NASA LANGLEY RESEARCH CENTER

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SITUATION AWARENESS & LEVELS OF AUTOMATION: EMPIRICAL ASSESSMENT OF LEVELS OF AUTOMATION IN THE COMMERCIAL COCKPIT

FINAL REPORT FOR MISSISSIPPI STATE UNIVERSITY

Prepared By:

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Period of Performance: May 11, 2000 to July 31, 2000

INTRODUCTORY MATERIAL

Legal Name of Organization: Mississippi State University

Address: Sponsored Programs Administration
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Originating Unit: Department of Industrial Engineering

Organization Type: Educational

Principal Investigator:
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Project Title: Situation Awareness & Levels of Automation: Empirical Assessment of Levels of Automation in the Commercial Aircraft Cockpit

Technical Contact: Paul C. Schutte, Crew/Vehicle Integration Branch, Flight Dynamics and Control Division

Desired Starting Date: 5/11/00

Closeout Date: 7/31/00

Elapsed Project Duration: 2.5 mos.

SUMMARY

This report has been prepared to closeout a NASA grant to Mississippi State University (MSU) for research into situation awareness (SA) and automation in the advanced commercial aircraft cockpit. The grant was divided into two obligations including $60,000 for the period from May 11, 2000 to December 25, 2000. The information presented in this report summarizes work completed through this obligation. It also details work to be completed with the balance of the current obligation and unobligated funds amounting to $50,043, which are to be granted to North Carolina State University for completion of the research project from July 31, 2000 to May 10, 2001.

This research was to involve investigation of a broad spectrum of degrees of automation of complex systems on human-machine performance and SA. The work was to empirically assess the effect of theoretical levels of automation (LOAs) described in a taxonomy developed by Endsley & Kaber (1999) on naïve and experienced subject performance and SA in simulated flight tasks. The study was to be conducted in the context of a realistic simulation of aircraft flight control. The objective of this work was to identify LOAs that effectively integrate humans and machines under normal operating conditions and failure modes. In general, the work was to provide insight into the design of automation in the commercial aircraft cockpit. Both laboratory and field investigations were to be conducted.

At this point in time, a high-fidelity flight simulator of the McDonald Douglas (MD) 11 aircraft has been completed. The simulator integrates a reconfigurable flight simulator developed by the Georgia Institute of Technology and stand-alone simulations of MD-11 autoflight systems developed at MSU. Use of the simulator has been integrated into a study plan for the laboratory research and it is expected that the simulator will also be used in the field study with actual commercial pilots. In addition to the flight simulator, an electronic version of the Situation Awareness Global Assessment Technique (SAGAT) has been completed for measuring commercial pilot SA in flight tasks. The SAGAT is to be used in both the lab and field studies. Finally, the lab study has been designed and subjects have been recruited for participation in experiments. This study will investigate the effects of five levels of automation, described in Endsley & Kaber's (1999) taxonomy and applied to the MD-11 autoflight system, on private pilot performance and SA in basic flight tasks by using the MD-11 simulator. The field study remains to be planned and executed. Experimental test scenarios need to be developed to assess commercial pilot ability to effectively interact with cockpit automation in conducting routine flight operations and dealing with emergency conditions. As well, a software utility for analyzing the SAGAT data collected during each study has yet to be developed.

These research activities were to be complemented by a survey of the state-of-the-art of human-centered automation research. Preparations have been made for a conference including calling for technical papers, reviewing abstracts, publishing a conference brochure and registration packet, scheduling conference presentations, and publishing a preliminary program. The conference is to be held this October 15-19 and a proceedings is to be compiled as part of this research program.

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Project Accomplishments:

Virtual Flight Simulator Development

During the past 2.5 months, the virtual flight simulator software was finalized. Microsoft Windows communications programming was completed to facilitate altitude and pitch control of the McDonald Douglas (MD) 11 aircraft, as presented through the Georgia Institute of Technology (GIT) Reconfigurable Flight Simulator (RFS). This was accomplished by developing and integrating a simulation of the MD-11 Multi-Control Display Unit (MCDU) with the RFS. The MCDU simulation was prototyped using E-Sim's RAPID© software. Other MD-11 manual flight controls and autoflight system components were also simulated using RAPID©, including thrust and aileron controls, the Flight Mode Annunciator (FMA) and the Flight Control Panel (FCP). These soft prototypes of flight displays and controls as part of the MD-11 cockpit were all integrated with the GIT RFS.

