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Investigating the Effects of the Mission Status Graphics Polar Star Display on Failure Detection Time and Situation Awareness for Mission and System Monitoring in General Aviation Aircraft

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This thesis was prepared under the direction of the candidate's thesis committee chair, Shawn Doherty, Ph.D., Department of Human Factors & Systems, and has been approved by the members of the thesis committee. It was submitted to the Department of Human Factors & Systems and has been accepted in partial fulfillment of the requirements for the degree of Master of Science in Human Factors & Systems.

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Abstract

For years, the aviation industry has been under severe scrutiny over the safety of flight when cockpit automation is over relied on and when it is under utilized. This double-edged sword raises the question of situation awareness in aviation. With the recent boom in cockpit automation and advanced avionics some fear that the pilots are being put outside "the loop". Unfortunately, humans are notoriously poor monitors of reliable systems over time. However, research is currently being conducted into a new form of display that has the ability to group a myriad of aircraft mission and system status information onto one display, thereby providing pilots with a clear and concise view of the "big" picture, in one glance. This display utilizes a regular geometric shape generated on a polar graphic plot to indicate whether all monitored parameters are within acceptable limits. Dubbed Mission Status Graphics, the regular geometric shape will warp to a non-symmetrical form indicating that a mission or system parameter has exceeded its normal operating range. NASA Langley Research Center is currently investigating this display system for application to commercial aircraft cockpits; however, it is believed that general aviation flight safety and pilot situation awareness could also benefit from the addition of this display in future cockpit designs.

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1.0 – Introduction

When given the task of monitoring reliable systems, humans perform poorly, especially over long periods of time (Mackworth, 1950). Aviation systems are becoming increasingly more automated, causing the role of a pilot on the modern flight deck to transform from operator to supervisor. As a result it has become necessary to find a method of conveying information so that even the least vigilant monitors can notice critical deviations of systems and mission parameters in a timely manner (Trujillo, 2002). The ability of an aircrew to generate an accurate internalized picture of the current state of their aircraft's mission and system performance is essential in order to achieve an overall high level of situation awareness (SA). Since one of the primary responsibilities of the modern aircrew is to develop SA and maintain it in a rapidly changing environment, it is crucial that they be capable of seeing the "big" picture"(Trujillo & Schutte, 1999). However, it is challenging to piece together the true state of the aircraft, at a given moment, due to the complexity and quantity of factors that must be taken into account. A pilot's ability to achieve a working understanding of the current state of their aircraft and the subsequent ability to predict the future state of the aircraft, in the short term, is indicative of the overall level of SA they are capable of reaching. Everyday, thousands of pilots are being forced to perform monitoring tasks for which both the aircraft and man are ill equipped. To aid in this effort, technology will need to be effectively employed in a manner consistent with human factors design. The next generation of aircraft cockpits will need to have the operator interface optimized for maximum human performance through the use of advanced avionics packages that can incorporate critical information in to a more usable dynamic interface then those currently seen in the aviation industry.

Perhaps polar-star displays, like those under development at NASA, will provide some of the much needed situation awareness enhancement on the modern flight deck. Polar star displays consist of a regular polygon generated on a polar graphic coordinate plot. Each vertex of the polygon represents a significant variable being monitored for fluctuation beyond acceptable ranges. When all variables are reading normal, the polygon will be symmetric and each vertex will lie on a circle. Conversely, when one or more variables are abnormal the polygon will transform into an obviously asymmetric shape. The figure below (Figure 1a) shows a polar star display with all variables normal and another (Figure 1b) with two variables abnormal. The polar star display format was originally developed for nuclear power plant

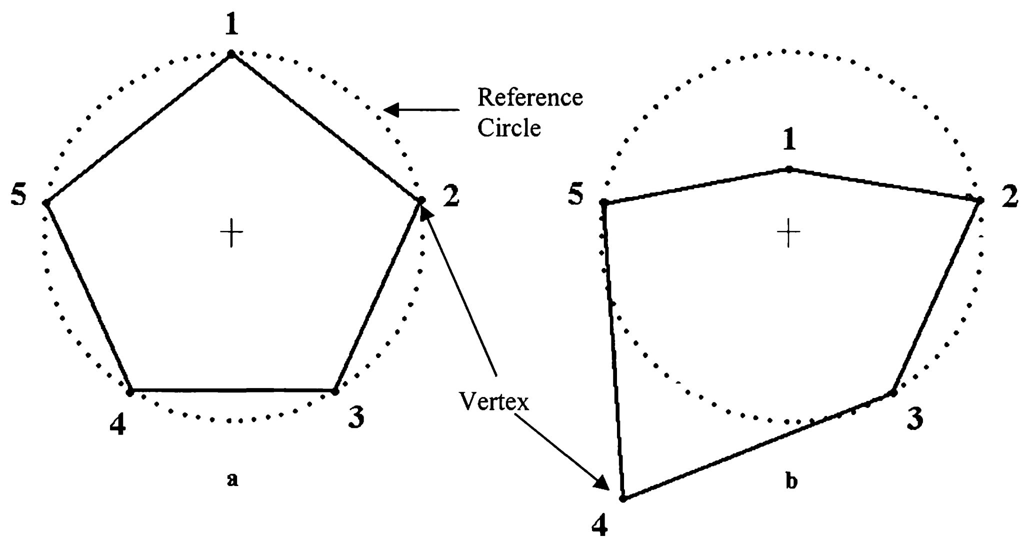


Figure 1 – Example polar star displays: all variables normal (a) and two variables abnormal (b)

control rooms however, NASA Langley recently took another look at polar star displays and their potential for application to the dynamic modern aircraft flight deck environment. In what they are calling mission status graphics (MSG), NASA's next generation polar star displays have the ability to logically group critical flight parameters onto one display, that currently are inconsistently scattered across the multitude of commercial and general aviation instrument panels in use in the aviation industry today. However, in order to understand the impact of polar star displays in aviation an overview of situation awareness factors needs to be examined. It needs to be emphasized that this area has not been well investigated and that the research proposed below is the first step toward understanding the benefits that the MSG polar star displays can provide in the fight to improve situation awareness in the cockpit.

1.1 Foundations of Situation Awareness and the Situation Awareness Rating Technique (SART)

Endsley (1988), formally defines situation awareness as, "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." Within this definition, Endsley alludes to the three distinct levels of SA. Level 1 SA involves the perception of the relevant elements in the environment. The second level of SA is based on the synthesis of the disjointed Level 1 elements into a seamless comprehension of the current situation (Level 2 SA). Finally, the ability to project the future actions of the elements in the environment, in the short term, is what forms the third and highest level of situation awareness (Level 3 SA).

Situation awareness is not new. In fact, it has always been needed in order for people to perform tasks effectively and accurately. However, as time passed, the physical tasks of old were replaced by more elaborate perceptual and cognitive tasks. With the coming of the machine age, emphasis shifted towards creating a new class of tools to help people perform tasks, primarily of a physical nature, more easily. The computer age and the information age quickly followed the machine age and the tools created by engineers suddenly became more complex, shifting focus from physical tasks that dominated the machine age to more elaborate perceptual and cognitive tasks associated with the ever growing dependence on computer interfaces. Unfortunately, when confronted with large quantities of data, supplied by the computers that have become a part of everyday life, many operators may be even less informed then ever before, lending support to Endsley's (2000) claim of an ever widening "information gap" between advanced systems and those humans sitting at the controls. Today's aircraft pilots, air traffic controllers, and power plant operators must perceive and comprehend a dazzling and bewildering array of dynamic data that, by definition, is always changing. Therefore, in today's complex environments, such as the modern flight deck, situation awareness must be maximized in order to ensure errors are minimized (Endsley, 2000). With the promise of even more technology in the future capable of generating an onslaught of information at speeds that exceed human capabilities, it is important that designers employ cognitive engineering principles in their effort to combat man's shortcomings as part of these advanced systems.

In the aviation domain, specifically on the flight deck of modern transport aircraft, the perception of cues, Level 1 SA, is fundamental. Pilots must be aware of critical elements such as terrain, other aircraft, warning lights, navigational data, and system status, along with their relevant characteristics. The likelihood of forming an incorrect internal mental image of the current state of the environment is dramatically escalated without a basic perception of the mission and system critical information. In fact, Jones and Endsley (1996) found that 76% of situation awareness errors in pilots could be traced to problems in perception of the needed information due to either failures or shortcomings in the way systems convey pertinent information or problems with the necessary cognitive process.

Level 2 of situation awareness can only be achieved once the perceptual process of Level 1 SA has taken place. With Level 2 SA, a working understanding of the significance, in light of ones goals becomes apparent to the monitors. For example, during the cruise portion of a flight, if a catastrophic failure of an onboard system occurs it will be conveyed via visible and audible warnings. The pilots must quickly take the holistic picture of the environment formed in Level 1 SA and come to a determination with regards to the airworthiness of the aircraft (Endsley, 2000). According to Flach (1995), a person with Level 2 SA is one that is able to derive operationally relevant meaning and significance from the Level 1 data perceived. The previous example illustrates this transition from Level 1 SA to Level 2 SA as the decision process to determine whether an emergency divert is warranted. Put more simply, Level 2 SA is analogous to having a high level of reading comprehension as compared to just being able to read words (Level 1 SA) (Endsley, 2000). In Jones and Endsley's (1995) research, 20% of situation awareness errors in pilots were found to involve problems with Level 2 SA. This may be as a result of the sheer quantity of variables that must be assimilated and digested in order to form a correct internalized view of the "big" picture.

Most experienced pilots tend to spend a significant amount of their time anticipating possible future occurrences thereby maximizing time and knowledge necessary to decide on the most favorable course of action to meet their objectives. The ability to execute this dynamic cognitive process is what separates Level 2 SA from Level 3 SA. The mark of a skilled expert, according to Endsley (2000), is one who can visualize, maintain, and rely on, future projections of their environment. Since Level 3 SA is the most difficult for pilots to achieve, only 3.4% of situation awareness errors can be attributed to problems with its highest level, according to Jones and Endsley (1995). Of the 3.4% of Level 3 errors, most can be attributed to the over projection of current trends into fictitious emergencies thereby resulting in prudent yet unnecessary actions.

However, the relationship between performance and situation awareness can be a problematic link. Good SA should increase the probability of good decisions and good performance but it is not necessarily guaranteed. Therefore, measuring SA can be complicated.

When measuring situation awareness subjectively, numerical values are typically assigned to the quality of SA during a particular period or event. Unlike other types of SA metrics, subjective estimations can be collected in controlled real world settings. Furthermore, subjective measures offer the ability to accurately gauge situation awareness during the evaluation of design concepts in simulator studies that mimic real world settings (Endsley & Garland, 2000).

One such subjective measure of SA is the Situation Awareness Rating Technique (SART). This self-rating scale is one of the best known and most thoroughly tested subjective techniques for measuring situation awareness. When using SART, one must assume that the operators used some understanding of situations in making decisions, that this understanding is available to consciousness, and that it can be readily made explicit and quantifiable when asked (Gawron, 2000).

