Summer 1992

The Effects of Automation and Task Difficulty on Crew Coordination, Workload, and Performance

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Recommended Citation
Thornton, Ruth C.. "The Effects of Automation and Task Difficulty on Crew Coordination, Workload, and Performance" (1992). Doctor of Philosophy (PhD), dissertation, Psychology, Old Dominion University, DOI: 10.25777/90y2-z703
https://digitalcommons.odu.edu/psychology_etds/321

THE EFFECTS OF AUTOMATION AND TASK DIFFICULTY ON CREW COORDINATION, WORKLOAD, AND PERFORMANCE

by

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B.S. August 1979, Old Dominion University
M.S. August 1987, Old Dominion University

A Dissertation Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

PSYCHOLOGY

Old Dominion University
August, 1992

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ABSTRACT

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The purposes of this research were two-fold: (1) to assess the reliability and utility of the Aircrew Coordination Observation and Evaluation scales in describing crew coordination behaviors exhibited during flight and (2) to investigate the effects of automation on crew coordination, workload, and performance. Two levels of automation (i.e., presence or absence of an autopilot) and two levels of task difficulty (i.e., presence or absence of wind and turbulence) were combined to yield a 2 x 2 design. Twenty-four two-person crews performed in both levels of automation and one of two levels of task difficulty. The results of the reliability assessment demonstrated that the training procedures and behavioral summary scale anchors that were developed produced adequate levels of interrater reliability in this investigation. The results of the crew coordination analyses revealed differences in the frequency and quality of crew coordination behaviors between levels of automation. Ratings of crew coordination were also shown to be related to performance. The results also indicated that although crews in the automated condition reported less workload, only one of the three measures of flight performance was improved. In addition, under high task difficulty, problem solving performance was worse in the automated condition than in the manual condition. Interpretation and suggestions for future research are discussed.

DEDICATION

Gloria in Excelsis Deo,

Et in terra pax hominibus bonae voluntatis.

Laudamus te,

Benedicimus te,

Adoramus te,

Glorificamus te,

Gratias agimus tibi propter magnam gloriam tuam:

Domine Deus, Rex caelestis,

Deus Pater omnipotens.

Domine Fili unigenite,/Jesu Christe;

Domine Deus, Agnus Dei,/Filius Patris:

Qui tollis peccata mundi, miserere nobis;

Qui tollis peccata mundi, suscipe deprecationem nostram;

Qui sedes ad dexteram Patris, miserere nobis.

Quoniam tu solus Sanctus,

Tu solus Dominus,

Tu solus Altissimus: Jesu Christe,

Cum Sancto Spiritu: in gloria Dei Patris. Amen.

ACKNOWLEDGMENTS

My appreciation and gratitude extend to the following:

Dr. "Glynn" Coates, whose looks of incredulity and patient explanations have kept me from permanently falling into the abyss of statistical mayhem, enabled me to teach undergraduates coherently, and hopefully helped me provide evidence that all girl babies should not be tossed without due consideration.

The honorable Dr. Raymond H. Kirby, alias Kirbasaurus, for his thoughtful wisdom and smiling face over the years.

Professors McIntyre, Dickinson, and Davis for sharing their knowledge and personal discipline. Don't become administrators only; you're too valuable.

Dr. Ben B. Morgan, Jr., who had the confidence to provide me with enough rope for me to hang myself with in these latter days. Keep that red pen sharp.

Drs. Fred Freeman and Don Ogdon, for their friendship, humor, and concern.

Curt Braun, whose encouragement and expertise came just when it was most needed. What comes around, goes around.

Dr. Eduardo Salas and his Naval Training Systems Center cohorts, whose direction and financial support made this research possible.

The inhabitants of 242 Sir Oliver, who daily shared degrees of encouragement, despair, and entertainment as we

asked only that the roof not leak again and that we get our Ph.D.s one day in our lifetime.

My personnel consulting peers and friends, Drs. Baker, Cesare, Fedorko, and Vanetti, who proved that one good training evaluation will recommend at least a thorough needs analysis and very possibly a revision of the entire system. A special thanks to the Slickster whose intelligence, charm, and friendship are in no way expressed in his nickname.

Jackie, Mary, and Evelyn, who always had a smile and provided some sanity in an otherwise insane existence.

Mike and Bev McAnulty, whose friendship and professional concerns encouraged me over the years.

Hayley Waters, whose thoughtful caring reminds me to practice what I preach.

Michele Terranova, whose effervescent personality gives new meaning to female role model in Human Factors and momma.

My family, who never asked "why" directly and patiently listened to "maybe next semester". Being proud of me is only a reflection of their own efforts and lives.

Salvatore J. Cesare, Ph.D., who has established the concept of "team" in my life as an entity that sacrifices toward common goals that are based in reality and tradition. I owe my life to you, and in turn, to your family who supported you.

To those whose prayers have been a source of strength, I say "Dominus vobiscum."

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I. INTRODUCTION

Most successful operations in military and civilian organizations stem from the integrated performance of individuals making decisions within a team framework. In order to achieve team objectives, the teams are required to coordinate their actions by sharing resources or information. Regardless of the organizational setting, the basic assessment of teams has proven most difficult. A great number of variables must be sifted through in order to pinpoint sources of a team's inadequacies and strengths, as well as to allow realistic predictions of future levels of achievement. In addition to this complexity, these teams frequently consist of individuals in remote locations performing different tasks that must be combined in a coordinated effort to accomplish their overall objectives (e.g., air traffic controllers and aircraft pilots).

Over the past 40 years, considerable energy and resources have been expended to determine the factors that strengthen team performance, particularly within the aviation context. Researchers in military aviation have been concerned with the enhancement of the coordinated performance of teams as early as the 1950s (Hood, 1960; Sherwood, 1953). In these investigations, training content and techniques were developed and evaluated to determine more effective methods of increasing the mission effectiveness of aircrews. Similar research was continued during the 1960s in a series of investigations conducted to identify key elements (e.g., task fidelity, training type, system criteria changes, member replacement) that influence the performance of teams (e.g., Briggs & Johnston, 1966a, b; Briggs & Naylor, 1965; Johnston, 1966; Naylor & Briggs, 1965). All of these efforts focused on tasks that involved the coordinated performance of individuals within teams.

