symposium (Williams, 1998).

A major design goal of the TAMMAC program is to enhance SA and aircrew mission effectiveness without further burdening pilot workload (Lohrenz, Trenchard, Myrick, Van Zuyle, Perniciaro, Gendron, and Brown, 1977a; Ruffner and Trenchard, 1997). Since every cockpit display and control is accompanied by some additional workload burden, it is important that new capabilities, such as a digital map system, be integrated into the aircraft so that informational elements are organized for the pilot's most direct comprehension and subsequent application (Rogers and Spiker, 1988).

Organization of the Paper

The paper is organized into six sections. In the first section, we briefly review the construct of SA as a precursor to the following discussion of the role of SA in the design and utilization of digital moving map systems. In the second section we review selected studies relevant to SA in digital moving map systems. We then briefly discuss the primary TAMMAC baseline and growth features. In the fourth section, we discuss SA-design guidelines. Following this, we identify human factors research and design issues for SA in digital moving map systems. In the final section, we present our conclusions and recommendations for promoting SA with the TAMMAC Digital Map System (DMS).

Situational Awareness

Situational awareness (SA) is a construct that has been applied to a variety of aviation tasks and settings and is usually considered important for mission effectiveness and safety. Even though it is not currently possible to specify how much SA is enough for a particular aviation mission or task, it is commonly believed that good performance is linked to good SA (Endsley, 1995).

Although many definitions for SA have been offered, they have several elements in common. For example, Wickens (1995, 1996) defined SA as the continuous extraction of information about a system or environment, the integration of this information with previous knowledge to form a coherent mental picture, and the use of that picture in directing further perception, anticipation, attention or responding. This definition closely parallels that proposed by Endsley (1995) in which SA is defined as the *perception* of the critical elements of an environment in time and space (Level 1), the *comprehension* of their meaning, particularly when integrated in relation the aircrew's goals (Level 2), and the *projection* of what will happen with the system in the near future. It is widely believed that the higher levels of SA allow pilots to function in a timely and effective manner.

In addition, SA can be global or local (Endsley, 1997a). Global SA information needs relevant to digital moving map systems include one's location within a broad geographical area, navigation information such as the relative location of important features, the current location and direction of movement of friendly and enemy units, and current commands and directions. All these factors are relevant to the aircrew's ability to navigate and plan strategically to meet their goals. Local SA needs include the location of a desired target in the immediate environment, the identity (friend, foe, or neutral) of an entity under current targeting, terrain and object location (as needed for maneuvering), and cueing of the presence and movement of threats in the immediate environment. This information is critical to the aircrew's basic awareness of threat presence in relation to the aircraft and the ability to react quickly in accordance with mission goals. Both global and local SA needs are critical for effective aircrew functioning in a given environment.

Recent research suggests that SA is most likely a multidimensional construct. For example, Endsley (1997a) proposed that several classes of elements were required for SA: geographical, spatial/temporal, system, environmental, and tactical. Wickens (1995) suggested that overall SA should be broken down into hazard awareness, system awareness, and task awareness. Furthermore, Coury and Wilson (1994) identified five SA aspects: spatial, identity, temporal, responsibility, and expectancy. Some of these classes of SA elements (e.g., geographical, tactical) will be more relevant to promoting SA in digital moving map systems than others (e.g., system, environmental).

Research Relevant to SA in Digital Moving Map Systems

Digital moving map systems are designed to replace cumbersome paper maps in aircraft cockpits. They provide information useful for navigation and tactical tasks, and can provide a means for enhancing SA. They allow the pilot to focus his or her attention on navigation with a minimum amount of head-down time. Digital moving map systems integrate information from several sources. When properly designed, they can serve to display information the pilot needs more efficiently such that the pilot should be able to obtain all the information needed to assess a situation and accomplish a task with a quick glance at the display (Unger and Schopper, 1995). In addition digital moving map systems provide the aircrew with control of the displayed information. A number of studies have been conducted during the last 20 years to identify the functional requirements and desirable features and capabilities for digital moving map systems. In this section, we briefly summarize selected digital moving map system studies relevant to SA.

U.S. Army Digital Map Functional Requirements Analysis

A comprehensive program to identify the functional requirements of ground based mission planning systems and airborne digital map systems for US Army aviators was conducted during the 1980's. This program drew on the findings of investigations on helicopter navigational requirements, map usage, and the effects of various display variables on the perception of topographic features and symbology (e.g., Rogers, 1983; Rogers and Cross, 1979; Rogers, Gutmann, and Ralstin, 1982).

During both mission planning and flight, the aviator must extract a great deal of information from maps. Rogers (1985) notes that the aviator must study and visualize the overall situation and topography; select engagement points, observation points, or landing zones; determine primary and alternate (masked) routes of flight; select air control points (ACPs), checkpoints, and barrier features; and determine flight modes, altitudes, speeds, and durations. Each of these activities places a large burden on the aviator's information compilation and processing skills.

Early map displays were designed for assisting in navigation; however the greatest contributions of a cockpit digital moving map display are likely to be in aiding the performance of both mission planning and tactical decision-making tasks. Rogers (1985) identified four potential advantages of a computer-generated topographic display system in addition to enhancing navigation capability:

1. ***Potential for comprehensive and rapid response and cartographic support.*** In contrast to the long lead time required for conventional or photo-based maps, it is possible to obtain the data required to support computer-generated display systems within hours vice weeks or months.
2. ***Control of the content of the displayed information.*** Because of the variety of roles that he or she is expected to fill, the aviator may need different types of information on different missions or in different phases of flight. Furthermore, map clutter must be avoided. Aviators using a computer-generated map can select the information that is optimal for the situation at hand, can control the classes of information that are displayed (e.g., vegetation, hydrography), and can select the specific features of a given class of information (e.g., deciduous trees, perennial streams). In addition the scale and contour interval can be altered to tailor the map to the aviator's changing requirements.
3. ***Powerful computational capability.*** The increased computational capability of a digital map system provides the basis for several improvements that can increase the interpretability of the map features. Examples of these are a) using shaded elevation bands to indicate areas where the surrounding terrain is equal to, higher or lower than the altitude at which the aircraft is currently flying; b) presenting a shaded relief map enhanced by contour lines; c) displaying the areas masked from visual or radar observation given known or likely enemy positions; and d) constructing perspective views to familiarize the aviator with the terrain as it will be seen during flight.
4. ***Increased degree of interactivity.*** An aviator can enter information such as map annotations, coordinates of objectives, planned routes, etc., which can be selected at will. The "intelligent" nature of the system can permit the interrogation by the aviator to determine certain characteristics of the portrayed features, such as tree height and crown cover. Thus, the interactive nature of the system can remove some of the natural limits to the aviator's decision-making capabilities and permit him to rapidly solve complex problems.

As a result of his research, Rogers (1985) identified several desirable functions or capabilities for a computer-generated digital map. These include the ability to:

- Present different map scales (e.g., 1:50,000, 1:250,000);
- Show different map areas (e.g., near, remote);
- Present different types of terrain information (e.g., contour lines, slope shading);
- Present different map orientations (e.g., north-up, track-up);
- Show areas of masking and intervisibility (e.g., clear line-of-sight);
- Select and depict a wide variety of features (e.g., topographic, tactical); and
- Depict elements of a flight plan with annotations (e.g., flight path, waypoints).

U.S. Air Force Survey of Desirable Digital Map Characteristics

Rogers and Spiker (1988) conducted a survey of U. S. Air Force pilot preference for digital map system capabilities to support the integration of a digital moving map system into advanced high-performance aircraft. The project approach consisted of a series of information-gathering and analytic activities that included a literature review, interviews with expert aviators, observations of aviator task performances, surveys, human factors engineering analyses, and perceptual studies. The participants were experienced Air Force active duty and reserve aviators.

The researchers' findings were organized under a systematic outline of mission phases and functions, and identified tasks that were geographic or spatial in nature. In addition, their findings were useful for defining the specific information items required to perform the tasks. On the basis of their findings, candidate digital map applications and formats were developed to potentially overcome existing interface deficiencies.

An additional group of pilots evaluated these formats using a questionnaire survey. The survey findings suggested that two characteristics, display of flight leg data, and perspective view of terrain, had high potential utility and thus could be considered to be extremely advantageous. In addition the utility ratings of several other characteristics suggested that they had high potential payoff and value for enhancing SA. These characteristics included position updating, integrated threat display, threat circles with terrain masking, air-to-air display, and terrain avoidance display. The findings from the survey were used to help direct technology development resources toward the application of the most critically needed capabilities.

Human Factors Analysis of AH-1W Moving Map Requirements

Ruffner and Puccetti (1996) conducted a survey of previous digital moving map system research and of existing or developmental digital map systems to identify desirable capabilities for the US Marine Corps AH-1W attack helicopter. The work of Rogers and his colleagues, described previously, was summarized in their report. One of the programs reviewed by Ruffner and Puccetti was the RAH-66 Comanche digital map development program. This effort represents a model developmental effort from a human factors perspective in which SA was a critical design driver (Hamilton, 1993; Hamilton and Metzler, 1992).

The Comanche digital map was designed using a pilot-centered approach. This approach that was characterized by a design philosophy in which data for SA and decision making were brought to a centralized display location in a manner that is quickly interpreted relative to the mission, phase, or task being performed. In addition, the map information was provided in a format compatible with the information demands of the crew and organized for the pilot's most direct comprehension and application. The Comanche digital map was designed to serve as a mission information database and crew-aircraft interface as well as a primary navigation aid.

Based on their findings, Ruffner and Puccetti (1996) recommended several capabilities that should be implemented in the AH-1W digital map that had the potential for enhancing SA. These included: (1) allowing the pilot to select the contour line interval appropriate for the mission phase; (2) showing areas of masking and intervisibility to depict the likelihood of being observed or detected; (3) allowing north-up, track-up, and heading-up map orientations; (4) allowing centered or decentered location of ownship; and (5) allowing slewing of the map to another selected area.

U.S. Navy Human Factors Digital Map Requirements Study

The Navy Research Laboratory (NRL) recently conducted a study of pilot preferences for map features and capabilities (Lohrenz et al., 1997a; Lohrenz et al., 1997b). The study consisted of one-on-one aircrew evaluations of digital maps and display parameters for military cockpits The researchers guided experienced aircrew through task-structured scenarios, presented a variety of tactical and topographic features for evaluation, and surveyed participants' preferences based on their platform applications. Representative scenarios were presented illustrating candidate map capabilities such as (1) map positioning (e.g., north-up, track-up, centered-decentered), (2) zooming (e.g., zoom in/out, continuous versus discrete zoom), (3) presentation of terrain elevation data (e.g., contour lines, plan versus perspective views), (4) map overlay data (e.g., threat location and range), and (5) vector map displays. Based on their findings, several capabilities (e.g., map overlay data, zooming) are being incorporated as baseline requirements in the TAMMAC DMS while others (e.g., perspective view, vector map displays) are considered growth capabilities and may be added at a later date. A detailed description of the study approach and findings can be found in Lohrenz et al., (1977a). Selected study findings relevant to SA are summarized in the following paragraphs.

Map Positioning. Most pilots preferred track-up orientation over a north-up orientation for improved SA and preferred a centered aircraft display while the map was in north-up orientation. The pilots judged that the bottom of the screen aircraft position results in loss of SA behind the aircraft. In addition the pilots considered the north-up orientation to be disorienting in flight but good for waypoint insertion

Zooming. The pilots preferred zooming up to scale of the next chart series, then switching series to maintain SA. They judged continuous zoom as desirable to maintain SA in a controlled, predictable, and fast manner. The pilots judged that one-step zoom made it hard to keep track of SA but that zoom out supported maintaining big-picture SA. They also preferred easily divisible display ranges for maintaining SA.

Terrain Elevation Data. There was no strong preference for a two-dimensional (2-D) versus a three-dimensional (3-D) view, with the judged effectiveness varying with terrain elevation display mode (e.g., chart data, imagery). The pilots considered sun angle shading a good SA builder for flying in terrain and judged that sun angle shading would increase SA and enhance their ability to develop an evasive plan. In addition, the pilots judged a fixed sun angle more appropriate than a dynamic sun angle for maintaining SA. Furthermore, contour lines were preferred more by helicopter pilots than by fixed-wing tactical pilots for maintaining SA.

Overlay Data. The pilots judged height above terrain (HAT) extremely valuable for terrain avoidance and recommended HAT as a user-selectable feature. The pilots responded favorably to the clear line-of-sight (CLOS) capability. The pilots preferred threat rings for displaying intervisibility, more so when the threat rings were overlaid over imagery than over chart data. Furthermore, the pilots preferred translucent overlays instead of spokes for displaying threat information. The translucent overlays made it easier to see the underlying map information.

Vector Maps. Vector maps are rendered from individually stored objects such as points, lines, and areas. The pilots favored the capability of vector maps for keeping text upright in track-up orientation and selectively decluttering the display. They judged the vector map capability to provide enhanced flexibility and display optimization and considered it good for building and sustaining SA. On the negative side, the pilots were concerned that vector maps might add complexity and increase workload. There were also concerns that vector maps may require additional pilot training. From a purely technical side, vector maps are likely to require additional processing and capability and some level of automated cartography.

Overall, the findings from the NRL study suggested that pilots favored using a more realistic base-map for SA, but overlaying the base-map with high contrast, mission-specific features. In addition, the pilots expressed a strong preference for keeping the map as simple as possible for more rapid assimilation of information during flight and for developing SA. Lastly, the pilots recommended putting more options in the mission planner and keeping in-flight options to a minimum for the greatest SA benefit while minimizing in-flight workload.

TAMMAC Digital Map System Features

The TAMMAC DMS will provide a number of features and capabilities. Some baseline features will be available upon fielding the TAMMAC system. Other growth features will not be implemented immediately. As noted previously, many of these features are described in Williams (1998) and, therefore, are not discussed in detail in this paper. The purpose of the following subsections is to provide the reader with sufficient information about key TAMMAC DMS baseline and growth capabilities to serve as a background for the ensuing discussion of SA guidelines and human factors research and design issues.

Baseline Features

TAMMAC DMS baseline features and capabilities include the following:

- Multiple Display Modes (e.g., chart, terrain elevation, imagery)
- Multiple Display Scales (e.g., 1:50,000, 1:250,000)
- Selectable Map Orientation/Reference (e.g., north-up, track-up)
- Overlay Symbology (e.g., ownship, waypoints)
- Dual Independent Outputs (e.g., pilot and copilot crew stations)
- Dynamic Display Overlays (e.g., preplanned/pop-up threats, elevation banding)
- Zooming Capability (e.g., zoom in, zoom out)
- Selectable Contour Lines Intervals (e.g., 50 feet, 100 feet)
- Trend Dots (indicating aircraft position in 10, 20, and 30 seconds)

For example, Figure 1 illustrates how the Dynamic Display Overlay capability might be implemented using elevation color banding and threat rings.

Figure 1. Example of a TAMMAC DMS baseline feature: Dynamic Display Overlay showing elevation color banding and threat rings.

Growth Features

Throughout the development of the TAMMAC system several advanced display features were considered that offer unique capabilities for enhancing and maintaining SA but will not be implemented immediately. TAMMAC growth features include:

- 3-D Perspective View
- Dynamic Threat Rings
- Declutterable Vector Map
- Picture-in Picture Inset Window
- In-flight Mission Re-planning
- Display of Map Feature Data
- Real-time Imagery in the Cockpit
- Three Independent Channels
- Predictive Ground Proximity Warning System (GPWS)

In addition, the TAMMAC system will be able to incorporate emerging databases from the National Imagery and Mapping Agency, (NIMA) such as the Vector Vertical Obstruction Database (VVOD). Figure 2 illustrates an example of the picture-in-picture growth feature. This feature would allow the pilot to have a smaller picture within the current map presentation that could be used to show an aerial photograph, a data frame (e.g. a list of threat characteristics), or reconnaissance imagery.

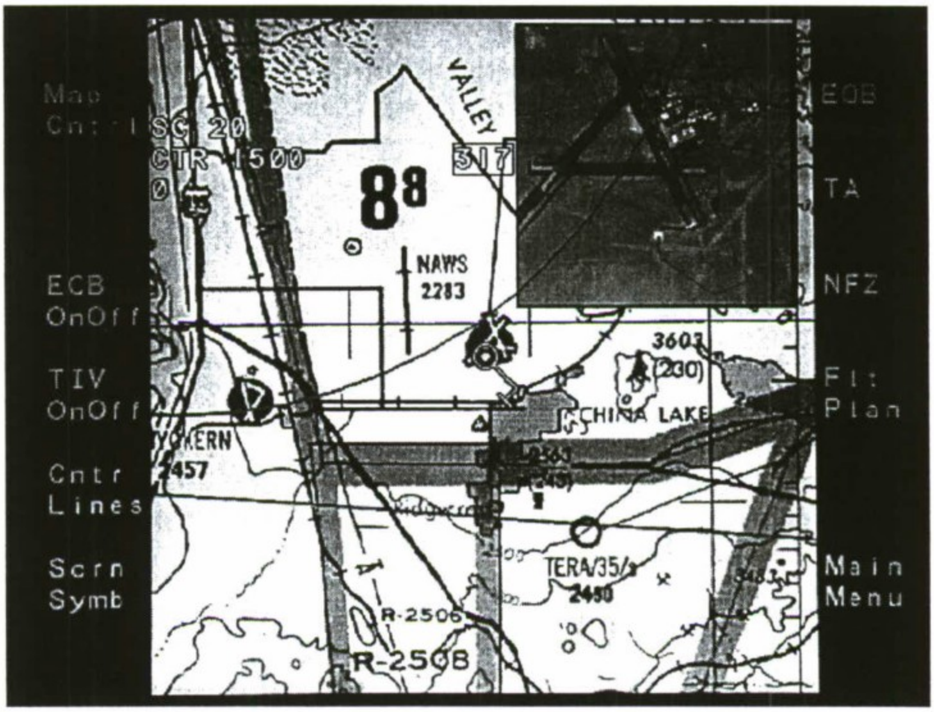

Figure 2. Example of a TAMMAC DMS growth feature: Picture-in-picture window showing image of the area of interest in the inset window.

Situational-Awareness Design Guidelines

Endsley (1997b) suggested several general design guidelines for creating display interfaces that enhance SA. For example, cockpit displays should:

- Provide information that is processed and integrated in terms of SA Level 2 and 3 needs,
- Provide global SA along with goal-relevant detailed information,
- Present information in terms of the operator's major goals,

- Make critical cues used for activating mental models and schemata salient,
- Filter extraneous information and reduce data by processing and integrating low level data, and
- Provide system-generated support for projecting future events and status of the system.

In their present form, the guidelines provide useful information for enhancing SA for cockpit display systems in general. However, they need to be tailored and selectively applied to the design and selection of digital moving map systems features and capabilities. For example, the guidelines should provide recommendations for color and shape symbology coding for the depiction of threat information in a dynamic overlay display to enhance the comprehension of threat status (SA Level 2) and projected ownship vulnerability (SA Level 3). As another example, the guidelines should recommend how a picture-in-picture capability could be utilized to provide global SA about the enroute situation while providing goal-relevant detailed information to assist the aircrew in planning their tactics for the terminal objective area.

Human Factors Research and Design Issues

As a result of our review of relevant research on digital moving map system design and utilization, we identified several human factors research and design issues that need to be addressed in the future to improve the contribution of the TAMMAC DMS to enhancing SA. Specifically:

- What are the individual navigational, and tactical tasks that require the development and maintenance of a high level of SA? What are the global and local SA information needs of these tasks? How can the capabilities in the TAMMAC DMS be best used to support the pilot's global and local SA information needs?
- What is the contribution of the baseline and growth TAMMAC DMS capabilities to promoting and maintaining Level 1 (Perception), Level 2 (Comprehension), and 3 (Projection) SA? Which growth capabilities offer the most potential for enhancing SA and warrant adaptation in the future?
- What is the best way to apply general SA guidelines to the design and selection of TAMMAC DMS capabilities? How should the guidelines be modified to better suit the requirements specific to the TAMMAC DMS?
- What is the most appropriate way to measure SA for the TAMMAC DMS so that the aircrew's global and local SA information needs are adequately reflected?
- What classes (e.g., geographical, tactical) of SA elements are most important for enhancing SA with the TAMMAC DMS? What is the best way to use or enhance DMS capabilities to meet the information needs of these SA classes?

Conclusions and Recommendations

The TAMMAC digital map system will have a variety of features and capabilities that have the potential for achieving the goal of enhancing SA and aircrew mission effectiveness without further burdening pilot workload. The extent to which this potential can be realized will depend largely on the successful application of previous digital moving map system research findings and the thoughtful tailoring of general SA-oriented design guidelines to the design and selection of DMS capabilities. The TAMMAC system provides a great deal of flexibility to the aircrew for selecting features and capabilities to support their specific aircraft mission. Care must be exercised that this flexibility does not become be a contributor to overall aircrew workload. Accordingly, more specific guidelines need to be developed and validated for designing and selecting DMS features to promote SA for different aircraft platforms.

The existing TAMMAC baseline and growth requirements and capabilities were validated based on user preferences from demonstrations of candidate moving map capabilities (e.g., Lohrenz et al., 1997a; Lohrenz et al., 1997b). However, there is evidence that preference and performance are not always consistent (Bailey, 1993; Nielsen and Levy, 1994; Wickens and Andre, 1994). While an important source of information to guide the design and selection of digital moving map system features and capabilities, preference data should be validated using part-task or full-task simulation scenarios with realistic task loadings and appropriate performance measures that are sensitive to critical digital moving map system parameters. Specifically, advanced capabilities planned for the TAMMAC DMS, such as in-flight mission re-planning, a declutterable vector map, and picture-in-picture should be evaluated in user-performance simulations. The results of these simulations could be used to optimize the map functions and capabilities to enhance SA while minimize the impact on pilot workload.

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"Inside-Outside" Spatial Strategies Employed by Pilots During Shipboard Operations

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Introduction

Aviation training specialists have established that, "*the pilot's perception of orientation serves as a backdrop for everything he does with the aircraft.*"(1) Based on this philosophy, efforts to improve flight safety have invariably emphasized enhancement of spatial awareness through improved training and display technology. Although much has been accomplished toward understanding human factors related to these issues, loss of spatial and situational awareness continues to plague the aviation community. Mishap summaries indicate sensory or cognitive misinterpretations are responsible for as much as 76% of all U.S. military aircraft losses (2). Each year, these hazards contribute to the destruction of over 77 U.S. military aircraft and result in the deaths of at least 68 crew members; in monetary terms, pilot error (caused by sensory or cognitive misperceptions) annually cost taxpayers over $360 million in lost aviation assets. Surprisingly, accident investigations also reveal that pilots falling prey to cognitive hazards are not typically novice aviators; instead they are often identified as highly proficient senior pilots with ten years of aviation experience and over 1500 hours in the cockpit (3).

Aviation accident summaries indicate Navy and Marine Corps mishaps (class "A") have a greater than 50% probability of occurring at sea (4). These same reports further suggest many over-water losses involve, to some degree, interaction between shipboard and aircraft operations (usually take-off or landing). Since loss of spatial awareness is often noted as a reoccurring cause factor among these accidents, it seems prudent to reevaluate human factor design issues related to "at sea" aviation operations.

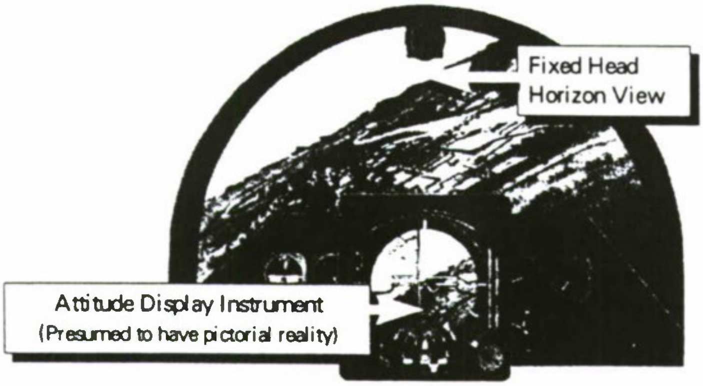
Close-in shipboard flight operations require that pilots maintain spatial awareness by integrating multiple sensory-spatial cues. Following shipboard launch and departure, pilots usually orient themselves by relying on traditional aircraft instruments or audio cues from air traffic controllers. In addition to these references, aviators also frequently use "outside" visual cues for direct and unambiguous spatial information relating aircraft attitude, altitude, and airspeed. During approach and landing, two additional sources of spatial information play a critical role in making safe shipboard recoveries: these two factors include a specially trained landing signal officer (who directly observes the aircraft on final approach) and specially designed deck mounted displays (ball) which provide direct visual information relating aircraft position relative to moving ship.