In order to simulate different modes of automation in the MD-11 cockpit, the RAPID© prototypes and the RFS have been combined in various ways. The five levels of automation (LOAs) described in Endsley & Kaber's (1999) taxonomy, which have been applied to the MD-11 cockpit and simulated through the virtual flight simulator include: (1) "Batch Processing" – This LOA resembles speed, heading and altitude control modes of the MD-11; (2) "Shared Control" – This LOA resembles switching between MCDU control and use of the FCP to set flight parameters, and monitoring control modes and current flight parameter settings through the FMA; (3) "Decision Support" – This LOA resembles using the MCDU to program a flight plan; (4) "Supervisory Control" – This LOA resembles full automation of flight control tasks with the capability for a pilot to intervene in automated processing and reprogram a new flight plan; and (5) "Full Automation" – This LOA represents completely automated control of the aircraft. Under Batch Processing the simulator presents the MCDU, the FMA, the Primary Flight Display (PFD), and the Navigational (NAV) Display. Shared Control involves the presentation of all simulator components including the FCP and throttle and attitude controls. Under Decision Support, Supervisory Control and Full automation, the simulator presents the same displays as presented in the Batch Processing mode. The manner in which the simulator interfaces receive and respond to input under different LOAs resembles the behavior of real MD-11 interface controls, however, personal computer peripherals and devices are used for input purposes.

Finally, a database of information on international airspace was developed to allow realistic flight scenarios to be re-created for testing the virtual flight simulator and user ability to fly the MD-11 simulator according to specific flight plans. Currently the database contains waypoint and route information for the Gulf of Mexico and Colombia, South America. It includes flight constraint information, such as minimum altitudes at waypoints in order to avoid terrain, maximum air speeds on particular routes, and approach paths to airports. This data can be presented to simulator users for flight path development or the database can be linked to the MCDU component of the simulator to allow users to select from predefined flight paths included in the database.

Simulator Control and Situation Awareness Measurement Software

In addition to the virtual flight simulator development work, a software application has been programmed to manage the arrangement of displays as part of the simulator on computer monitors. A "parent" process was created to position an out-of-cockpit view, the PFD, NAV Display, MCDU, FMA and FCP across two high-resolution graphics monitors. The process arranges the displays of the flight simulator in a manner similar to their arrangement in a real MD-11 cockpit. Beyond this, the parent process integrates the virtual flight simulator with the Commercial Pilot Situation Awareness Global Assessment Technique (SAGAT) software developed by SA Technologies. The SAGAT package presents queries on pilot perceptual knowledge, comprehension of the state of an aircraft, and projections of future aircraft states for different phases of flight, including take-off, en route and landing. The package is used to develop a "picture" of pilot SA at specific points in time during a flight. The parent process manages the execution of the virtual flight simulator and the SAGAT software. It has the capability to halt or freeze the flight simulator at any point in time during a simulated flight and to present the SAGAT application to a user. The parent process is capable of delivering SAGAT queries at specific points in time during a flight or when the aircraft reaches specific waypoints in a flight plan.

The SAGAT application includes approximately 45 queries relating to the levels of SA defined by Endsley (1995), including "Level 1" SA – perception; "Level 2" SA – comprehension; and "Level 3" SA – projection. The application includes 20 queries concerning Level 1 SA, 16 queries concerning Level 2 SA and 9 queries on Level 3 SA. The application allows an experimenter to select a phase of aircraft flight to be studied and to select specific queries for presentation to simulator pilots. The queries include closed and open-ended questions requiring pilots to specify, for example, flight parameter settings (heading, altitude, air speed, etc.). The application also allows an experimenter to define the number of queries to be posed to a simulator user and the amount of time available for a pilot to respond to them. Or, the experimenter may allow an unlimited response time. Finally, the application stores pilot responses to queries for later analysis by comparison with actual aircraft states recorded during a flight simulation. The application is very powerful for describing a pilot's state of awareness during flight as well as errors in SA that could impact flight task performance.