The search for ways to enhance team performance has continued more recently in the commercial air transport industry. Conclusions derived from research projects (Ruffell Smith, 1979) and from commercial aviation accident and incident data bases (Billings & Reynard, 1981; Lauber, 1980) have identified Cockpit Resource Management (CRM) as an important ingredient in safe and efficient aircraft operations. CRM is defined as the utilization of information, equipment, and people as resources to achieve safe and efficient flight operations (Lauber, 1980). Over the past decade, numerous programs have been instituted to train aircrews to manage aircraft resources more effectively.

The military also has begun to take another look at crew coordination (i.e., another term for CRM used by the military) as a means of enhancing safety and mission effectiveness of flight. A critical incident analysis of Army aviation accidents indicated that poor crew coordination contributes to poor flight safety (Thornton &

Zeller, 1990). In addition, experimental evidence obtained from B-52 crews identified improved crew coordination as an enhancer of performance on mission tasks (Povenmire, Rockway, Bunecke, & Patton, 1989). Although crew coordination is not a new concept, renewed interest in crew coordination as a moderator of aircrew performance has changed the focus of team training research in the past few years. Initial studies (e.g., Krumm & Farina, 1960; 1962) examined the effects of training aircrews within an individual context in contrast to being trained in an integrated context. Current efforts are directed at training crew skills above and beyond the individual skills required for the mission (Bowers & Morgan, in preparation).

Another variable that has recently been considered a moderator of team performance is the automation of previously manually operated aircraft systems. Automation is frequently cited as an additional resource that requires special management by the aircrew in order to maintain the cockpit environment safely and effectively. Because automation affects the design and function of aircraft systems, changes in the training of aircrews who operate these systems are required. The development of training that includes a strategy for managing automation as a resource appears to be a worthy aspiration for those responsible for aviation safety; however, researchers must first provide a more thorough documentation of the automated related changes in crew behaviors before instituting new programs.

Automation has been conceptualized and defined by many scientists (e.g., Fitts, 1951; Hess, 1987; Wickens, 1984). Morgan, Herschler, Wiener, & Salas (in press) have expanded the concept of automation to include its effects on team performance. They define human-centered automation "to include (a) programmed electronic or mechanized support systems which are under the control of system operators, and (b) system-state information displays which permit effective system management, facilitate interaction and transfer of control among crew members and allow timely interventions when degradation occurs." Unfortunately, until the past few years, the automation of support systems and displays has been technology-centered, rather than human-centered (Woods, 1988). The technology driven focus on automation (i.e., how to automate, not if to automate) has produced a number of effects, not always positive, on the management of aircraft flight systems.

The determination of whether automation actually produces better performance than manual modes appears inappropriate (Wickens, 1984). Because arguments for and against the benefits of automation can be advanced by using different research findings, Wickens, Marsh, Raby, Straus, Cooper, Hulin, & Switzer (1989) recommend examining other variables that may interact with automation features.

Workload and crew coordination are two such likely moderators of performance.

Initially, the relationship between automation and workload was assumed to be inverse; as automation increased, the workload of the crew would decrease. The acceptance of this belief is shown by the 1982 Presidential task force that endorsed the two-person cockpit in commercial aircraft. The task force presumed that automation could sufficiently replace the third crew member without increasing the workload of the other two crew members (Wiener, 1985). In support of the move to the smaller aircrew, it must be noted that only one major accident has occurred in the advanced cockpit airframe since the implementation of the automated crew member. Sabotage, rather than human error in the cockpit, has been hypothesized to be the cause of that accident (Proctor & Mecham, 1991). However, an inverse relationship between automation and workload does not hold true in all situations (Wickens, 1984).

Speculation about the exact relationship between automation and crew coordination behaviors also has arisen in relation to the safety and effectiveness of the flight. The introduction of automation in flight systems has been hypothesized to affect the manner in which the crew members coordinate their activities (Norman & Orlady, 1988a). In addition, other researchers have expressed concern that the automation of flight systems may produce unanticipated negative consequences in the overall performance requirements for flight crews (Buley, 1985; Morgan et al., in press; Wiener & Curry, 1980). To provide evidence for these concerns, an experimental examination of the potential moderating effects of automation on the workload, the coordination behaviors, and the performance of the crew is needed.

Other circumstances may also interact with automation to produce differential effects on workload and coordination behaviors displayed by the crew. These include situations which involve changes in the environment (e.g., decreased visibility due to weather) or within the aircraft (e.g., engine failure). The crew must deal effectively with similar circumstances to complete the flight successfully (e.g., land safely and on time). Situations like these have been used previously in experimental paradigms designed to examine decision-making and planning behaviors in experienced aircrews (Johannsen & Rouse, 1983; Oranasu, 1989). Increases in the difficulty of the flight are made by requiring additional or more complex responses from the crews. Such responses are also likely to change the workload, crew coordination requirements, and subsequent performance of the crew.

The current research examines the role of automation in creating a new task structure with different requirements for successful performance. Specifically, the research explores the potential effects of automating the primary flight controls in a low fidelity flight simulator. The ways in which automation may affect workload, coordination behaviors, and crew performance are investigated. Each of these topics is discussed in the following sections.

The Individual in Automated Systems

The advent of the industrial revolution brought basic changes to the design of jobs as a function of mechanization and automation (Rosenbrock, 1983). Task fragmentation frequently occurred to the extent that human skills were no longer central to the job; the principal role was given to the machine. The traditional approach to the allocation of functions was to assign the human the remainder of the tasks that could not be automated (Macek, 1982). Combining the leftover tasks into a single job often produced one consisting of unrelated tasks. Increased human mistakes and decreased job satisfaction followed. The automation of jobs using this allocation approach defined the human role by default. The resultant breakdown in job cohesiveness frequently created undesirable consequences for both the individual and the organization.