In order to develop scales appropriate for this SA measurement process, knowledge elicitation techniques were utilized to determine which elements an aircrew considered to be essential for good SA. From these interviews, ten generic SA constructs emerged that could be clustered into three broad domains. The attentional demand domain is composed of following constructs: instability of situation, variability of situation, and complexity of situation. The second domain, attentional supply, is composed of arousal, spare mental capacity, concentration, and division of attention. Understanding, the third and final domain, incorporates information quantity, information quality, and familiarity (Endsley and Garland, 2000). From these constructs two types of SART were developed. For in-depth subjective ratings a ten dimensional method is preferred where subjects are asked to indicate on a continuous scale their ratings in response to each of the ten constructs listed above, for a given situation. However, the combination of the three broad domains make up an abbreviated and easily applied three dimensional SART scale that can be used when task complexity and the degree of intrusiveness permitted by the measured tasks is minimal, making a shorter scale advantageous. When using a 3-D SART, the subjects will indicate their ratings for the three domains on a continuous 100-millimeter line from low (0 mm) to high (100 mm). In the end, the ratings on the 3-D SART can be combined to create a single value for subjective SA by employing the following formula derived from theoretical considerations of how the three domains interact: SA (calc) = Understanding – (Demand – Supply). For the proposed mission status graphics research, a 3-D SART is preferred due to its unique advantages over other subjective techniques beyond the inherent advantages of subjective measures in general. One advantage of SART is its high level of ecological validity due to the fact that its dimensions were procured directly from operational aircrew. Second, the constructs are general in nature and therefore have the potential to be applied to non-aircrew domains thereby further bolstering validity. And finally, SART data lends itself to easy interpretation when correlated with performance measures. Furthermore, SART is simple to implement, easy to administer, economical, and non-intrusive, when employed in either real world or simulated environments (Endsley & Garland, 2000). However, SART does have limitations as well. The confounding process of having operators rate their own SA without knowing what they don't know or what errors may be present in their internal representations of the situation; the possible influence of their performance on their ratings; and the intermingling of the supply and demand on attention metrics with workload measurement techniques, all serve as potential limitations to the SART method (Endsley, Selcon, Hardiman, & Croft, 1998). In light of the pros and cons, the Situation Awareness Rating Technique (SART) will be used to quantify experimental data on situation awareness for the proposed experiment outlined below. In addition, accuracy questions will be combined with the 3-D SART to qualify the subjective questionnaire and insure that the participants truly do understand the information presented to them.

Looking beyond the accepted definitions and approved measurement methods, fundamentally good situation awareness in the cockpit depends on a pilot's ability to possess and process specific categories of geographical, spatial, system, environmental, and tactical data. This data constitute the five general classes of elements needed for SA; the substructure for the definition and the three distinct levels of SA described above.

1.2 – The Basic Elements of Situation Awareness

Situation awareness, on the modern flight deck, involves identifying what things the aircrew needs to perceive, understand, and project into the future. In general, across many types of aircraft systems, the five general classes of elements are needed in order for situation awareness to be present (Garland, Wise, & Hopkin, 1999). The first class of SA elements required is geographical situation awareness. Geographical SA refers to the location of the aircraft, other aircraft in the vicinity, pertinent terrain features that may impact the flight path, navigational way points including the desired path to destination, climb and descent points, as well as, taxiway and runway arrangements when on the ground. The second class of required elements for good aviation SA is spatial/temporal situation awareness. This class includes variables like altitude, heading, attitude, velocity, flight path, and clearances, combined with aircraft specific performance capabilities. System SA is the third class of situation awareness elements that must be present for a correct visualization of the flight deck environment to be possible. System SA includes system status, functioning, and settings; air traffic control communications; flight modes and automation entries; the impact of malfunctions and system degradation on flight safety; in addition to fuel constraints. Weather formations, icing, ceilings, temperatures, clouds, fog, sun, visibility, turbulence, winds, IFR and VFR conditions and requirements, and overall flight safety combine to make up environmental SA, the fourth class of situation awareness elements required for an overall high level of situation awareness. The fifth and final class of situation awareness elements, critical to the formation of a correct composite SA model, is tactical situation awareness. Tactical SA includes identification, tactical status, type, capabilities, location and flight dynamics of other aircraft; the aircraft's capabilities in relation to other aircraft; and threat detection, prioritization, and projection (Garland, Wise, & Hopkin, 1999). However, it is important to remember that each of the classes of SA elements previously mentioned may not directly map on to Endsley's three levels of situation awareness for all human senses (i.e. aural SA, tactile SA, etc) because a pilot's tasks are primarily visual.

Mission status graphics polar star displays, the focus of this study, are designed to logically group the most pertinent flight parameters critical to spatial and system SA into a one-glance display. Of the elements mentioned previously, MSG will monitor and display information about onboard systems status (e.g. electrical, hydraulic) and mission status (e.g. altitude, fuel). Therefore, it can be reasonably assumed that MSG will facilitate a more rapid perception of cues (Level 1 SA) and a more accurate working understanding of the significance of the perceived elements (Level 2 SA) with respect to the spatial and system parameters it was designed to convey. That is to say, the mission status graphics display, in its current form, is not intended to enhance all five elements of SA described previously but is designed to address spatial and system situation awareness shortfalls that currently plague commercial and general aviation. Also, it is important to note that neither mission status graphics nor polar star displays have been investigated to determine their exact impact on situation awareness thereby creating a need for the research proposed in this paper.

In addition to the basic elements of SA, there are several cognitive factors that can influence situation awareness in both negative and positive ways that must also be considered when designing and testing the next generation of cockpit automation.

1.3 – Cognitive Factors that can Influence Situation Awareness

The modern cockpit poses several challenges to even the most diligent flight crews. Human attention capacity, one of the factors that can influence SA and measured directly in SART, can be and often is strained by information overload, task complexity, and the requisite multi tasking that comes as part of the complex and dynamic aviation environment (Endsley, 2000). Over time, situation awareness may suffer due to the allocation of attention to compelling information drawing it away from less striking information that may be of equal or greater importance. The lack of SA that occurs as a result can lead to poor decision-making that ultimately is the underlying cause of human error.

Perhaps this is one area where the superior capabilities of polar star displays to portray critical parameters more saliently then traditional methods will benefit SA. The asymmetric polygon indicating one or more parameter is out of bounds, vertices that change color to indicate problem severity, and the normal operating range reference circle, all "pop-out" out of the visual scene to create emergent features that lead to pre-attentive visual processing (Pomerantz & Pristach, 1989). Furthermore, the simplicity and the clarity of the uncluttered polar star display format supports rapid information transfer to the pilot; in one glance, the critical mission and system parameters can be viewed speeding up the perceptual process of Level 1 SA. Achieving a working understanding of the perceived elements (Level 2 SA) can then be rapidly accomplished by comparing each vertex to the reference circle. This allows the pilot to spend more time anticipating possible future problems, leaving more decision time to arrive at the most favorable course of action and final result (Level 3 SA).

Poor SA resulting from attention problems in acquiring data, as evidenced by Endsley's (1995) review of NTSB accident reports that showed that 31% of accidents involving human error were due to this factor. In order to avoid such errors, pilots typically employ a process of information sampling to bypass attention limits, according to Endsley (1995). This allows them to attend to information in a rapid sequence following a predetermined pattern stored in long-term memory with consideration given to the relative priority of the data and the frequency with which the data changes. However, humans do not always optimally sample the information presented before them, demonstrating a need for a display like MSG that logically groups critical parameters on one display thereby greatly reducing the size of a pilots scan pattern and the time required for information sampling. Furthermore, the ever-present problem of information overload can also lead the pilots to alter their normal sampling pattern causing them to allocate too much attention to one or more elements while neglecting the other elements in the environment that may be of equal or greater importance. In order to overcome attention problems and correctly know which information to focus on and which information can be ignored, the pilot(s) must have, at some level, an understanding about all of the data as a whole, that is to say they must possess the "big" picture (Endsley, 2000). In addition, the speed and accuracy with which information is perceived during Level 1 situation awareness can be affected by the contents of both working memory and long-term memory through the presence of preexisting knowledge of the location of specific information, the form which the information takes, and the element specific characteristics of the information (Davis, Kramer, & Graham, 1983). With mission status graphics, the contents of working and long-term memory would be reduced since the location of specific information, the form it takes, and its characteristics would be the same across many of the critical flight parameters thereby shrinking the scan pattern, reducing the time needed to view elements, and overall improving the accuracy of the perceptual process.

Another limiting cognitive factor affecting situation awareness is working memory. Level 2 SA requires that a pilot must combine new data with existing knowledge in working memory to successfully paint a composite mental picture of the current state of his or her aircraft. According to Miller (1956), the human working memory is capable of maintaining a "magic number 7 plus or minus 2" chunks of information, at one time. Millers' analysis implies that most or all limits on mental processes can be attributed to a single source. Functionally, working memory is where all cognitive operations receive their data and produce outputs or responses. Furthermore, working memory allows a pilot to retain relevant information like airspeed, altitude, heading, and tail-number, for tactical operations. In addition, working memory relies heavily on long-term memory for the cognitive tasks of information organization, decision-making, and problem solving. Time dependant processes like attention capacity and forgetting all serve as limitations to working memory. Therefore, working memory clearly permeates every aspect of a pilot's ability to assimilate and process information. Subsequently, achieving Level 2 SA in such environments can often tax an already overloaded working memory, thereby stretching a pilot's attention capacity leaving fewer resources to direct toward the process of acquiring new data that may be occurring simultaneously. Reaching Level 3 SA similarly affects working memory because forecasting future status and predicting the appropriate course of action to take will burden working memory as well (Endsley, 1996). The prediction of future states imposes a strong load on working memory by requiring the maintenance of current conditions, future conditions, and the actions appropriate to address the predicted future conditions, according to Wickens (1984). Therefore, it becomes clear that this heavy and highly undesirable load that the working memory is forced to endure, especially in the higher levels of situation awareness, can seriously impact the formulation and selection of responses in addition to hindering simultaneous and subsequent actions or decisions.

Just as overload in working memory can lead to decrements in situation awareness, the type of information displayed and the manner in which it's conveyed can also affect overall situation awareness.

1.4 – The Role of Mental Processing and Mechanisms in the Formation of Situation Awareness

. When presented and asked to process dynamic and complex information people may switch between data-driven and goal-driven processing. With a data-driven or bottom-up processing, a variety of environmental features are detected and their inherent properties are used to determine which information will receive further focalized attention and processing (Endsley, 2000). Cue salience plays an important role in this process and to situation awareness as a whole, by impacting which segments of the environment receive attention. When people function in a goal-driven or top-down fashion, SA can be influenced by the operator's goals and expectations, which in turn can have a direct influence on how attention is directed, how data are perceived, and eventually how the data are interpreted. In the cockpit, an aircrew's goals and plans primarily direct their attention to the mission critical parameters that must be integrated, interpreted, and acted upon, in light of these goals, to form and maintain level 2 SA. However, it is possible to observe the interchange between top-down and bottom-up processing, allowing the pilots to process large quantities of information dynamically in the cockpit. The ability of an aircrew to juggle multiple competing goals effectively comes with experience and maintaining these goals has been associated with distributed attention, critical in the aviation domain where human performance has a direct effect on safety (Endsley, 2000).