With respect to the integration of the SAGAT application and the virtual flight simulator, when the parent process freezes the flight simulator in order to execute the SAGAT application, the process minimizes the simulator displays and opens the SAGAT application screen. A user is not permitted to view the simulator displays in responding to the SAGAT queries. Once all queries have been answered, the parent process minimizes the SAGAT application screen, opens the flight simulator displays and resumes the simulation from the point at which it was frozen prior to the execution of the SAGAT application.

Laboratory Study Plan and Subject Recruiting

A study plan has been formulated to assess the effects of the MD-11 modes of automation currently simulated through the virtual flight simulator on naïve subject performance, SA and mental workload in flight control tasks. The experiment is to identify LOAs that optimally integrate human and automation in flight tasks. Specifically, the study is to demonstrate LOAs

that maximize performance under normal operating conditions and failure modes and minimize decrements to SA.

A large sample of private pilots from the Starkville, Mississippi area has been recruited for participation in the experiment. The subjects will be required to fly the MD-11 flight simulator through a recreation of the situation encountered by the pilots of the American Airlines (AA) Flight 965, which crashed near Cali, Colombia in 1995. The experimental scenario will involve en-route flight tasks and approach programming, as well as an approach revision due to a runway change in flight. The en-route tasks will include monitoring simulated MD-11 autoflight systems, flying the simulator under manual control, or using the aircraft FCP or FMS for programming flight paths. Subjects will be expected to deal with the approach revision under high time pressure (near the estimated time of landing). The approach revision requirement will be exploited to assess the impact of LOAs on human recovery of the aircraft from an erroneous flight path in terms of programming performance, SA and workload.

During the experiment, performance data, including time-to-flight-task completion and flight plan programming errors will be recorded. Using the SAGAT for commercial piloting software, we will assess SA. The virtual flight simulator will be frozen at random points in time during experiment trials and subjects will be asked to respond to SA queries intended to assess their knowledge at perceptual, comprehension and projection levels. The percentage of correct responses to these queries will be recorded as a measure of their level of SA. Mental workload will be assessed using the NASA-Task Load Index (TLX).

All experimental testing is expected to be complete by the close of August 2000 and data analysis will be performed during the first half of the Fall term. Effects of LOAs on the various response measures will be tested using multivariate and univariate analyses of variance. Any significant effects will be further investigated using conservative multiple comparison procedures including Tukey's Honestly Significant Difference tests. Results will be explained in terms of the allocation of flight control functions to pilots and automation under the various LOAs.

Field Study Plan

The laboratory study is to be replicated in a field situation using alternate flight scenarios and error conditions, as well as experienced commercial pilots. The objective of this experiment is to gain a more realistic understanding of the effects of actual and theoretical modes of advanced commercial aircraft automation on pilot performance, SA and cognitive workload. The virtual flight simulator and supporting systems will be transported to Atlanta, Georgia and setup in a secure facility adjacent to Atlanta/Hartsfield International Airport and the Delta Airlines training facility.

A large sample of Airline Pilots Association members is to be recruited from the Atlanta, Georgia region. They will be required to perform en-route and approach flight tasks using the virtual flight simulator under various LOAs selected from Endsley & Kaber's (1999) taxonomy. During their experiences with the simulator, pilot accuracy and speed in flight tasks will be recorded along with SA using the SAGAT for commercial piloting. As in the lab study, we will also subjectively assess mental workload using the NASA-TLX or Modified Cooper-Harper mental workload rating scale depending upon the workload results of the first experiment.

At this point in time, SA Technologies, the Subcontractor, is developing experimental test scenarios for use in the field study. The key constraint in this task is that commercial airline

pilots are usually familiar with major aviation incidents, including the AA Flight 965 incident, its causes, and the consequences. Therefore, recreating this type of scenario for testing with the virtual flight simulator would be ineffective in terms of attempting to develop a realistic "picture" of pilot performance capabilities and SA under novel error conditions because of pilot a priori knowledge of the accident circumstances and potential safety control measures.