As automation capabilities spread throughout various industries, Bright (1958) posited changes in the work requirements as a function of automation. He noted a general trend indicating that increasing levels of automation tended to reduce the job content and the human contribution required (e.g., physical effort, training, mental effort); however, he suggested that aviation was a possible exception to his thesis. Increased responsibility for more systems, higher caliber duties, and new skills were three factors expected to counteract the decreases in human requirements found in automated industries.

Researchers during the 1960s verified that technological changes frequently lead to changes in the job activities of the individuals. In actual investigations conducted in factories, automation was found to increase the mental demands of the job (Whyte, 1961), feelings of responsibility (Mann & Hoffman, 1960) and pressure (Mann & Hoffman, 1960; Whyte, 1961), and to decrease control (Blauner, 1964). Increased automation was shown to affect workers in a number of ways.

More recent analyses of automated systems (offices, robotics, computer-assisted manufacturing, and process control environments) also indicate evolving roles for the individuals involved with these systems. Czaja (1987) reported that automation in the office affects the structure and content of jobs leading to the routinization, simplification, and fragmentation of jobs. In addition, office automation can decrease control over workload and make current skills obsolete. Bullinger, Korndorfer, & Salvendy (1987) summarized the effects of robots on the work force as follows: (1) more psychological stress and less physical strain, (2) decreased skills to operate equipment and more skills to maintain and program equipment, (3) decreased direct control of activities and more indirect activities such as monitoring, maintenance, repair, (4) different safety issues, (5) and changes in the work situations available to personnel (e.g., situation determined by the tools rather than by the subject of the work). Similarly, when the effect of computerized manufacturing automation on the workplace was examined in four organizations (Office of Technology Assessment, 1984), the automation was found to increase the need for skills such as programming, monitoring, and maintenance, but required less decision making and motor skills. Boredom in some jobs, safety from physical hazards, and stress also increased.

As a final example, process control environments such as nuclear power plants have also seen an evolution in the role of individuals. The human role has become one of information processor and decision maker (Woods, O'Brien, and Hanes, 1987). When performing as a supervisor, "the individual monitors and manages a partially self-controlling process, handles the unexpected, and provides backup control when automatic systems fail or when disturbances are beyond automatic response capabilities" p.1738. The human's primary function becomes cognitive (e.g., setting goals, solving problems); sensing is only a secondary function.

Woods (1988) recently summarized the effects of automation on the human's role based on field studies and controlled studies from non-aviation industries (computerized numerical control in manufacturing, banking information systems and processes, steel processes, and nuclear industries). The studies were conducted to identify the effects of technology on productivity and quality of human performance. When technology centered automation was applied, Woods found that the human role in system performance was altered in unexpected ways. The patterns of human skills were changed and the ability to adapt to unanticipated variability became the critical human function. As a result, new error forms and types of system breakdowns typically occurred.

The role of the pilot in increasingly automated cockpit environments has also been altered in unexpected ways, generating a host of accompanying problems. Issues such as complacency and inattentiveness (Miles, Miller, & Variakojis, 1982), flexibility and vigilance (Wiener, 1987a), types and severity of errors (Bainbridge, 1987), diffusion of responsibility between crew members and aircraft systems (Farrell, 1987), training techniques (Bohem-Davis, Curry, Wiener, & Harrison, 1983), and maintenance of expertise and technical skills (Gannett, 1982) have been associated with automation in advanced technology aircraft. In some cases the problems may be related to poorly designed systems or improper training for the aircrews. In other cases, the problems are suggested to be related to fundamental changes in the inherent role of the pilot.

Analogous to process control operators, the role of the pilot has shifted from that of a control manipulator to that of a systems manager (Chambers & Nagel, 1985; Graeber, 1989). Although the pilot retains responsibility for the operation and safety of the aircraft, repetitive and mundane tasks are performed by automated systems. The role of automation may be viewed as to provide assistance to the aircrew in the performance of their tasks and in the management of aircraft systems (Norman & Orlady, 1988b). Although automation plays a large role in controlling and stabilizing the aircraft, automation should especially support the aircrew in guidance, control, navigation and systems monitoring. In contrast, the basic pilot functions are to "aviate, navigate, communicate, and operate" (Norman & Orlady, 1988b, p. 139). The maintenance of situation dominance, an awareness of and control over the status of the aircraft, is viewed as the central activity of the pilot.

Norman & Orlady (1988c) argue that the fundamental role of the pilot has not changed. In accordance with Federal Aviation Regulation 91.3, the pilot in command of the aircraft is still directly responsible for and has final authority over the operation of the aircraft. Regardless of the machinery used, the pilot's primary role of monitoring systems and flight path management is not altered, even though some machinery can simplify or abolish the demand for certain tasks (Norman & Orlady, 1988c). Yet, it may also be argued that the manner by which monitoring and managing must transpire has been altered with the introduction of more sophisticated systems.

The prevailing doctrine over the past 30 years concerning the relationship of machines and humans has been that automated devices should control systems and humans should supervise and monitor the devices' actions, intervening when necessary (Wiener, 1985; 1987a). Wiener notes ironically that the doctrine thus fostered places humans in a predicament for which they are poorly skilled. Monitoring is not a task in which humans are known to excel. Speyer (1989) reports that vigilance research has shown humans to be ineffective monitors, less likely to detect system faults or incorrect setups, and more likely to commit large blunders.

Yet, many traditional vigilance studies involve tasks and subjects bearing little similarity to operational aviation (Wiener, 1987a). Robert, Hockey, & Tattersall (1989) assert that the vigilance required to monitor automated systems involves an active involvement in searching, problem-solving, predicting, and planning in contrast to a passive involvement in receiving or detecting signals typically demanded in earlier watchkeeping tasks. The maintenance of vigilance in automated systems requires participation from the individuals beyond that of maintaining a state of perceptual readiness.