Yet another manner in which situation awareness can be affected is through automaticity in processing information. Automaticity, a characteristic of cognitive processing in which practiced consistent behaviors are performed rapidly, with minimal effort, and with automatic allocation of attention to the processing of the stimulus, has its advantages and disadvantages. It is often useful in overcoming attention limitations but can simultaneously leave the pilots susceptible to missing novel stimuli that may impact the safety of flight (i.e. system or mission parameter deviations) (Garland, Wise, & Hopkin, 1999). In complex environments, like the modern flight deck, it is easy for actions to become habitual over time, demanding less attention then required. When the stimulus changes ever so slightly it is possible for the pilots to miss it and carry out the habitual action. Automaticity can impact every aspect of a flight from air traffic control clearances, altitude changes, system performance properties, etc. As time goes by and pilot experience increases, automatic processes tend to be fast, autonomous, effortless, and can occur without conscious awareness or attention (Logan, 1988). However, automatic processing, for the most part, is advantageous in that it provides reliable performance with minimal attention allocation even though it may foster an increased risk by making highly experienced pilots less responsive to new stimuli because automatic processes operate with limited use of feedback. Maintaining a high level of situation awareness when using automatic processing is crucial in order to avoid non-typical situations that may decrease decision-making timelines and overall decision effectiveness (Endsley, 2000).

By providing pilots with a polar star display like mission status graphics, it may be possible to reduce the transitions pilots must perform between goal-driven and data-driven processing required by them to maintain situation awareness in a dynamic and information rich environment. Such a reduction could translate directly into performance improvements like a decrease in failure detection time, while improving the reliability of automaticity by fostering a more accurate and complete understanding of the "big" picture in the minds of the pilots sitting at the controls.

Engineers and designers of the next generation of cockpit avionics and automation have a daunting responsibility to improve situation awareness on the modern flight deck. Careful consideration must be given to human factors when determining ways to: effectively deliver critical cues, ensure and safeguard expectation of accuracy; develop systems for assisting pilots in deploying attention efficiently; develop methods for preventing the disruption of attention especially during non-normal events with high workload and stress factors; and to develop systems that are compatible in achieving the aircrew's goals. Each new piece of technology provides a potential advantage for delivering new information, more accurate information, new ways of providing or displaying information, or the reduction of crew workload (Endsley, 1996). However, that is not to say that each new system may not also a ffect SA in unpredicted a nd possibly negative ways. Innumerable factors surrounding the implementation and integration of new technology and design concepts may act to degrade situation awareness. To prevent adverse affects from future automation, significant care must be taken to evaluate the impact of proposed systems on the overall situation awareness of its operators. It is only through thorough testing and carefully controlled studies that the actual significance of new technology can be ascertained (Garland, Wise, & Hopkin, 1999).

Aircraft are evolving with every new breakthrough in technology. More systems are being added which implies that more parameters will need to be monitored by the pilots in their quest to achieve and maintain high levels of situation awareness. Since instrument panel space is limited, and may become even smaller in the next few decades due to aerodynamic constraints, simply adding more digital representation of analog "steam-gauge" style displays will not be an option. One possible way to employ technology to improve situation awareness on the modern flight deck is to use polar-star displays that will show deviations from normal in a more salient manner by employing a polygon's vertices to report pertinent mission and systems values.

2.0 – Background and Theory of Polar Star Displays and Mission Status Graphics

2.1– Polar Star Displays

The notion of displaying critical parameters via a polar graphic plot has been around for decades. First employed in the domain of nuclear power plants, in 1981, Westinghouse Electric Corporation, under contract with the Electric Power Research Institute (EPRI), investigated a new format for displaying various nuclear power plant safety parameters that involved employing what they called an "Iconic Polargraphic Safety Parameter Display System" that uses the points of a polygon on a polar graph plot to depict system status.

After the accident at the Three Mile Island nuclear power plant in Pennsylvania during March 1979, an assortment of investigations revealed significant deficiencies in the area of man-machine interface design. More specifically, the preexisting methods of data display failed to present a concise picture of the overall safety state of the power plant to the operators. In response to the events at Three Mile Island a variety of safety parameter display systems (SPDS) were researched and designed with the overall goal of conveying the safety state of the power plant in a concise and timely manner in order to enhance detection and assessment of potential threats that may compromise safety (Woods, Wise, & Hanes, 1981). From the wide range of proposed SPDS prototypes, Westinghouse chose two concepts for the EPRI study.

The first SPDS, deemed Safety Panel A, brought together several key variables grouped according to five major safety functions: primary coolant inventory, core heat removal, secondary heat removal, reactivity control, and radioactive containment integrity. The aforementioned variables were displayed as a thirty minute trend using a standard Cartesian graph format, plotted on a logarithmic scale to provide operators with wide range indications about overall plant status (Woods, Wise, & Hanes, 1981).

The second SPDS, Safety Panel B, used an iconic polar star display format to present a comprehensive summary of plant health. The display took on the form of an octagon with each of the eight spokes in the figure representing the scale for a particular safety parameter. Normal conditions were plotted on the polar graph as fixed points equidistant from the center of the plot. The resulting regular geometric pattern created a frame of reference from which to judge abnormal conditions. Parameters with increasing magnitudes were plotted as points further away from the center of the figure while parameters with decreasing magnitudes were potted as points closer to the center of the plot. Furthermore, the reference parameters were dynamically scaled as a function of operational mode of the power plant so that the reference figure was always perfectly octagonal. Therefore, abnormal conditions would result in an irregular geometric pattern that clearly would deviate from the reference octagon (Woods, Wise, & Hanes, 1981).

Westinghouse went on to conduct an experiment at a nuclear power plant simulator designed primarily for operator training. In addition, the experiment was created to mesh the study with a previously scheduled regular training session for a four-loop pressurized water-cooled reactor in both normal and non-normal states. Eight crews of three experienced, licensed operators per crew, at the simulator for a routine five-day refresher course, served as subjects for the Westinghouse experiment. Each crew, according to the experimental design, experienced all sixteen abnormal reactor events that consisted of both diagnostic problems and multiple failure events. Four of the crews were run through the sixteen scenarios with only the existing control panel whereas the remaining four crews experienced the scenarios with one of the SPDS prototypes added to the standard control room. Only one SPDS was available per crew and experimental control was achieved through counterbalancing transients and SPDS prototypes across crews (Woods, Wise, & Hanes, 1981).

Data was collected from two sources by the researchers. The first source was a computer record of all control actions and process parameter values during each event. The second source of data collected during the experiment was from observation of crew behavior from video and audio recordings of each event. Woods, Wise, and Hanes' (1981) cumulative, untraditional, three-fold data analysis focused on how the prototype SPDS aided operator performance. First, event timelines were produced for each scenario that crews encountered, based on the computer records and video/audio of each of the events. By mixing together these data sources a record of each data collection run was created that correlated plant state, operator problem solving behavior, and operator actions. Second, decision charts that captured the links between decision and operator actions (e.g. crew strategy) were compiled to highlight the cumulative decision making process for each event. The third part of the data analysis process was to separate categories of key decisions and identify patterns of SPDS usage as a function of the predetermined decision categories (Woods, Wise, & Hanes, 1981).

The authors stated that the decision analysis approach helped achieve the experimental goals of this nuclear power plant control room evaluation, according to the researchers, by helping to assess how the SPDS prototypes influenced operator behavior. " In the domain of nuclear power plant operation, it is not enough to know what the operator did, it's also important to understand the decision/action context so future training modules can be modified appropriately to reflect what was learned in this study." according to Woods, Wise, and Hanes (1981). By knowing the decision context, operator actions were aggregated into decision/action paths thereby allowing the researchers to evaluate the SPDS in terms of the role the addition played in the evolution of the decision paths. This was a critical clue to the researchers in their efforts to refine the decision making process that nuclear power plant operators undertake when troubleshooting problems (Woods, Wise, & Hanes, 1981).

The results of the Westinghouse decision analysis study found no clear quantitative or qualitative benefits with one SPDS over the other. In other words Safety Panel A did not do any better than Safety Panel B, and vice-versa, but the results of the decision analysis did suggested that in the test situations where an SPDS was used the crew was able to return the plant to a safe configuration sooner and with fewer parameter excursions than in situations when the SPDS was either not available or not utilized. However, a complete safety panel effectiveness evaluation based on plant state was not performed because some crews either chose not to use the panel or were unsuccessful accessing the safety panel. During the experiment, the safety panels – relatively unfamiliar tools, attempted to compete with a very familiar tool – the standard control board instrumentation. As experimenters expected, the SPDS were not used at times when it could have provided useful data to the operators. Primarily, the person acting as shift supervisor tended to access the safety display panels more frequently then the other two support crew members (Woods, Wise, & Hanes, 1981). A multitude of factors such as display placement, display access, crew training, standard control room procedures, and individual crew differences had an impact on the usage, or lack thereof, of the SBDS prototypes. The researchers went on to say that SPDS usage might have been higher had the panel been located more centrally. However, the researchers did not state how they arrived at these conclusions.

Overall, according to Woods, Wise, & Hanes, (1981), the Westinghouse experiment achieved its major objectives. The experimenters stated that the analysis of key decisions made by the crews while responding to simulated plant accidents provided important insights about nuclear power plant crew performance in the domains of crew decision behavior, safety panel usage, decision analysis, and the use of a training simulator as a research tool. Furthermore, crew decision behavior was found to be based on a bottom-up, or data-driven, view of the control room panel. Safety panel usage occurred successfully on most trials, as demonstrated by the fact that the shift supervisor frequently accessed the safety panel, with numerous recorded instances where reference to the SPDS aided in problem recognition and plant control tasks but were little or no help with crew decision planning. "The decision analysis method developed and applied in this research proved to be a very useful tool for identifying crew decisions and actions," according to Woods, Wise, and Hanes (1981). In addition, it provided a context for the researchers that helped them understand the basis for their decisions and actions along an event timeline. Finally, according to the research, it became clear that a training simulator could be used during normal training as an effective tool for evaluating potential control room modifications such as the Safety Parameter Display Systems in their experiment. The experimenters went on to state that the limited use of the SPDS was as a result of: variations in crew styles, differences among crew response strategies, the small number of operator difficulties, the amount of wide variation of safety panel usage, the small sample of crews, the difficulties of defining meaningful performance measures, and the limitations imposed by the retraining program in which the experiment had to be incorporated (Woods, Wise, & Hanes, 1981).

This research clearly indicates that integrated information displays, like safety parameter displays systems, have the potential to enhance situation awareness in complex environments where numerous parameters need to monitored and projected into the future by the operator because of the inherent capabilities of the SPDS to logically display critical parameters in a more salient and clear method. The decision analysis approach utilized in this study showed that by presenting the needed information about status in a more salient manner on the SPDS panel the often complicated cognitive functions of problem recognition and control tasks could be simplified. Admittedly, the authors of the EPRI report call for more research into the SPDS prototypes. However, it was not until recently that one of the display types was resurrected for further research, this time for an aerospace application.