Subsequent to this task, the Subcontractor will develop a relational database and custom spreadsheet to accurately analyze the SA data recorded during both the lab and field study using the SAGAT software package. The database will be used to store actual naïve subject and pilot responses to SA queries administered during experimental trials. It will also contain information on the "real" state of the virtual flight simulator at the times queries that were administered. The database will allow for comparison of the system data with subject perceptions of simulator states. The relational database will facilitate analysis of subject responses to open-ended questions and will allow for grades of accuracy to be established for responses to queries. This work is to occur through an additional obligation of NASA funds in Spring 2001.

Survey of the State-of-the-Art in Human-Automation Interaction

A conference on human performance, SA and automation has been planned and organized through support as part of this research grant. The conference is to be held this October 15-19 in Savannah, Georgia. At the time of this report, 60 technical papers, 5 panel submissions and over 20 technical posters had been reviewed and accepted for presentation at the meeting. Through NASA funding, a conference brochure, registration packet and preliminary program have all been published and distributed to potential attendees. It is anticipated that over 200 of the leading researchers in human-automation interaction and SA will attend the conference.

The meeting is intended to develop a synergy of research results on theoretical work in SA assessment and applied studies of human-automation interaction. A conference proceedings (research survey) will be edited and published through NASA support committed as part of this research award. It is expected that papers included in the proceedings will present successful approaches to system design to facilitate high levels of operator SA in conjunction with automation. The book will provide readers with information on integrated approaches to system design considering automation and information systems technology and human SA to optimize human/system performance. The survey will serve to advance research in directions similar to, and including, that pursued as part of this project.

Deliverables:

This technical report and the development of a research World Wide Web site were identified as the key deliverables of this project in the research proposal. A web site presenting all the information developed as part of this research project to date has been published at: http://www.ie.msstate.edu/people/faculty/kaber/nasa/index.html. The site presents reviews of the Delta Pilot's Reference Manual, hierarchical analyses of the functions of MD-11 autoflight systems, information on the virtual flight simulator including the RFS and prototypes of the MD-11 MCDU, FCP, and FMA developed using RAPID©. It also presents information on the research team involved in the project activities, including three Mississippi State University graduate students. Finally, the site provides virtual tours of the MD-11 cockpit and the aircraft itself.

Other Research Outcomes

At this point in time the project has generated five publications, including those listed in the final report for Grant No. NCC1330 99050488 and an additional archival journal article. The current reference for the latter publication is:

Kaber, D. B., Tan, K-W. and Riley, J. R. (in review). Improved usability of aviation automation through direct manipulation and graphical user interface design. Submitted to the International Journal of Aviation Psychology.

References:

Endsley, M. R. (1995) Towards a Theory of Situation Awareness, Human Factors, 37(1), 32-64.
Endsley, M. R. and Kaber, D. B. (1999). Level of automation effects on performance, situation awareness and workload in a dynamic control task. Ergonomics, 42(3), 462-492.

Personnel:

Biographical Sketch: David B. Kaber, Ph.D., E.I.T.

David Kaber is an Assistant Professor in the Department of Industrial Engineering at Mississippi State University and Director of the Cognitive Engineering and Systems Laboratory. Prior to joining Mississippi State, he worked as an instructor of Engineering Science and Mathematics at Amarillo College. He received his Ph.D. in Industrial Engineering at Texas Tech University, with a specialization in cognitive ergonomics. While completing this degree, he received the Air Force Office of Scientific Research Fellowship in Human Factors. He received his Masters and Bachelors degrees in Industrial Engineering with specializations in human factors and occupational safety from the University of Central Florida. Dr. Kaber's research interests include cognitive engineering, adaptive systems and modes of automation in complex systems, teleoperations and virtual reality systems. He has published several refereed papers in technical journals and conference proceedings concerning these interests. His current projects include advanced interface design for teleoperation systems, investigation of the role of telepresence (the sense of being present at a remote site) in teleoperation performance, virtual environment design for scientific data visualization tasks including meteorological and oceanographic model analysis, and assessment of the impact of modes of automation and adaptive automation on human operator workload and situation awareness in complex system control tasks.

List of Principal Publications

Kaber, D. B. and Endsley, M. R. (1997). Out-of-the-loop performance problems and the use of intermediate levels of automation for improved control system functioning and safety. Process Safety Progress, 16(3), 126-131.

Kaber, D. B. and Endsley, M. R. (1998). Team situation awareness for process control safety and performance. Process Safety Progress, 17(1), 43-48.