Indeed, it appears that the demands made on pilots in automated systems are reflected in more than one area of the flight task. Additionally, different levels of effort for various functions are required to preserve task performance. During a workshop on flight deck automation and crew coordination, Norman & Orlady (1988a) concluded that flight deck automation alters the actual structure of the flight task in five areas: systems operations, primary flight control, navigation systems, checklists, and flight deck communication. As a result of automation, changes in task structure affect the role of the pilots. These authors indicate that in automated systems, pilots monitor systems less actively, perform less mental arithmetic, and use more cognitive rather than motor skills. The pilot flying assumes more of managerial role; the pilot not flying participates more in flight control, but less in the monitoring of systems. Changes in the flight task structure also have implications for the aircrew as a team.

Teams in Automated Systems

Just as changes in task structure affect the role of individuals by altering the behaviors required in the task, evidence suggests that it also compels changes in the behaviors of teams. Small group research conducted by Sorenson (1971) found significant relationships between task type (production or problem solving) and task behavior (i.e., interaction processes such as structuring, generating, elaborating, evaluating, and requesting behaviors). Further analyses suggested that different types of tasks placed different demands on groups by systematically altering the behaviors required to accomplish the task.

The findings of research specifically designed to examine the effects of technological change also indicate a change in the working relationships among individuals. For example, increased automation decreased the opportunities the workers had to interact with their coworkers (Whyte, 1961; Goodman & Argote, 1984). In another situation, Williams and Williams (1964) found that the introduction of numerical control machines required more coordinating activities between production and support personnel. Automation in offices affected communication and interaction patterns between workers and created perceptions of support loss and distance from coworkers (Czaja, 1987). Finally, in a computerized manufacturing automation environment, Office of Technology (1984) reported that interactions among workers involved greater interdependence, collaboration, and need for cooperation among workers. Autonomy typically decreased. As suggested by Zuboff (1981), changes in areas such as information technology affect the relationships between the people, the tasks, and the organization.

Small group and technological change research findings are supportive of the observations made by Norman & Orlady (1988a) regarding changes in interpersonal relationships and procedures in advanced technology aircraft. In addition to changes in individual roles, changes have been observed in aircrew interrelationships related to task structure and cultural modifications. More specifically, they reported task structure changes that increased cross-check workload, flight path control coordination, and more evenly distributed workload between crew members. Cultural changes also occurred. For example, although the captain and first officer roles did not change, the individual roles of the pilot flying (PF) and pilot not flying (PNF) did. Specifically, the cultural changes included a more even distribution of responsibility between PF and PNF with the PNF assuming more responsibility and a reversed flow of information between the PF and PNF.

These observations suggest that the processes by which crew members interact in an automated setting differ from traditional settings and merit further examination. Although speculation exists regarding the nature of aircrew interactions in advanced technology aircraft, little empirical evidence has been gathered. Wiener, Chidester, Kanki, Palmer, Curry and Gregorich (1991) are presently conducting an investigation in operational aircraft to examine differences in interaction requirements between traditional and technologically advanced aircraft. Hopefully, this and similar inquiries will shed some light on the nature of any differences present.

In Sorenson's terminology, it appears that different demands are placed on aircrews as a function of the new behaviors required to perform the automated task. The role of teams in automated systems may center around changes in the interaction behaviors and requirements that evolve from modifications in the tasks being performed. A relevant concept, coordination demand, is described as "the extent to which a given flight task paces a requirement (demand) for the crew to interact, cooperate, or coordinate their activities in order to accomplish the task" (Bowers, Morgan, & Salas, 1991). If crucial requirements for the successful performance of teams are determined by the characteristics and demands of the task which influence team interactions, as Roby & Lanzetta (1958) suggested, accompanying changes in crew training may be indicated after changes in task structure and any resultant interaction behaviors are identified.

Workload in Advanced Technology Aircraft

Pilot workload has been defined as "the cost incurred by the human operators of complex airborne systems in accomplishing the operational requirements imposed on them" (Hart, 1987, p.1). This cost reflects a combination of demands such as the mission requirements, the amount and clarity of information and equipment provided, the flight environment, and the pilots' skills, experience, adopted strategies, exertion of effort, and emotional responses to the situation. An increasingly complex and variable environment is presented to the aircrews with the development of advanced technology aircraft, such as the environment of the "glass cockpit".

The cost to an individual pilot for the operation of flight systems is frequently evaluated as a dependent variable in terms of mental workload. Although physical workload is much easier to define and measure in terms of energy expenditure, the actual physical workload of a pilot is not usually a concern in the advanced technology aircraft. Unfortunately, mental workload has no simple, single definition or measure. Individual, rather than team workload, is typically measured. The three most common measures are defined according the manner in which workload is measured: subjective rating scales, secondary tasks, and physiological measures.

Automation, probably more than any other factor, has altered workload drastically, and may both decrease and increase the workload of the crew. For example, although workload is reduced when automated devices perform tasks previously accomplished by the crew, the responsibility for the operation of the device remains with the crew, thus increasing their monitoring requirements. In a related field study conducted by Wiener (1989), pilots reported sometimes turning off automatic features (e.g., of a flight guidance system) and reverting to manual mode because of their difficulty in managing the system during periods of particularly high workload. Wiener indicates that many automatic features originally designed to decrease workload are not reaching their potential because of software and hardware problems.

Phase of flight and the presence or absence of system failures or of other unplanned events (e.g., deteriorated environmental conditions) also introduce different workload levels to crews by changing the difficulty of their tasks. The interaction of automation with these factors may influence workload in unintended ways. For example, flight performance and subjective workload were found to be affected differentially by the presence of automation, emergency conditions, and crew composition (Wickens et al., 1989). Fifty aircrews flew a twin-seat GAT II flight simulator either with or without autopilot controls both in normal flight conditions and in conditions of system failure. Crews were divided into homogenous (i.e., similar experience) and heterogeneous (i.e., dissimilar experience) groups. Use of the autopilot resulted in better performance and lower subjective workload.