2.2 – Mission Status Graphics

The flight deck of an aircraft is an extremely complex environment – especially during busy non-normal situations, similar to the control room in nuclear power plants. Situation awareness often suffers as this complexity increases. In an information rich environment, like the cockpit of an aircraft, individual details can often become compelling, causing the human to overlook other prominent sources of information. In environments such as this, the operators need a way to quickly assess the situation when critical information is spread across multiple displays (Trujillo & Schutte, 1999). Previous research has shown that automated monitors, like the terrain collision avoidance system (TCAS) recently approved by the FAA, can aid humans in recognizing and dealing with failures or emergencies (Trujillo, 2002). Polar star displays are an ideal candidate for implementation as an automated monitor due to its emergent features mentioned earlier. Global failure detection can be effectively supported by these emergent features if they clearly carry information about important system states, according to Buttigieg and Sanderson (1991). Polar star displays, by design, consist of a polygon where each vertex of the polygon represents an abstracted parameter as an emergent feature of the display (Woods, Wise, & Hanes, 1981). When all the parameters are in the normal or expected range, the polygon is regular (i.e. symmetrical) and can be reinforced by the addition of a dotted circle added around the polygon representing the normal operating range. During non-normal situations, the parameters deviate from the reference circle either outwardly or inwardly respective to the sign of the value of the parameter with regard to the normal or expected value. Therefore, an irregular polygon indicates a possible problem (Trujillo & Schutte, 1999).

Recently, NASA has resurrected the polar star display for application to the next generation of glass cockpit avionics research. Dubbed Mission Status Graphics (MSG), the display consists of two polar star graphics, one mission oriented and the other system oriented. The mission graphic consists of parameters like altitude, speed, fuel, course, heading, and vertical speed. Similarly, the system graphic consists of parameters like hydraulic, electrical, avionics, communication, engine, and fuel, systems. The figure below shows hypothetical polar star mission status graphics displays (Figure 2).

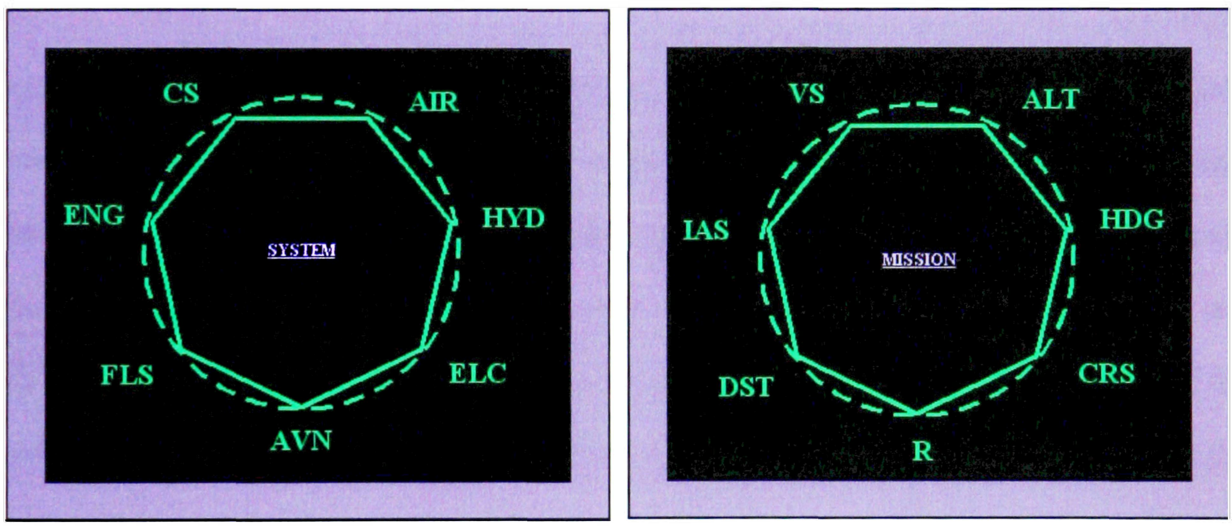


Figure 2 - Hypothetical polar star mission status graphics displays

The manner in which these displays are designed is under some scrutiny. For example, Bartolone and Trujillo (2002), conducted a survey of forty-one glass cockpit airline transport pilots investigating various aspects of a hypothetical mission status graphics display. The survey results indicated that the MSG system display should indicate that a parameter is out of bounds by advancing and retreating the vertex according to the respective system/component value in a continuously updating (i.e. free-flowing) manner. Pilots prefer to confirm receipt of the information by depressing an "acknowledgement button" on the MSG display screen rather then allowing problem resolution to act as acknowledgment. The survey also showed preference for the MSG display panel to be the same size as current glass cockpit CRT's and should be ideally located in the center of the primary instrument panel for clear viewing from either the pilot or co-pilot positions. Furthermore, the pilots surveyed felt MSG would be beneficial for observation, problem investigation and isolation, and overall that the system would be a valuable item to include of future flight decks (Bartolone & Trujillo, 2002).

After receiving a favorable response to the mission status graphics display from the glass-cockpit commercial airline pilots surveyed, NASA began a series of controlled experiments incorporating the MSG display into a high-fidelity flight simulator. To date, the findings of only one experiment have been published. This initial experiment was designed to investigate two issues with regards to how the display should move: (1) whether the display movements should be continuous or discrete, and (2) if the parameters that make up each vertex should move in one direction only (independent of sign) or move in both directions with movement indicative of the parameters sign (Trujillo, 2002). The within subject variables for the experiment were the movement type and movement direction of the vertices during six experimental trials.

During each trial, only one parameter would reach an "alert" condition and then it would maintain that condition until the subject clicked the stop button indicating that he was ready to answer questions about what was just observed. The subjects were then asked to rate, on continuous Likert-scales, their responses to five questions about how easy or difficult it was to use the MSG display. Furthermore, the subjects were encouraged to use a figure provided to them that detailed the parameters that made up each vertex in order to provide a frame of reference and enhance realism of the study. Once the subject submitted their answers for the first data trial, the next trial would begin. The process was repeated for the remaining trials for the first display and then would begin all over again for the second display, following the within subjects experimental design. After all the data runs were complete, the subject was asked to answer the NASA-TLX questionnaire so a measure of workload could be established (Trujillo, 2002).

In this experiment, several dependent measures were recorded. The amount of time spent looking at the display and the amount of time to answer the associated questions were recorded by the computer as objective data measures; the computers clock started and stopped each time the subject transitioned between scenario and questionnaire or vice versa. The rankings the subjects provided during the display questionnaires, NASA-TLX, and final comprehensive questionnaire, were recorded as the subjective dependent measures for the experiment.

Based on the results of the experiment, Trujillo concluded that relative movement of the polar star display is best. Not only did subjects prefer this type of display movement, statistical evidence showed that they actually performed better with relative movement direction of the polar graphic. Unfortunately, no clear advantage was evident for either continuous or discrete movement type. Therefore, Trujillo determined that future NASA Langley experiments involving the MSG display would feature a continuous-relative polar-star graphic and will occur in a high-fidelity fully programmable flight simulator running a full mission simulation. This real world setting would help researchers determine whether or not the MSG display does, in fact, aid in monitoring aircraft mission and system health and overall problem detection and diagnosis (Trujillo, 2002). Although situation awareness was not addressed with this initial NASA research, the fact the subjects in the NASA experiment found the display useful indicates that further research in this domain is warranted, hence the need for the research in this thesis.

Due to mission status graphics concise integration of pertinent information, its strong emergent features, and its potential to enhance information processing, it is believed that pilot situation awareness will improve. Although none of the information included in the MSG display is new, it represents the next step in cognitively organized display technology designed with regard to human factors from the out set. The addition of another display panel to the modern flight deck is a precarious decision. However, when the display has the potential to increase situation awareness and overall have a positive impact the safety of flight, industry cannot ignore it. Thus far, Trujillo's research has demonstrated that the MSG displays can be useful for integrating complex information in a meaningful manner, but the link to SA hasn't been made yet. That is the purpose of this study. Pilots are being overloaded with information in an intense and stressful environment. However, the mission status graphics display has the ability to improve the delicate relationship between machine and operator as has been shown in previous polar star display research and the underpinning of situation awareness outlined previously. Furthermore, integrated display technology already in use in corporate and commercial aviation cockpits like the next generation of weather displays, terrain avoidance displays, navigation displays, and traffic avoidance displays, have already demonstrated that automated monitor type systems that group logical data together efficiently can serve to enhance situation awareness. Therefore, it is logical to assume that the mission status graphics polar star display, with its integrated data display format, will also improve situation awareness. However, investigating the application of integrated displays to a general aviation cockpit has thus far not been considered; there are many benefits for such an application.

All pilots must first begin their flight training in general aviation aircraft making this environment ideal for the introduction of a display such as mission status graphics. During training, keeping your head up and looking outside the aircraft is critical, however, maintaining situation awareness is also of equal importance. With the incorporation of a MSG display, pilots will be able to acquire, at a glance, the overall mission and system health of the aircraft they are piloting without the time and resource intensive process of data assimilation from a myriad of dials, gauges, screens, and displays.

The proposed study outlined below is expected to uncover improvements in pilot failure detection time, situation assessment, and situation awareness. According to Endsley (2000), the problem with today's systems is not a lack of information, but finding what is needed when it is needed. An ever-widening gap exists between the illogically scattered volumes of data being produced by today's avionics and a pilot's ability to find the data that are important. Endsley (2000), calls this the "information gap" and labels it as a primary challenge to situation awareness. Therefore, it is up to the designers of future systems to provide the operator with the needed information and capabilities while insuring that it is provided in a way that is useable cognitively as well as physically (Endsley, 2000).

3.0 – Hypotheses

3.1 – Failure Detection Time

Based on the experiment outlined below and the previous research in the domains of situation awareness and polar star displays, it is expected that the addition of the mission status graphics display will improve performance of pilots with respect to time required for failure detection. Although failure detection time specifically has not been measured in previous polar star research, Woods, Wise, and Hanes' (1981), investigation of safety parameter display systems (SPDS) did show that the crew was able to return the nuclear power plant to a safe configuration sooner and with fewer parameter excursions using an SPDS display than in situations when the SPDS was either not available or not utilized.

3.2 – Situation Awareness

Situation awareness (SA) will be improved for the instrument panels that include the mission status graphics (MSG) polar star display compared to the conventional instrument panels as measured by scores on the SART questionnaires administered to each subject at the end of each trial. It is important to remember that situation awareness has not yet been measured for polar star displays, making this research long overdue. Furthermore, all of the scenarios utilized in the experiment are expected to demonstrate situation awareness in the subjects to some degree based on the measure of their responses to the post scenario SART questions.

3.3 – Scenario Type

Since mission status graphics are designed to integrate critical mission and systems parameters onto one display, the evaluation of the display will involve seven mission and seven system scenarios, constituting the two levels of the independent variable "scenario type". However, such an application of polar star displays has not yet been researched there is no clear evidence to indicate that mission status graphics will be more useful for one type of scenario over another. Furthermore, it is hypothesized that there will be no interaction between the two independent variables of scenario type and display type.

4.0 – Methods

4.1 – Participants

As with any credible scientific research, subject selection is critical. For the proposed experiment, volunteers from the Embry Riddle Aeronautical University Daytona Beach Campus were used. Since the display being evaluated in this experiment was aimed toward application in future general aviation cockpits, only Aeronautical Science majors (those training to become professional pilots) were considered for subject selection. A total of ten subjects were used for data collection in the pilot study and each possessed a minimum of a FAA Private Pilot License with an instrument rating due to the instrument reading tasks required for this experiment.