With nighttime operations, rotary-wing pilots may also utilize night vision goggles (NVG) to enhance their "outside" visual spatial cues. In addition to making "outside" cues more visible, updated NVGs systems attempt to augment spatial awareness by overlaying heads-up-display (HUD) symbology over the enhanced NVG imagery. Although both old and new NVG systems were introduced as a means to improve spatial awareness, several published mishap reports suggest, "*....use of night vision devices is associated with increased risk of spatial disorientation*" (5). In collaboration with this assertion, USMC reports indicate over a recent five year period (1991-95) spatial disorientation (SDO) was the primary cause factor behind 15 of their 33 helicopter mishaps; many of which involved NVG flight (6). During a comparable five year span (1987-92), the U.S. Army reports a similarly hazardous situation in which 187 helicopter losses were attributed to pilot disorientation compounded by loss of situational awareness (5). Of additional interest are documents indicating most disorientation mishaps do not typically involve "text book" causes of SDO (which are vestibular or visual illusions); instead, U.S. Army investigators have found cognitive hazards such as distractions or failure to successfully transition to instruments, appear as primary factors behind most NVG and non-NVG "pilot error" incidents. In support of this conclusion, several published mishap summaries indicate visual transition from "outside" to "inside" is a factor commonly associated with aviation spatial disorientation (4, 7-9). In view of these circumstances, it seems prudent to further examine why switching from "outside" to "inside" the aircraft increases risk of disorientation and loss of situational awareness.

Current Design Issues

Since an aviator's spatial or situational awareness is largely dependent upon how well he interfaces with cockpit displays, it is imperative that cockpit designers have accurate information relating which display designs are most sensory compatible and therefore most resistant to cognitive hazards. Conventional wisdom describing aviation spatial awareness assumes pilots view a moving horizon through the windscreen {Figure 1}(10-12). This assumption presupposes head alignment with the vertical cockpit axis during both visual (VMC) and instrument (IMC) maneuvers. Even though this visual-spatial paradigm has been incorporated with many aircraft designs, its accuracy has never been verified.

Figure 1



Conventional assumptions related to pilot spatial awareness:

- Pilots maintain head alignment with the aircraft during both IMC and VMC maneuvers.
- The view through the windscreen is a moving horizon against a fixed cockpit perspective.

In contrast to the conventional design theories portrayed in figure 1, recent human factors research has identified a sensory-spatial reflex (opto-kinetic cervical reflex or "OKCR") that causes pilot head tilt toward the horizon when looking "outside" during VMC roll or pitch maneuvers {Figure 2} (13-16). Presumably, this intuitive head tilt response improves spatial awareness by establishing the horizon retinal image as a stabilized <u>primary visual-spatial cue</u>.

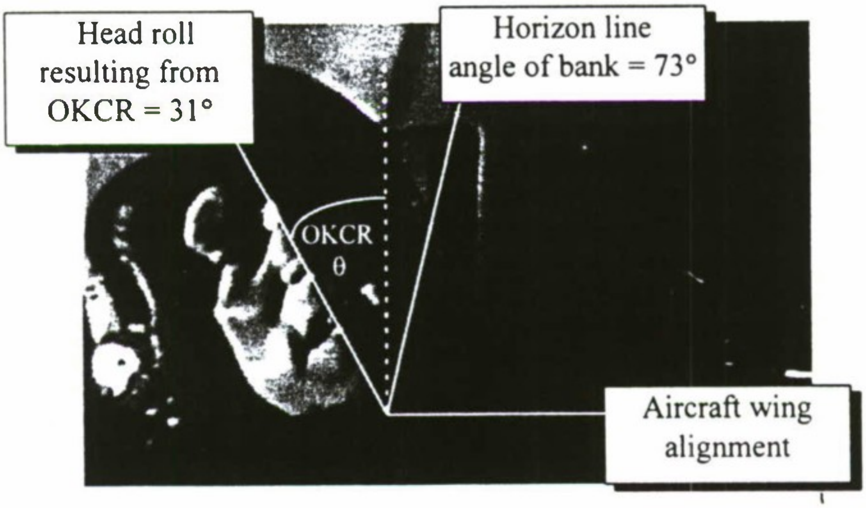
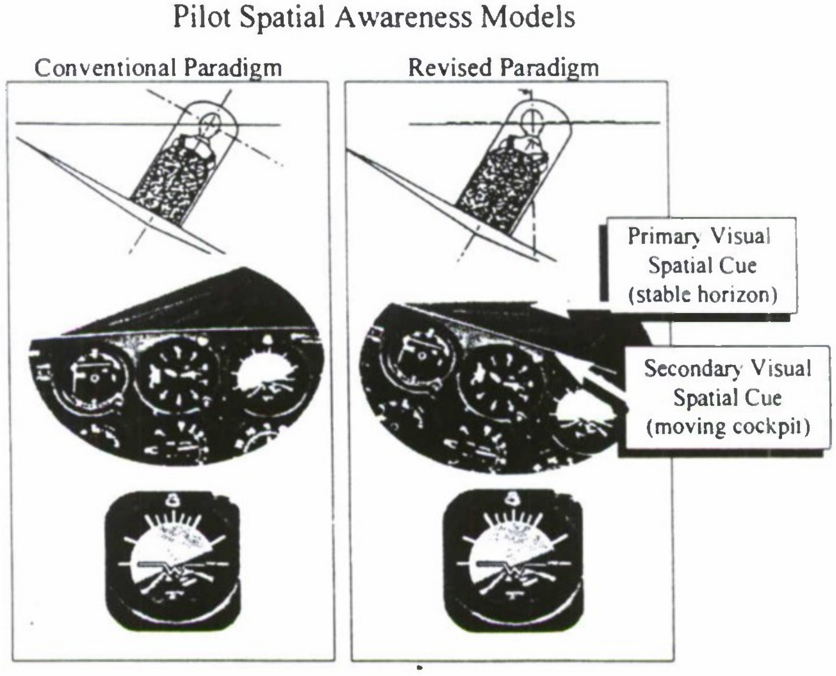


Figure 2: Blue Angle pilot during 73 ° bank in F/A-18 aircraft.

OKCR head tilt toward the horizon, also results in head movement away from the cockpit vertical axis. An important outcome of this movement is peripherally viewed cockpit images will appear to move with respect to the retinaly stabilized horizon view. Presumably, this visual perspective aids pilot spatial awareness by establishing peripheral cockpit images as secondary visual-spatial cues (visual-control feedback) that move (on the retina) in the same direction as stick control inputs (i.e., push stick **left** - peripheral cockpit images move **left**) (Figure 3). By adapting this visual-spatial strategy, pilots are able to achieve motion compatibility between control movement and visual feedback; this beneficial spatial relationship ("*principle of compatible motion*") is known to reduce both mental workload and episodes of disorientation (11,17).


Pilot Spatial Awareness Models

Conventional Paradigm

Revised Paradigm

Primary Visual Spatial Cue (stable horizon)

Secondary Visual Spatial Cue (moving cockpit)

Figure 3: Pilot spatial awareness theories depicting the older assumed (conventional) paradigm and the recently documented (revised) paradigm.

Research efforts first linking OKCR head tilt with spatial awareness also confirmed that sensory-spatial reflexes change when switching from VMC to IMC. During visual transitions from "out-to-in," pilot's consistently realigned their heads with the aircraft vertical axis once the OKCR stimulus (outside horizon) was removed. The implications of this sensory transformation are:

- An IMC pilot's view of the cockpit suddenly becomes stationary as his view of the (artificial) horizon begins moving.
- When transitioning from VMC to IMC, pilots must instantly reverse their orientation strategy from a *"fixed horizon-moving cockpit"* to a *"moving horizon-fixed cockpit"* perspective.
- In conjunction with reversal of spatial cues (out-to-in), VMC-to-IMC pilots also lose sensory-spatial compatibility between stick control motion and visual feed back (i.e., push **left**- visual feedback (display symbol) moves **right**).

Once pilots completely transition from one spatial perspective to another, they are usually able to control the aircraft without difficulty. It is the point of transition, when movement of spatial cues (visual feedback) is suddenly reversed and control compatibility is lost, that spatial disorientation and loss of situational awareness is most likely to occur (13, 16, 18).

The most common spatial disorientation error associated with instrument transition is mistaking horizon symbology motion (located on the attitude indicator) as relative movement of the aircraft wings. This misinterpretation, referred to as *control reversal error*, becomes apparent when a pilot inadvertently executes a control input resulting in aircraft movement opposite what was intended. Early research evaluating frequency of control reversal error suggested pilots commit reversal errors approximately 7% of the time, during relatively easy transitions (18). More current evaluations aimed at evaluating control problems with difficult VMC-IMC transitions (such as formation flying or unusual attitude recovery) report much higher reversal error rates ranging between 25 and 65 % (13, 16).

In respect to head-mounted-displays (HMD), which include NVGs, recently completed U.S. Army research found pilots using NVGs experienced the same reflexive (OKCR) head tilt as reported with daytime VMC (16). The inference of this research is pilots flying at night (with NVGs) apply the same *stabilized horizon-moving cockpit* strategy as normally used during day VMC. However, of concern with NVG flight is the fact that peripherally viewed cockpit images, which provide critical control-visual feedback, fall beyond the enhanced NVG (40°) field of view; subsequently, these secondary spatial cues become significantly degraded by the low peripheral light levels. In view of these circumstances, the following sensory-spatial factors are germane to NVG safety and flight performance:

* During certain phases of flight, particularly during execution of high angle of bank maneuvers, secondary spatial cues become seriously degraded or made altogether invisible by the subsequent loss of peripheral visual acuity.

* Loss or degradation of these secondary references can be expected to significantly reduce pilot spatial awareness while at the same time causing an increase in mental workload.

In addition to dealing with reduced primary and secondary visual-spatial cues, pilots flying with NVGs may also experience the need to suddenly transition to instruments during unexpected IMC or brownout/whiteout conditions. Depending on the aircraft type and NVG series, pilots who lose outside cues may transition to one of two available instrument attitude references. Currently, the most common method of NVG-to-instrument transition is to look under the goggles at the head-down displays located on the forward instrument panel. From a cognitive standpoint this method is comparable to going IMC during daylight conditions in that it also causes loss of secondary spatial cues and necessitates a reversal of spatial strategies.

A second, less widely available method, is to focus attention on HUD attitude symbology superimposed over the NVG field-of-view (Figure 3). This newly introduced technology, brought on line by rapid prototyping methods (19), consists of traditional HUD symbology overlaid onto standard ANVIS NVG images. Although this form of sensory fusion first appeared as a means of improving spatial awareness, there exists some concern regarding the sensory-spatial compatibility of this system. These concerns center around the fact that HUD symbology, which was originally designed as a fixed forward looking reference, may not be well suited as an off-axis (head turned) visual attitude reference.

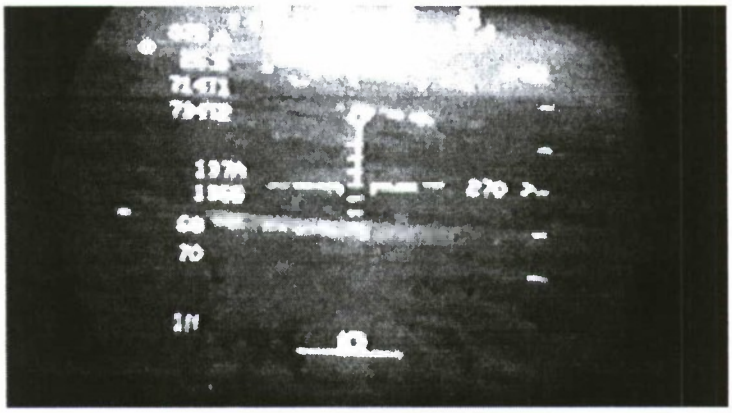
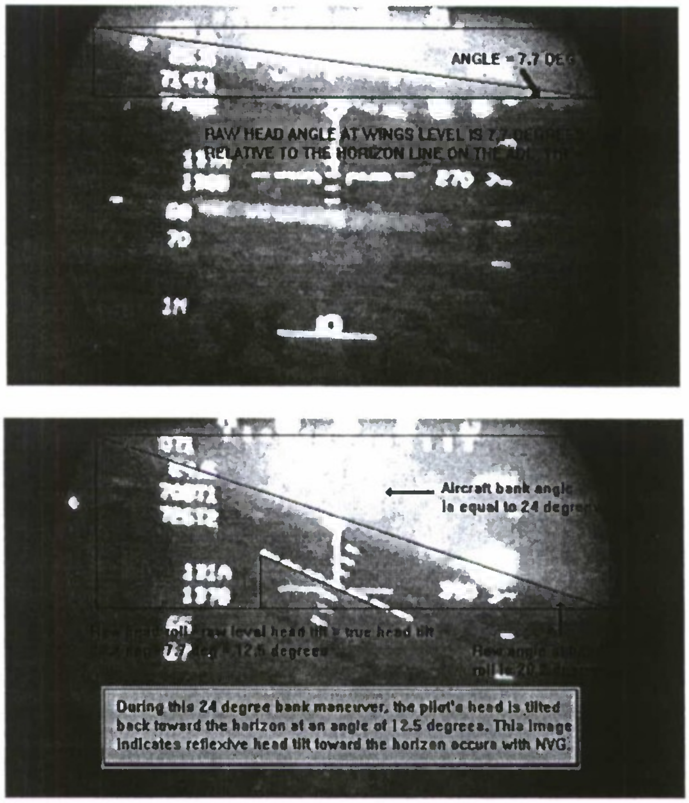


Figure 3: HUD symbology superimposed with NVG images (AN/AVS-7)

Human factor engineers have determined current "fixed head" NVG-HUDs have an orientational perspective that is difficult to interpret and prone toward inducing spatial disorientation (20-23). The primary problem associated with this fixed head perspective is NVG-HUD symbology moves with the head during voluntary or reflexive (OKCR) head movements. Under these conditions, orientation of HUD symbology becomes dependent on changing head positions; as a result, the horizon line symbol becomes out of alignment with the real world and the aircraft waterline symbol is not aligned relative to the airframe, pilot, or the actual horizon (Figure 4). In essence, during NVG-HUD flight the pilot's attitude display symbology will, most of the time, remain significantly out of alignment with the real world horizon (primary spatial cue) and aircraft axis (secondary spatial cue). As suggested by the cited references, this mismatch between attitude display symbology and the real world environment leads to a significant increase in mental workload (with potential for task saturation) and an increase likelihood of experiencing spatial disorientation or loss of situational awareness.



During this 24 degree bank maneuver, the pilot's head is tilted back toward the horizon at an angle of 12.5 degrees. This image indicates reflexive head tilt toward the horizon occurs with NVG.

Figure 4: NVG-HUD images indicating loss of alignment that occurs between horizon symbology and real world horizon visual reference.

Conclusions

Current design standards for NVG, HUD, HMD and head-down (HDD) symbology require pilots to make use of an instrument spatial strategy that is quite different (opposite) from the one employed when looking outside the cockpit. As a result, pilots transitioning between "inside" and "outside" during high workload conditions (such as shipboard approaches) are likely predisposed toward increased mental workloads or cognitive hazards, which may contribute toward spatial disorientation and loss of situational awareness.

Recommendations

In order to make the cockpit a more human-sensory compatible environment, and thereby improve spatial or situational awareness, the following areas of research and training are proposed:

1. *Investigate the cause and prevention of disorientation and loss of situational awareness related to sensory-display incompatibility.*
2. *Develop sensory compatible display symbology for HMDs (including NVG) systems.*
3. *Develop virtual reality (HMD-VR) or monitor training software that emphasizes cognitive hazards, such as sensory-spatial incompatibility, reversal error, task saturation, and visual problems.*

Disclaimer: The views expressed in this article are those of the authors, and do not necessarily reflect the official policy or position of the Department of the Navy, Department of Defense, nor the U.S. Government.

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Supporting Situation Awareness in Tactical Air Environments Using 3-D Auditory Displays

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The purpose of this paper is to consider the potential utility of 3-D auditory interface technology to support situation awareness (SA) in tactical aviation environments. Indeed, advances in computer and virtual environment technology over the past decade have permitted the development of 3-D auditory systems that are capable of generating effective spatial auditory cues. Moreover, numerous laboratory investigations have demonstrated the efficacy of this technology for enhancing performance and reducing workload on tasks that are relevant to tactical air environments (i.e., virtual 3-D auditory displays have been shown to enhance performance on visual target detection and identification tasks using projection and helmet-mounted displays). Yet, empirical evidence demonstrating the effect of virtual 3-D audio technology on improving pilot's SA has been extremely sparse.

In our opinion, this state of affairs is primarily due to the elusive nature of the SA construct, and not to limitations in the functional utility of virtual auditory interfaces. To be sure, some researchers have recently questioned, or in some cases denounced, the concept of SA as autological and purely descriptive. We believe, however, that the concept of SA is useful, especially for human factors researchers who are designing interfaces for tactical aircraft.

In formulating our position, we will adopt a view of SA articulated by Smith and Hancock (1995); that is, we maintain that tactical SA exists in the invariant interaction between crew members and the tactical air environment. Within this framework, tactical SA specifies what crewmembers must know to successfully resolve the challenges of tactical air environments. Accordingly, it will be important to consider (1) whether current virtual 3-D auditory technology has matured sufficiently to specify the invariant information conveyed by tactical situation awareness; and (2) how best to design virtual aural interfaces so that they transfer the critical aspects of the tactical air environment.

Accordingly, we will argue that to the extent which virtual 3-D auditory displays can be designed to convey meaningful spatial information, they will support tactical SA. Viewing SA in this way, we will propose that spatial auditory displays may be particularly useful for augmenting interfaces used for specific navigation, spatial orientation, and Instrument Flight Rules (IFR) and Instrument Meteorological Conditions (IMC) applications.

(Reprint of executive summary; formal paper not available.)

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Spatial Disorientation in U.S. Army Rotary Wing Aircraft

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Spatial Disorientation (SD) is currently a major hazard in U.S. Army Rotary Wing (RW) Operations. A study of Class A-C Aviation Accidents by the U.S. Army Safety Center (USASC) and the U.S. Army Aeromedical Research Laboratory (USAARL) noted that SD played a major role in 32% of Class A-C accidents and was responsible for 60% of Army RW aviation fatalities during the 1987 - 1992 timeframe. A follow-up study by USAARL adding 3 1/2 more years data noted that SD played a major role in 30% of Class A-C RW accidents and was responsible for 59% of aviation fatalities for the 1987 - 1995 timeframe. As a result of these studies, recommendations for controls to address this problem were developed. Efforts in education of aircrew, adoption of the British SD sortie, adaptation of simulators to include SD accident scenarios, and efforts to recommend technology controls will be presented.

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NEUROPSYCHOLOGICAL GUIDELINES FOR AIRCRAFT CONTROL STATIONS

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Introduction

Ideally, workstations used in controlling aircraft should allow the operator to process information according to the way that the human brain naturally does so. In our everyday existence, humans ordinarily process and act upon an enormous amount of information, much of it preconscious. For instance, we continuously monitor and update our present and future geographical location, local meteorological conditions, and the significance of various other external objects and events, along with our posture in space, nutritional status, and other information emanating from our bodily senses. It is arguable that, in our normal terrestrial existence, we process much more information than do even pilots of high-performance aircraft, despite the fact that the latter are task-saturated much of their time. Moreover, our natural information processing occurs at high speeds--e.g., the optical flow speeds associated with vehicular locomotion on earth are often of considerably higher velocity than that encountered by pilots in aircraft. The fundamental problem facing pilots and other aircraft operators, then, is not the amount and speed of their required information processing but rather the quality and intuitiveness of the information provided to them.

Unfortunately, it is impossible to duplicate much of the information processing that we naturally engage in as we move about on the face of the earth. For one, signals concerning the status of our motion platform (e.g., the body) are transmitted by means of interoceptive sensory systems that cannot be used to infer the status of the aircraft in flight. Second, nonvisual sensory systems (e.g., the vestibular and somatosensory ones) that provide rapid and accurate information concerning our position in space during natural movements are rendered unreliable in flight due to the existence of gravitoinertial force vectors that deviate from the direction of true gravity. Third, the full three-dimensional (3-D) extent of the natural visual world cannot be duplicated within the finite confines of the aircraft or any other portable platform housing an aircraft control display. Finally, the motor systems used in locomoting on earth (i.e., the trunk and lower limbs) cannot be as easily utilized in controlling the motion of the aircraft, thereby forcing operators to over-rely on manual-control systems that are ordinarily used in reaching, object manipulation, and other sophisticated visuomotor interactions unrelated to locomotion. Although an ideal aircraft control station should attempt to duplicate the normal terrestrial environment whenever possible, it should to an even greater extent be commensurate with the *mental models* used by different brain systems involved in carrying our everyday perceptual-motor interactions. A recent neuropsychological model of how humans interact with our 3-D spatial environment (Previc, 1998) may prove especially fruitful in this regard. This model, shown in Figure 1, proposes that four major brain systems mediate our perceptual-motor interactions in 3-D space. A dorsolateral cortical system subserves our interactions in *peripersonal* space, in which reaching and object manipulation occur. A ventrolateral cortical system is used in *focal extrapersonal* space to search for

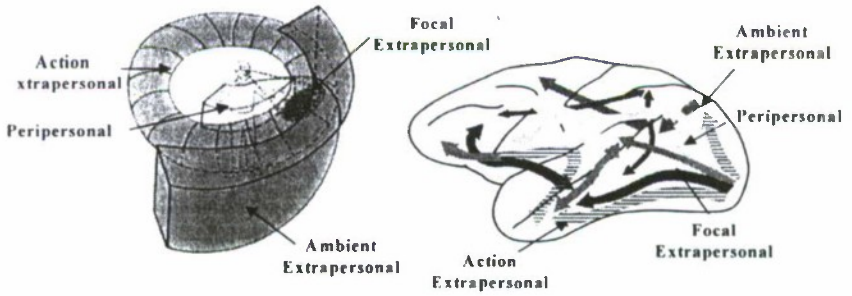

Figure 1. *The neuropsychology of 3-D space. The four behavioral realms are shown at left, while the four cortical systems corresponding to each are shown at right. From*

and recognize objects and other detailed information (e.g., alphanumeric symbology). A ventromedial cortical system is used to navigate and orient in *action extrapersonal* space, which is defined as our topographical (geographical) environment. Finally, a dorsomedial system is used to orient in and locomote about *ambient extrapersonal* space, which is defined in earth-fixed or gravitational coordinates.

As further delineated in Table 1, each of these four brain systems interacts with its own region of the 3-D world, has a unique combination of predominant sensory and motor systems, and uses a unique coordinate system for carrying out perceptual-motor interactions within that space. For example, our peripersonal system is 1) biased to the lower, proximal visual field, 2) relies on visual, vestibular, and somatosensory sensory inputs, 3) uses upper-limb movements as its major motoric instrument, and 4) has a spatial coordinate system that is centered around the upper limbs and torso. Conversely, the action extrapersonal system is 1) biased to the upper, distant visual field, 2) relies on visual and auditory sensory inputs, 3) uses primarily horizontal head movements in orienting and navigating, and 4) has its coordinate system centered around the position of gaze.