However, a closer inspection of the workload measure produced unexpected results. When workload was analyzed during system failures, automation produced differential workload according to the composition of the crew. Heterogeneous groups showed little increase in workload between manual and automated conditions during system failures; yet homogeneous groups showed a much greater increase in workload when automation was present. Thus, the perception of workload level may not be affected consistently by level of automation and crew composition.

Crew Coordination in Advanced Technology Aircraft

As with the concept of workload, no single, universally accepted operational definition of crew coordination is found in the literature. When viewed as an interactive behavior, it becomes difficult to describe, define, and measure (Hall & Rizzo, 1975). Turney, Cohen, & Greenberg (1981) indicated that the operational definition of coordination is determined by the context of the task itself. For example, Army aviation emphasizes the verbal and behavioral responses in rotary wing flight in their definition. Crew coordination is defined as the interaction between crew members (communication) and action (sequence & timing) necessary for flight tasks to be performed efficiently, effectively, and safely (Leedom, 1990). One

Navy definition emphasizes skills and resources, defining it as an organized interaction of crew skills and resources for the safe and effective conduct of flight (MacCuish & Morgan, in press). The central concept found in these definitions is an interaction that has safety and effectiveness as its goal.

Closely related concepts have been identified in research conducted with Naval training teams. Glickman, Zimmer, Montero, Guerette, Campbell, Morgan, and Salas (1987) identified taskwork and teamwork as the key components of team performance. Taskwork involves individual, technical and operational skills needed to perform the job tasks. Teamwork is the component more pertinent to crew coordination because it involves behaviors that compose interdependence, coordination, and adaptation. Teamwork is defined as "the set of values and behaviors necessary for a team to achieve its common goals and to adapt to the circumstances that it confronts in the work environment" (McIntyre, Morgan, Salas, & Glickman, 1989). Five essential elements are involved in teamwork: the group's self awareness as an intradependent unit, monitoring team performance, providing feedback based on the monitoring, communicating in a closed-loop fashion, and backing up the actions of others. Again, implicit in the definition of teamwork is an interaction to achieve a common goal.

Krumm (1960) identified two perspectives from which crew coordination is most frequently viewed: a time-bound synchronization of actions or a response improvisation. When individuals involved in a common activity perform adequately within a specified time period, a synchronization of action occurs. In this type of coordination, the responses made by crew members are structured through the use of formalized procedures (e.g., standard operating procedures). In contrast, when individuals involved in a common activity perform as needed in problem solving situations that have no immediate, prepackaged solutions, response improvisation occurs. In this type of coordination crew members recognize and share crew problems and objectives, maintain an awareness of others' responses and responsibilities, and provide responses in recognition of other's responses. These two perspectives are reflected in the distinction between established and emergent task situations (Boguslaw & Porter, 1962). Again, the task type or structure appears to drive the coordination demands made of the crew.

Approaches to crew coordination measurement. Two approaches to the measurement of crew coordination are typically found. The analyses of communication pattern and content are often used as one approach to the measurement of the coordination effort among crew members (e.g., Krumm & Farina, 1962; Povenmire, Rockway, Bunecke, & Patton, 1989;

Thornton, Kaempf, Zeller, & McAnulty, 1991). The analyses of verbal communication is assumed to provide an assessment of coordination interactions.

A second approach is to use trained evaluators to rate performance on several dimensions of crew coordination. Helmreich and Wilhelm (1989) developed a worksheet, Line Oriented Flight Training (LOFT), for check airmen to evaluate CRM in both simulators and aircraft. This evaluation tool is frequently used to assess crew performance in training situations.

Another promising measure of crew coordination is based on a series of investigations that identified and analyzed the critical behaviors and subsequent behavioral dimensions found to be crucial in the development of effective crew coordination (Glickman et al., 1987; Morgan, Glickman, Woodward, Blaiwes, & Salas, 1986; Oser, McCallum, Morgan, & Salas, 1989). Using this earlier research as a foundation, a systematic, extensive review was conducted of crew coordination programs, both commercial and military, the tream research literature, and aviation data sources (Prince, Salas, & Franz, 1990). Behaviorally defined management skills that were extracted from a review of the management literature and skill behaviors identified for team training were compared to skills previously identified as important for crew coordination. Franz, McCallum, Lewis, Prince, and Salas (1990) identified 37 aircrew coordination behaviors that they categorized into the following seven behavioral skill dimensions: mission analysis, decision making, assertiveness, flexibility, leadership, communications, and situational awareness.

An examination of the criticality and frequencies of the behaviors that compose the seven dimensions established the utility of the behaviors (Franz, Prince, Cannon-Bowers, & Salas, 1990). In-depth interviews with 20 pilots from the Naval helicopter community yielded 18 additional behavioral examples of crew coordination. Twenty-one job experts verified the importance, difficulty and frequency of occurrence of behaviors. Revisions were made to reduce item ambiguity, and the behaviors were administered to 134 additional job experts. Finally, the behaviors were classified independently by instructor pilots and aircrew coordination researchers under the seven dimensions previously indicated. As part of this process and revisions, the number of behaviors was further reduced to 42. These final refinements permitted the development of the Aircrew Coordination Observation and Evaluation (ACOE) scale for use in the evaluation of crew coordination skills.

Prince, Chidester, Cannon-Bowers, and Bowers (1991) have suggested that in spite of differences in equipment and operations, enough similarity in coordination requirements exists so that the skill dimensions included in the ACOE are relevant to the behaviors of various types of aircrews.

Although developed independently, these coordination skills are similar to those recommended by the FAA for inclusion in crew training, and have been shown to be related to skills and behavior definitions ordinarily used in managerial assessment (Maher, 1983).

Unfortunately, the potential of the ACOE to increase an understanding of crew coodination has not been fully realized. A review of published research indicates limited use of the scales in examining crew coordination issues (e.g., Franz, McCallum et al., 1990; Franz, Prince, Baker, Zalensny, & Salas, in preparation; Lassiter, Vaughn, Smaltz, Morgan, & Salas, 1990). In addition the reliability of the scale has not been established at this time. Therefore, an opportunity exists to establish the utility of this measure as a means of assessing crew coordination and its potentially moderating effects.