Normally, a statistical power analysis would be performed to ensure enough subjects to exceed a statistical power of 0.80. However, in this case, the lack of previous research in the domain of mission status graphics polar star displays precluded the possibility of performing such an estimate. Therefore, an investigative pilot study was performed in order to arrive at an estimate of sample size for a follow-up experiment.

4.2 – Materials and Apparatus

To perform the experiment, several items needed to be acquired or created. A PC running customized software capable of displaying high-resolution picture files of a generic general aviation aircraft instrument panel was the primary piece of experimental equipment. In addition, fourteen uniquely different scenarios that correspond to realistic in-flight events common to general aviation aircraft were scripted. The scripted scenarios were based on similar scenarios scripted for a dynamic high fidelity Cessna Citation X flight simulator experiment scheduled by NASA Langley for the near future. However, since the research called for a static scan of a generic general aviation (GA) instrument panel, only the failure or event concepts are similar between this study and the one planned by NASA. With that said, two slides of the static GA "instrument panel view" for each scenario were created. One slide had the MSG display included in the "instrument panel view" (Figure 3), the other had a weather display in place of the MSG display (Figure 4). In this case, the weather display served as ambiguous filler for the space occupied by the MSG display in the experimental instrument panel, thereby achieving balance between the panels. A simple timer within the software measured the subjects' failure detection time to each scenario and the time was recorded in a hidden file for analysis. Worksheets of the standard 3-D SART questionnaires (Appendix A) and situation accuracy questions were created as well, so that situation awareness measures could be quantified and qualified before being included in the data analysis. Finally, a laminated copy of the "all conditions normal" instrument panel with the appropriate experimental display were created and provided for each subject to refer to while participating in the experiment.

The generic general aviation instrument panels used in this experiment were all composed of the same gauges and instruments with the exception of the MSG display. Each gauge or instrument was capable of being set to depict the necessary information appropriate for each experimental scenario so that the entire panel would contain the same information as if the scenario were a real world situation. The gauges and instruments that made up each panel were identical to those found in a pressurized single engine general aviation aircraft with retractable landing gear as viewed from the pilot in command position (Figures 3 & 4).

4.3 – Experimental Design

A randomized 2 x 2 mixed factorial design was adopted for this experiment. This design called for the random assignment of subjects into two experimental groups. Each group was exposed to the appropriate levels of both the display type and scenario type independent variables, simultaneously. The control group saw the "instrument panel view" slide for each of the fourteen different scenarios (7 mission and 7 system) with the weather display in place of the MSG display, as seen in Figure 3. The experimental group was run through the same fourteen scenarios (7 mission and 7 system) as the first group with the addition of the MSG display to the "instrument panel view" in place of the weather display, as seen in Figure 4. The dependant variables for this experiment were the time that elapses between the onset of the scenario and the point when the subject acknowledged the detection of the problem (i.e. failure detection time) and the subject's perceived situation awareness (3-D SART scales). Scenario type and the presence of the MSG display acted as the independent variables as it was unknown whether MSG would aid the subjects equally regardless of scenario type or more for mission or systems situation awareness.

The scenarios that were employed for this research constituted an assortment of common system failures and mission deviations within the general aviation domain. Prior to entering a scenario, the subjects had knowledge of what the status of the aircraft should be. When the scenario began, it was the subject's job to scan the instrument panel, perceive the data (Level 1 SA), and comprehend the data (Level 2 SA). Once this had occurred and the subject was confident they knew what the scenario depicted, they acknowledged such by clicking stop, the scenario was terminated, and the SART questionnaire designed to quantify SA was administered.

4.4 – Experimental Procedures

Upon arrival, every subject was greeted and asked to read and sign a consent form. Individually, each subject was exposed to the appropriate level of the independent variable based on a group assignment by the experimenter. For the pilot study, the subjects were scheduled to sit for the experiment in two groups of five subjects per group. In order to avoid the difficulties of group scheduling, the subjects for the follow-up study were allowed to sit for the experiment individually when it was convenient for him or her.

For both experiments, each subject was seated in front of a PC, the software was initialized, the subject viewed the first slide, when ready he or she clicked the stop button indicating that they knew the state of the aircraft, the slide went black, the failure detection time was recorded by the software, and finally the subject responded to the post scenario 3-D SART and situation accuracy questionnaire. Each subject's responses to the three metrics of the 3-D SART were recorded by the subject drawing a short perpendicular line through the continuous 100-millimeter scales for each of the three measures: understanding, demand on attentional resources, and supply of attentional resources (Appendix A). This data was later translated into numerical values in the form of distance from zero in millimeters and input into the accepted formula of SA (calc) = Understanding – (Demand – Supply). Finally, the numerical value of SA was combined with the accuracy data (accuracy questionnaire) and performance data from the experiment (failure detection time) and a composite overview of each subject's situation awareness was arrived at for each scenario in each level of the experimental variable.

Once all the necessary data were collected from a subject, he or she was debriefed, thanked, and allowed to go. The elapsed failure detection time and each subject's SART responses were coded for statistical analysis. Furthermore, if a subject indicated they knew the status of the aircraft, yet gave an incorrect response with regard to status via the post scenario accuracy questions, their data was still recorded for analysis. Subject scheduling differed from the pilot study to the follow-up study. In the pilot study, the subjects performed the experiment in two groups of 5 whereas in the follow-up study each subject was scheduled individually.

Figure 3 – "Instrument Panel View" with Mission Status Graphics Display

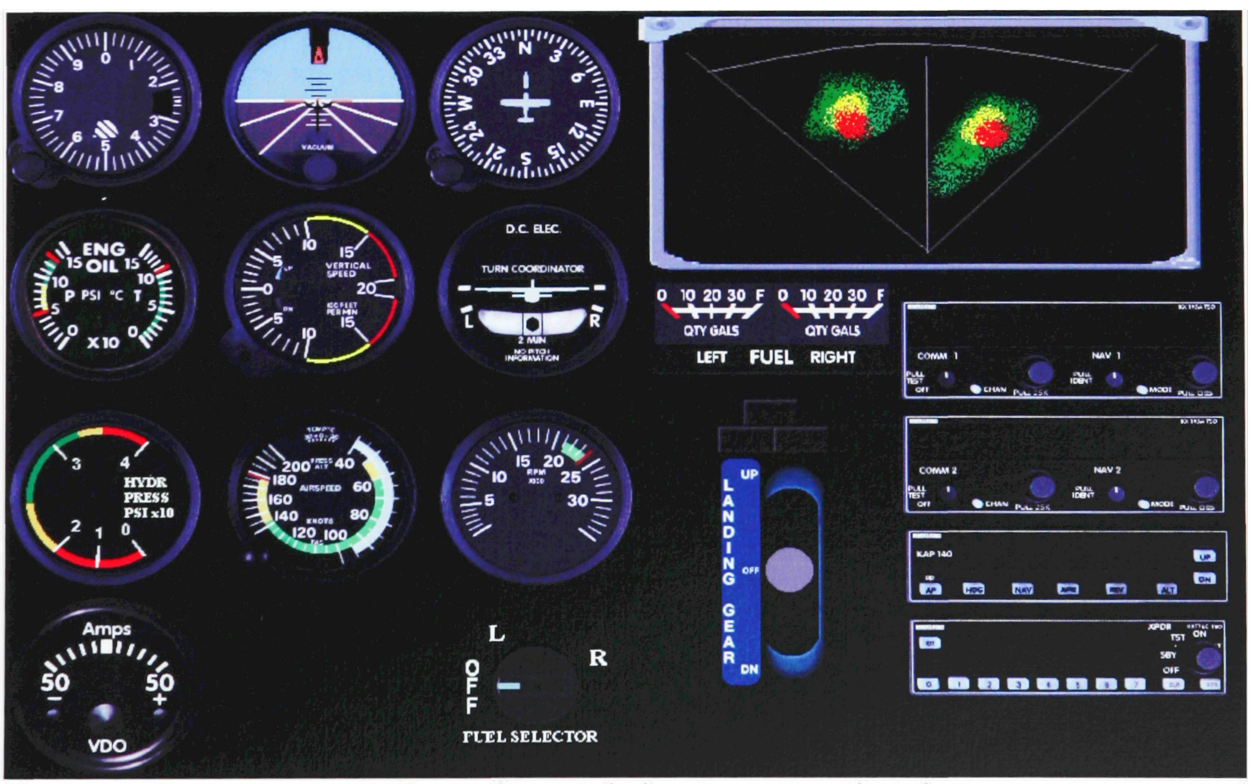


Figure 4 – "Instrument Panel View" without Mission Status Graphics Display

5.0 – Results

5.1 – Experiment 1

The data collected during Experiment 1 for failure detection time, SART scores, and accuracy, were organized so that the data gained for each subject were grouped by SCENARIO TYPE, (the within subjects variable), and by DISPLAY TYPE, (the between subjects variable). With respect to SCENARIO TYPE (i.e. mission scenario vs. system scenario), the means for failure detection time and SART were calculated for each subject. The means were then entered into SPSS's repeated measures analysis component with SCENARIO TYPE as the repeated measure. The accuracy questions that followed each scenario were not statistically analyzed.

This experiment was initially intended to serve as a pilot study in order to estimate an appropriate sample size for a subsequent experiment. Ten Embry Riddle Aeronautical University students working towards their Aeronautical Science bachelor degrees were recruited to serve as subjects for this experiment. The tables (1 & 2) below list the results of a brief background questionnaire administered to each volunteer before the experiment.

Table 1 Experiment 1: Average Age and Flight Experience

Display	Demographic	Mean	Std. Deviation	N
WX	Age (yrs)	22.6	1.14	5
	Experience (hrs)	308.00	61.09	
MSG	Age (yrs)	22.0	2.00	5
	Experience (hrs)	345.00	127.96	

Table 2 - Experiment 1: Subject Gender and Training Location

	Gender		Training Location	
Display	Male	Female	ERAU only	ERAU & Non-ERAU
WX	5	0	3	2
MSG	5	0	1	4

Failure detection time was found to be substantially larger in this experiment for those subjects whose generic instrument panel did not include the Mission Status Graphics (MSG) polar star display; DISPLAY TYPE, $F(1,8) = 26.85$, $p<0.001$. Furthermore, in the group of subjects who saw the generic weather display in place of MSG on their instrument panels, failure detection time was larger for system failure or deviation detection than for mission failure or deviation detection as evidenced by the statistically significant factor of SCENARIO TYPE, $F(1,8) = 49.18$, $p<0.001$. Within the group of subjects who saw the MSG, display failure detection time stayed virtually the same across both mission and system scenarios. Essentially, those subjects in the MSG display group were, on average, able to detect system failures or deviations four times faster then those without MSG. Similarly, mission deviations or failures were, on average, detected twice as quickly by those subjects with MSG then those without. These unequal variations in detection time are supported by the statistically significant interaction of DISPLAY TYPE by SCENARIO TYPE, $F(1,8) = 48.59$, $p<0.001$. Additional output from SPSS can be seen in the table of means (Table 3) and the statistical source table below (Table 4).