Table 1

BEHAVIORAL SYSTEMS INVOLVED IN 3-D SPATIAL INTERACTIONS

	Peripersonal	**Extrapersonal (focal)**	**Extrapersonal (action)**	**Extrapersonal (ambient)**
Function	Visual Grasping, Manipulation; Consumption	Visual Search; Object, Face Recognition	Navigation; Scene Memory; Target Orientation	Spatial Orientation; Postural Control; Locomotion
3-D Locus				
Lateral extent	Central 60 deg	Central 20-30 deg	Full 360 deg	Front 180-deg
Vertical bias	Lower Field	Upper Field	Upper Field	Lower Field
Radial extent	0 - 2 m	0.2 m - Distance	2 m - Distance	Most Distant
Primary Co-Ordinate System	Body-centered (upper-torso)	Retinotopic	Gaze- (view-) centered	Gravitational/ Earth-fixed
Sensory Systems	Visual Somatosensory/ Proprioceptive Vestibular Gustatory	Visual Proprioceptive	Visual Auditory Olfactory	Visual Somatosensory/ Proprioceptive Vestibular
Motor Systems	Arm Movements Smooth Eye Movements Head Movements Upper-Torso Motion Saccades	Saccades	Head movements (horizontal) Saccades Upper-torso Motion	Leg Movements Head (neck) movements

Before proceeding to discuss how aircraft control stations can be designed commensurate with the operations performed in each realm of 3-D space, two general points will be noted about the ecology of our 3-D world. First, one of the factors that helps to unify the four 3-D realms is the fact that all rely on vision as their primary sensory system, although the type of visual processing that predominates in each realm is not always the same (e.g., "global" motion processing is used extensively in peripersonal space, whereas sustained "local" visual processing is relied on in focal extrapersonal space). Hence, purely visual displays should be able to provide a good awareness of the position of the aircraft in relationship to its surrounding space. Second, one of the most fundamental features of the visual environment is that the ground plane slopes up and away from the observer; thus, the more proximal and distal portions of the visual world are located in the lower and upper visual fields, respectively. Not surprisingly, the preferred viewing angle for a given display becomes elevated as the distance to it increases (Hill & Kroemer, 1986), just as optical vergence and accommodation becomes more distant with increasing elevation of our eyes (Heuer & Owens, 1989). Any truly well-designed workstation--whether used for controlling aircraft or not--should embrace this cardinal feature of our 3-D environment.

The next section of this paper will illustrate how a neuropsychological understanding of how humans interact with our 3-D spatial environment can lead to specific predictions concerning the location and features of particular displays and controls.

3-D Spatial Realms: Functional Characteristics and Relevance for Aircraft-Control Stations

Peripersonal. The primary functions carried out in peripersonal space are reaching for objects and other manipulations that, at least in nonhuman primates, are closely tied to consummatory behavior. The primary sensory inputs (visual, somatosensory/proprioceptive, and vestibular) are used to align gaze and limb position with the object, while the primary motor outputs are designed either to grasp and manipulate the object using the arm and hand or to track (using head and smooth ocular movements) the arm and hand as they reach for the object and as it is manipulated (Previc, 1998). The visual specializations of our peripersonal system lie in 1) "global" motion processing, which is necessitated by the impossibility of processing the rapid and optically degraded motion usually found in this realm by "local" contour mechanisms, and 2) "coordinate" processing, which is required of the precise visuospatial distance judgments needed to reach and grasp objects. Because of the close affinity with feeding, peripersonal behaviors are also linked to homeostatic signals concerning the state of the body itself.

In tapping into the natural proclivities of our peripersonal brain system, aircraft-control stations should facilitate the use of "analogue" (trajectory- or movement-based) visuomanual mechanisms in directly interacting with visual displays. This manual behavior should occur in the normal location of peripersonal activity--namely, the mid-to-lower portion of the station and within +/-30 deg of the midline of the control station. In fact, most aircraft control-stations grossly violate this guideline by 1) requiring that the manual system be used primarily for controlling the aircraft in space (normally a task of our whole-body locomotory systems), 2) forcing manual behavior to be carried out well outside of its normal range (e.g., control panels that extend 90 degrees or more to the side of the cockpit or above the pilot), and 3) using only "digital" responses (e.g., "button-pressing") to interact with arbitrarily located switch settings whose combinations run into the thousands. The first violation can be solved by allowing aircraft control to be partly assumed by the feet (see later section), which would thereby free up at least one hand for purely visuomanual activity. The second and third violations could be dealt with by minimizing the overall number of switches and locating them in normal reaching space. One way to do this would be to use touch-screen or cursor (mouse) technologies that facilitate direct and/or "analogue" interactions with the information that is being manipulated at a particular moment. Alternatively, one could control displays by means of voluntary saccadic eye movements, voluntary head movements, or vocal commands. However, the saccadic and vocal systems are not normally used in peripersonal space, and both are subject to signal-to-noise problems in psychologically stressful (e.g., high-workload) and environmentally stressful (e.g., noisy) aircraft-control environments. By comparison, smooth head movements are naturally used in conjunction with smooth pursuit and vergence movements in peripersonal space and are being used in specific applications such as tracking of out-the-window targets using helmet-mounted displays. However, head movements are more likely to be used in certain tracking directions than others (Andre-Deshays et al., 1993), are supplemented under natural circumstances by eye movements, and can create disorientation at high G-levels (Gilson et al., 1973); hence, optimal helmet-mounted tracking systems should not rely on head-tracking alone.

Because global motion and coordinate processing are important in peripersonal visuomanual activity, they are also tied to the proximal lower visual field (Previc, 1998). Thus, another neuropsychological guideline concerning peripersonal operations would be to place many moving or coordinate-type displays (e.g., pictorial or nonverbal) related to weapons and aircraft status in the mid-to-lower portion of the control station. Integrated graphical displays have not only proven superior in many psychological studies (Bennett & Flach, 1992) but have met with good acceptance by pilots (Way et al., 1984) and are widely used in commercial products.[1] The use of transient warning cues should also be effective in this region of the control station, given the natural role of transient visual cues in peripersonal processing (Previc, 1998).

Focal Extrapersonal. The main function of focal extrapersonal operations is to search for objects and other forms and to recognize them. The focal extrapersonal system is the primary one involved in processing alphanumeric

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[1] Although many pictorial displays involve, to some extent, object-based recognition processes that are normally applied in focal-extrapersonal space, a knowledge of aircraft status itself is (like bodily physiological status) a fundamentally peripersonal activity. Another reason for placing the aircraft status displays in the lower portion of the console is that they do not have to be as continuously monitored as critical alphanumeric and global situation information that is much more advantageously presented in the upper portion of the console (see ensuing discussion).

information from control displays. Generally, its "retinotopic" coordinate system is tied to the position of the eyes in the orbit and moves with the eyes in depth. The most important sensory input by far is vision, while the main motoric instrument used by the focal extrapersonal system is saccadic eye movements.

The most critical control-station guidelines based on an understanding of focal-extrapersonal operations relates to the size and positioning of various display elements. Focal extrapersonal operations are limited to the central 30 degrees of the visual field, wherein our visual acuity is adequate to support the high-resolution "local" contour analysis required for alphanumeric processing (Previc, 1998). Even in an uncluttered visual field, targets presented more than 15 degrees away from the fixation point cannot reliably be detected without moving the eyes. In a cluttered visual field, eye movements may be required when local form information exceeds more than a few degrees in eccentricity, and head movements may occur when the target exceeds 15 degrees in eccentricity (Bahill et al., 1975). Based on visual search studies (Previc, 1996; Previc & Blume, 1993), the range of focal extrapersonal vision in most individuals is extended in the upper visual field (particularly the upper-right quadrant) and limited in the lower field (especially the lower-left quadrant) (Figure 2). The upper-field bias of the focal extrapersonal system is attributable to 1) the fact that focal-mode operations are usually carried out at a greater distance from the individual than are peripersonal operations, and 2) the need to offset the latter's lower-field attentional and oculomotor biases. Thus, a given display should not exceed 30 degrees in diameter (to avoid head movements) and individual readouts on the display panel should not exceed 10 degrees (to allow the information to be processed in a single fixation). The most critical readouts should be located above the center of the display and toward the upper portion of the control-station. Whereas transiently presented information may better simulate the natural visual cues found in peripersonal space, such a mode of presentation is less desirable in focal extrapersonal operations because high-resolution information processing is degraded when presented transiently.[2] On the other hand, color is a salient cue for the focal-extrapersonal brain pathways and should be used in depicting solid display objects; however, color is less desirable for line and character symbols (Way et al., 1984), given the poorer spatial resolution for purely chromatic stimuli as opposed to achromatic stimuli.

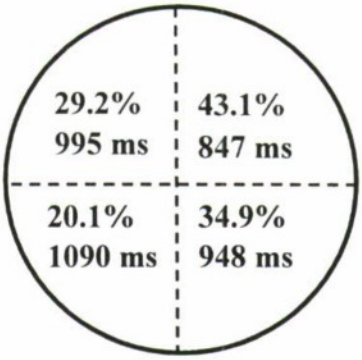

Figure 2. *Visual search performance as a function of target location in the four quadrants of the visual field. Data are expressed as percentage of trials in which an eye movement was not needed to locate the target (above) and*

Action Extrapersonal. Operations in this realm are associated with navigation and other types of orientation in topographically defined space. Although the coordinate system used in topographical space is ultimately based on the position of gaze (i.e., viewpoint), action extrapersonal operations are most closely linked to movements of the head, which generally precede changes in heading during locomotion (Grasso et al., 1996) and predominate in orienting to targets beyond 30-40 degrees in eccentricity (Barnes, 1979). The two major sensory systems used in action extrapersonal space in humans--the visual and auditory--require the integration of head position signals to define target orientation in relationship to viewpoint in topographical space. The predominant role of head movements in topographical space is consistent with the increasing use of helmet-mounted systems for localizing tactical targets.

Although topographical visual space can extend to the edges of the visual field and topographical auditory space can completely encompass the individual, our mental representation of such space is actually quite compressed, especially in its nonvisible portions (Beer, 1993). Studies of scene memory, for example, have shown that immediate memory representations are severely distorted such that a wide-angle, gaze-centered prototypical view is assumed (Figure 3). Thus, the global situation display in an aircraft that is designed to

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[2] One example of target-stabilization is the Forward Looking Infrared Imaging (FLIR) display, which helps the boresight to be placed on the target by stabilizing the latter.

present geographical, tactical, and other topographical information should probably adopt a wide-angle perspective based on how the pilot would normally view the world--from above and behind. Because our action extrapersonal system apparently moves in yaw but not pitch and roll--as evidenced by the sensitivity of parahippocampal neurons involved in topographical memory to horizontal head movements but not to pitch and roll head tilts (Taube et al., 1996)--the global situation display should ideally adopt a track-up (variable-heading) depiction that shows a stable horizon. In fact, a track-up (variable-heading) depiction seems to be most consistent with our mental models of heading changes during forward locomotion (Shepard & Hurwitz, 1984) and is generally preferred by pilots and other operators (Wickens et al., 1996).

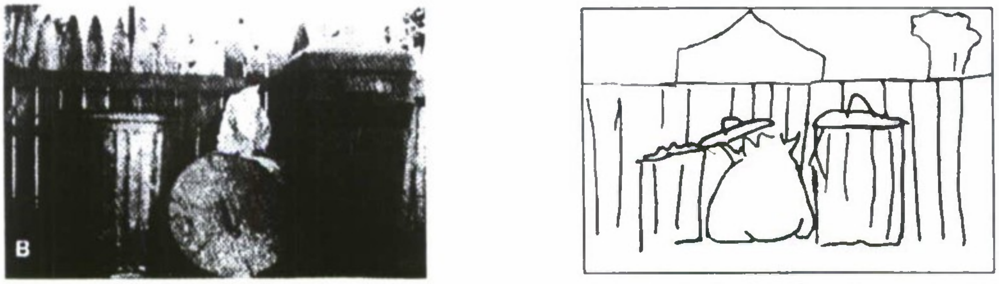

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Figure 3. *Wide-angle topographical memory representation in humans. Original illustration is shown at left; reproduced drawing from memory is shown at right. (From Intraub*

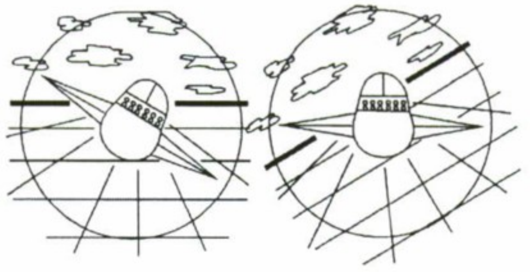
Like focal extrapersonal space, action extrapersonal space is biased toward the upper, distant portion of the visual world. One way to simulate both the wide-angle and prototypical distance of the mental representations associated with this realm is to use a planoconvex collimating (e.g., Fresnel) lens in front of the global situation display. Such a lens, when placed over a standard video monitor or diffusing screen, creates an expanded (by about 50%) and optically distant image that can easily depict a 180-degree view of the world within its boundary. In general, global situation displays should be placed at the highest point of the control-station, which in an aircraft would be near "head-level," just beneath the cockpit shroud.

Because the auditory system provides an important sensory input to the action extrapersonal neural system, the recent use of 3-D auditory cueing devices to orient to out-the-window tactical targets (McKinley et al., 1995) is commensurate with the natural role of auditory inputs in altering us to distant sources. However, 3-D auditory cueing may be of less value in a *confined* aircraft control-station, for the following reasons: 1) auditory cueing devices are much less effective inside the focal extrapersonal visual realm (e.g., less than 30 degrees of eccentricity) (Barfield et al., 1997), 2) auditory cues are no more salient than visual orientation cues (e.g., pulsing of targets) in eliciting head movements at eccentricities less than 40 deg (Goossens & Van Opstal, 1997), and 3) the spatial resolution of the auditory system (~1 degree) is about 50 times poorer than that of the visual system inside the central visual field (Perrott et al., 1987).

Finally, the action extrapersonal system provides important predictive navigational information concerning our heading in space to the rest of the brain, as illustrated by the anticipatory role of head movements during locomotion (Grasso et al., 1996); hence, it is desirable to provide predictive aircraft path information in an aircraft control display. Although the flight path marker on current head-up displays provides predictive information concerning the current trajectory of the aircraft in earth-fixed space, flight path directors are also required in topographical space for navigational purposes. The most well-known of such directors is the "highway-in-the-sky," which reportedly leads to improved situational awareness and navigational performance relative to traditional steering bars (Reising et al., 1996).

Ambient Extrapersonal. The major function performed by our ambient extrapersonal system is to spatially orient our heads and bodies within a coordinate frame defined by the gravity vector and the horizontal plane of the earth. Spatial orientational information is used for postural control (involving predominantly the lower limbs) and to perceptually stabilize the world up to roll angles of 60 degrees, which then greatly simplifies the perceptual operations carried out by the other systems (Previc, 1998). In our terrestrial environment, transient vestibular and somatosensory inputs are complemented by more sluggish visual inputs in achieving effective spatial orientation, but the two nonvisual systems are rendered unreliable in the abnormal acceleratory environment of flight by virtue of the fact that the gravitational force that they ordinarily sense is replaced by a resultant gravitoinertial force vector that can deviate quite substantially from the direction of true gravity. Hence, pilots tend to be more visually field-dependent than novices as they rely on the most critical sources of spatial orientation (attitude) information available to them--namely, the ground plane and horizon. It has been shown in numerous studies that the visual stimulus characteristics that are most critical for achieving "visual dominance" in spatial orientation are depth (distant images are more powerful) and field-of-view (generally, stimulus motion within the central 50 degrees is ineffective in achieving visual dominance) (Previc & Neel, 1995).

Although many efforts to duplicate the ambient visual realm have been made in aircraft-control workstations--ranging from peripheral visual devices to wide-field-of-view helmet-mounted displays (Previc et al., 1992)--it has heretofore proven impossible to provide the full complement of cues that allow a scene to be truly stabilized perceptually. Thus, it has been argued that the artificial horizon in attitude displays should not move in concert with the image of the actual horizon on the retina, but rather it should be perceptually stabilized like the actual horizon is in our "psychic reflection" of 3-D space (Previc & Ercoline, 1998). The stabilized horizon attitude concept--also known as the outside-in attitude indicator (Figure 4) because it assumes a view that lies directly behind the aircraft, as is consistent with the way we view ourselves in space (Parsons, 1987)--is especially desirable in controlling aircraft remotely. Regardless of which type of attitude display is selected, however, the primacy of attitude awareness in aircraft control and operations requires that it be present at all times and preferably at or near the center of the display console.



Moving-aircraft **Moving-horizon**

Figure 4. *An illustration of the "moving-aircraft ("outside-in") attitude display concept vs. the moving-horizon ("inside-out") concept. (From Johnson and Roscoe, 1972).*

Because of the tremendous demands on visual processing in the cockpit, there have been several attempts to use nonvisual sensory systems to relay attitude information to pilots. One effort has been to use auditory cues to provide primary flight information to the pilot, much as older aircraft did by virtue of changes in the amplitude and frequency of airframe noise with changes in airspeed and attitude. While partly beneficial in the absence of visual cues (Lyons et al., 1990), auditory orientation devices are hindered by the fact that ambient auditory cues do not normally contribute greatly to maintaining spatial orientation on earth (Lackner, 1977). A more recent effort has been to use tactile information to convey changes in pitch and bank attitude to the pilot (Rupert et al., 1996). While the tactile sense is one that is naturally used in spatial orientation (Table 1), the only tactile orientation vest that has heretofore been prototyped does not actually attempt to recreate the natural stimulation patterns relayed by the somatosensory system with changes in orientation relative to gravity and so may not create a truly ambient (preconscious) orientational percept.

From the standpoint of motor control, the major guideline would be to use the primary system involved in postural control and locomotion on earth--the lower limbs (feet). Although the data are not extensive, foot-control is very effective in the control of displays and is comparable to hand-control in this respect (Kroemer, 1969). Historically, the feet have been used to control aircraft yaw by means of the rudder pedals, but this is no longer necessary with fly-by-wire control systems. Advanced force-sensitive foot pedals could either be used to control actual attitude in space (as is done by skiers) or to control speed (as is done in automobiles, sewing machines, etc.). Yaw control could then be easily integrated with bank movements in a single control-stick. This would free up at least one hand at a given moment for control operations of a peripersonal nature (e.g., cursor movements on a screen).

Finally, the neuropsychological model of 3-D space also leads to predictions concerning how orientational information should be presented in helmet-mounted displays when the pilot looks away from the longitudinal axis of the aircraft. Because spatial orientation is referenced mainly to the position of the torso and legs in space (Previc, 1998), head movements relative to the body should not alter the way the body is perceived as being oriented in the pilot's mental representation. Thus, attitude information should arguably be less slaved to where the pilot is looking than to where the aircraft (and the pilot's torso) are pointed in space (see also Worringham & Beringer, 1989). Although pilots have noted that traditional aircraft-referenced inside-out attitude symbologies are more difficult to interpret when the head is moved off-axis, this may not be as true of outside-in and other displays that do not attempt to conform to the retinal projection of the outside world.

An "Ideal" Aircraft Workstation Based on Neuropsychological Principles

A depiction of an actual aircraft control-station that adheres to most of the neuropsychological guidelines put forth in the previous section is shown in Figure 5. It features a sloping console, a large global situation (topographical) display in its uppermost portion, an outside-in attitude display in its center, dedicated targeting and "God's-eye" topographical map displays just below, an aircraft status display located in the lower portion of the console, a single control-stick surrounded by panels that fall within normal reaching space, and foot pedals for at least airspeed control. This control-station could be transferred to almost any environment, with room available for additional visual displays above the console, and it could be easily built with existing technologies.

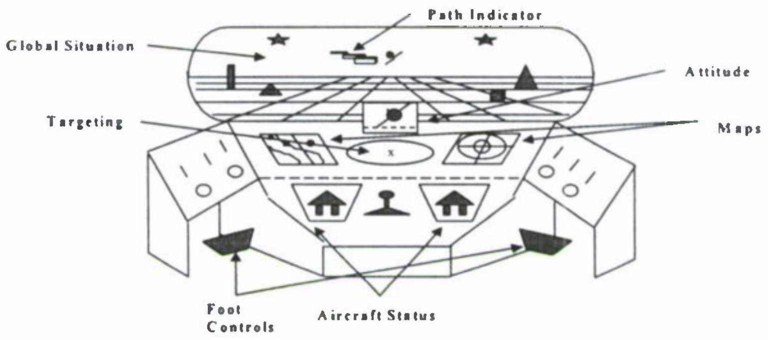


Figure 5. *An "ideal" aircraft workstation based on*

At first glance, the "neuro-spychologically compatible" cockpit shown in Figure 5 may not appear to represent a major departure from current advanced cockpit stations which already incorporate many of its key features, such as the Boeing (McDonnell-Douglas) Advanced Technology Crew Station. Nor would such a control station eliminate all of the task-saturation problems facing pilots of single-seat fighter aircraft. With minimal training, however, pilots with this cockpit console would arguably experience enhanced situational awareness, greater motoric flexibility, reduced cognitive stress, and an major overall performance edge relative to those flying with current cockpit designs. The ability to incorporate large amounts of electronic flight information into control-stations that can be managed with great ease and minimal training could also revolutionize the general aviation world, and could enable the safe and effective control of uninhabited combat aerial vehicles to be conducted from mobile platforms using "nonpilot" operators.

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The Role of Intelligent Software in Spatial Awareness Displays

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Executive Summary

The Tactile Situation Awareness System (TSAS) is a display that uses the under-utilized sensory channel of touch to provide spatial awareness information to pilots. The TSAS system accepts data from various sensors and displays this information via vibrators or tactors integrated into flight gear. Using TSAS, pilots have demonstrated improved control of aircraft during complex flight conditions. The tactile display has been shown to increase Situation Awareness (SA) and provide the opportunity to devote more time to other instruments and systems when flying in task saturated conditions. The TSAS system reduced pilot workload and thus has the potential to increase mission effectiveness.

TSAS has the capability of providing a wide variety of flight parameter information; attitude, altitude, velocity, navigation, acceleration, threat location, targets, etc. However, it was found that presenting two or more different types of information simultaneously and in close proximity makes the system non-intuitive and difficult to use. This is due in part to limitations of current tactor technology. This problem of "information overload" is also seen in visual and audio displays. The concept of intelligent software that presents the most critical piece of information when needed is under development. For example, during a night carrier launch, angle of attack is of prime concern, at cruise altitude, navigation information is important until perhaps threat or target information is required. When and how to transition from one mode to another is a current software development effort of the TSAS project. The software system allows different types of information to be displayed through automatic, rule-based mode switching.

TSAS, integrated with visual and audio display systems represents the basis for the next-generation human systems interface for the tactical aircraft of tomorrow. Mode switching software development will facilitate the eventual integration of visual, audio, and tactile displays into a synergistic spatial awareness display that will provide the right information at the right time by the right sensory channel(s).

Introduction

Spatial disorientation (SD) mishaps have occurred ever since man, who evolved in an essentially two-dimensional terrestrial environment, entered the three-dimensional aerospace environment. In our day-to-day terrestrial activities, spatial orientation is continuously maintained by accurate information from three independent, redundant, and concordant sensory systems: vision, the vestibular system or inner ear, and the somatosensory system (skin, joint, and muscle sensors). These complementary and reliable sources of information are integrated in the central nervous system to formulate the appropriate perception of orientation and motor response.

However, in aerospace environments, the vestibular and somatosensory (tactile) sensations no longer provide accurate information concerning the magnitude or direction of the gravity vector. For example, in the military aviation environment, the almost continuous changes in acceleration and direction of aircraft motion expose aircrew to a resultant gravito-inertial force that is constantly changing in magnitude and direction. Under such circumstances, somatosensory and vestibular information concerning the direction of "down" may be incorrect, and increased reliance must be placed on visual information.

As long as aviators can maintain visual reference with respect to the ground or horizon, spatial orientation does not pose a significant problem. However, in early aviation, "cloud flying" and other forms of flight in reduced visibility claimed the lives of aviators with an alarming frequency. The incidence of SD declined significantly when Sperry introduced the gyro-stabilized artificial horizon. However, SD mishaps were not eliminated completely because the gyro-stabilized artificial horizon or attitude indicator is a visual instrument and only provides orientation information when the aviator is looking at the instrument.

Today, the typical SD mishap occurs when the visual system is compromised (e.g., temporary distraction, increased workload, transitions between visual and meteorological conditions, or reduced visibility). The central nervous system must then compute spatial orientation with the remaining information, vestibular and somatosensory, at its disposal, which is frequently incorrect. In fact, it is a physiologically normal response to experience SD in such circumstances. The opportunities for SD mishaps are constantly increasing due to more frequent night operations, requirements for all weather flying, increased low-level or "nap of the earth" flight, the use of night vision goggles (which decreases peripheral vision) and improved agility of aircraft. In addition, a more demanding pilot workload produces fatigue during sustained operations. All of these factors are conducive to SD.

When aircraft mishaps are categorized by causation factors, the largest single factor is consistently pilot error. The U.S. Air Force has indicated that the most significant human-factors problem is SD. In the aviation environment, SD occurs when pilots incorrectly perceive the attitude, altitude, or motion of their aircraft relative to the earth or other significant objects. SD is a triservice aviation problem that annually costs DoD in excess of $300 million in lost aircraft. Of the 15 Navy aircraft lost to noncombatant action in the Desert Shield/Storm conflict, 7 were SD mishaps.