Changes in crew coordination. Crew coordination and automation are no longer considered be two model-independent concerns in aviation safety (Wiener, 1989). Observational and opinion data collected from pilots of high technology aircraft by Wiener indicated that cockpit automation affects crew coordination by influencing the way the automated flight is managed. Five main factors were reported to affect CRM in these cockpits: the physical difficulty of seeing what the other crew member is doing, cross-monitoring difficulties, a breakdown in traditional roles and responsibilities, a redistribution of authority, and an increased tendency to assist others with programming during periods of high workload. Each factor alters the interaction of the crews, and potentially, their flight task performance.

Clothier (1991) has provided evidence that crews do interact differently dependent upon the technology level of the aircraft. The data for her analysis were obtained from a major domestic airline in both LOFT simulator missions and on the flight line. In LOFT simulations crews in advanced cockpits performed better than those in standard cockpits. In evaluations made on the line, CRM performance was better in standard aircraft. One year later, after all pilots had completed CRM training, CRM performance remained better for crews in advanced technology aircraft than those crews operating in standard aircraft; however, no differences were found between crews on the line. The author suggested that the advantage of advanced technology aircraft in the LOFT scenarios was related to the extra time the technology afforded the crews to utilize their knowledge in the abnormal situations.

Further support for notion that crew coordination may be altered in relation to the level of automation employed is shown by an experimental examination of the relationship of automation, crew composition, and communication. Straus and Cooper (1989) conducted a communication analyses on 24 of the 50 crews who participated in Wickens et al., (1989). The results indicated that more information exchange took place in the automated condition. Performance was better for crews who made a higher ratio of task relevant to task irrelevant statements. Several types of communication and performance measures were significantly correlated. The interactions between automation and crew composition were not significant. The preliminary results of this study provided some evidence of a relationship between automation, communication (i.e. crew coordination), and performance in a flight task.

Regardless of the level of automation in the cockpit, the need to maintain vigilance in aviation related tasks indicates that the aircrew must remain actively involved with the aircraft, the environment, and each other. Unfortunately, a frequent criticism of advanced technology cockpits is that the pilot may be placed out-of-the-loop, thus increasing the difficulty of maintaining an up-to-date awareness of and control over the aircraft's status. The maintenance of such knowledge provides the aircrew with a basis from which to respond quickly and appropriately should any emergency or abnormal situation occur.

Norman (1991) suggests that the current level of intelligence for automated systems is inadequate when humans must take over control of the system. An absence of needed feedback and interaction from the automated system during abnormalities in flight may prevent the aircrew from effectively dealing with the situation. Feedback and diagnostic interaction would normally occur between the aircrew. If inappropriate forms of automation are indeed a root problem, extra, joint effort on the part of the aircrew to problem solve in the absence of automated feedback may be required until design issues are remedied.

In addition, behaviors such as cross-monitoring, assertiveness, and information exchange as taught in traditional aviation settings may require readjustment to prevent such problems as complacency and inattentiveness (Foushee & Helmreich, 1988), diffusion of responsibility between crew members and aircraft systems (Foushee, 1982) or to prevent new and potentially more severe blunders from occurring (McDaniel, 1988). An aircrew may need to develop something akin to a finely-tuned dynamic allocation of function approach when interacting with each other and the automated system in order to readjust the distribution of tasks according to skill and processing load on an ongoing basis during a flight. Perhaps this is the area in which specialized crew training may prove itself most useful.

Changes in the difficulty of a task may also introduce changes in the coordination behaviors exhibited in flight situations. Although most training programs for coordination skills assume that more coordination is better, investigations of team performance by Naylor & Briggs (1965) and Williges, Johnston, & Briggs (1966) demonstrated that increased communication under high levels of workload interferred with performance. However, this association does not always hold true, as evidenced by Jensen (1962) and Kinkade & Kidd (1959), and the relationship between task difficulty and coordinaiton remains unclear.

Other research has illustrated that the task situation itself may influence the effectiveness of the coordination behaviors. Kleinman & Serfaty (1989) conducted an experiment in which two-person teams performed a computerized resource allocation task. Teams coordinated their resources for maximum performance through computer-mediated communication. As task demands increased from low to moderate levels, communication was utilized more frequently; however, communication was reduced as the workload (i.e., task difficulty) increased further, even though subjects continued to transfer resources. Only communication, as a subset of coordination behaviors, is typically examined. Further exploration of the link between task difficulty and crew coordination in flight situations is therefore warranted.

Present Research

One purpose of the present research is assess the reliability and utility of the ACOE scales in describing the crew coordination behaviors exhibited during flight. The development of rater training procedures and the subsequent identification of satisfactory interrater reliability provide initial support for the usefulness of this instrument in the present and future research.

A second purpose of the present investigation is to examine the relationships among crew coordination, automation, and workload. A review of the automation and team performance literature suggests the need for an organized research approach to delineate these relationships. An additional consideration is the difficulty level of the task. If differences in workload and crew coordination behaviors can be distinguished as a function of changes in level of automation and task difficulty, guidelines for planning crew training schemes may be developed.

Four contexts of task structure related to automation and task difficulty may be devised producing a 2 x 2 factorial experimental design utilizing two levels of automation (automated and manual) and two levels of task difficulty (high and low). Verification of the effects of these variables on subjective workload, crew coordination, and the flight performance of the crew is required before attempting to recommend specific crew training.

Summary of Automation Hypotheses

The use of automation in the cockpit, as in other automated environments, has introduced changes in the structure of the tasks performed by the crew members (Norman

& Orlady, 1989a). In turn, these changes potentially alter the performance, subjective workload, and coordination behaviors of the crew members. Although conflicting reports exists as to the actual consequences of increased automation, automation is designed ideally to improve performance and decrease the workload of the crew. Additionally, as the roles of the pilots are altered, coordination behaviors may be expected to vary as a function of automation level. The use of automation may provide the crew with more opportunities to coordinate their behaviors and in some circumstances, increase the demand for coordination. Given the limited research literature regarding the introduction of automation in the cockpit, the following hypotheses are offered.