Table 3 – Experiment 1: Table of Means for Failure Detection Time

Failure Detection Time	Display Condition	Mean (ms)	Std. Deviation	N
Mission Scenarios	WX Display	7084.63	2632.48	5
	MSG Display	3088.63	238.36	5
System Scenarios	WX Display	12106.40	3149.13	5
	MSG Display	3103.60	342.52	5

Table 4 – Experiment 1: Source Table for Failure Detection Time

Source	df	SS	MS	F	Eta^2	Observed Power
Display	1	211211002	211211002	26.85**	0.77	0.99
Error	8	629224927	7865616			
Scenario	1	31710973	31710973	49.17**	0.86	1.00
Interaction	1	31335058	31335058	48.59**	0.85	1.00
Error	8	5159496	644937			
Total	19	908641455	282767586			

**($p < 0.001$)

The Situation Awareness Rating Technique (SART) provided a numerical estimate of subjective situation awareness for each scenario viewed by the subjects. In general, the larger the value returned for SA the better the subjects' situation awareness. The subject's responses to the SART metrics were also analyzed via a repeated measures ANOVA, with SCENARIO TYPE again serving as the repeated measure. A main effect for DISPLAY TYPE was found however, there was no effect for SCENARIO TYPE or the interaction of DISPLAY TYPE by SCENARIO TYPE. SA was substantially larger for the MSG display group than the weather display group, as evidenced by the statistically significant mean differences for the between subjects variable DISPLAY TYPE, $F(1,8) = 126.26$, $p<0.001$. For both mission and system scenarios, the average SA was nearly twice as large for the MSG group as the weather group. Additional statistical data for the SART repeated measures ANOVA can be seen in the table of means (Table 5) and the statistical source table (Table 6) below.

Table 5 – Experiment 1: Table of Means for SA Scores

SA	Display Condition	Mean	Std. Deviation	N
Mission Scenarios	WX Display	90.29	7.92	5
	MSG Display	172.54	17.04	5
System Scenarios	WX Display	87.77	8.95	5
	MSG Display	167.40	12.13	5

The accuracy questions that followed the 3-D SART on the post scenario questionnaires were not statistically analyzed due to the fact that nearly ever subject responded correctly to the questions for all scenarios presented to them with the exception of the Fuel Low – Left Tank mission scenario. Three subjects in the weather display group incorrectly indicated that "Fuel Low-Left Tank" scenario was a system failure or deviation. Excluding these incorrect responses, every subject was able to classify and identify the failure or deviation seen in each scenario thereby lending support to the subjective SART metrics by insuring that each SA score computed was based on confirmed knowledge of the scenario depicted.

Table 6 – Experiment 1: Source Table for SA Scores

Source	df	SS	MS	F	Eta^2	Observed Power
Display	1	32759	32759	126.26**	0.94	1.00
Error	8	2076	259			
Scenario	1	73	73	2.38	0.23	0.28
Interaction	1	9	9	0.28	0.03	0.08
Error	8	246	31			
Total	19	35162	33131			

**($p < 0.001$)

Table 7 – Experiment 1: Estimates of Effect Size

Measure	Display	Mean	Std. Dev.	Cohen's d	Effect Size
Failure Detection Time (ms)	WX	9595.51	6194.24	1.48	0.59
	MSG	3096.11	618.37		
Situation Awareness	WX	89.03	8.80	5.00	0.93
	MSG	169.97	21.13		

For Experiment 1, estimates of effect size were calculated using Cohen's descriptive method. The values for Cohen's d for Experiment 1 can be seen in Table 7 above. The results indicated that 59% of the variability in the failure detection time variable was explained by the difference in the display type viewed by the subjects in the experiment. In addition, 93% of the variability in situation awareness variable could be accounted for by the difference in the display type viewed by the subjects during the experiment.

5.2 – Experiment 2

Experiment 2 was conducted as a follow-up experiment to Experiment 1. Based on the observations of strong main effects of DISPLAY TYPE for both failure detection time and SA shown by the SPSS output for Experiment 1, the experimental design was not altered. Ten different ERAU Aeronautical Science student volunteers served as subjects for the second experiment. The data collected during Experiment 2 for failure detection time, SART scores, and accuracy, were again organized by SCENARIO TYPE, (the within subjects variable), and DISPLAY TYPE, (the between subjects variable). With respect to SCENARIO TYPE (i.e. mission scenario vs. system scenario), the means for failure detection time and SART were calculated for each subject. The means were then input into SPSS's repeated measures analysis component with SCENARIO TYPE as the repeated measure. Once again, the accuracy questions that followed each scenario were not statistically analyzed. The tables (8 & 9) below list the responses to the background questionnaire administered to each subject prior to the experiment.

Average failure detection time was again more rapid for those subjects in the MSG group than the weather group. For both mission and system scenarios the MSG group detected the failure or deviation three times quicker than those without the benefit of the MSG display. This

Table 8 Experiment 2: Average Age and Flight Experience

Display	Demographic	Mean	Std. Deviation	N
WX	Age (yrs)	21.20	1.64	5
	Experience (hrs)	282.00	43.24	
MSG	Age (yrs)	23.60	5.81	5
	Experience (hrs)	282.00	99.12	

Table 9 - Experiment 2: Gender and Training Location

	Gender		Training Location	
Display	Male	Female	ERAU only	ERAU & Non-ERAU
WX	5	0	2	3
MSG	4	1	3	2

observation is supported by the significant mean differences for the between subjects factor DISPLAY TYPE, $F(1,8) = 28.00$, $p<0.001$. However, unlike the first experiment, there was no statistical significance for SCENARIO TYPE nor for the interaction between SCENARIO TYPE and DISPLAY TYPE. Table 10 below lists the computed means and Table 11 is the statistical source table for the failure detection time data collected during Experiment 2.

Average SA computed from the subjective SART questionnaires for Experiment 2 repeated the results found in Experiment 1. Again, a main effect for DISPLAY TYPE was found however, there was no effect for SCENARIO TYPE or the interaction of DISPLAY TYPE by

Table 10 – Experiment 2: Table of Means for Failure Detection Time

Failure Detection Time	Display Condition	Mean (ms)	Std. Deviation	N
Mission Scenarios	WX Display	11439.97	3333.20	5
	MSG Display	3874.91	1184.54	5
System Scenarios	WX Display	12019.51	3909.77	5
	MSG Display	3830.63	1001.56	5

Table 11 – Experiment 2: Source Table for Failure Detection Time

Source	df	SS	MS	F	Eta^2	Observed Power
Display	1	310233394	310233394	28.00**	0.78	0.99
Error	8	88638855	11079857			
Scenario	1	358125	358125	0.11	0.01	0.06
Interaction	1	486457	486453	0.15	0.02	0.06
Error	8	26572325	3321541			
Total	19	426289152	325479370			

**($p < 0.001$)

SCENARIO TYPE. The MSG display group again had average SA scores that were nearly twice the average of those in the weather display group, regardless of the type of scenario. This observation is supported by the statistically significant mean differences seen for the between subjects factor DISPLAY TYPE, $F(1,8) = 16.91$, $p<0.003$. However, like Experiment 1, average

SA did not fluctuate across SCENARIO TYPE for either the weather display or MSG display groups, which explains why SCENARIO TYPE and the interaction of SCENARIO TYPE by DISPLAY TYPE were not found to be statistically significant for Experiment 2. Table 11 is an overview of the sample means and Table 12 is the statistical source table for the SART for Experiment 2.

Table 12 – Experiment 2: Table of Means for SA Scores

SA	Display Condition	Mean	Std. Deviation	N
Mission Scenarios	WX Display	81.26	37.93	5
	MSG Display	153.03	23.56	5
System Scenarios	WX Display	76.54	19.26	5
	MSG Display	142.40	32.22	5

Unlike Experiment 1, the accuracy questions did not show any indication of the "low fuel" classification confusion evident in the first experiment for the weather display group. Every subject that participated in Experiment 2 correctly classified and identified each scenario. Therefore, a statistical analysis of the accuracy questions was not performed

As in Experiment 1, estimates of effect size were calculated using Cohen's descriptive method. The values for Cohen's d for Experiment 2 can be seen in Table 14 below. The results indicated that 61% of the variability in the failure detection time variable are explained by the difference in the display type viewed by the subjects in the experiment. In addition, 69% of the variability in situation awareness variable can be accounted for by the difference in the display type viewed by the subjects during the experiment.

Table 13 – Experiment 2: Source Table for SA Scores

Source	df	SS	MS	F	Eta^2	Observed Power
Display	1	23677	23677	16.91*	0.68	0.95
Error	8	2076	259			
Scenario	1	294	294	0.98	0.11	0.14
Interaction	1	44	44	0.15	0.02	0.06
Error	8	2412	301			
Total	19	28502	24576			

*($p < 0.01$)

Table 14 – Experiment 2: Estimates of Effect Size

Measure	Display	Mean	Std. Dev.	Cohen's d	Effect Size
Failure Detection Time (ms)	WX	11729.74	7061.99	1.54	0.61
	MSG	3852.77	1655.10		
Situation Awareness	WX	78.90	38.33	1.90	0.69
	MSG	147.71	34.01		