Kaber, D. B., Endsley, M. R. and Onal, E. (in press). Design of automation for telerobots and the effect on performance, operator situation awareness and subjective workload. Submitted to the International Journal of Human Factors in Manufacturing.

Kaber, D. B. and Endsley, M. R. (1997). Level of automation and adaptive automation effects on performance in dynamic control environments. Proceedings of the 13th Triennial Congress of the International Ergonomics Association (pp. 202-204).

Kaber, D. B. and Endsley, M. R. (1997). The combined effect of level of automation and adaptive automation on human performance with complex, dynamic control systems. In the Proceedings of the 41st Annual Meeting of the Human Factors and Ergonomics Society (pp. 205-209). Human Factors and Ergonomics Society: Santa Monica, CA.

Kaber, D. B., Onal, E. and Endsley, M. R. (in press). Level of automation effects on telerobot performance and human operator situation awareness and subjective workload. In Proceedings of the Third Automation Technology and Human Performance Conference. Lawrence Erlbaum Associates: Mahwah, NJ.

Kaber, D. B. and Riley, J. (in press). Adaptive automation of a dynamic control task based on workload assessment through a secondary-monitoring task. In Proceedings of the Third Automation Technology and Human Performance Conference. Lawrence Erlbaum Associates: Mahwah, NJ.

Biographical Sketch: Mica R. Endsley, Ph.D., P.E., CPE

Mica Endsley is President of SA Technologies in Marietta, Georgia where she specializes in situation awareness issues in advanced aviation systems. She recently left her post as a Visiting Associate Professor at MIT in the Department of Aeronautics and Astronautics and Associate Professor of Industrial Engineering at Texas Tech University. Prior to joining Texas Tech she was an Engineering Specialist for the Northrop Corporation, serving as Principal Investigator of a research and development program focused on the areas of situation awareness, mental workload, expert systems and interface design for the next generation of fighter cockpits. She received a Ph.D. in Industrial and Systems Engineering from the University of Southern California. Dr. Endsley has been conducting research on situation awareness, decision making and automation in aircraft, air traffic control and aviation maintenance for the past twelve years. She is the author of over 90 scientific articles and reports on numerous subjects including the implementation of technological change, the impact of automation, the design of expert system interfaces, new methods for knowledge elicitation for AI system development, pilot decision making, and situation awareness.

List of Principal Publications

Endsley, M. R. and Kaber, D. B. (1999). Level of automation effects on performance, situation awareness and workload in a dynamic control task. Ergonomics, 42(3), 462-492.

Endsley, M. R., & Robertson, M. M. (in press). Situation awareness in aircraft maintenance teams. International Journal of Industrial Ergonomics.

Endsley, M. R., & Rodgers, M. D. (1998). Distribution of attention, situation awareness, and workload in a passive air traffic control task: Implications for operational errors and automation. Air Traffic Control Quarterly.

Endsley, M. R. and Smolensky, M. (1998). Situation Awareness in Air Traffic Control: The Picture. In M. Smolensky and E. Stein (eds.) Human Factors in Air Traffic Control (pp. 115-154). New York: Academic Press.

Endsley, M. R., Mogford, R. H., & Stein, E. S. (1997). Controller situation awareness in free flight. In Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting (pp. 4-8). Santa Monica, CA: Human Factors and Ergonomics Society.

Endsley, M. R. (1996). Situation Awareness Measurement in Test and Evaluation. In T. G. O'Brien & S. G. Charlton (Eds.), Handbook of Human Factors Testing & Evaluation (pp. 159-180). Mahwah, NJ: Lawrence Erlbaum.

Jones, D. G. and Endsley, M. R. (1996). Sources of situation awareness errors in aviation. Aviation, Space and Environmental Medicine, 67(6), 507-512.

Endsley, M. R. and Kiris, E. O. (1995) The Out-of-the-Loop Performance Problem and Level of Control in Automation, Human Factors, 37(2), 381-394.

Endsley, M. R. (1995) Towards a Theory of Situation Awareness, Human Factors, 37(1), 32-64.

Endsley, M. R. (1995) Measurement of Situation Awareness in Dynamic Systems, Human Factors, 37(1), 65-84.