Hypothesis 1: The level of automation is hypothesized to have an effect on the ability of the aircrew to perform their flight tasks. Crews in the automated condition perform their flight tasks better than crews in the manual condition.

Hypothesis 2: The level of automation is hypothesized to influence the ability of the aircrew to develop an optimal flight route. Crews in the automated condition develop more optimal flight routes than crews in the manual condition.

Hypothesis 3: The level of automation is hypothesized to affect the subjective workload of the crew members. The crews in the automated condition perceive less workload than the crews in the manual condition.

Hypothesis 4: The level of automation is hypothesized to affect the distribution of crew coordination behaviors displayed by the crew. Crews in the automated condition display different coordination behaviors than those in the manual condition.

Hypothesis 5: Automation level is not hypothesized to affect the quality of the crew coordination displayed by the crew. The quality of crew coordination displayed does not differ in relation to the level of automation available.

Summary of Task Difficulty Hypotheses

Although changes in the difficulty of a given task may produce changes in performance, other consequences (e.g., decreases in workload or changes in coordination behaviors) may provide additional information about the nature of the task. An examination of different levels of task difficulty may be particularily useful if expected changes in performance do not immediately appear. For example, inclement weather, systems failures, or unplanned events that can increase the difficulty of flight tasks may not prevent an aircraft from reaching its destination. However, if the presence of these conditions is sustained over time, changes in the workload of an individual may eventually produce decrements in performance.

Hypothesis 1: The level of task difficulty is hypothesized to affect the ability of the crew to perform their flight tasks. Crews in the low task difficulty condition perform their flying tasks better than the crews in the high task difficulty condition.

Hypothesis 2: The level of task difficulty is hypothesized to affect the ability of the crew to develop an optimal flight route. Crews in the low task difficulty condition develop better flight routes than the crews in the high task difficulty condition.

Hypothesis 3: The level of task difficulty is hypothesized to affect the subjective workload of the crew members. Crews in the low task difficulty condition perceive less workload than crews in the high task difficulty condition.

Hypothesis 4: The level of task difficulty is hypothesized to affect the distribution of crew coordination behaviors displayed by the crew. Crews in the low task difficulty condition display different coordination behaviors than those in the high task difficulty condition.

Hypothesis 5: The level of task difficulty is not hypothesized to affect the quality of the crew coordination displayed by the crew. The quality of crew coordination displayed does not differ in relation to the level of task difficulty.

II. METHOD

In the present investigation, the crew coordination performance, task performance, and workload of 48 crews were assessed in a low fidelity aircraft simulation. The following sections describe the participants, apparatus, and procedures used. In addition, the development of the flight scenarios, task performance and crew coordination measures that were employed is also described in detail.

Participants

The participants were 96 students attending Embry-Riddle Aeronautical University (86 male and 10 female). The median age of the participants was 20. The median flight hours attained was 140. All participants held a current private pilot's license; 30 participants held more advanced ratings. Participants received $10.00 for their involvement. Ninety-six students formed 48 crews of two individuals each.

Design

Two levels of automation and two levels of task difficulty were combined to yield a 2 x 2 factorial design. The level of automation was manipulated by the presence or absence of an autopilot (i.e., automation or manual mode). That is, when the autopilot is engaged in the navigation lock mode, the airplane automatically maintains a preselected altitude and flies directly toward a very high frequency Omnidirectional Range (VOR) radial. Task difficulty was manipulated by the presence or absence of turbulence and wind in the simulator scenario (i.e., high or low task difficulty).

The flight task consisted of four variations: (1) manual-low difficulty, (2) manual-high difficulty, (3) automation-low difficulty, and (4) automation-high difficulty. Each of the flight task variations were examined by having 24 crews perform in both levels of automation and one level of task difficulty. The participants were randomly assigned to one level of task difficulty.

Apparatus

The low-fidelity flight simulation, Flight Simulator 4.0 (Microsoft), was employed for this investigation. Flight Simulator was modified by the manufacturer to provide flight performance measures. The software presents external visual scenes above the instrument panel on the monitor (see Figure 1). The aircraft configuration used was that of a Cessna 182-RG. Only one navigation radio was provided.

The hardware configuration comprised: (1) a Personal Computer with two monitors, (2) three headsets with microphones, (3) an audio system capable of combining several channels of verbal communication, (4) a mouse, (5) a joystick, and (6) video recording equipment. A partition separated the experimenter's station from the crew's station. A video camera placed above the experimenter's