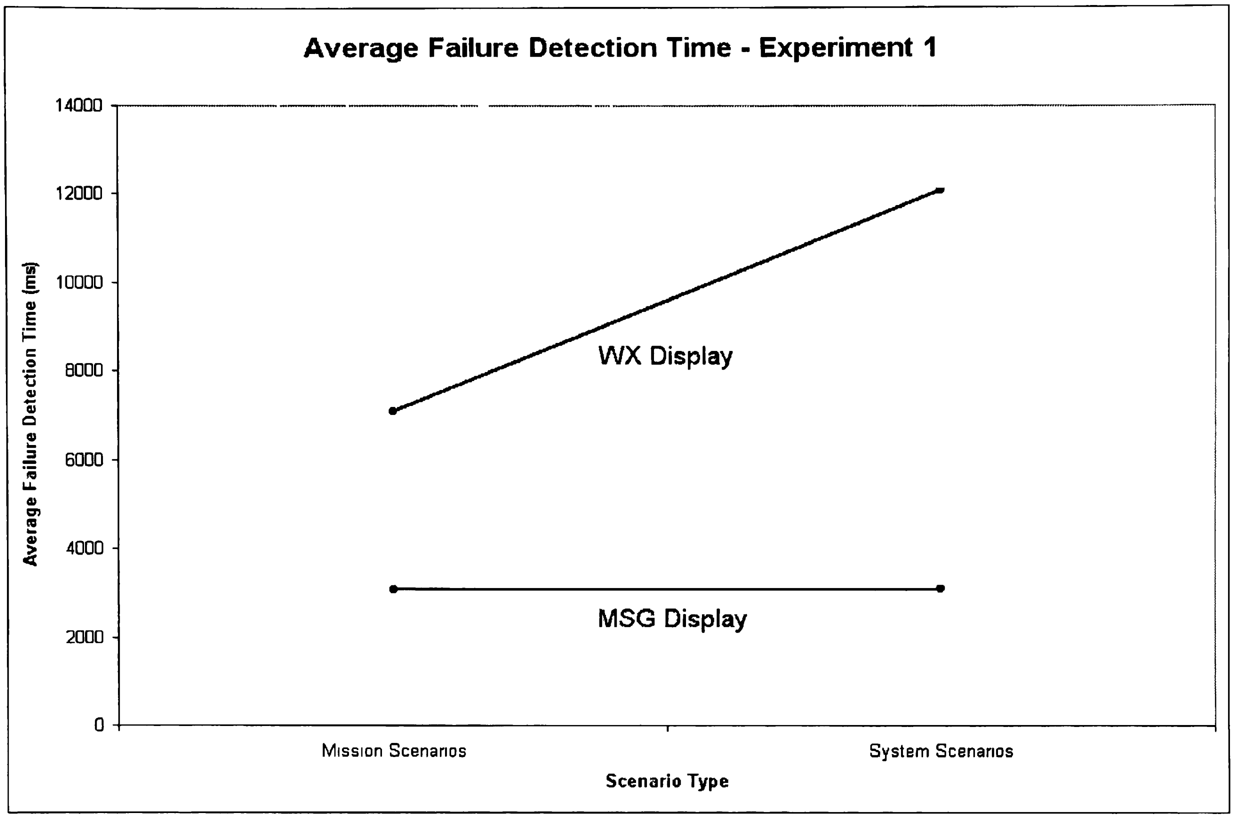
6.0 – Discussion

6.1 – Experiment 1

The robust results detected by this experiment support the hypotheses put forth earlier in this research. The MSG display clearly sped up failure detection time, and subjective situation awareness scores doubled when the MSG display was present. The emergent features of the polar star design, the logical groupings of pertinent system and mission parameters, and the simplicity of the uncluttered display layout have fulfilled the claims of fostering a more rapid perception of cues in the environment. Average failure detection time was dramatically lower for the MSG group then the weather display group; however, an interaction was found to be present that was not expected between the within subjects variable of SCENARIO TYPE and the between subjects variable of DISPLAY TYPE. Subjects in the weather display group had substantially lower failure detection times for mission scenarios then system scenarios. This trend was not evident in the MSG group. This is possibly due to the fact that the gauges and instruments such as the altimeter, heading indicator, and airspeed indicator, used to depict mission deviations or failures are fairly universal in the general aviation domain. Conversely, the hydraulic pressure indicator, oil temperature gauge, and fuel gauges, used to depict system failures or deviations can and often do change from aircraft to aircraft. Therefore, one possible explanation for the effect of SCENARIO TYPE found in this study is that the subject's unfamiliarity with the system gauges used in this experiment was likely a factor in how quickly pertinent information was absorbed from these gauges and instruments. Regardless, MSG has clearly demonstrated that it can fill the role of an automated monitor while serving to reduce the amount of time required for pertinent information to be transferred from source to human processor.

Quicker detection of a failure or deviation by using MSG was only one of the hypotheses intended to be tested by this research. The other primary hypothesis was that the subjects would have a more complete and accurate view of the "big picture", otherwise known as higher situation awareness. This experiment took an initial step in investigating the impact that MSG displays have on situation awareness. Trujillo (2002), concluded that her research, thus far, has demonstrated that the MSG displays can be useful for integrating complex information in a meaningful manner but never made the connection to situation awareness. The subjective SA scores computed from the data collected in this experiment, on average, were twice as large when the MSG display was present than when it was replaced by the weather radar display. Endsley's (2000) "information gap" between the illogically scattered volumes of data being displayed and a pilot's ability to find the data that are important, proclaimed to be the primary challenge to situation awareness, seems to shrink dramatically with MSG based on the comparison of the SA scores between the two display groups. The accuracy questions that followed each subjective SART questionnaire served to confirm that the subjective SART scores were indeed based on an accurate internalized view of the current state of the aircraft. The fact that every subject in the MSG display condition was able to correctly classify and specifically identify every deviation or failure they saw, consistently, provides strong credibility to the claim that MSG truly did serve to enhance situation awareness in those subjects belonging to the MSG display group.

Figure 5 consists of two plots of means from the data gathered in Experiment 1. The unexpected interaction of SCENARIO TYPE by DISPLAY TYPE can be seen in the upward sloping line for the weather display condition in the plot labeled Average Failure Detection Time – Experiment 1. The parallel sloping lines seen in the SA data plot for Experiment 1 are evidence of the lack of a statistically significant interaction between SCENARIO TYPE and



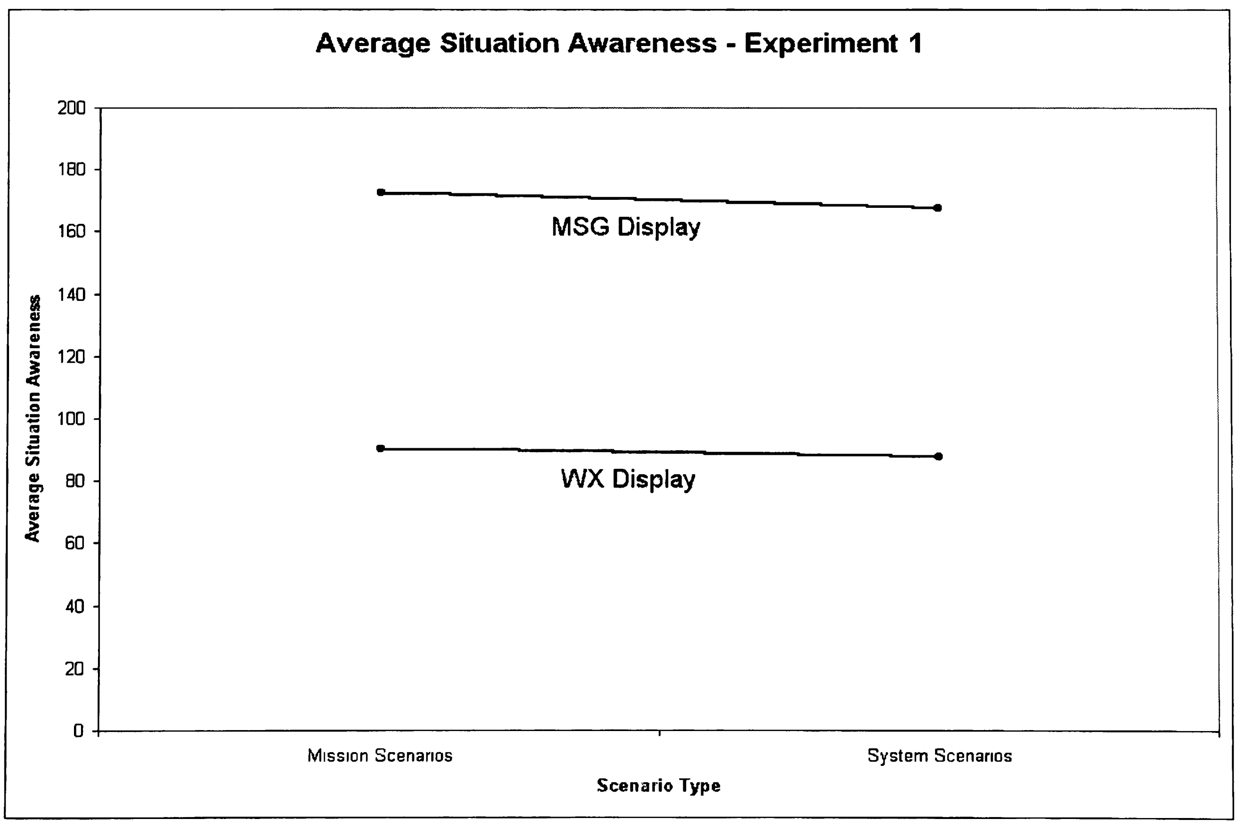
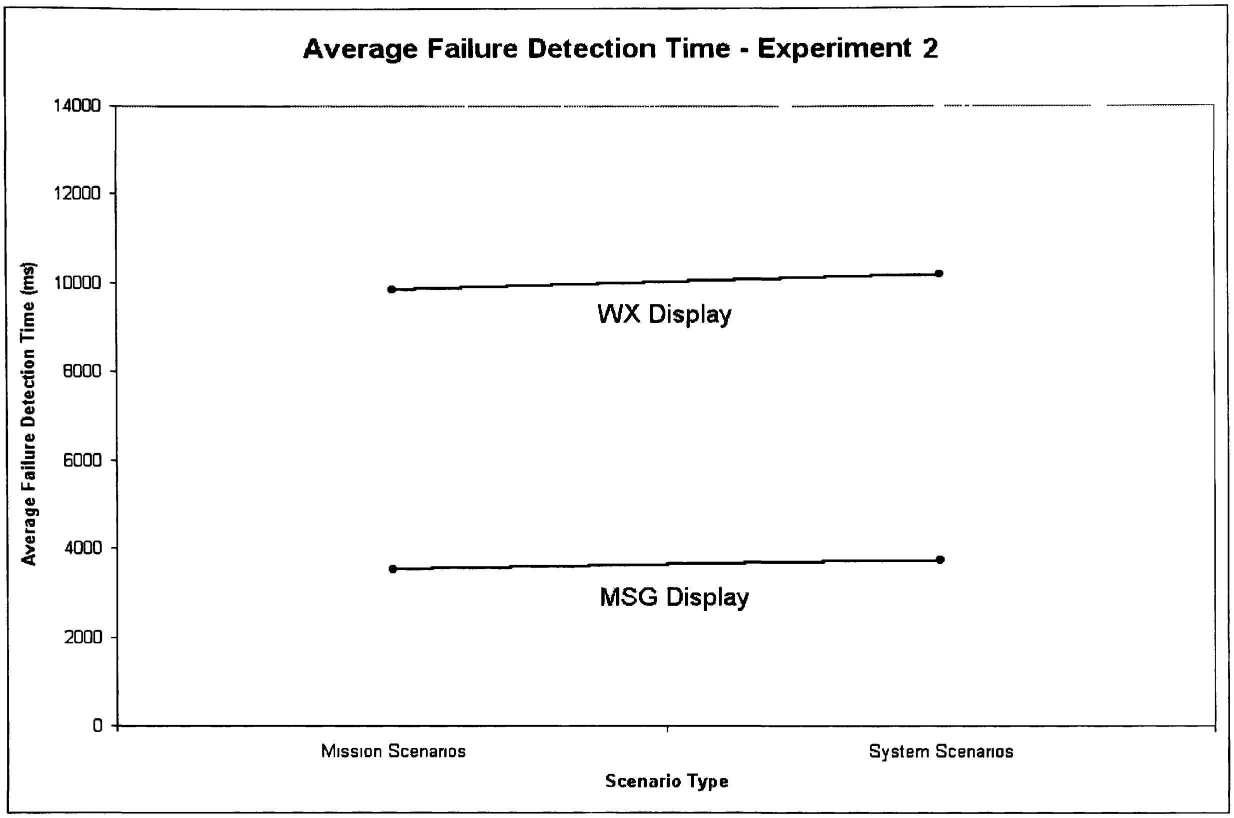


Figure 5 – Plots of means for Experiment 1

DISPLAY TYPE. The lack of an interaction, in this case, was not alarming. The type of scenario was hypothesized to not have an impact on the subjective value of SA that would be reported by the subjects. A second experiment was conducted to test whether the results of Experiment 1 could be repeated, thereby adding support to this research, overall.