In an effort to provide the aviator with orientation and other mission critical information, sophisticated visual displays including Multi-Function Displays (MFDs) and Head Mounted Displays (HMDs) have been developed. MFDs and HMDs are capable of displaying large amounts of information by using different modes or "pages". Each display page contains specific information (engine, hover mode, horizontal situation or vertical situation, etc.). Switching between pages to obtain the required information is either automatic or pilot selectable. Just as in Sperry's time, these sophisticated displays provide no information when the visual system is compromised. Why is it that since Sperry there have been no further landmark developments by the human-factors engineers in introducing displays or instrumentation to solve orientation problems?

Studies by the U.S. Army (Simmons, et al. 1978a,b) indicate that pilots in instrument flight conditions spend more than 50 percent of their visual scan time attending to two instruments, the attitude indicator and the directional gyro (ADI). By presenting this information non-visually, pilots will be free to attend to other tasks and instruments that do require vision attention.

The Tactile Situation Awareness System (TSAS) is a non-visual display that uses the under-utilized sensory channel of touch to provide orientation information to pilots (Rupert et al. 1989, 1993). The approach, as shown in Figure 1, is to use a tactor locator system fitted with multiple vibrating tactors that can continuously update the pilot's awareness of position--analogous to how our brain obtains orientation information in the terrestrial environment. Thus the pilot will be able to maintain orientation in the absence of a visual horizon or during inevitable temporary gaze shifts from the aircraft instrument panel.

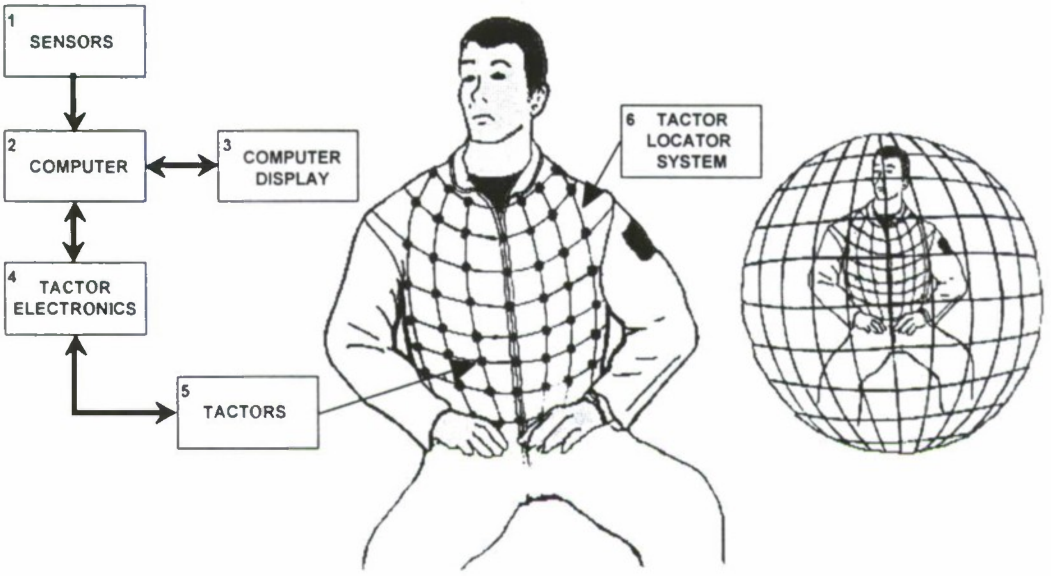

Figure 1: TSAS System Configuration

TSAS has the capability of providing a wide variety of flight parameter information, such as attitude, altitude, velocity, navigation, threat location, targets, etc. However, we have found that presenting two or more different types of information simultaneously and in close proximity makes the system non-intuitive and difficult to use. This is due in part to limitations of current tactor technology. This problem of "information overload" is also seen in visual and audio displays.

The concept of developing intelligent software that presents the most critical piece of information when needed is under development. This is similar to the "page" concept of state-of-the-art visual displays. A page presents certain specific information on the visual display (about engines, aircraft attitude, radar, etc.). For example, during a helicopter instrument take-off, pitch attitude, positive rate of climb, and heading are of prime concern, whereas at cruise altitude, navigation information is important. When and how to transition from one mode to another is a current software development effort of the TSAS project. The software system allows different types of information to be displayed through automatic, rule-based mode switching.

TSAS, integrated with HMDs and 3D audio systems, represents the basis for the next-generation human systems interface for the tactical aircraft of tomorrow. Development of mode-switching software mechanisms for the tactile display will also be applicable to advanced HMD and 3D audio displays. Such software development will facilitate the eventual integration of visual, audio, and tactile displays into a synergistic display that provides the right information at the right time by the right sensory channel(s).

TSAS Flight Demonstration Review

T-34: NAWCAD, NAS Patuxent River, MD. October 1995.

The T-34 Tactile Situation Awareness System (TSAS) flight demonstration project (Rupert et al. 1996) was originated at the NASA Johnson Space Center and the Naval Aerospace Medical Research Laboratory with funding provided by the Office of Naval Research (ONR) through the Advanced Technology Demonstration (ATD) program. The T-34 TSAS project integrated a tactile display into a T-34 aircraft (Raj et al. 1996). A 7-event test operation was conducted to demonstrate that a pilot could maintain aircraft orientation using a tactile display during flying operations. One Unites States Navy (USN) test pilot was selected to fly the flight events. Objectives of the T-34 TSAS flight demonstration program were to demonstrate:

- That a significant amount of orientation and awareness information can be intuitively provided continuously by the under-utilized sense of touch
- The use of the TSAS display to show that a pilot, with no visual cues, can effectively maintain control of the aircraft in normal and acrobatic flight conditions.

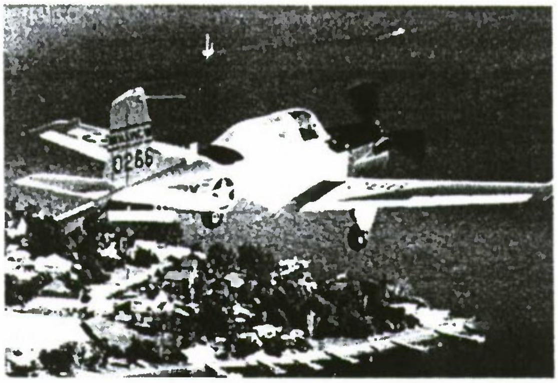

Figure 2: *TSAS equipped T-34*

The first flight of the TSAS-modified T-34 (Figure 2) was 11 October 1995, and 7 flight test events were successfully completed by 19 October 1995. Summary results showed that veridical roll and pitch tactile cues could be provided via a matrix array of vibrotactors incorporated into a Tactor Locator System (TLS). The TLS was a torso harness of cotton and fire retardant NOMEX with elastic and velcro straps that was worn underneath the flight suit. The TLS positioned the 20 electro-mechanical tactors on the torso of the body as an array that consisted of four columns of five tactors located 90 degrees apart on the front, left, back, and right of the test pilot. The test pilot in the rear seat was shrouded to block any outside visual cues and all flight instruments in the rear cockpit were removed. The test pilot flew the following maneuvers: straight and level for 5 minutes; climbing and descending turns; unusual attitude recovery; loops; aileron rolls; and ground controlled approaches (GCA). The test pilot successfully performed all maneuvers without visual cues, relying solely on tactile cues for attitude information.

For this flight demonstration, two different "tactile pages" were developed using variations of tactor stimulus selected from intensity, and location. The first tactor page was used for fine control of the aircraft, and the second program was used for acrobatic control. The first or "fine" page had a pitch and roll range of +/- 40 degrees and used only three tactors per column, and the second or "acrobatic" page had a pitch and roll range of +/- 180 degrees and used five tactors per column. Flight performance showed that it was more intuitive and easier to distinguish between a low, middle and high tactor, therefore during non-acrobatic maneuvers improved performance was noted using the fine page as compared to using the five tactor acrobatic page. Only the acrobatic control program could be used for the acrobatic maneuvers. This result indicates that the tactile display should provide information optimized for a particular flight regime, and that the test pilot could distinguish between tactor "pages."

UH-60: USAARL, FT Rucker, AL. December 1995

The UH-60 TSAS flight demonstration project was a follow-on effort to the fixed-wing T-34 TSAS flight demonstration and integrated the tactile display into an UH-60 helicopter. A 9-event test operation was conducted to demonstrate that a rotary wing pilot could receive aircraft orientation and performance information using a tactile display during flying operations. Three US Army (USA) pilots were selected to fly the flight events. Objectives of the UH-60 TSAS flight demonstration program were to demonstrate:

- That a significant amount of orientation and awareness information can be intuitively provided continuously by the under-utilized sense of touch

- The use of the TSAS display to show that a pilot, with no visual cues, can effectively maintain control of a helicopter in the complex rotary wing environment.

The first flight of the TSAS-modified UH-60 was 11 December 1995, and 9 flight test events were successfully completed by 20 December 1995. The flight demonstrations showed that controlled flight maneuvers in a rotary wing aircraft using tactile information was possible. Roll and pitch tactile cues were provided via a matrix array of vibrotactors incorporated into a torso harness as used for the T-34 effort. Additionally, airspeed and heading error tactile cues were provided by tactors located on the arms and legs, respectively. The "blindfolded" test pilot in the right seat had no visual cues. The test pilots flew the following maneuvers: straight and level; standard rate turns; unusual attitude recovery and GCA. The test pilots were able to successfully perform all maneuvers without visual cues, relying solely on tactile cues for the necessary attitude and performance information.

The auxiliary tactile cues off the torso caused some difficulties. Heading control remained problematic during the demonstration, pilots had some difficulty picking up the heading error signal when the other pitch and roll channels were active. This suggests that keeping the heading tactors off, until the pilot approached straight and level flight would improve the ability to return to a base course following unusual attitude recovery.

JSF / UH-60: NAMRL/USAARL, NAS Pensacola, September 1997

The Joint Strike Fighter (JSF) -Tactile Situation Awareness System (TSAS) flight demonstration project (Rupert and McGrath, 1998) was a short-duration technology maturation and flight demonstration program funded by the JSF Program Office. The JSF-TSAS project integrated a tactile display, F-22 cooling vest, and global positioning system/inertial navigation system (GPS/INS) technologies into an UH-60 Helicopter (Figure 3). A 10-event test operation was conducted to demonstrate the utility of this advanced human-machine interface for performing hover operations. Four test pilots were selected to fly the flight events.

***Figure 3**: TSAS equipped UH-60*

Objectives of the JSF-TSAS flight demonstration program were to demonstrate:

- The potential for TSAS technology to reduce pilot workload and enhance Situation Awareness (SA) during hover and transition to forward flight.
- The use of the TSAS display to show that pilots, with no outside visual cues, can effectively hover and transition to forward flight in a vertical lift aircraft.

The first flight of the TSAS-modified UH-60 was 09 September 1997, and 10 flight test events were successfully completed by 19 September 1997.

Summary results showed that TSAS technologies increase pilot SA and reduce pilot workload when using the tactile display, especially during simulated shipboard operations in Instrument Meteorological Conditions (IMC). Prototype hardware development showed that tactile displays could be integrated into existing flight gear (Figure 4). The test pilots successfully performed all maneuvers with degraded outside visual cues, relying on tactile cues for the necessary information. Using TSAS, pilots demonstrated improved control of aircraft during complex flight conditions. The tactile display reduced pilot workload and provided the opportunity to devote more time to other instruments and systems when flying in task saturated conditions. These effects can potentially increase mission effectiveness. One USA test pilot commented that "in IMC, the TSAS vest could be the difference between mission success and a mishap."

The awareness of aircraft velocity over the ground or "drift" without looking at a visual instrument was the biggest advantage of the JSF-TSAS. The maintenance of SA during hovering in reduced visual conditions was enhanced. Overall, TSAS decreased pilot workload and enhanced SA.

Figure 4: TSAS Experiment Pilot Showing TSAS Tactor Locator System

In conclusion, the three TSAS flight demonstrations have shown that a pilot can maintain control of an aircraft using tactile cues, and that a tactile display can reduce workload and enhance SA. However, development of the following issues is necessary:

1. The need for improved tactors. The prototype tactors used in the flight demonstrations could only be turned on and off. The amplitude, frequency, and stimulus type (vibration, stroking) could not be controlled in the prototype system. This is analogous to a black and white vs. a color visual display. A "richer" tactile sensation that could convey multiple information can be achieved with improved tactors.
2. Incorporating the absolute minimum number of tactors into existing flight gear. Today's aviator is asked to wear an ever-increasing amount of equipment. A tactile display that has a minimum number of tactors that still provides the necessary information will be lighter, more robust, and easier to maintain than a tactile display with a large number of tactors.
3. Keeping the tactile display intuitive and easy to understand.

To achieve goals 2 and 3, the concept of developing intelligent software that presents the most critical piece of information when needed is required. When and how to transition from one mode to another is a current software development effort of the TSAS project. The software system allows different types of information to be displayed through automatic, rule-based mode switching.

Intelligent Knowledge-Based Software

Intelligent knowledge-based software is a computer program that enables a computer to make a decision that is normally made by a human with special expertise. This is also termed expert system. The architecture of intelligent knowledge-based software is somewhat reminiscent of human cognitive structures and processes. The first part of human expertise is a long-term memory of facts, structures, and rules that represent expert knowledge about the domain of expertise. The analogous structure in intelligent knowledge-based software is called the knowledge base. The second part of human expertise is a method of reasoning that can use the expert knowledge to solve problems. The part of intelligent knowledge-based software that carries out the reasoning function is called the inference engine. In this analogy the inference engine mimics thinking, while knowledge is contained in the knowledge base.

A rule-based inference engines centers on the use of IF THEN statements. For example,

1. If the helicopter forward airspeed is less than 20 knots, then the helicopter is hovering.
2. If the helicopter is hovering and the helicopter pitch and roll attitude is less than 15 degrees then the tactile display should provide hovering information.

When the current problem situation satisfies or matches the IF part of a rule, the action specified by the THEN part of the rule is performed. Because intelligent knowledge-based software is dealing with fast moving data, rules offer the opportunity to examine the state of the data at each step and react appropriately. The use of rules also simplifies the job of explaining what the program did or how it reached a particular conclusion.

The architecture for the intelligent knowledge-based software under development for the TSAS project is shown in Figure 5. The software system is comprised of the following major components:

1. Input modules that provide the system with actual information on aircraft state, aircraft performance data, pilot inputs, and pilot procedures.
2. Model modules that provide theoretical information about the aircraft and pilot to the knowledge base.
3. The knowledge base interacts with the inference engine and organizes and stores all available information.
4. Rule-based inference engine which interacts with the input modules, model modules and the knowledge base and then determines the right information to be displayed in a particular situation.

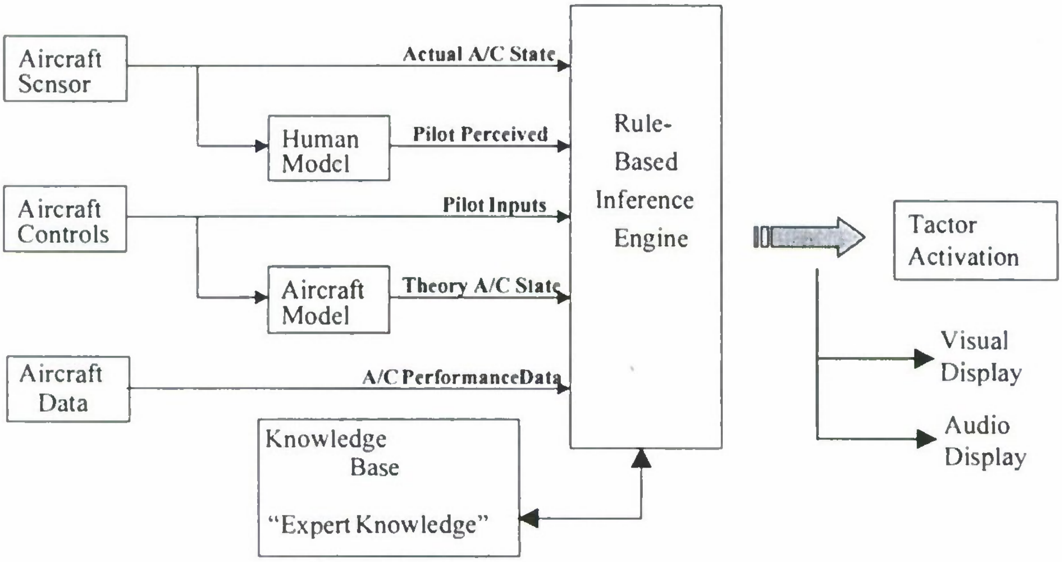

Figure 5: TSAS Intelligent Knowledge-Based Software Architecture

Aircraft Sensor Module is an *input* module to the knowledge base and provides the actual state of the aircraft (air speed, attitude, etc.) and the actual state of aircraft systems (engine temperature, rpm, etc.).

Aircraft Controls Module is an *input* module that provides the actual pilot inputs on the controls (throttle, cyclic, etc.).

Aircraft Data Module is an *input* module that provides aircraft performance data. This data are typically empirical in nature and is supplied by the aircraft manufacturer.

Human Model Module is a *predictive* module that contains a model of the perceived human orientation. The input to this model are data from the aircraft sensor module. This model uses observer theory techniques to estimate the perceived orientation of the pilot. The observer theory model of human orientation was described by Oman (1982), and subsequently enhanced by Borah et al. (1988), and Pommellet (1990). In the inference engine, data from this module, estimated pilot perception of orientation, is compared to actual pilot and aircraft orientation, and an estimate of the potential for SD is predicted. Tactor activation together with visual and auditory displays is modified when an SD situation is predicted. One possible implementation of this concept is to increase the magnitude of the tactile sensation during periods of high probability SD situations.

Aircraft Model Module is predictive model of the actual aircraft. The input to this model is data from the aircraft control module. This model uses a computer motion model of the aircraft to estimate the state of the aircraft. In the inference engine, data from this module, estimated aircraft state, is compared to actual aircraft state and an estimate of a potential aircraft sensor failure or unusual meteorological condition is predicted.

The Knowledge Base contains "expert knowledge" of aircrew procedures in different situations. For example, an instrument takeoff in a SH60 requires the following procedure (Naval Air Training and Operating Procedures Standardization - NATOPS - 13.1.1.402.c):

> At 50 KIAS, as the Automatic Flight Control System (AFCS) switches to airspeed hold, level the wings, place feet on the pedals and center the ball if required. Accelerate to 100 KIAS and establish a minimum of 500 FPM Rate of Climb (ROC). Take up a heading to account for drift.

Information like this is provided to the rule-based inference engine by the knowledge base. The knowledge base organizes and stores all available information.

The Rule-Based Inference Engine determines the right information to be displayed in a particular situation. As described earlier, the rule-based inference engine makes extensive use of IF THEN statements. When the current problem situation satisfies or matches the IF part of a rule, the action specified by the THEN part of the rule is performed.

The intelligent knowledge-based software described above controls the tactile presentation of information, and this software must be adaptive, and "smart" about which information to provide, and how, when, what, where, to provide that information.

How to provide tactile information?
The presentation of tactile information should be intuitive and easy to interpret. It should be neither annoying nor something that the pilot completely habituates to. Additionally, information concerning threats or warnings must be clearly and easily differentiated from routine information.

When to provide tactile information?
The software system must monitor a variety of flight parameters, pilot inputs, and model estimates and prioritize the information depending on the current context. Some examples of "when" to provide tactile information may include:

- continuously provide orientation information to help the pilot maintain spatial awareness
- when aircraft is in autopilot mode and during transition between autopilot and pilot control
- when there is a threat from hostile aircraft
- when the input and predictive modules indicate that the aircraft might soon be at risk or that the pilot may be experiencing SD.

What information to provide?

There is a wide range of information that can be provided via the sense of touch, however, flight demonstrations have shown that pilots using the current limited prototype display can only usefully accommodate a subset of this total. Some examples of "what" information to provide the pilot via tactile input might include:

- roll and pitch information
- helicopter or VSTOL aircraft drift information
- navigation information
- relative location of hostile aircraft
- SD episode recovery information
- instrument landing information

Where to provide tactile information?

The tactors must be located to achieve the goal of intuitive and easy to interpret tactile information. Some examples of "where" to provide information might include:

- attitude information during acrobatic and normal flight situations.

Intelligent knowledge-based software will be an essential and complex component of a tactile display system that provides critical information to the pilot in a non-visual manner.

Conclusion

TSAS technologies have shown that tactile displays can play an important role in improving situation awareness in modern military aircraft. However, to achieve a complete solution to the problem of SD and subsequent loss of situation awareness, tactile displays must be integrated with helmet-mounted displays (HMDs) and 3D audio systems. Intelligent knowledge-based software that uses mode-switching software mechanisms developed for the tactile display will facilitate the eventual integration of visual, audio, and tactile displays into a single synergistic spatial awareness display. The switching software must be adaptive, and "smart" about which information to provide, and how, when, what, where, to provide that information. The spatial awareness display will provide the right combination of information at the right time by the right sensory channel(s).

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Right information at the right time by the right display.

Controlled Flight into Terrain Hazards Associated with Army Rotary Wing Aircraft

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Background. This study was initiated to provide information on Army accidents to help with a decision to pursue installation of Ground Proximity Warning Systems (GPWS) on Army rotary wing aircraft. The GWPS was touted to be an effective technology to reduce incidence of Controlled Flight into Terrain (CFIT).

Vision. In keeping with the focus of the Army Safety Program, this study sought to support the Army chain of command with risk management information. Specifically, this study was to provide; (1) a list of hazards, (2) the cost associated with accidents caused by these hazards, and (3) the projected impact that GPWS could provide given previous accidents. It is expected that the Army will base an acquisition decision on the safety risk reduction that a given technology provides weighed against cost and availability. Thus, this study provides a framework to compare GPWS with the potential effectivess of other technologies.

Methodology. Several challenges needed to be overcome during this study. The first challenge was the lack of an official DoD definition for CFIT. The other challenges were that the ASMIS neither categorized CFIT accidents nor readily identify hazards associated with accidents. With an assumed definition for CFIT, the ASMIS was queried for accident profiles that fit the CFIT definition. Digital data concerning these accidents were reviewed and a list of hazards was developed and continuously improved during the review process. The list of hazards was developed using the US Army Safety Center (USASC) model for hazard identification.

Results. Out of 249 class A & B accidents from FY88 through FY97 were examined, 137 (55%) were determined to be CFIT accidents. From these accidents, 15 hazards were identified among 3 families: (1) loss of visual cues, (2) crew workload/task saturation, (3) other maneuvering profiles.

Conclusions. A high payoff for the Army would be to develop short term (operational user and commander), medium term (doctrine, training, standards, and combat developer), and long term (materiel developer) solutions to reduce accidents related to hazards in the following two areas. First, loss of visual cues resulting in hover drift specifically for the AH-64A and the OH-58D aircraft. Second, workload and loss of visual cues hazards where, generally, the aircrew's ability to judge obstacle clearance or other altitude requirements during low level flight, and specifically, for the AH-64A, UH-1 (all) and OH-58A/C. These two areas made up 20% of all aviation Class A and B accidents from FY93 through FY97.

Recommendations. Based on the conclusion of this study, the following are submitted as recommendations: (1) the USASC begin work to articulate the risks associated with the hazards identified in this study, (2) the USASC oversee the risk management of these hazards throughout the Army using the Chief of Staff Army (CSA) Safety IPR as a medium to begin the process, (3) the Director of Army Safety propose objectives for reductions in specific hazards to the CSA to implementing a performance based safety program, (4) the USASC develop a methodology to articulate future CFIT accidents as an expected loss rate given exposure of known hazards and currently existing controls, (5) the USASC apply the methodology used in this study to develop hazards associated with other aviation accidents (e.g., multiple aircraft accidents/midair collisions, materiel failures, etc) and begin to apply the same methodology to a family of ground systems.

(Reprint of executive summary; formal paper not available.)

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Validated
Performance Measures/Measurement Techniques

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Practical Considerations for Measuring Situational Awareness

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I. Issues/Rationale for Development of an In-Flight SA Scale

Situational Awareness (SA) subjective metrics that are commonly available are in many cases too intrusive to use during flight test. The China Lake Situational Awareness (CLSA) features a method to gather Situational Awareness data during flight test on a pass by pass basis to permit execution of multiple test events per flight. Pilot kneeboard cards and voice annotated Head Up Display (HUD) tapes are used to gather pilot subjective SA ratings in the cockpit as flight test/demonstration profiles are flown. CLSA is administered similar to the Bedford Workload Scale developed by DRA Farnborough. The Bedford Scale (Figure 1) is used as a Workload measure in flight since it is unidimensional and has a clearly defined set of criteria for ratings.

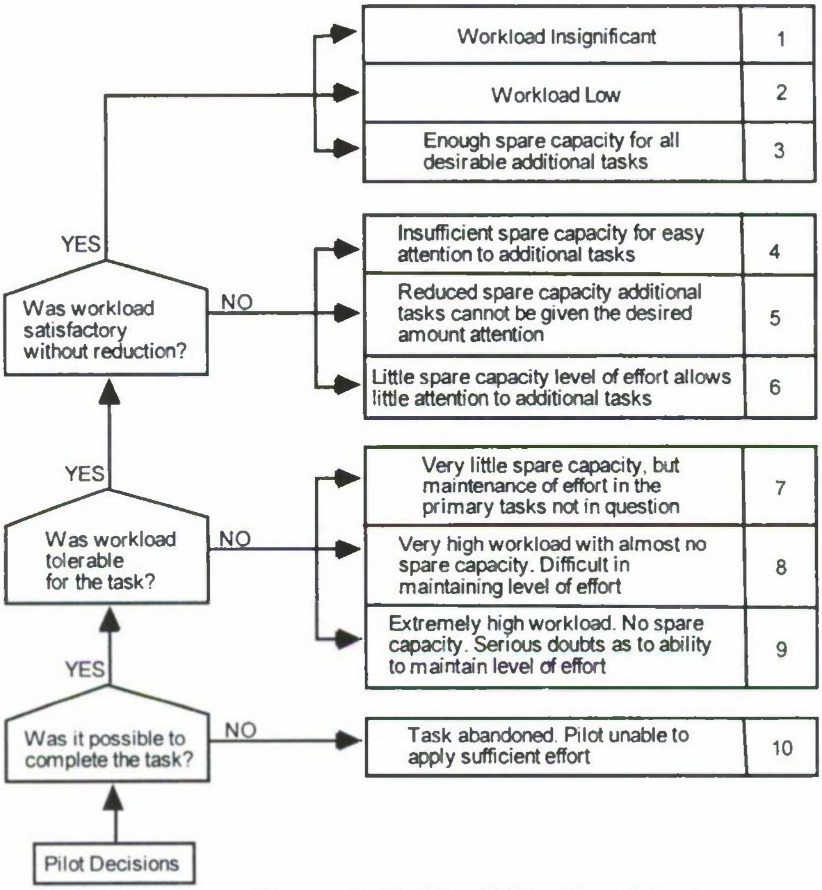

Figure 1. Bedford Workload Scale.

Similarly, CLSA (Figure 2) uses a five point, "Bedford-like" SA scale that was abstracted from the Situational Awareness Global Assessment Technique (SAGAT) model of 1) environmental status and trends, 2) mission status and trends, and 3) awareness of what will happen if present status/trends continue (and needed interventions are made or omitted). However, SAGAT is objective and is simulator based, whereas CLSA is subjective and is intended for flight test. Other flight test/demonstration resources to be used in the protocol for SA measurement with CLSA include the

Bedford Scale itself, trainer aircraft if available (for the two-seat architecture), a safety pilot (if available), cockpit cameras, real time data downlinking, hot mic, VHS flight tapes, and extensive debriefs/questionnaires.

SA SCALE VALUE	CONTENT
VERY GOOD 1	• FULL KNOWLEDGE OF A/C ENERGY STATE/TACTICAL ENVIRONMENT/MISSION; • FULL ABILITY TO ANTICIPATE/ACCOMMODATE TRENDS
GOOD 2	• FULL KNOWLEDGE OF A/C ENERGY STATE/TACTICAL ENVIRONMENT/MISSION; • PARTIAL ABILITY TO ANTICIPATE/ACCOMMODATE TRENDS; • NO TASK SHEDDING
ADEQUATE 3	• FULL KNOWLEDGE OF A/C ENERGY STATE/TACTICAL ENVIRONMENT/MISSION; • SATURATED ABILITY TO ANTICIPATE/ACCOMMODATE TRENDS; • SOME SHEDDING OF MINOR TASKS
POOR 4	• FAIR KNOWLEDGE OF A/C ENERGY STATE/TACTICAL ENVIRONMENT/MISSION; • SATURATED ABILITY TO ANTICIPATE/ACCOMMODATE TRENDS; • SHEDDING OF ALL MINOR TASKS AS WELL AS MANY NOT ESSENTIAL TO FLIGHT SAFETY/MISSION EFFECTIVENESS
VERY POOR 5	• MINIMAL KNOWLEDGE OF A/C ENERGY STATE/TACTICAL ENVIRONMENT/MISSION; • OVERSATURATED ABILITY TO ANTICIPATE/ACCOMMODATE TRENDS; • SHEDDING OF ALL TASKS NOT ABSOLUTELY ESSENTIAL TO FLIGHT SAFETY/MISSION EFFECTIVENESS

Figure 2. China Lake Situational Awareness (CLSA) Scale.

An aggressive flight test/demonstration schedule does not often permit the use of workload metrics like NASA Task Loading Index (NASA TLX) or Subjective Workload Assessment Technique (SWAT) or situational awareness metrics like Situational Awareness Rating Technique (SART). Time in the cockpit (as well as flight test hours) is in short supply: Workload/SA ratings must be given quickly and in a manner that does not intrusively affect what is already a potentially Workload-intensive and SA-starved environment for the test pilot. Yet adequate sensitivity, diagnosticity, and construct validity must be maintained. CLSA is intended to satisfy these needs.

II. Strengths and Limitations of CLSA

The CLSA was developed for use only in the circumscribed environment of flight test, with the adjunct measures of the other resources (Bedford Scale, HUD cameras, hot mic, etc.) to provide de facto methodological coverage where the CLSA has not yet been formally validated.

A. Strengths

- High face validity. When queried, pilots generally indicate that CLSA jibes with "common sense" and the way they are trained.
- Clear criteria. The criteria for the ordinal scale values in CLSA are clear and concise.
- Easily understood. The intent and rationale for the scale are easily comprehended, and the criteria are easily used.
- Easily incorporated into deck of flight cards. CLSA fits onto one flight card for hot mic ratings or can be placed on a small number of cards in case written ratings are desired.
- Unidimensional rating scale. The CLSA format and protocol are based on the Bedford Workload Scale.
- Quick turnaround of data. Data are gathered quickly and unobtrusively, and can be gathered pass by pass.
- Economical and efficient. Flight test dollars and hours are conserved.
- Easily used during debrief. HUD tapes with ratings on hot mic can be used to examine flight test events in a structured and detailed manner.
- Assumes same model as SAGAT. SAGAT has been extensively evaluated, though in the simulator environment.
- Pilots are Subject Matter Experts (SMEs). The test pilot is not only a trained combat aviator with thousands of flight hours; he is also a trained test engineer. He is the closest thing available to a calibrated human observer in the cockpit. He and only he gives the CLSA ratings. By extension, a subjective rating given by a pilot becomes as legitimate a flight test metric as any other employed in the test plan.

B. Limitations

- Adaptation of simulator-based model. SAGAT has been extensively evaluated, but is a simulator-based metric with a "pause and query" protocol. The CLSA protocol does not call for pause since it is used during actual flight. Instead, CLSA relies on use of HUD tapes with ratings on hot mic for use during debrief. Validation of this approach is required.
- Subjective metric. Ideally, pilots should be briefed on any subjective metric scale, so that, as trained SMEs, they give ratings based on a clearly defined set of criteria. But, CLSA is still a subjective metric. It is not based solely on objectively observed events.
- Unidimensional scale. All the statistical evidence is on one scale as opposed to several subscales; SART and NASA TLX are both multidimensional.
- Small sample sizes during flight test. Pilots are SMEs giving "expert" CLSA ratings during flight test; but there is a limit to the number of trained fighter/test pilots. Research is necessarily done with small sample sizes and restricted opportunities of flight test/flight hours.
- Norming. All subjective rating scales, including CLSA, should be held to the same criteria as any other psychometric scales. This means that validity and reliability must be properly established, and that the scale should be properly normed against its intended subject population. The intended subject population is trained test pilots; the sample size is bound to be small compared to the sample sizes usually used for norming scales.
- Limited universe of discourse. At this juncture, CLSA is only intended for use in flight test and its generalizability to other areas is circumscribed. It should not be assumed to be valid when employed in simulator work or for use in the real world until further studies are performed.

- Intrinsic limitations of SA metrics. First, any SA data that were gathered successfully were obtained from the pilot. Therefore, he was in a benign SA environment. Total loss of SA can mean loss of the aircraft or the pilot, as in a Controlled Flight into Terrain (CFIT) event. Unless a safety pilot is available so that the pilot can safely encounter extremely low SA, then SA ratings are limited to a benign range. Second, any metric is used in an artificial situation like flight test or a simulator; not real life/field conditions. This is additionally limited by mapping simulator data to the real world: very few actual fatalities have occurred in a dome.

III. Data Requirements/Thresholds for CLSA

Data are on an ordinal scale and must be treated accordingly when statistical analysis is applied. No interval or ratio scale properties may be inferred. Nonparametric statistics would be the most appropriate analysis method. Nonparametric frequency tests such as Chi-Square or Kolmogorov-Smirnov should be used when checking similarity or difference to another scale.

IV. Norming/Validation Concerns for CLSA

- CLSA has already been used with success in the Integrated Helmet and Audio-Visual System (IHAVS) flight demonstration; it was developed for the demonstration to permit execution of multiple test events per flight.

- Comparison of CLSA with accepted SA scales (Tables 1 and 2, Figure 3):

    1. The Situational Awareness Supervisory Rating Form (SASRF) was developed for use in measuring the SA capabilities of F-15 pilots. Thirty-one items rate pilot traits and tactical capabilities. Its format and protocol are unsuitable for pass-by-pass SA measurement.

    2. Crew Situational Awareness (CSA) measures the SA of flight crews in terms of performance and coordination. It is crew-based rather than based on the individual pilot, and has a protocol that is unsuitable for pass-by-pass SA measurement.

    3. Situational Awareness Global Assessment Technique (SAGAT) has a useable model but is simulator based and has a protocol unsuitable for pass-by-pass SA measurement.

    4. Situational Awareness Response Technique (SART) has a good model, but its format and protocol are unsuitable for pass-by-pass SA measurement.

Component	SASRF	CSA	SAGAT	CLSA	SART
Internal State			√		√
External State	√	√	√	√	√
Relationship of System to Environment	√	√	√	√	
Environment	√	√	√	√	

Table 1. Ability to measure SA components.

Level	SASRF	CSA	SAGAT	CLSA	SART
Perceive Environment				√	√
Comprehend Current Situation	√	√	√	√	√
Project Future Status			√	√	

Table 2. Ability to measure SA levels.

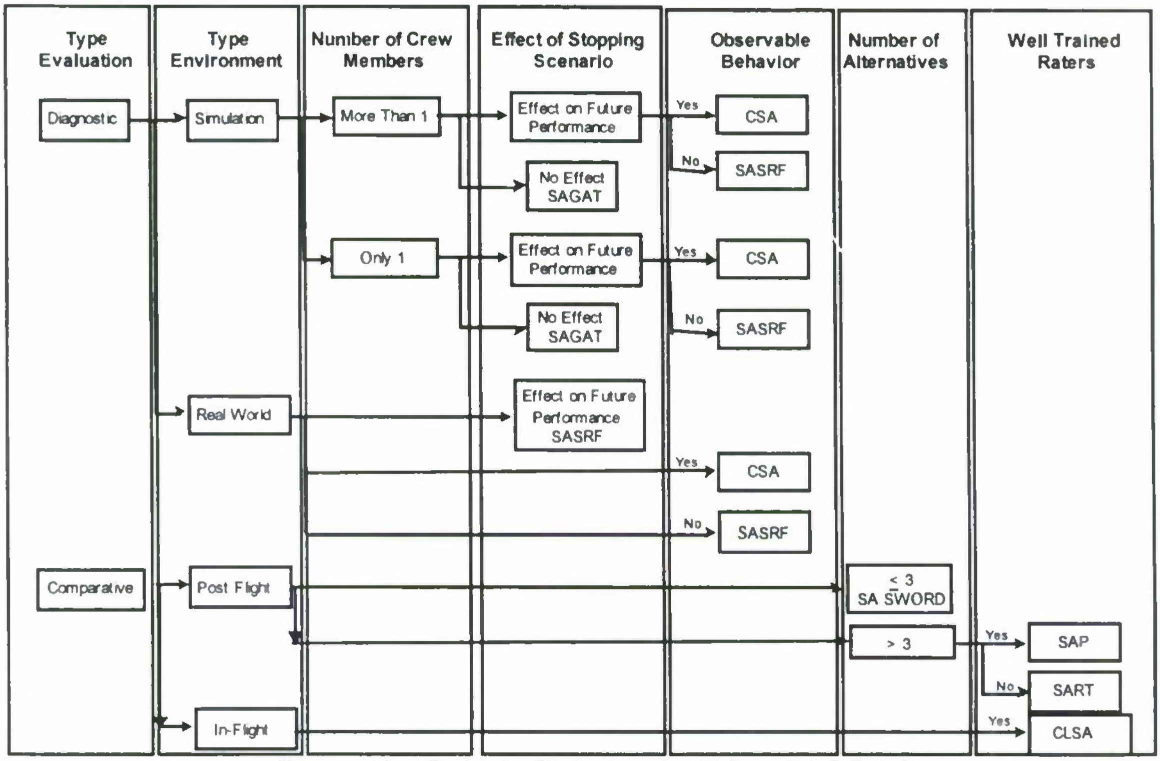

Figure 3. CLSA in Relation to Other SA Metrics.

- Situational Awareness has many competing conceptual and operational definitions, as does workload. Ultimately, SA has to depend on the operational definition. For instance, NASA TLX and 3D SART share the same dimensions. It can be inferred that, since these scales are intended for use in similar situations, that they have similar forms though different functions. In addition, SASRF has a different format and, not surprisingly, also has a different use, function, and theoretical basis. Not all SA metrics are alike, and they are not interchangeable, any more than are all Workload metrics.

- Confounding variables like motivation or arousal may cause differences in subjective scale ratings. Arousal could affect ratings: overstimulation or understimulation can influence efficiency of processing and the degree to which the situation is observed to be pleasant or aversive to the subject. Motivation could affect results in that the task could be perceived by the pilot as irrelevant, a waste of time, or arduous because he is not getting enough of the right information at the time. The pilot could be highly motivated and yet simply be overloaded or unable to secure the right information in a timely manner for the task, and rate the situation accordingly.

- Evaluation of CLSA as an adequate SA model: (Table 3).

Table 3. Satisfaction of SA Model Requirements by CLSA.

Requirement	Satisfaction				Content of Item
	OK	In Work	TBD	N/A	
Psychometrics					
• Accuracy		√			Is output precise?
• Objectivity		√			Does model change as data changes?
• Reliability	√				Are there consistent outputs for inputs?

• Sensitivity	√				Output calculated at least 5X input rate?
• Validity		√			Face/concurrent/content/ construct/ operational validity OK?
Utility					
• Acceptability	√				Acceptable for users?
• Detail	√				Usable with individuals/ teams/crews/separate groups?
• Diagnostic		√			Determine causes of good/bad SA?
• Flexible	√				Model can be easily changed in future?
• Inexpensive	√				Model inexpensive to use?
• Provide Quantitative Output	√				Quantitative output?
• Simplicity	√				Simple to administer, understand, and interpret?
Human Characteristics					
• Attention	√				Any limitations to attention from any source?
• Perception	√				Any limitations for characteristics of perception?
• Memory	√				Limitations to working memory?
• Automaticity	√				Limitations to automaticity/ accommodation of change?
• Goal-Driven or Data-Driven Processing			√		Does model discriminate between goal-driven and data-driven processing?
• Individual Differences			√		Does individual processing/ coping make a difference?
System Characteristics					
• System Design	√				Does the system provide everything operator needs when needed?
• Stress and Workload	√				Are stress and workload limitations to model?
• Complexity	√				Is model complexity a limiting factor?
• Automation				√	Is degree of system automation a limiting factor?

Table 3. Satisfaction of SA Model Requirements by CLSA. (Continued)

V. Future Efforts

During CLSA development, this researcher was forced to delay some of the methodological steps needed to validate CLSA as a subjective rating scale in order to fit it into the IHAVS flight test regime. The functions performed by these methodological steps were taken up by reliance on structured debriefing techniques/expanded protocols: in particular, structured interviews, HMD videotapes, hot mic, and detailed questionnaires were used to address the functions of Accuracy, Objectivity, Diagnosticity, Goal/Data Driven Processing, Individual Differences, and

Automation. Therefore, the delayed Concurrent (e.g., alternative measure) and Construct (e.g., internal state measures) Validities shall be addressed by proposed experiments.

These proposed experiments will employ an existing SA measure (3D-SART) and a neuropsychological test (NASA Spaceflight Cognitive Assessment Tool (S-CAT)) concurrently with CLSA in statistical validation studies.

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Terrain Navigation Training for Helicopter Pilots Using a Virtual Environment

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INTRODUCTION

To date, virtual environments applied to aviation training have been created under the assumption that flying is flying and that tools to train pilots are basically independent of the type of aircraft in question. This is in fact not the case at all. Most of the training tools that have been developed over the years for the fixed wing community are fundamentally inappropriate for the rotary wing community. Systems such as TOPSCENE [1], which has been widely regarded as an excellent mission rehearsal system for fixed wing pilots, is seldom even used by rotary wing pilots because it does not represent the information helicopter pilots need in the form that they will see it. High and fast is different from low and slow. These differences must be accounted for in training systems for helicopter pilots by providing tools *specifically* designed for their needs and missions.

Navigation is an essential component of all helicopter missions. While most training time is spent on mission-specific items and procedures, all goes for naught if the pilot cannot find the target. Surprisingly, navigation does not receive much attention at all in the training curriculum. At Helicopter Antisubmarine Squadron Ten (HS-10), the SH-60F and HH-60H Fleet Replacement Squadron (FRS), three days of the 160 day curriculum are spent on Combat Search and Rescue (CSAR) ground school, a part of which is MITAC (Map Interpretation and Terrain Association Course). Of course, with such little emphasis spent on map reading and navigation, pilots tend to struggle with the two flights they must make to demonstrate mastery of these skills. A lot of time is spent in the air circling checkpoints, recovering from errors, and generally showing student pilots that flying over Southern California is very different from flying over Pensacola, Florida, where they conduct initial terrain navigation training.

Background

Historically, CSAR ground school was a two week long school and MITAC training received much greater emphasis. However, even then, training techniques were less than optimal, and in some cases, counterproductive. Many of the pilots in the fleet today received MITAC training from a videotape filmed from a Huey UH-1 and played back at about double speed. The task was to watch the video and chart progress with a grease pencil on a laminated contour map. This type of training has a number of shortcomings. With the limited field of view available on a videotape, pilots do not learn how to use peripheral vision to maintain orientation. At accelerated speeds, pilots learn that the only way to maintain position on the map is to pick out landmarks (peaks or other terrain features) at great distances. This causes them to stop paying attention to what is right in front of the aircraft. There is also a complete lack of interaction in the video. If a mistake is made, there is no way for the student to go back and determine what caused it. This is a fundamental part of learning.

What has resulted is a situation where navigation skills today are almost entirely learned in the aircraft. Considering the maintenance costs of a typical military helicopter, this is an expensive way to learn. Even if it wasn't so expensive, there is another problem. Flight instructors at HS-10 are restricted as to what routes they can fly. They are not free to make up new routes at will. Consequently, once a student pilot has flown a route, all map and terrain interpretation stops. It then becomes a memory or landmark recognition task of "How did I do this last time?" rather than map reading. The ability to fly unique routes would greatly enhance the flight instructor's ability to teach this skill. Even if alternate routes were available, flight instructors would not be able to evaluate student's navigation ability over terrain types other than Southern California and Arizona. How well can they navigate over the desert? How well can they navigate over relatively featureless terrain? Navigation training in the air is not only excessively expensive, but also limited in effectiveness.

Helicopters are flown by two pilots -- one maintains control of the aircraft and is responsible for avoiding hazards (e.g. power lines and vegetation) and for verbally identifying features for the navigator who is responsible for charting the current position and for guiding the flying pilot. This is typically done with verbal commands. The important factor here is that the navigating pilot is not doing the flying. These pilots already know how to fly. Our objective is not to teach flying but to teach navigation skills. Therefore, if a single pilot is to learn how to navigate, the interface to the training system must have no learning curve associated with it. It should be as near to "walk up and use" as possible.

Requirements

In summary, what HS-10 needs is a way to allow student pilots to fly unique routes over real (or topologically similar) terrain while reading a contour map. They must be able to review their flights to get appropriate feedback as to where mistakes were made. They should not be left in a disoriented condition for prolonged periods of time. This causes frustration, diminished self confidence, and is otherwise not helpful to the training process. Ideally, much of this can and should be done outside of instructor view. Students who are not adept at navigation skills know it. If they had a way to develop and hone their skills before a graded flight, they would certainly do so. However, no such mechanism currently exists other than extra map study. The interface to this system must be simple to use. It doesn't need to be like real flying since the navigator doesn't do the flying anyway. This training capability must be made available at the squadron level. If an expensive large-scale solution were to be developed, it would not be used due to a lack of availability by individual pilots on an as-needed basis.

APPROACH

There are a number of practical constraints, in addition to those defined by the needs of HS-10, to constructing, evaluating, and eventually fielding a trainer of this type. Since the system must be available on an as-needed basis at the squadron level, it must therefore be relatively inexpensive and easy to maintain. HS-10 does not have the manpower nor the financial resources to accommodate another large expensive training system in addition to the full motion flight simulators they already maintain. We envisioned a small system that could occupy a corner in a classroom or ready room. This would allow for asynchronous training to occur – the student can use the system without instructor intervention.

Ideally, the system would be implemented on general purpose hardware. This would make it easier to maintain and develop further. The current implementation almost achieves this goal. It is small and transportable but uses specialized graphics hardware. We felt that this was a reasonable compromise at this time since PC graphics hardware is improving at such a rapid pace. We believe that in the time it takes us to determine what the system has to look like and we evaluate that it is effective, the time will be right to port the system to a graphics PC. This work is in its early stages at this time.

After determining what the general training need was at HS-10, we developed a rough implementation and brought it to HS-10 for their feedback. We learned that they specifically did not want a mission rehearsal system like TOPSCENE but rather needed something to help students learn to read contour maps. As we worked on the second iteration, we used students at the Naval Postgraduate School and specifically the Aviation Safety School in several usability tests to work out the details of the interface. At this point, the system was brought to HS-10 to begin data collection on the actual training effectiveness experiment.

IMPLEMENTATION

The prototype navigation trainer was implemented on an Indigo2™ graphics workstation from Silicon Graphics, Inc. (SGI). The system contains a single R4400 200 MHz CPU with 128 Mbytes of RAM, a High Impact™ graphics board, and IMPACT™ Channel Option Board to allow the use of multiple graphics monitors from a single machine. The display setup uses three 19" monitors in a semicircular configuration. The three monitors provide about 95° field of view when sitting 27" from the screens. The control device is a Flybox™ from BG Systems, Inc. Figure 1 shows the basic configuration of the system. The fourth monitor shown is used as a console and is not used as a display during training.

Figure 1. The apparatus for the prototype helicopter navigation trainer.

Software

The software was developed entirely at the Naval Postgraduate School using the Performer™ application programmers interface (API) from SGI. At its heart is a simple terrain fly through program augmented with the necessary maps and gauges required for this application. The flight control was designed to be as simple as possible. We use a terrain following technique such that the pilot sets a course (bearing), altitude above ground level (AGL), and ground speed in knots. There is a minimum altitude of 50' AGL so that crashing into the ground is impossible. There is no maximum altitude. The pilot can then look at the map or attend elsewhere as the virtual helicopter flies itself. There are absolutely no aerodynamics applied to the flight model. This is not what we are training.

The display is divided into three VGA resolution screens, one for each monitor. However, there is a 7° gap between each of the monitors for the plastic casing. We account for this by leaving a 7° gap in the graphics rendering. Consequently, as a pixel leaves one monitor, it does not instantly jump the gap to the next. These gaps are analogous to the aircraft's vertical windscreen support frames. Figure 2 shows a typical three screen view with gaps between screens.