6.2 – Experiment 2

The second experiment was essentially a repeat of the first. Due to the significant results of the first experiment and the observed power indicated by SPSS, the number of subjects was held at ten. Average failure detection time was again much more rapid for those subjects in the MSG group than in the weather group. For both mission and system scenarios the MSG group detected the failure or deviation three times quicker than those without the benefit of the MSG display. However, unlike the first experiment, there was no interaction between the SCENARIO TYPE and DISPLAY TYPE and subsequently, SCENARIO TYPE alone also did not show an effect. The lack of interaction in the second experiment is not alarming and may simply have been a chance occurrence observed in the first experiment. Since interaction in Experiment 1 occurred solely within the weather display condition group, it would be only mildly worth watching for in future MSG experimental research. Furthermore, the interaction, or lack thereof, may possibly be explained by the difference in strategy employed by the subjects in the different experiments. In Experiment 2, the subjects may have been attempting to provide their best possible effort thereby cautiously scanning the panel with a more consistent investment of time then those subjects in Experiment 1 whose familiarity with the gauges used to depict mission failures or deviations made them more comfortable stopping the scenario sooner. The lack of the aforementioned interaction can be easily seen in the parallel sloping lines for both the weather display condition and the MSG display condition in the plot labeled Average Failure Detection



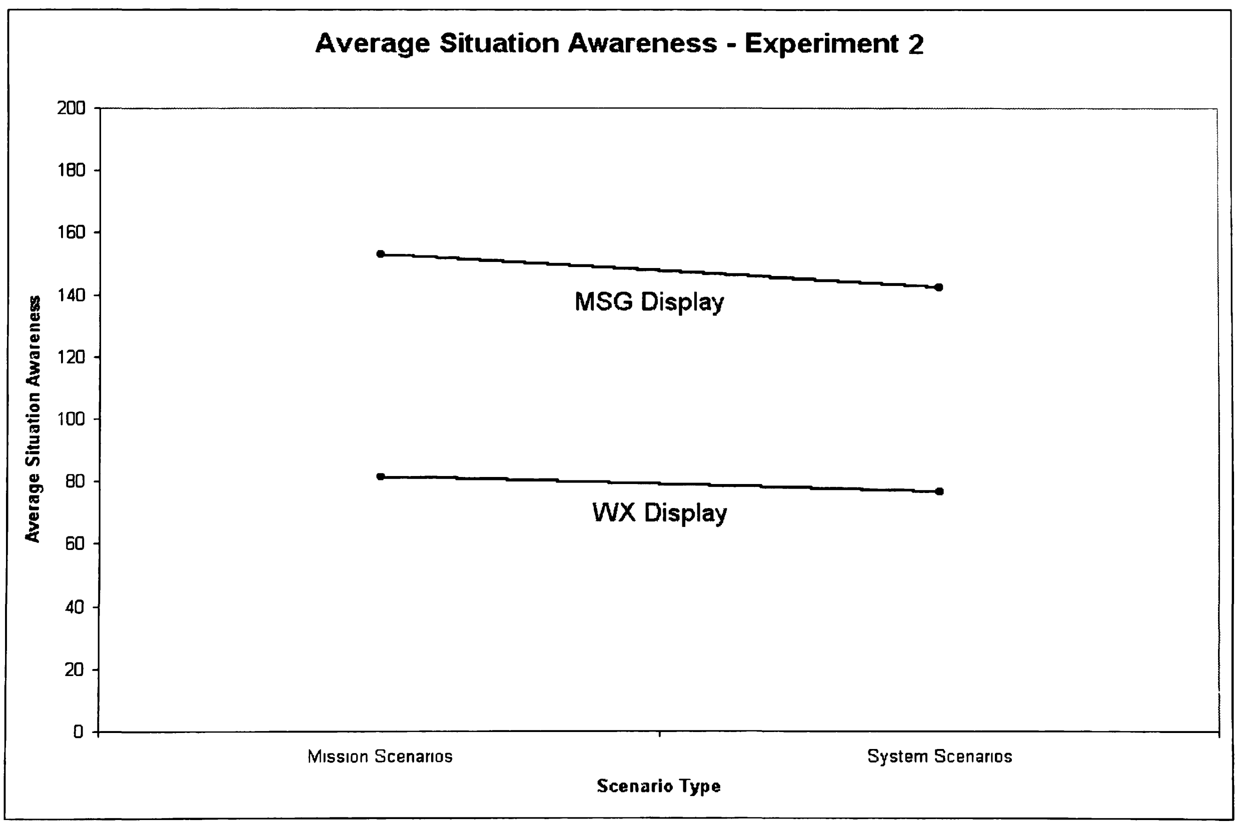


Figure 6 – Plots of means for Experiment 2

Time – Experiment 2 (Figure 6). In Experiment 2, failure detection time again supported the hypothesis that the MSG display group would have lower Failure Detection times than the weather display group. The confirmation of this main effect, received by conducting this follow-up experiment, shows that the Mission Status Graphics display is reducing the amount of time required for pilots to scan the available instruments by drawing their eye to the MSG display which in turn tells the pilot where to focus his attention. The color changing vertices, the relative movement of the parameters, and the presence of the reference circle, come to together to serve as emergent features that have the ability to facilitate pre-attentive visual processing, thereby substantially shortening the time required to perceive critical information.

The average SA computed from the subjective SART questionnaires for Experiment 2 repeated the results found in Experiment 1, as well. The MSG display group again had average SA scores nearly twice the average of those in the weather display group, regardless of the type of scenario. Furthermore, a review of the accuracy questions did not show any indication of the "low fuel" classification confusion evident in the first experiment for the weather display group. Every subject that participated in Experiment 2 correctly classified and identified each scenario shown to them, thereby further strengthening confidence in the subjective SART data collected. The variability inherent in any subjective measure requires that a measure of caution be used when drawing conclusions from data of this type. However, the average computed SART scores for both experiments can be reasonably trusted to be true after confirming that all subjects, regardless of SCENARIO TYPE or display group, correctly identified every deviation or failure. Again, MSG has clearly lived up to its theorized potential by demonstrating repeatable results for nearly doubling the average situation awareness scores reported by the MSG display group when compared to the weather display group. This statistically significant main effect is not surprising given the fact that both the research by Woods, Wise, and Hanes (1981) and Bartolone and

Trujillo (2002) have both stated that the benefits of displaying information in the polar star display format have substantial potential. That potential has been tested in this research and statistically confirmed.

6.3 – General Discussion and Conclusions

In light of the results of both experiments it can reasonably be stated that the presence of the Mission Status Graphics polar star display facilitates a more rapid detection of failures or deviations than when only the traditional instrumentation is used. Furthermore, the consistently sharp difference in the subjective SART scores between the weather and MSG display conditions indicates that, at the very least, the subjects who were exposed to the MSG display felt it markedly improved their situation awareness. Additionally, the large effects estimated by the Cohen's d calculations performed on the data bolster confidence in these statements.

With the MSG display, average failure detection time was decreased by at least one half in Experiment 1 and by two-thirds in Experiment 2, when compared to the weather display. Average subjective SA scores were approximately twice as high with the presence of the MSG display in both experiments, indicating a higher perceived level of situation awareness. However, subjective measurement of situation awareness can be inconsistent and difficult to verify but the presence of the accuracy questions in this research raises confidence in the conclusions drawn from the SA data. Caution in how these conclusions should be interpreted is still warranted due to the known limitations of SART and its close resemblance to workload measurement techniques. However, the observed statistical power was large for both experiments and the effect of the presence of the MSG display yielded significant statistical results for Experiment 2, just as it had in Experiment 1, showing that this experimental design is capable of replication. The lack of a significant interaction between SCENARIO TYPE and

DISPLAY TYPE in Experiment 2 and the subsequent missing significance for SCENARIO TYPE alone, may have been influenced by a difference in the strategy employed by the different subjects in each experiment.

The fact that the results from this pair of experiments were significant and in support of the hypotheses warrants further research into the capabilities of the MSG display within the general aviation domain. At the time when this research was concluded, NASA Langley Research Center continued to pursue MSG as an active research program for commercial aviation application. The demonstrated capabilities of the Mission Status Graphics display to serve as a one-glance automated monitor that is capable of rapid and accurate information transfer to the human operators who traditionally have poor performance monitoring reliable systems over time is very encouraging. Such a display has potential for application not only in aviation but possibly in other domains where human operators are forced to act as monitors in information rich environments like the control rooms of nuclear power plants, air traffic control facilities, or within the healthcare industry. This two decade old display methodology has the potential to save lives and therefore should be further researched so that all its capabilities can be identified and subsequently utilized to their fullest potential. Since all pilots must first begin their flight training in general aviation aircraft, this would be the ideal environment for the introduction of a display such as MSG. With the incorporation of a MSG display, pilots will be able to acquire, in one glance, the overall mission and system health of the aircraft they are piloting without the time and resource intensive process of data assimilation from a myriad of dials, gauges, screens, and displays.

7.0 - References

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Appendices

Appendix A: Situation Awareness and Accuracy Questionnaire

Demand on Attentional Resources

Please place a mark on the line below that reflects your combined opinion of the instability, complexity, and variability of the situation you were just presented with.

Low **High**

____

Supply of Attentional Resources

Please place a mark on the line below that reflects your degree of arousal, your level of concentration, and the amount of space attentional capacity leftover, that you experienced while performing the panel scan you just completed.

Low **High**

____

Understanding of the Situation

Please place a mark on the line below that reflects the amount of information you received and understood, as well as, the overall value of the information you gained by performing the scan of the instrument panel you just completed.

Low **High**

____

How would you classify the situation depicted by the instrument panel you just viewed? (choose one)

☐ **Mission Deviation/Failure** ☐ **System Deviation/Failure** ☐ **No deviation or failure was depicted**

In your own words, what specific deviation or failure was depicted on the instrument panel you just viewed? (Example: Electrical Failure)

____

Appendix B: Failure/Deviation Scenario Table

Scenario	Failure/Deviation	Critical Conventional Gauge/Instrument	Initial Reference Value	Indicated Scenario Value	MSG Parameter
1	Hydraulic Pressure - Low	Hydraulic Press Gauge	28 psi	20 psi	HYDR
2	Airspeed - High	Airspeed Indicator	120 KTS	160 kts	IAS
3	Altitude – High	Altimeter	12,000 ft	15,000 ft	ALT
4	Oil Temp – High	Engine Oil Gauges - Temp	80 deg C	130 deg C	OILT
5	Engine Failure – Zero RPM	Engine RPM Gauge	2100 rpm	0 rpm	ENGN
6	Airspeed - Low	Airspeed Indicator	120 KTS	60 kts	IAS
7	COM 1/NAV 1 Failure	COM 1/ NAV 1	On - Normal	Off	AVNC
8	Fuel Low– Left Tank	Fuel Gauge - Left	3/4 L & R tanks	0 L & 3/4 R	FUEL
9	Gear – Right Main Stuck	Landing Gear Indicator Light	Gear up and locked	R Main	GEAR
10	Heading	Directional Compass	270 deg (due West)	295 deg	HDG
11	Alternator Failure	Amp Meter	+40 amps	-40 amps	ELEC
12	Vertical Speed – Ascent	Vertical Speed Indicator	0 fpm	1200 fpm	VS
13	Oil Pressure – Low	Engine Oil Gauges - Pressure	110 psi	6o psi	OILP
14	Altitude - Low	Altimeter	12,000 ft	8,000 ft	ALT