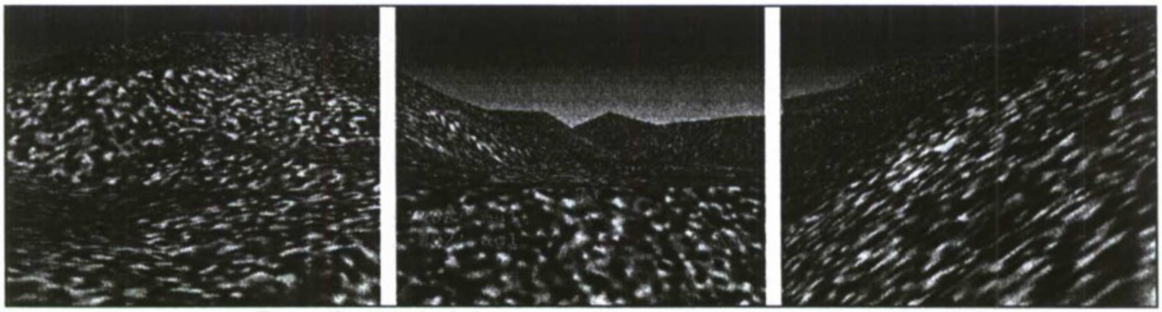


Figure 2. A typical three screen view with gaps between monitors.

Interface

The interface was designed to be easy to learn and consistent with the task of moving a viewpoint through the terrain as practice for contour map interpretation and visualization. However, there is one basic problem: Flying is generally a two-handed task. Map reading and interpretation is at a minimum a one-handed task under the best of conditions. In the aircraft, a pilot would never attempt both tasks simultaneously. For training, our contention is that interactive control is important [2]. We did not want pilots to feel like passive passengers but rather active participants. Therefore the interface needed to support completing both tasks simultaneously. It was important to design an interface that could be operated as easily by a single pilot as by a pair of pilots.

Although we had a wealth of specific domain knowledge actively involved in this project, we decided to bring the problem and our ideas to HS-10 and the helicopter pilot community at large to find out if we were on the mark. When helicopter pilots were presented with stick and throttle type controls, they were nearly split on which device should control each axis of movement. The transformation of stick and throttle to cyclic and collective is ambiguous. A narrow majority believed the throttle should act as a collective. When the stick is pulled back toward the user, the model should respond as a helicopter would if the collective were raised. A slight minority believed the throttle should act as a fixed wing throttle, i.e. it should control forward speed. Clearly, the results of our flight control usability study suggested our goal of building a system that was easy to use for everyone was not entirely achievable. After looking at our target user group, we still did not have a definitive answer to the question of control mechanism. We decided to look not only at the user group at large but also at the user group executing the training task at HS-10. This study brought out an issue we had not considered. If students rely on dead reckoning (DR) techniques, maintaining a constant ground speed should require little or no cognitive workload. However, if the speed is set by the cyclic, maintaining a constant ground speed requires excessive cognitive workload. The final compromise was to adopt a fixed wing mode where cyclic controls climb and yaw while throttle controls speed. There are no flight dynamic characteristics associated with the helicopter model motion. However, it was decided that extraordinary motion seemed like a good way to compensate for inherent limitations of training media. Since we can't provide the same horizontal and vertical field of view of the real aircraft and are restricted with limited model fidelity, we can attempt to make up for such shortcomings by allowing users to do things only possible in a virtual world -- specifically flying backwards and the ability to detach the viewpoint from the helicopter.

The Exocentric View

While navigating, we typically only have an egocentric view available to us. This is our individual view from where we currently are looking through our own eyes. Previous research suggests that an exocentric view is a useful mechanism for acquiring information about a large-scale space [3, 4]. An exocentric view is one where the view is detached from the position of the egocentric view but is not necessarily perspective-less (infinitely far away and directly above) as would be the case in a conventional map. This view can be useful for navigation because it shows the local context around the viewpoint without losing perspective.

We originally considered using a "wingman" camera position tethered to the virtual helicopter. This was discarded because it fundamentally changed the navigation task. It is important that movement take place in the egocentric view only. The exocentric view was meant to provide help when needed but we feared it would become a crutch which, when taken away for the actual flight, would actually serve to lower performance rather than raise it. We also considered a separate window for the wingman view but also discarded it for similar reasons. If an exocentric view was to be used, it was essential that the transformation from it to the egocentric view be completely obvious.

We finally decided to integrate the exocentric and egocentric views. To minimize problems of disorientation associated with teleportation (e.g., a discontinuous transition), we decided on a fluid transition from the egocentric to the exocentric perspective. It is necessary that the user remain oriented throughout a training session. We developed a metaphor whereby the user detaches the camera from the model and controls the viewpoint with the flight stick. Holding the cyclic trigger switch while pulling back on the stick detaches the camera from the helicopter and moves it up a shallow 10° slope away from the helicopter. The viewpoint's speed of movement away from the helicopter is proportional to the stick displacement and distance squared from the helicopter. The viewpoint can be rotated about the helicopter by pushing the flight stick either left or right. When the trigger switch is released, the viewpoint reverses the path the user controlled and returns to the egocentric view. The animated motion is fluid and continuous. Figures 3 and 4 show exocentric views at two points along the glide slope. In Figure 3, the viewpoint has just been detached. The virtual helicopter model has been highlighted in this image. In Figure 4, the user has pulled further away such that the helicopter model has been replaced by its symbol. This has also been highlighted.

Figure 3. An exocentric view shortly after the view was detached.

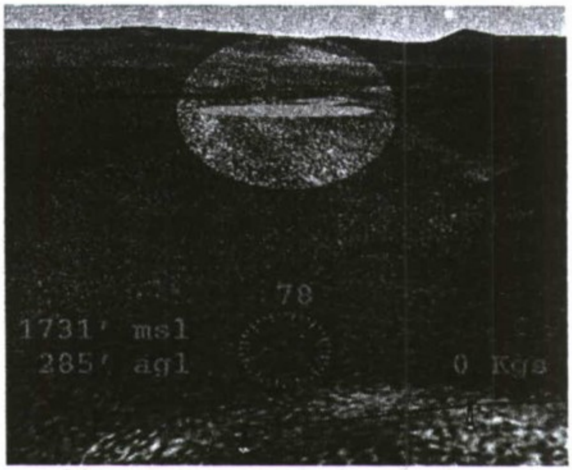


Figure 4. An exocentric view after the user has backed away from the helicopter position.

The Heads-Up-Display

The Heads-Up-Display (HUD) used is extremely simple. Again, we did not make any attempt to replicate the actual cockpit displays. We determined the essential flight parameters of interest to the terrain navigator and provided only that information: Mean Sea Level (MSL) altitude in feet, Above Ground Level (AGL) altitude in feet, true heading in degrees, and ground speed in knots. Figure 5 shows an enlarged image of the HUD from Figure 4. The display is red over mostly brown and green terrain and is therefore easier to read than might be suggested here in grayscale. In this example, the heading is 78°, the ground speed is 0 knots, and the altitude is 1731' above sea level or 285' above the ground at this point.

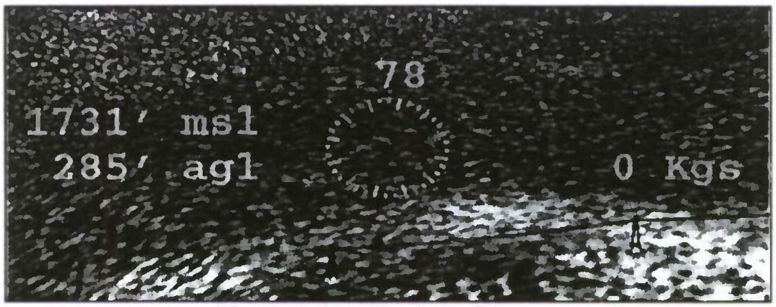


Figure 5. The Head-Up-Display.

The You-Are-Here Map

It is essential that the student pilot not be lost for any extended duration during a training session. If the pilot becomes disoriented, pressing the spacebar calls up a You are Here (YAH) map. This map is a digital replica of the paper map they are using. The YAH map window can be moved, resized, and iconified. The spacebar toggles the YAH map on and off. When the YAH map is displayed, helicopter motion is frozen. If the student could view the map and move concurrently, the map would become a crutch. We observed pilots in earlier evaluations flying exclusively off of the map, not attending to the primary displays at all. By halting motion while the map is displayed, we have eliminated this counterproductive strategy. In principle, the map acts like standard moving map display. The helicopter remains centered with the map oriented in the helicopter's direction of travel (track-up). This is consistent with previous work showing that track-up maps are most appropriate for egocentric tasks such as active navigation [5, 6]. This is reinforced by instructors at HS-10 who direct students to always turn their maps in the direction of travel. The symbology on the map includes the intended track for various training routes (only one at a time), the own ship path showing where the virtual helicopter has been, and an icon representing the current position and orientation. The user can control the zoom factor on the map with a lever on the Flybox™. Pushing the lever forward, away from the user, zooms in while pulling back on the lever zooms out. Other map-related functions available to the user include going back to the last point at which they checked the map, erasing their track, selecting a different training route, and returning to the starting point. Figure 6 shows the YAH map with track data and helicopter symbol. The intended track is black while the actual track and helicopter symbol are red.

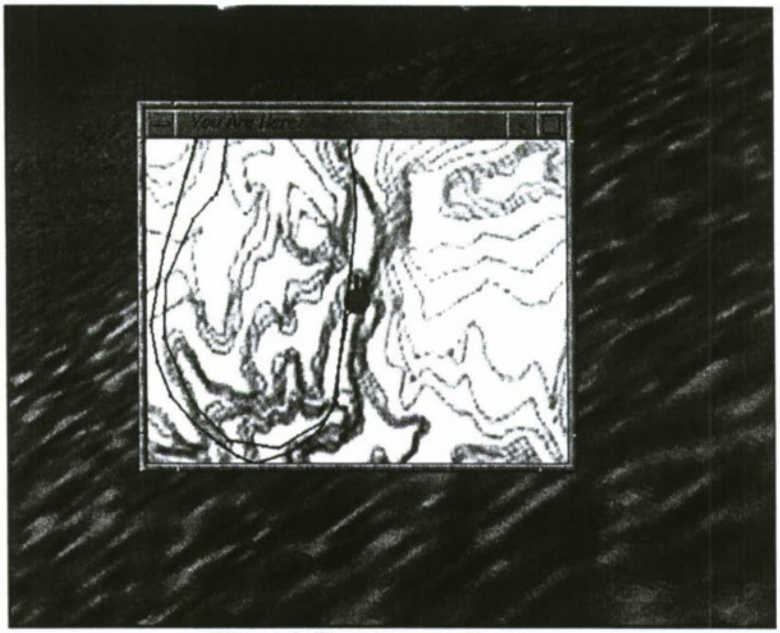


Figure 6. The You-Are-Here map.

The Terrain Database

The area we chose to model for the prototype system is the same terrain that student pilots will actually fly over -- specifically Marine Corps Air Station (MCAS) Camp Pendleton, California. However, we chose routes through this environment that differ significantly from those used by flight instructors. The modeled area is an 18 by 21 nautical mile (NM) region bounded by N33.25 W117.60 and N33.35 W117.25. We first obtained the Digital Elevation Terrain Data (DTED) for this area from the National Imagery and Mapping Agency (NIMA). We used DTED level one which is 100 meter resolution, unclassified, and publicly available. This was imported into the EasyTerrain™ terrain modeling tool by Coryphaeus, Inc. to produce a polygonal model. We then obtained geo-rectified multi-spectral satellite imagery from the Naval Space Command which we used for texture over the polygonal model. The resolution of the satellite imagery is 30 meters and is also unclassified and publicly available. The imagery texture works well for distant views or high fly-over applications such as those typical of TOPSCENE. However, from low altitudes, the local area appears very pixelated with large colored blocks where texture pixels are spread over a large region. This lack of realism did not disturb us until it was determined that it had a strong negative effect on navigation performance. It became difficult to determine relative ground speed via optical flow. This makes dead reckoning techniques difficult if not impossible. To remedy this, we added a detailed texture which, when viewed up close, overlays the imagery texture. The detail texture was created using the random noise generation features of Adobe Photoshop™. Colors were selected to match the general appearance of Camp Pendleton foliage -- dry grass and low chaparral. This texture management technique is intended to preserve the quality of information available from satellite imagery for distant terrain while improving the appearance of terrain close to the viewer. We do not believe that detailed texture completely eliminates problems associated with ground speed estimation. However, it was made clear through our usability tests that the task was not always possible without the use of detailed texture.

We did not include vegetation in the model. Our intent was to focus on terrain navigation. Vegetation can be used as a landmark. After a landmark can be recognized, there is no longer a reason to resolve the contour map to cockpit views. In other words, map reading stops and the navigation skills necessary to be a successful pilot do not develop further. If we add vegetation in the future, it will be to add velocity, height, and depth of field cues. We will not try to replicate the real world. We believe that randomly placed vegetation of uniform size and appearance may be a great benefit in helping pilots use dead reckoning techniques which are an essential part of resolving terrain to contour maps.

For similar reasons, very few man-made features are modeled. While military pilots are trained not to use cultural features such as roads and power lines for navigation, they do. It is not our intent to reinforce bad habits. However, during our usability tests, we discovered that in practice, power lines are far too important a hazard to not be modeled. Therefore we made exceptions to add primary roads and power lines to the model.

EXPERIMENT

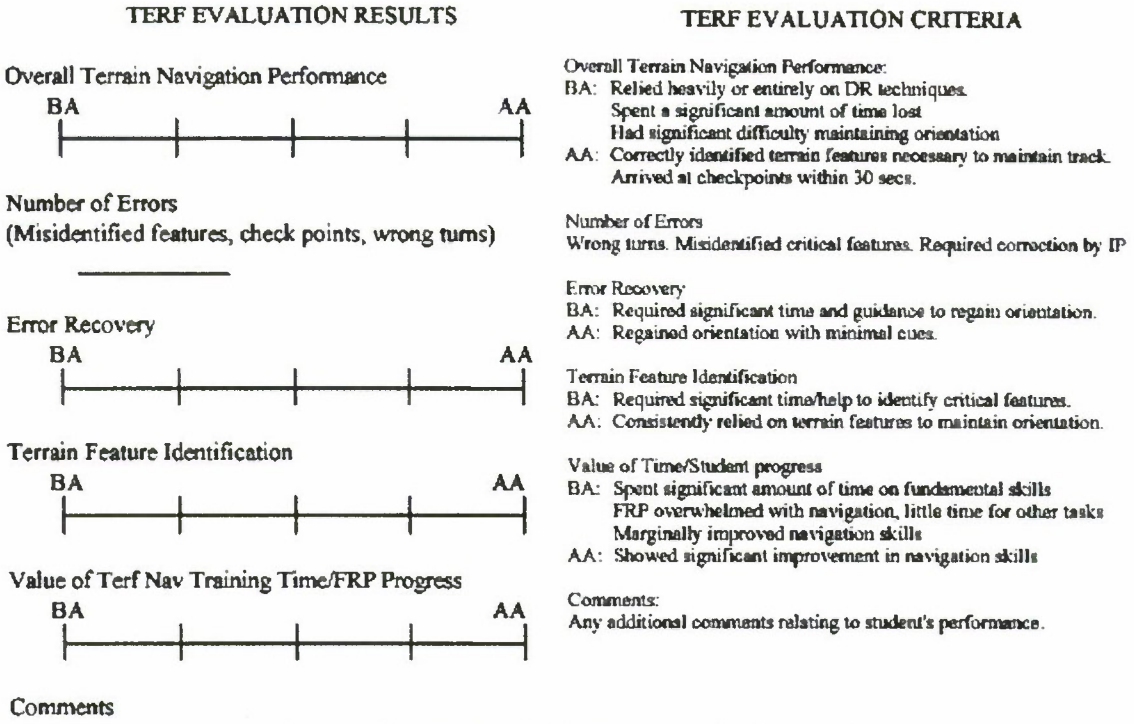
To determine if our prototype implementation was actually improving navigation performance, we designed an experiment with the cooperation of HS-10 to evaluate student pilots' navigation abilities. Although there are probably other ways of determining if transfer of training is occurring, we decided that the only reasonable measure was to use conventional evaluation techniques already in place. However, the curriculum at HS-10 is extremely full so we had to fit our experiment into their schedule as time would allow. The positive side of this is that we did not disturb the training process, so if an improvement is detected, we can be confident that it was due to differences we introduced (e.g., the VE trainer). The negative side of this is that we had less control than we would have liked. In particular, we were not allowed in the aircraft during the training flight. Consequently, there may be variability in instructor evaluation we cannot attribute to student performance.

There were two experimental groups of twelve students each; the control group which received only conventional map study and ground school preparation, and the virtual environment group which received the same preparation as the control group in addition to one hour on the virtual environment trainer. As of the writing of this paper, six CAT-1 pilots have completed training in the virtual environment group. CAT-1 pilots are recent flight school graduates who are not switching platforms but are entering their first graduate level instruction specializing in one helicopter – in this case, the H-60 Seahawk. Our students are all males, ages 22 to 25, with ranks of LTJG (O-2) to LT (O-3).

After an introductory brief of the procedure and instructions, participants in the virtual environment group were given a quick test to ensure that they understood and were able to use the system properly and that they were familiar with the available features. Only one planned route was given in this experiment. This route is depicted on both the virtual and paper maps. They were instructed to try to fly the route as closely as possible. We measured the number of times the virtual map was accessed and the location of the virtual helicopter. A "perfect" run is one in which the student flies the route without mistakes and does not need to access the virtual map or exocentric view at any time – all navigation is done off of the paper map alone. This is the best case since this is what will occur later in the aircraft. However, students are not discouraged from accessing the virtual map. A "think aloud" verbal protocol was used to gather qualitative information about confidence and strategies used by the student. This is far more indicative of navigation abilities than quantitative measures because a disoriented or confused student cannot describe upcoming terrain features with any accuracy. It is possible, however, to guess correctly as to which way to go.

The control group receives only conventional map preparation. They are given 1:50,000 topological maps of the Camp Pendleton area. They are told the route they will fly. There are a number of checkpoints they must pass along the way. Their task is to familiarize themselves with the area via the map such that they will be able to navigate in the aircraft. Conventional preparation does not include any three-dimensional tools whatsoever.

All participating pilots are evaluated in an identical fashion. When in the aircraft, they are the navigating pilot. It is their task to direct the flight instructor who is the flying pilot. The flight instructor will usually ask questions about features they see to determine if the student is cognizant of the surrounding area. Students are asked to describe upcoming features and cues used to direct flight. Following the flight, the flight instructor will evaluate the student as usual on a typical grade card. These cards ask specific questions about performance on the flight – in this case on navigation ability. In addition, we added a number of questions on a grade card addendum that are specific to this experiment (Figure 7).



TERF EVALUATION RESULTS

Overall Terrain Navigation Performance
BA AA

Number of Errors
(Misidentified features, check points, wrong turns)

Error Recovery
BA AA

Terrain Feature Identification
BA AA

Value of Terf Nav Training Time/FRP Progress
BA AA

Comments

TERF EVALUATION CRITERIA

Overall Terrain Navigation Performance:
BA: Relied heavily or entirely on DR techniques.
Spent a significant amount of time lost
Had significant difficulty maintaining orientation
AA: Correctly identified terrain features necessary to maintain track.
Arrived at checkpoints within 30 secs.

Number of Errors
Wrong turns. Misidentified critical features. Required correction by IP

Error Recovery
BA: Required significant time and guidance to regain orientation.
AA: Regained orientation with minimal cues.

Terrain Feature Identification
BA: Required significant time/help to identify critical features.
AA: Consistently relied on terrain features to maintain orientation.

Value of Time/Student progress
BA: Spent significant amount of time on fundamental skills
FRP overwhelmed with navigation, little time for other tasks
Marginally improved navigation skills
AA: Showed significant improvement in navigation skills

Comments:
Any additional comments relating to student's performance.

Figure 7. The grade card addendum used for the experiment.

RESULTS

Without a control group to compare to, it is premature to draw strong conclusions about student performance in the aircraft. However, based on students' interaction with the training system, we can draw several significant conclusions.

It is feasible to use an unaltered pre-existing task (training CSAR skills to helicopter pilots) as the measure of effectiveness of a proposed training aid. At the outset, it was uncertain if it would be possible to implement and measure the effectiveness of a terrain navigation training aid without altering the existing training syllabus. While coordinating the implementation around a fixed training course presents many unique logistic challenges, it eliminates all questions related to training transfer. If navigation performance in the aircraft improves for those students who use the navigation trainer, there can be no question concerning its effectiveness. Although there is considerably more overhead associated with data collection and less empirical data to study, improved student performance in the aircraft is the ultimate goal of a training system, and was precisely what we measured. We believe this is the ideal situation since it raises few questions regarding effectiveness and definitively answers the one question we needed an answer to. A downside to this method is that it does not lend itself easily to discovering unanticipated effects that might lead to even better training systems in the future. We need to rely on flight instructors as the final judge and jury of the system. We were not present in the aircraft ourselves.

The task of navigating through a model of Camp Pendleton is an achievable goal. This was not a foregone conclusion prior to evaluating students at HS-10. Although several helicopter pilots familiar with the Camp Pendleton area felt comfortable navigating through the virtual model, they relied primarily on memory rather than the feedback provided by the system. While it was encouraging that pilots were able to accurately identify their location based exclusively on the forward field of view provided in the simulation, this did not tell us what would happen when people without prior exposure to the Camp Pendleton area were tasked with navigating through the model. One of the key areas of uncertainty is whether the digitally recreated contour map correlated closely enough with the scene. All six students tested were able to complete the depicted route within the allotted time. Additionally, after initially completing the route, four of the six students were able to either complete the route in the reverse direction or repeat the route in the same direction a second time. Furthermore, it was clear from verbal data that they were working to resolve the map to what they saw on screen. They were not simply trying to get familiar with the region in question. Students commented on the shape of the ground around them in great detail. They stated well ahead of time what they expected to see and where it would appear. When they made errors or drifted off course, they were able to quickly recover by resolving what they saw on screen to the map rather than vice versa. This is taught in flight school as working "outside-in" rather than "inside-out". The navigator's eyes should be outside as much as possible, not inside scanning the map.

This study also validated the fact that the interface and feedback are effective. Although the interface had been evaluated during usability studies, it was never evaluated with the precise target user group. The usability study used non-aviators (including USMC Infantry, USN Surface Warfare and Supply Corps Officers), fixed wing aviators and helicopter pilots. Although it may be assumed that the helicopter pilots would provide the closest approximation to the target user group, there were significant differences between the pilots tested and the ultimate user group. The minimum flight time of the helicopter pilots tested was approximately 1500 hours. All had extensive fleet experience with overland terrain navigation. One of these subjects successfully completed initial test routes without reference to feedback mechanisms. The non-aviators more closely approximated the level of terrain navigation experience of the target user group. However, the target user group would have an average of 90 fixed wing and 120 helicopter hours. Additionally, fixed wing training involves approximately 43 hours in various simulators. Helicopter training involves approximately 34 hours in the simulator. We were uncertain if this would impact their expectations and thus adaptation time (learning curve) to the interface.

All of the students tested at HS-10 adapted quickly to the interface and were able to control motion and access feedback mechanisms easily. As predicted by the usability studies, two of the students initially expected the throttle lever to act as a collective. These students did not appear to have any more difficulty interacting with the system than the other students after the first few minutes of exposure. Based on observations of students interacting with the system, we conclude that the interface was in fact consistent with the task of learning to interpret contour maps. It allowed students to experience the terrain model with adequate attention to resolving the egocentric view to the contour map.

The training system appears to do what it was designed for -- provide students the opportunity to improve their ability to resolve an egocentric view with a contour map representation. Based on observations and verbal protocol, it was apparent that all of the students showed at least incremental improvement in this skill. This will require final validation after their training flights but we are optimistic that we will see at least moderate gains in performance by the estimation of their flight instructors. Additionally, students showed a wide variance in both initial skill level and progress made during the training sessions. The variance in both initial skill level and progress supports the concept of asynchronous access and easy availability. Clearly, if performance during the training sessions can be shown to correlate to performance in the aircraft, the training system should be readily available to all pilots. If initial skill level and rate of progress vary, students should be able to access the system as many times as they need to for how ever long than feel they need it.

CONCLUSIONS

This experiment is incomplete as of the writing of this paper. Nevertheless, we feel confident that the ability to practice this skill in a system such as this one will prove valuable to HS-10. Our future plans include an actual field test of a system to allow instructors there the opportunity to see if it has a place in the curriculum. This will also allow us the opportunity to study long term evaluation periods that were not possible in this first experiment. The steps left to complete this goal include porting the system to the Windows NT platform and a further analysis of exactly what effect this trainer has on navigation ability.

Before the Navy can take any steps toward training navigation on the ground in lieu of in the air, this effect must be a known quantity. However, navigation is a part of every task in the air, so this trainer would never completely replace experience in the aircraft. The primary benefit would be that navigation would not *explicitly* be trained in the air.

Most people who have seen the system point out its potential as a mission rehearsal system. We agree that the potential exists. However, there is a hidden danger in this thinking. It is easy to fall into the trap of training only routes when mission rehearsal system are used. In these cases, the pilot knows how to get to the target one and only one way. If problems occur during the mission forcing a change in route, the pilot is actually worse off than if no rehearsal had taken place. There are ways around this pitfall that we are attempting to identify for the helicopter community. Again, solutions from the fixed wing community may not apply since flight profiles for helicopter missions are so completely different. Nevertheless, our intention is to continue to learn more about the uniqueness of rotary wing aircraft and how this burgeoning technology can be brought to bear on their training and operational problems.

ACKNOWLEDGMENTS

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Methodology for Evaluating Off-Axis Helmet-Mounted Display Ownship Information

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INTRODUCTION

It is likely that helmet-mounted display (HMD) technology will be fully integrated into next-generation tactical aircraft. The exact utility of HMD technology can not yet be stated as confidently. On one end of the spectrum, the HMD may simply provide an aimsight reticle and symbology for purposes of target cueing and sensor guidance. The other end of the spectrum sees the HMD as a complete replacement for the head-up display (HUD) and the primary source of all head-up information. Because each end of the spectrum has its respective advantages and disadvantages, the evolution of the HMD will most likely lie somewhere between these extremes. The challenge to the designer tasked with determining the information content and utility of the HMD is to ensure that the technology provides the correct information at the correct time. As idealistic as this statement sounds, it is in essence achievable through a systematic design and validated evaluation approach. This paper describes what we hope to be a significant contribution toward this end.

It is understood that the primary purpose of the HMD is to provide target cueing information to the pilot. The HMD and the information associated with it should first be designed to get the pilot's eyes on a target and lead a weapon sensor to a point-of-interest. In parallel arises both the capability and even the need to provide other types of information via the HMD. For instance, a unique capability of the HMD is to present ownship status information (including airspeed, altitude, heading, and attitude) to the pilot regardless of head location or movement relative to the aircraft axes. Figure 1 depicts a simple generic example of how this type of information may be formatted within the HMD field-of-view.

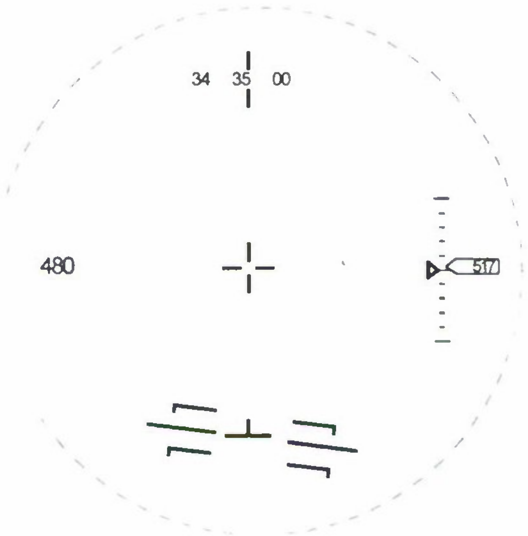

Figure 1. Generic HMD off-axis ownship information symbology.

Given that the HMD is primarily for purposes of target cueing, significant questions remain: what is the effect of including, or not including, ownship information to the pilot when the pilot's visual attention is concentrated along a line-of-sight (LOS) away from the "head forward" display areas in the cockpit (off-axis)? If in fact off-axis target cueing information increases targeting situation awareness (SA), what is happening to the spatial orientation component of SA in the mean time? The objective of this paper is to propose an evaluation methodology developed to address these important questions.

BACKGROUND

The following is intended to provide brief background into past research which has suggested SA effects related to the use of HMD presented information. One study was a low altitude flight task which included a with and without manipulation of off-axis ownship information. Another study investigated the effects of various types of HMD presented target cueing information during air-to-air engagements. A third study, also air-to-air, included an investigation of the HMD information content level. Included were HUD-only, HMD target cueing only, and HMD target cueing with off-axis information levels.

Low altitude ingress study:

One of the first studies addressing this topic included a simulated, low-level, high-speed, airborne surveillance / reconnaissance mission (Osgood, Geiselman, and Calhoun, 1991). A with and without manipulation of a simple off-axis ownship information display was performed. Pilots were instructed to maintain a 400 foot, 480 knot flight profile along a prescribed heading. Both the ground and the threat of surface to air missiles were included as adverse consequences for excess altitude deviations. In addition, subjects were instructed to look for airborne threats (hostile aircraft) and take evasive action if fired upon. The threats were designed to "pop-up" behind the ownship location. Each trial scenario was formed of a search phase (looking for the threat), and a monitoring phase (watching the threat to make sure it did not take hostile action). During both the search and monitoring tasks, HMD presented ownship information resulted in the pilots looking farther off-axis for a longer period of time. This effect was observed in the absence of a flight task performance difference. Two other interesting effects were found. First, during the 142 trials of the experiment, no ground strikes occurred when HMD ownship information was available. Without the HMD, five ground strikes were recorded. Another potential insight to the SA benefits of the technology was gleaned by taking a snap-look at pilot behavior at the instant a significant event occurred: specifically, the point where an air-to-air missile was launched against ownship. As seen in figure 2, pilot LOS when HMD aided tended to be at angles much closer to the location of the threat when the missile was launched. In fact, during trials where HMD information was not available, the average LOS angle actually resulted in the hostile aircraft location being beyond the reasonable FOV of the pilot (Figure 2).

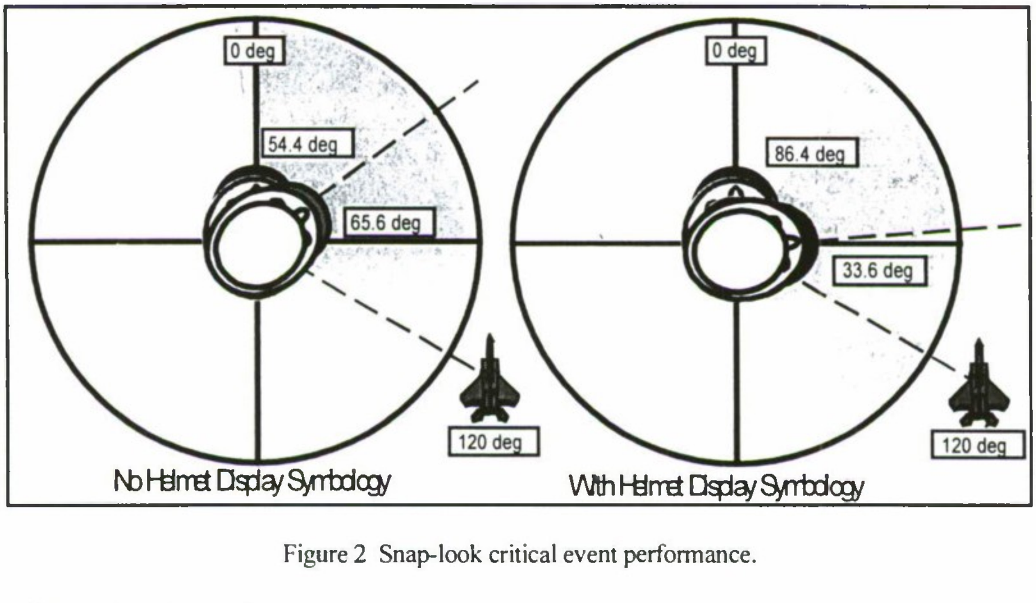

Figure 2 Snap-look critical event performance.

Air-to-air target cueing study:

Another experiment was performed to investigate the effects of HMD resident target location information reference frame during air-to-air target acquisition and intercept tasks (Geiselman and Osgood, 1995a). The objective of the study was to determine if off-axis locator information should indicate the position of the target relative to the nose of the aircraft (fly-to), relative to the nose on the pilot's face (look-to), or a combination (both). Ownship attitude information was not presented off-axis for this study. Eight Air Force pilots participated in the study. Each experimental trial included target search, intercept, tracking, and attack components within an air-to-air tactical engagement simulation. During the target intercept task, the pilots looked farther off-axis longer when HMD target location information was available. This relationship was consistent throughout the tracking and attack tasks as well. The pilots looked farther off-axis for a longer period of time due to the target location information presented via the HMD. Although not supported by the performance data, the subjective results strongly suggested that the pilots favored the combination (multiple coordinate reference frame). The effect of this behavior, looking farther off-axis for a longer period of time without the assistance of off-axis attitude information, on the ownship awareness component of overall SA under degraded visual conditions has yet to be studied.

Air-to-air ownship information study:

A third study was performed to explore the effect of various levels of HMD resident information on performance during air-to-air target acquisition tasks (Geiselman and Osgood, 1994). The information levels included a HUD-only baseline (including ownship status and target location information), a HMD with target location information only, and a HMD with both target location (look-to oriented) and ownship status information. This experiment was designed as a combination of the previous two with the exception that the interest area was limited to the higher altitude air-to-air arena (where the ground was not an immediate threat). For this study, the targeting tasks were emphasized over the flight tasks. It was quite possible that ownship information presented within the HMD would result in more clutter than it was worth. The tasks included target search, acquisition, and attack components. Nine Air Force pilots volunteered to participate in the study. Task performance and pilot head behavior was recorded and analyzed. In addition, pilots were asked to record subjective judgment ratings of situation awareness benefits attributable to the information condition levels and ownship information formats. The following operationally oriented definition of SA was adopted for the study: "A pilot's (or aircrew's) continuous perception of self and aircraft in relation to the dynamic environment of flight, threats, and mission, and the capability to forecast, then execute tasks based on the perception." (Carroll, 1992). The subjective SA ratings were collected using the SWORD technique (Vidulich, Ward, and Schueren, 1991) modified for SA rather than workload reporting. Subjects were asked to compare all possible pairs of the information levels and rate the extent that each helped to enhance SA relative to the others.

Again, during the search task, the pilots looked farther off-axis for a longer period of in the HMD ownship status information condition compared to either the HUD only or HMD target location information levels. This of course was expected because no target location information was displayed until a radar lock was established and the attack phase was initiated. During the attack phase, the pilots looked farther off-axis for a longer period of time with both the HMD target location and HMD ownship information levels. This indicated that both target location information and ownship status information results in pilots looking off-axis. According to the SWORD data, the pilots rated off-axis ownship information as contributing most to an increase in SA. HMD presented target location information was second and HUD only information was last. Again, all of this was accomplished in the absence of any performance trade-off.

Research conclusions:

The overall conclusions from the literature are: 1) HMD presented information, compared to HUD-only information, enabled (or compelled) the pilots to look farther off-axis for longer periods of time during an air-to-air task. 2) The effects were seen independent of information type (target information vs. ownship attitude). 3) Flight performance was not affected across information condition levels within the experimental tasks. 4) The pilots preferred that off-axis ownship status information be included within the HMD symbology set. 5) As described below, specific symbology formats intended for use in the air-to-air arena should be designed to minimize the visual area they occupy.

In general, it appears that, any information presented on the HMD compel the pilot to look farther off-axis for a longer period of time. This may result in increased targeting SA but the effect on the spatial orientation component of overall SA is not yet known. It is important that we avoid an increase in targeting performance only to accrue a cost elsewhere. Though a good systematic design process, we are looking for a solution where we get something for nothing. It is the authors' opinion that ownship information should be included within the HMD FOV, provided the information is well designed and mechanized.

PROBLEM

Intuitively, it makes sense that ownship information is included in the off-axis HMD symbol set. But, the symbology projected onto the HMD occupies valuable visual real-estate. For this reason, incorporating symbology must be justified by an accompanying performance advantage or critical need. Small display area exacerbates the visual occlusion problem (the instantaneous field-of-view of operational HMDs is typically 25-40 degrees subtended visual angle). In the highly visual environment of air-to-air combat, it is of critical importance to maintain an unobstructed central FOV. Subjective results indicate that pilots believe more information is better. In some cases, this belief is not reflected in the objective findings. This is evidence that a good performance-based evaluation methodology is needed to differentiate "nice to have" from information that will produce a significant advantage. What remains is to ensure that the proper information in the proper format earns it's way onto the HMD. The main reason this is so difficult to do is that there are many different forms and features by which off-axis ownship information can be conveyed (see below). And, there is no comprehensive way to evaluate these variations during off-axis targeting representative tasks.

HMD resident ownship information variations:

The ownship attitude display is designed to convey the dynamic relationship between ownship axes and the earth (heading and horizon). The design and evaluation of this symbology is complicated by the number of features available to the designer which may, in some interrelated combination of form and function, provide optimized performance under specific phase of flight and mission conditions. Form is the shape of the symbology, how it is drawn, while function is how the symbology is dynamically mechanized and referenced to the earth. Some functions can only be created via certain forms and vice versa. Also, because of the availability of a unique helmet coordinate reference system, attitude information can be presented to the pilot via unconventional formats. For this reason, a comprehensive evaluation methodology should incorporate a multi-task phased approach designed to flesh out those features of the HMD presented information that may be most effective across applications.

The following are short descriptions of some of the options available to the designer: included are symbol compression ratio, frame of reference, observer perspective, and axis separation.

Symbol compression ratio (SCR):

The ratio of the angle represented by the symbol to the symbol's subtended visual angle. A symbol which represents 90 degrees and subtends five degrees has a SCR of 18:1 (symbol to world). Compression is designed into the vertical dimension of some attitude display symbologies in order to reference more area than the display surface would otherwise be capable. SCR is a critical feature and will influence performance in a flight-path maintenance task (Geiselman and Osgood, 1995b). High symbol compression results in formats which represent large angles, and therefore have slow rates-of-motion when compared to their uncompressed counterparts. A by-product of compression is the formation of an artificial horizon which does not consistently conform to and overlie the real horizon. This situation has traditionally been avoided in transparent display applications such as the HUD. An HMD application affords the use of a non-conformal head-up artificial horizon because the symbology location is de-coupled from the aircraft axes. Geiselman and Osgood (1995b) compared two similar compressed attitude display symbologies to an uncompressed HUD format. The more highly compressed formats resulted in the best performance. Presumably, HUD symbology has been designed under the assumption that low compression ratio is effective for high precision tasks, such as flight-path maintenance, and a high SCR is preferable for low precision tasks, such as unusual attitude recovery.

Frame of reference (LOS or forward):

Forward-referenced information on the HMD depicts a view as if looking out the front of the aircraft regardless of LOS location, orientation, or movement. A forward-referenced attitude display will only update due to aircraft maneuvering. The only time a forward-referenced attitude display can appear to conform to the movement of the outside world is when the observer is looking along the forward axis of the aircraft. LOS-referenced information is a depiction of a view along the observer's LOS. In this way, both head movements (LOS changes) as well as aircraft maneuvering will change the appearance of the display. A LOS-referenced display can be drawn to conform to the movement of the outside world relative to the viewing perspective at any combination of azimuth and elevation angles. A LOS-referenced approach can be used to stabilize information with the earth in order to present virtual orientation cues. Both an earth-stabilized pathway in the sky and a conformal horizon reference are examples of this approach. The effects of a frame of reference feature manipulation can be best described using an example where the observer views symbology on a transparent HMD while looking at the outside world with a LOS 90 degrees off the aircraft flight path (fixed wing). For a forward-referenced display, during a rolling maneuver, the artificial horizon component of the display will appear to be completely inconsistent with the movement of the natural horizon. For a LOS-referenced display, in the roll input condition, the movement of the artificial and natural horizon are consistent (conformal) but the artificial horizon will appear to indicate a pitch-like vertical translation in response the actual rotational movement of the aircraft relative to its flight path. Also, because a LOS-referenced display will respond to head movement, changes to the display depiction due to LOS movement may be confused with display changes due to ownship maneuvering.

Observer perspective (inside-out or outside-in):

This concept refers to the perspective from which the observer relates ownship attitude to the earth. The perspective can either be from inside ownship looking out, or from outside ownship looking in. The dynamics of the display differ dramatically depending on which orientation is incorporated into the design. With a consistent inside-out orientation, a moving horizon is compared to a fixed ownship symbol. The ownship symbol moves against a fixed horizon reference in a pure outside-in display (the observer interprets the display as if standing outside of the aircraft).

Axis separation (consistent and inconsistent):

This concept refers to the extent the above features are applied to the various axes of the ownship attitude display. A consistent feature is applied the same way across the display axes of rotation. Likewise, features can be applied inconsistently: For instance, rotations about the ownship lateral axis (pitch) may be depicted as outside-in while rotation about the longitudinal axis (roll) is represented from a inside-out perspective.

APPROACH

Given the complexity of the options and their combinations, a common method to evaluate the relative benefit (or cost) afforded by the various HMD ownship attitude symbology approaches is called for. The concepts need to be evaluated in manner which affords a consistent comparison across various representative tasks that are characteristic (unique) to the HMD application.

Proposed Evaluation Methodology:

Held constant across the methodology design is the belief that the primary purpose of the HMD is target cueing. Therefore, representative evaluation tasks are those which include off-axis target searching, designating, and tracking. The objective of the present effort is to develop an evaluation methodology that can be used to compare the effect of off-axis ownship information on these tasks. The methodology is designed to be flexible so future candidate symbologies, and other technologies, such as multi-sensory displays, can be reliably compared to previously collected data. A second major objective is to develop a methodology that is both empirically and operationally valid. A final objective is to produce an evaluation methodology that is experimentally controlled but is recognized by subject matter experts (SMEs) as operationally relevant. The proposed methodology will include the following features:

A multi-phased trial approach will be used to help ensure trial continuity. Each trial will be formed of separate phases which will be treated and analyzed as separate tasks. A dual task paradigm will be employed with off-axis targeting (search, location, designation, and tracking) primary tasks. The secondary tasks include flight tasks such as attitude maintenance, maneuvering, and extreme attitude recovery. Because of the operational nature of the tasks, at least the initial evaluations will use SMEs as experimental subjects. Independent variable manipulations include HMD ownship symbology format type, a no off-axis ownship information baseline condition, and natural horizon presence (on or off). Measurement metrics will include task performance, subject behavior (head movement), and subjective feedback. Subjective feedback will include preference questionnaires, workload estimates, and SA ratings.

The methodology is being designed to run in the Air Force Research Laboratory's Synthesized Immersion Research Environment (SIRE) facility (Figure 3), Wright-Patterson AFB, Ohio.

SIRE Facility:

SIRE provides a generic single-seat fighter cockpit with out-the-window visuals presented on the surface of a dome projection system (40 feet diameter). The projection surface is 150 degrees horizontal by 70 degrees vertical field of view. The subject will be seated in the cockpit located 20 feet from the surface of the dome and elevated 7.5 feet above the floor. This provides a vertical separation of the viewing area (50 degrees above the horizon and 20 degrees below the horizon from the design eye point). The horizontal separation is 75 degrees on either side of center. The display is produced by six highly modified BARCO projectors each capable of a resolution of 1280 by 1024 pixels at 60 Hz. The resolution of the system is approximately 2 arc minutes per pixel. The projectors are stacked two high and three across to cover the entire viewing area. The edges of the viewing area generated by each of the projectors are blended (two to four degree overlap) in order to create a uniform, uninterrupted, high-resolution image across the entire field of view. The image generator consists of a Silicon Graphics Onyx system with eight processors, three graphics pipelines, and six channels of video.

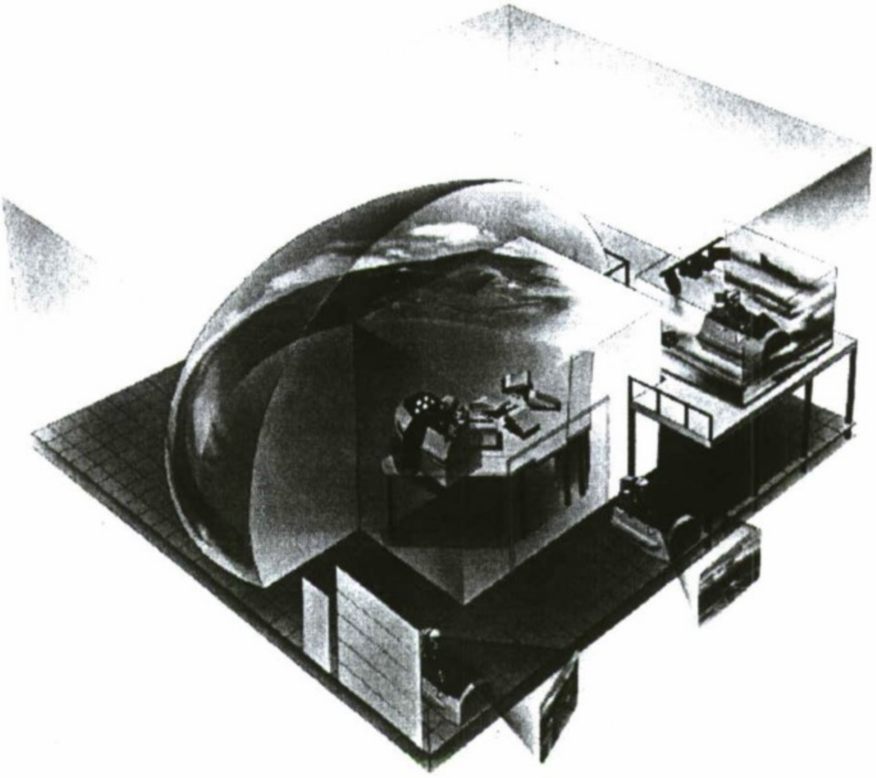

Figure 3. The Synthesized Immersion Research Environment Facility.

The SIRE cockpit currently includes three head-down displays and one head-up display. A simulated helmet-mounted display is added in addition to the standard cockpit displays. Two of the head-down displays are 6.6 inch square color displays that each have a 30 degrees by 20 degrees field of view. These displays flank a center display, and are mounted one on the left and the other on the right side of the crewstation. For all phases of the evaluation trials, the following information will be presented on the head-down display surfaces independent of the HMD off-axis symbology mechanization: (1) integrated ownship primary flight information suite (attitude, airspeed, altitude, heading, vertical velocity, and angle of attack), (2) radar display, and (3) horizontal situation display. The HUD provides collimated monochrome imagery on a 30 degrees by 22 degrees field of view. The HUD is capable of producing computer-generated imagery (e.g., FLIR) or symbology. For all phases of this effort, the following information will be included as a HUD presentation independent of the HMD off-axis attitude symbology manipulation: (a) ownship attitude, airspeed, altitude, angle of attack, and magnetic heading and (b) aircraft referenced (fly-to oriented) locator line indicating the ownship pursuit vector to the target location.

Head-Mounted Display (HMD):

All HMD symbology will be displayed overlaid upon the external out the window (OTW) scene presented on the SIRE dome. The symbology will be slaved to the pilot's head via a magnetic position tracker attached to the top of the helmet. Thus, the symbology will always be centered within the helmet line of sight and steered about the display via head movement. The following components will be included in the HMD symbol set independent of the HMD off-axis attitude symbology manipulation: (a) Radar LOS reticule, (b) target designator (TD) box, (c) HMD LOS magnetic heading and elevation, and (d) look-to oriented head referenced locator line (to indicate the azimuth / elevation vector and vector length to the target location).

Procedure:

Each trial will be comprised of three distinct task phases with initial conditions to test the efficacy of each symbology set in terms of providing attitude information to the pilot. Specifically, the simulated air combat scenario will emphasize: a target search task, a dynamic attitude maintenance task, and an extreme (unusual) attitude recovery task. The specifics of each of these phases will be detailed in the individual sections to follow. In general, each pilot will fly an equal number (6-8) of evaluation trials using each of symbology sets of interest. The symbology set presentation order will be counter-balanced between pilots to guard against learning and order effects. In general, for each evaluation, a with and without manipulation of HMD off-axis information will be included as a baseline performance measure. Visual condition will also be treated as a general independent variable. The nighttime lighting conditions will be used across trials but the presence of the visible horizon will be manipulated.

The following paragraphs present the basic anatomy of a single experimental trial:

Phase one – Target search task:

The phase one objective is to differentially evaluate how well the candidate off-axis symbology is used to maintain flight during a primary task (visual search for a point-of-interest).

During phase one, ownship will be initialized straight and level at a medium altitude on a cardinal heading at 450 kts. The primary task is to perform a visual search of the OTW scene for a target that will randomly pop-up at a fixed azimuth and elevation location on the dome display surface. Different locations will be used from trial to trial. While performing this task, the pilots are to maintain their prescribed flight parameters. An auditory tone will command left and right heading changes (90 degrees each time). In this way, the flight path will be variable but task performance will be independent of the navigation information provided to the subject. Initial target location relative to the ownship location will be designated as an independent variable. A hard deck altitude will also be assigned for the scenario. The hard deck altitude will be approximately 10,000 feet below the initialization altitude. Once the target appears (as a small designator box), the pilot's task is to slew a head stabilized aimsight reticle over the target location as quickly as possible. Once the target is inside the aimsight reticle (pilot LOS aligned with the target location), the pilot presses a button and the trial automatically transitions to phase two.

Phase one dependent variables: primary task measures will include target search variability, reaction time, and trial phase time. Head movement (angles, duration, and rates) will enhance the performance data. Secondary task performance will include measures of airspeed, altitude, and flight path (including heading) error and variability.

Phase two – Dynamic attitude maintenance task:

The phase two objective is to differentially evaluate how well the candidate off-axis symbology is used to maintain maneuvering flight while maximizing LOS time on a point-of-interest located off-axis.

During phase two, the aimsight reticle that was head fixed during phase one becomes aircraft fixed at the azimuth and elevation angle where the button press occurred. Now, the target location that was aircraft fixed begins to maneuver relative to ownship. We essentially start to drive the TD box along a pre-recorded flight path at rates that are representative of high-performance aircraft maneuvering. The pilot's task is to try and maintain the TD box location within the aircraft-fixed aimsight reticle by maneuvering ownship simultaneously about the roll and pitch axes. This is basically a formation flight task. If followed well, the movement of the TD box will eventually fly ownship into an extreme attitude (both isolated and combinations of extreme pitch (<60 degrees) and roll (<90 degrees)). The TD box will then disappear to simulate a lost lead or lost target condition. This event completes phase two and initiates phase three.

Also during phase two, some catch trials will be included in order to test specific SA components. In these cases, the target will maneuver ownship into a situation that, if continued, will result in a hard deck violation. Another variation of this may result in dangerously low airspeed. In these cases, the pilot's proper response is to break off the tracking task to keep from violating the hard deck or avoid departing controlled flight. These trials should address some target fixations issues.

Phase two dependent variables: The primary task measure of interest will be target tracking performance. Head movement (angles, duration, and rates) will enhance the performance data. Secondary task performance will include measures of ownship energy and maneuvering performance.

Phase three – Extreme attitude recovery task:

The phase three objective is to differentially evaluate how well the candidate off-axis symbology is used to recover from extreme attitudes while maximizing LOS time off-axis without an external orientation cue.

Once the target disappears, phase three begins in the lost target condition. A target search task immediately resumes (similar to phase one) while the pilot is tasked to fly ownship from the extreme attitude incurred during phase two, to a new commanded altitude and heading. This phase is formed of two sub tasks. During the initial recovery, the subject will perform the target search task. Once the target is located (later in the recovery process), the task will include maintaining LOS on the target location as much as possible while refining the recovery. This is an attempt to collect unusual attitude-like performance data while maintaining a high level of task realism. This phase, and the experimental trial, will end when the subject flies ownship to within a specified combination of heading, altitude, attitude, and airspeed for a specified period of time.

Phase three dependent variables: The primary task measure of interest will be target search and tracking performance. Head movement (angles, duration, and rates) will enhance the performance data. Secondary task performance will include measures of reaction time, initial input error, control reversal, recovery time, recovery error, and ownship energy.

Subjective feedback:

Questionnaires will be included to address pilot preference and suggestions. Included in the subjective feedback will be measures of both workload and SA. The SWORD technique is being considered as the workload metric while Cognitive Compatibility-Situational Awareness Rating Technique (CC-SART) is being considered as the subjective SA measurement technique. Performance data will be compared to the subjective findings as a validity check.

DISCUSSION

Presently, the laboratory is completing the software development for this project. The first data collection activity will include two goals: First, we hope to validate the methodology as well as collect SME input for improvement. The second goal is to begin evaluation data collection for candidate symbol sets. Future plans for the project include broadening the scope of the test functionality to include more application generalizability. It is likely that the methodology can be expanded to address both off-axis ownship information issues as well the combined use of various target cueing symbology candidates. Eventually this approach can grow to be a valid and reliable method by which future HMD symbology can be efficiently compared. From this comparison, performance-based design decisions can be confidently quantified.

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The Validation of a Team Situational Awareness Measure

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ABSTRACT

In this effort, we describe a theoretically based methodology for assessing team SA named SALIANT (Situational Awareness Linked Instances Adapted to Novel Tasks). SALIANT results in an event-based scenario and measurement tool that provides multiple opportunities to evaluate teams based on behaviors associated with team SA. In addition, we report an initial validation study conducted to evaluate the psychometric properties of SALIANT (i.e., reliability and validity). Results indicated that team SA ratings derived from SALIANT were related to team communication and performance ratings; however, no relationship was found between team SA ratings and indices of team shared mental models. Based on these results, we discuss lessons learned in designing and validating team SA measurement tools.

INTRODUCTION

The success of today's military operations depends heavily on the effective performance of teams. Given their crucial role in these complex settings, it is important to understand what determines such effective performance. One factor often reported to affect a team's functioning is situational awareness (SA) (Prince & Salas, 1993). SA is important for teams because it allows team members to be attentive to changes in the environment and anticipate the consequences of these variations (Stout, Cannon-Bowers, & Salas, 1996). A breakdown in a team's process of acquiring and maintaining SA often leads to disastrous consequences. In fact, aviation mishap reports often associate a large percentage of human error related accidents in military settings to problems with SA (Hartel, Smith, & Prince, 1991). Such evidence reflects the importance to learn about the components that ensure the effective achievement of SA in teams. Moreover, increasing our understanding of team SA will facilitate the development of strategies such as training programs and advanced displays designed to deter team failures associated with SA deficiencies. These strategies, in turn, need to be evaluated to determine their impact on enhancing a team's SA. To accomplish this, it is necessary to develop valid and reliable instruments that can provide an index of a team's SA level. Unfortunately, few measures of team SA exist (Muñiz, Stout, Bowers, & Salas, 1998; Stout et al., 1996). To address the current needs in team SA measurement, this effort sought to develop and validate a theoretically based methodology for assessing SA in a team context. Before we elaborate on details about this methodology, some background information that was used as a foundation for this research will be reviewed, including SA, SA measures, and team SA.

Situational Awareness. Previous research that focuses on SA has contributed primarily to our understanding of how individual team members acquire SA. One of the most commonly accepted theoretical frameworks that centers on explaining individual SA is provided by Endsley (1988; 1995). In this theory, she defines SA as "the perception of elements in the environment within a volume of time and space [level 1], the comprehension of their meaning [level 2], and the projection of their status in the near future [level 3]" (Endsley, 1988; p.7). These components are defined in three levels, and they are proposed to be hierarchical in nature for the achievement of SA.

The components derived by Endsley have some implications for measurement. More specifically, she derived a measurement methodology which attempts to capture an individual's SA at different levels with the third level suggesting to be the highest SA that could be achieved {Situation Awareness Global Assessment Technique (SAGAT), Endsley, 1988}. In addition to the SAGAT technique, a number of measurement methodologies are available if the goal is to assess the level of SA acquired by *individual* team members (e.g., memory probes, Wellens, 1993; subjective ratings, Arbak, Schwartz, & Kuperman, 1987). A review of these measures is beyond the scope of this effort. However, such measures have been criticized on a host of grounds, primarily because of the lack of empirical data that demonstrates their psychometric value (i.e., reliability and validity) (Fracker, 1991). More importantly, *these measures are insufficient, if one is concerned with capturing the team element of situation awareness.* This is because team SA is more than simply combining individual team members' situation awareness (Schwartz, 1990). In the next section, we briefly address the team component of SA and its impact on measuring it.

Team Situational Awareness. Team tasks that are complex, dynamic, and information rich, often require that every team member obtain a certain level of SA based on the assessment of cues and events present in the environment. In turn, each team member's SA is modified as information is exchanged between members who may have observed a cue or event that could be vital for the effective performance of the team. Attaining SA at the team level is a complicated process given that there are a number of interactive behaviors (e.g., information sharing, coordination) that play a crucial role in the achievement and maintenance of SA for all team members (Stout et al., 1996; Schwartz, 1990). In fact, a review of literature on team situation awareness revealed that at least two components are crucial for its achievement: (a) individual SA, and (b) team processes that help build the SA of a team (Stout et al., 1996; Salas, Prince, Baker, & Shrestha, 1995).

The team element of SA has been addressed by a number of researchers at the cognitive level (Stout et al., 1996), and behavioral level (Stout et al., 1996; Prince & Salas, 1993; Mosier & Chidester, 1991; Bunecke, Povenmire, Rockway, & Patton, 1990; Schwartz, 1990; Leedom, 1990; Foushee, 1984). In addition, there have been numerous studies which have investigated constructs theorized to be related to team SA (e.g., *communications*, Schwartz, 1990; Palmer, 1990; Wellens, 1993; Bowers, Braun, & Kline, 1994; Muñiz, Stout, & Salas, 1996, *shared mental models*, Stout, 1995; Stout et al., 1996, and *performance*, Bowers, Barnett, Weaver, & Stout, 1998).

The available literature on team SA delineates components that can be used to derive measurement methodologies for evaluating SA in teams. Measures of team SA should consider both cognitive and behavioral processes that indicate its presence and absence. While both of these team SA components are equally important (i.e., behaviors and cognition), at this point, we focus on the behavioral component of team SA and its implications for measurement.

A METHODOLOGY FOR MEASURING TEAM SA

Previous team research has created event-based measurement methodologies for evaluating the performance of aviation teams. (For further details on event-based scenario measurement methodologies please refer to Fowkles et al., 1994). These methodologies are believed to have the potential for measuring SA in teams (Muñiz et al., 1998; Bowers et al., 1998.) Thus, we build upon this work to create an event-based approach for measuring team SA.

The methodology that provides opportunities to capture team SA has been termed SALIANT (Situational Awareness Linked Instances Adapted to Novel Tasks) (Muñiz et al., 1998). By implementing this methodology one can derive (a) theoretically based team SA behaviors, (b) scenario events which provide teams with opportunities to manifest SA behaviors, and (c) a structured behavioral checklist to determine a team's level of SA. The SALIANT methodology is comprised of five phases. Each phase is necessary to ensure that team SA is assessed reliably and objectively.

PHASE 1. Delineation of Behaviors Theoretically Linked to Team SA. Twenty-one (21) generic behaviors theorized to manifest a team's level of SA were identified via literature reviews and investigations with a focus in aviation (e.g., reports of aviation mishaps, observations of aviation teams, and aviator's responses to critical incident reviews). Although a comprehensive review of this literature is beyond the scope of this effort, a summary list is provided in Table 1. These generic behaviors were used as the foundation for the next four phases.

Table 1. Generic Behavioral indicators of team situation awareness (Muñiz et al., 1998).

Demonstrated Awareness of Surrounding Environment
•Monitored environment for changes, trends, abnormal conditions (Prince 1998) •Demonstrated awareness of where he/she was (Bunecke et al., 1990)
Recognized Problems
•Reported problems (Prince & Salas, 1993; Foushee, 1984) •Located potential sources of problem (Prince & Salas, 1993) •Demonstrated knowledge of problem consequences (Prince, 1998) •Resolved discrepancies (Schwartz, 1990) •Noted deviations (Prince & Salas, 1993)
Anticipated a Need for Action
•Recognized a need for action (Prince, 1998; Prince & Salas, 1993; Foushee, 1984) •Anticipated consequences of actions and decisions (Prince, 1998) •Informed others of actions taken (Leedom, 1990) •Monitored actions (self & others) (Prince & Salas, 1993)
Demonstrated Knowledge of Tasks
•Demonstrated knowledge of tasks (Schwartz, 1990) •Exhibited skilled time sharing attention among tasks (Schwartz, 1990) •Monitored workload (self & others) (Prince, 1998) •Shared workload within station (Bunecke et al., 1990) •Answered questions promptly (Prince, 1998)
Demonstrated Awareness of Information
•Communicated important information (Bunecke et al., 1990) •Confirmed information when possible (Bunecke et al., 1990; Leedom, 1990) •Challenged information when doubtful (Prince & Salas, 1993; Leedom, 1990; Bunecke et al., 1990) •Re-checked old information (Mosier & Chidester, 1991) •Provided information in advance (Prince & Salas, 1993; Schwartz, 1990) •Obtained information of what is happening (Foushee, 1984) •Demonstrated understanding of complex relationships (Bunecke et al., 1990; Schwartz, 1990) •Briefed status frequently (Prince, 1998; Schwartz, 1990)

PHASE II. Development of Scenario Events. Aviation related scenario events were developed to provide teams with multiple opportunities to demonstrate team SA behaviors. These events were developed based on: (a) input from subject matter experts (SMEs); (b) the level of simulation in which the scenario is performed, and (c) an analysis conducted to ensure the scenario is complex, dynamic and demands team interactions. Each of these events was designed to elicit specific behavioral indicators of team SA. The requirement of linking generic indicators to specific scenario events is a key component of SALIANT because it provides opportunity to delineate specific manifestations of team SA from which one can infer the level of SA acquired by a team.

PHASE III. Identification of Specific Observable Responses. Researchers and SMEs identified a number of specific observable responses that were expected to be exhibited by a team exposed to the scenario. These responses were then clustered into one of the five flight factors identified by Wagner and Simon (1990) (i.e., mission objectives, orientation in space, external support, equipment status, and personal capabilities). These factors were identified as critical for aviation teams to attend and maintain effective SA. The objective of clustering specific responses into these categories is to ensure their task relevancy to the aviation domain. In addition, in each of these categories, we included specific behaviors that take in consideration the anticipatory component to acquire high levels of SA (Stout et al., 1996, Endsley, 1995). The identification of these anticipatory behaviors is what differentiates these behaviors from other team processes associated with teamwork.

PHASE IV. Development of a Script. After all the acceptable responses for each scenario segment were delineated, a scenario script was developed. The objective of the script was to ensure that teams were presented with similar information and situations. In addition, the script contained information on how the experimenter should respond if anticipated problems arose.

PHASE V. Development of an Observation Form. The work accomplished in Phases I – IV was used to develop a structured observation form to rate teams on the number of specific observable behaviors exhibited. The form was organized into 4 columns that specify scenario segments, specific observable responses, specific team SA behaviors being measured. The specific observable responses were coded using a dichotomous system (i.e., present or absent).

In summary, the SALIANT methodology was developed to attempt to capture team manifestations of SA based on theoretically derived behaviors. (A summary of this methodology is depicted in Figure 1). This methodology was used as a basis to conduct an initial study to: (a) evaluate the extent to which team SA can be measured reliably by using a SALIANT based tool, and (b) determine the relationship of a SALIANT based measure to constructs theorized to be related to team SA (i.e., communication, shared mental models, and performance). The goal of this effort was to determine the effectiveness of a SALIANT based methodology at assessing team SA.

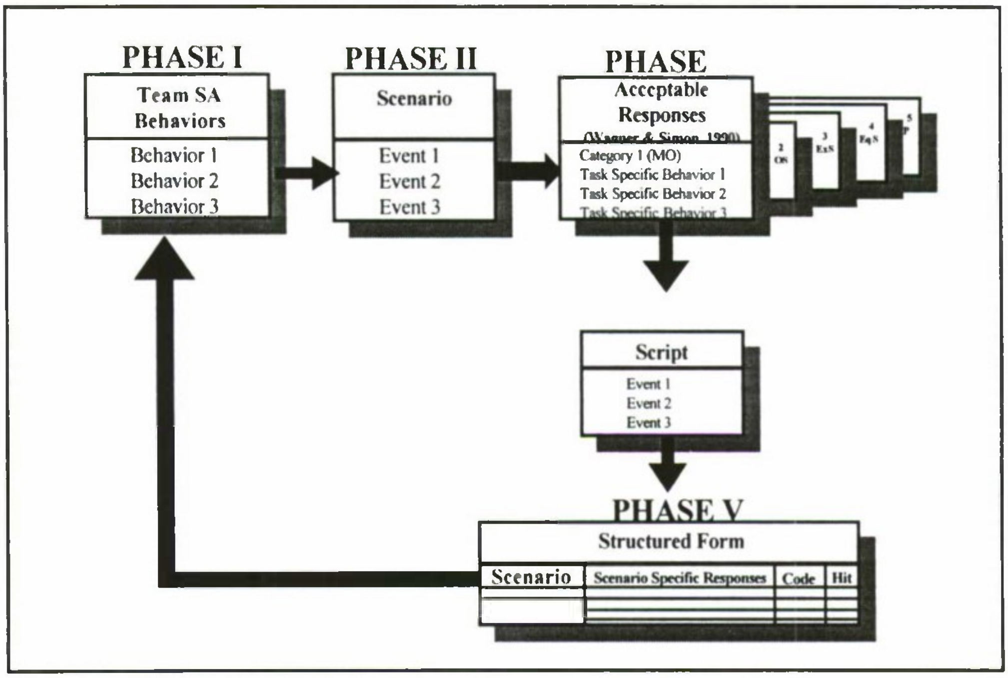

Figure 1. SALIANT Methodology

SALIANT VALIDATION STUDY

Methodology

Participants. Twenty undergraduate students from a Southeastern university participated in a 4-hour experiment. These students received extra credit for one of their psychology classes for participating in this study.

Materials and Equipment.

Simulator. A tabletop, commercially available, software simulation named Comanche was employed in this investigation. This software was created to simulate the characteristics of a Reconnaissance/Attack Army helicopter (Boeing Sikorsky RAH-66 Comanche). The software presents an instrument panel and external visual aids on a computer monitor. This software was operated in a 486 personal computer. Other materials/peripherals were used to simulate communication (e.g., live and pre-recorded messages occurring outside the cockpit), and navigation equipment (e.g., headphones, a joystick, a clock, and a map with pre-determined routes).

Evaluation Scenario. Using the SALIANT methodology, an event-based scenario was developed to elicit team SA behaviors. In this scenario, participants were required to role-play an Army attack helicopter aircrew from an air cavalry unit. The scenario required participants to fly in enemy territory, report the location of targets to an Air Mission Commander (played by an experimenter), and destroy the targets. To accomplish these tasks, participants were required to perform in 2-person teams. One participant played the role of the pilot, who was responsible for flying the aircraft and communicating over the headsets with other aviation units. The other participant played the role of the co-pilot, who was responsible for providing directions to the pilot and destroying targets. As previously discussed, a script was developed for the experimenter which specified when events were introduced, what to verbalize during the scenario, and how to respond to anticipated problems.

Data Acquisition. The teams' performance was recorded by two methods. A video camera was used to capture a view of the teams from the back of the experimental room. A second device called "Tvator" ™ was used to convert computer signals from the simulation into a television signal, which was then recorded on videotape. In addition, the audio signal from the headphones was transferred to the audio track of both types of recordings.

Measures.

Team SA. Two trained raters, using a structured observation form derived from the SALIANT methodology, assessed the videotapes depicting each teams performance from the back of the room. Teams received a point for each behavior exhibited. Thus, the total number of behaviors exhibited was considered to be the level of team SA acquired by a team.

Communications. Videotapes were also used to code the frequency of communications exhibited by the teams. A different pair of raters documented the communication frequencies exhibited by the teams, and these frequencies were coded into nine categories: commands, inquiries, statement of intent, suggestions, acknowledgments, replies, non-task related, and uncodable (Bowers et al., 1994; Bowers, Deaton, Oser, Prince, & Kolb, 1995; Oser, Prince, Morgan, & Simpson, 1991). The number of communications was added to obtain an overall communication score.

Shared Mental Models. A questionnaire was provided to participants after completing the scenario. In this questionnaire, participants were asked to give likelihood in which they expected themselves and their teammates to exhibit certain behaviors in a subsequent mission. The teams' agreement on this questionnaire was calculated by using the Lawlis and Lu (1972) agreement coefficient. These coefficients were considered to be an index of the teams shared mental models with regards to team expectations about the task and team member roles (Blickensderfer, 1996).

Performance. The team's overall performance was assessed by the number of targets destroyed in their mission.

Results.

Data were examined to determine the viability of SALIANT for team SA measurement. Specifically, data were examined for evidence of reliability and validity.

Inter-observer Reliability.

Team SA Ratings. Analyses were performed to determine the level of agreement between the two observers that used a checklist derived using the SALIANT methodology to assess the SA of teams. Significant correlations were found between the team SA ratings made by the two observers ($r = .94, p < .05$). Thus, the strong relationship found between the ratings made by the two observers suggests that they were agreeing substantially in the ratings of team SA behaviors by using a SALIANT derived measure.

Communications Ratings. Analyses were performed to determine the level of agreement between the two observers that used the communication rating form to determine the total number of communication frequencies engaged in by each team. Significant correlations were found between the communication ratings made by the two observers ($r = .98, p < .05$). Thus, the strong relationship between the communication ratings made by the two observers suggests that they were consistent in using the communication frequency form.

Validity. Analyses were performed to assess the relationship between teams' SA scores and total number of communication frequencies, index of shared mental models, and performance. Significant correlations were found between team SA scores and total number of communication frequencies ($r = .74, p < .05$), and between team SA scores and performance ($r = .63, p < .05$). Non significant correlations were found between team SA scores and teams' shared mental model indices ($r = -.04, p > .05$). These results suggest that the

SALIANT-derived measure might be a good indicator of the relationship of team SA and communication and performance, but not for shared mental models.

DISCUSSION

Findings in this effort are significant because they begin to advance our understanding of situation awareness at the team level. Further, the current effort begins to address recent measurement problems raised within the SA literature. Specifically, many researchers have noted the psychometric deficiencies in available SA measures (i.e., little reliability and validity evidence), and the lack of methods and measures that capture the team element of SA. The development of these measures is crucial to advance our understanding of factors affecting SA in teams, as well as to evaluate strategies developed to augment SA in teams. Given the importance of measurement for both researchers and operators, the current effort sought to accomplish two goals. One goal was to document a theoretically based methodology that aims at assessing SA in teams. The second objective was to report evidence from an initial validation study to assess the psychometric properties of this methodology.

Findings indicate that there was a significant agreement among raters that used an observation checklist derived from SALIANT, which provides evidence of how reliably we can assess SA across teams. In addition, results indicated there was a high relationship between team SA scores and communication ratings. Also, there was a relationship between team SA scores and performance ratings. These findings show some promise that the scale derived from SALIANT might be useful for predicting these two constructs after further analysis. Our results also suggested a non-significant relationship between team SA scores and teams' shared mental model indices.

There are several hypotheses to explain the non-significant correlation. First, the shared mental model questionnaires were completed at the end of the experiment and perhaps the length of the experiment resulted in fatigued participants. Second, the adaptation of these questionnaires to another team setting and team task needs further validation itself. Finally, given that shared mental models is a cognitive based construct, there is possibly the need to use a combination of measures that tap various dimensions of this construct.

Based on these results, several lessons learned can be derived. First, while the importance of cognitive processes for acquiring team SA is acknowledged, this issue was not addressed with the SALIANT methodology. Cognitive based measures are recommended to complement SALIANT. Second, the 21 behaviors used as a foundation for SALIANT are considered to be manifestations of high team SA. More work needs to be conducted to determine behavioral indicators of low team SA to develop a measurement methodology to supplement SALIANT. Third, event-based scenario development requires individuals with extensive experience with the tasks and methodology to ensure the scenario is properly constructed (i.e., elicit natural responses from the teams). Finally, the identification of specific responses is a labor-intensive effort. In some occasions, the teams may not exhibit specific responses, and at other times teams may exhibit unanticipated responses.

On a more positive side, the current effort found evidence that SALIANT has potential for measuring SA in a team context. Given the documented importance of SA in team performance, it is important to identify what factors modify its achievement. These factors, in turn, need to be addressed in strategies developed to augment SA in teams. Thus, more studies are encouraged to be conducted that continue to test and refine SALIANT for the benefit team SA researchers, practitioners, and, more importantly, teams who rely on this skill for the effective and safe accomplishment of their missions.

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