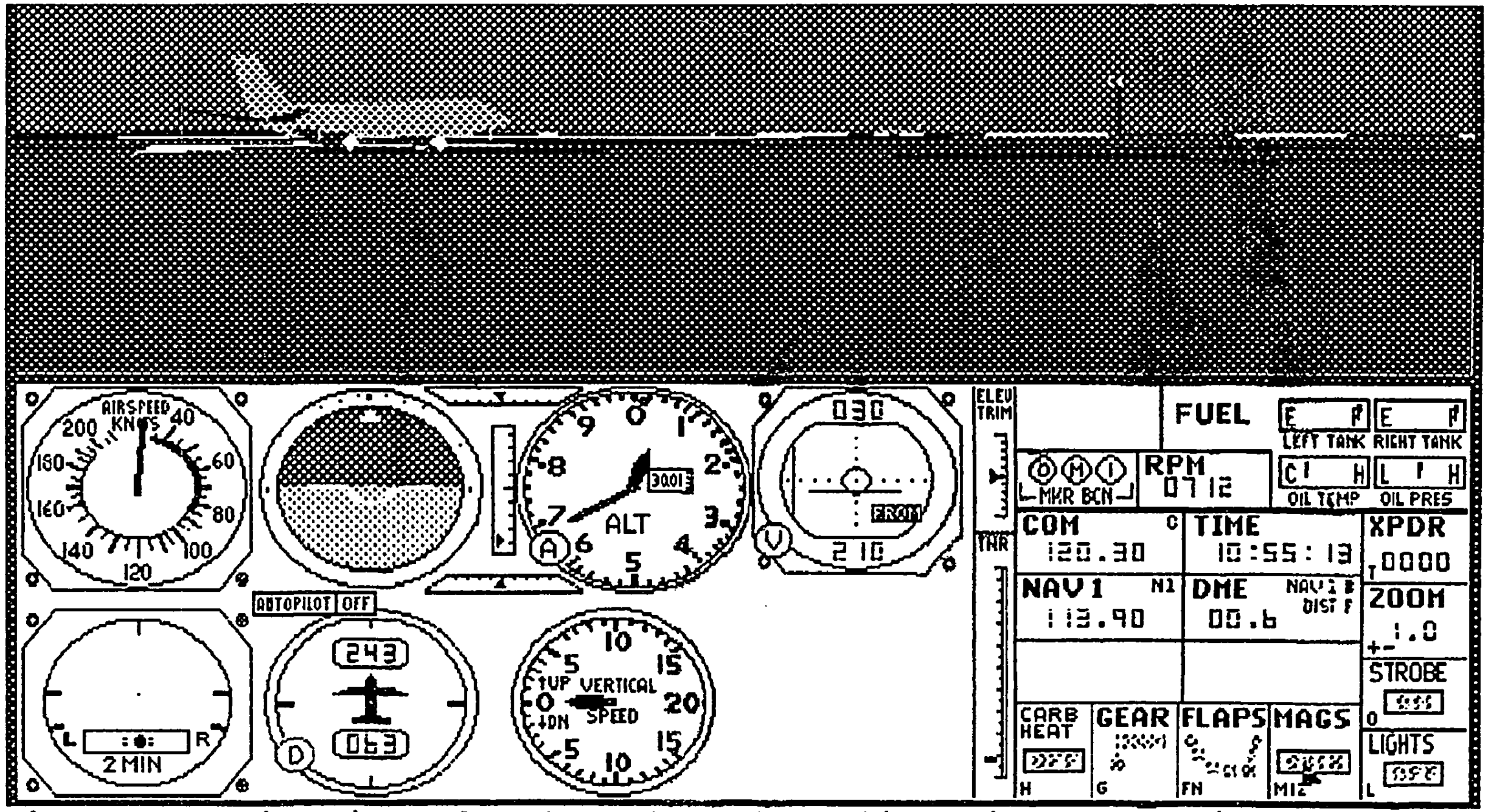

Figure 1 Outside View and Instrument Panel of Flight Simulator Configuration

station was used to record the crews during the flight scenario. The camera was positioned to provide a distinct view of the crews' faces and was connected to an audio/video recorder. Participants communicated with each other and the experimenter via headsets with microphones. All utterances transmitted on the intercommunication system were recorded.

Flight Simulator Task Separation

Flight Simulator is designed to be performed by one individual using a keyboard, mouse, and joystick to fly the simulator. However, participants in this research performed the flight scenarios as two-person crews, with one individual (the pilot) controlling the joystick and the other (the copilot) controlling the mouse. Control of the keyboard could be assigned at the discretion of the pilot. This division of tasks required the coordination of the activities of both participants for successful mission completion.

Simulated Flight Scenario Overview

Several criteria were used to develop the two flight scenarios for this research project. First, the scenario was designed to present events that were likely to be affected by crew coordination (e.g., events that would require interaction between the crew members). Second, the scenario was designed to evaluate the crews' performance on tasks for which they might reasonably be asked to perform given an emergency situation. Third, the scenario was designed to allow replication in different modes of automation.

The two scenarios that were developed involved flying relief supplies to one of two types of disaster: a tornado or gasoline pipeline rupture. The scenarios were similar except for type of disaster, airfield names, and supplies available. The duration of each scenario was approximately 45-minutes.

The scenarios required that the crew work together to obtain and deliver supplies to one of three disaster sites (e.g., the tornado touched down in three locations). Both flying and navigation skills were required to obtain supplies from different airfields. The crew members could share the responsibility of determining which supplies to deliver and developing a flight plan to do so. The efficiency with which crew members performed their roles influenced the accomplishment of the crew's overall objectives.

The experimenter played the role of three control centers (i.e., Tower, Center, and Operations) during the scenario. Tower provided clearance for takeoff and handed off the crew to Center. Center informed the crew of their expected time of arrival (ETA) to each airfield check point. Operations provided the crew with specific information and instructions regarding the status of the disaster and their overall mission.

The crew had three primary flight tasks to perform throughout the experimental scenarios. First, they were to maintain an altitude throughout the scenario as specified in the premission briefing. Second, they were to maintain the course to each airfield check point as accurately as possible. Third, the crew were to reach each check point at the appropriate time as instructed by Center. A check point was reached when the aircraft flew through a large box placed in the air directly over the check point's VOR. The box was 1,000 feet wide and high; the center of the box was located at 4000 ft. Landing the aircraft was not required.

Mission briefing materials. Both a written and a prerecorded, verbal mission briefing containing the flight requirements and details of the mission were presented to each crew before the scenario began. Appendix A contains the mission briefing for the tornado scenario in the high workload condition. The briefing materials also included a navigation map and a mission log (see Appendices B and C for the tornado scenario). The map was a quasi-low altitude navigation chart that presented airways and VORs. The mission log provided the crew with information which, for the most part, was also verbally presented to them by Operations. The contents of the log were not reviewed until the crew received instruction from Operations.

Experimental scenario composition. Each scenario was divided into five flight segments that were conducted contiguously. In the cockpit prior to takeoff, Operations instructed the crew to record flight data (e.g., destinations, expected time of arrival (ETA), actual time of arrival (ATA) on the form provided throughout the mission. In addition, the crew was to rank individually the supplies available for delivery in order of usefulness in providing relief to the disaster scene. They were given an approximate departure time and a course for the first two segments of flight.

The first flight segment was designed to give the crew time to consider together the supplies that would be useful in providing disaster relief and to become familiar with the locations of the supplies. Thus, Operations instructed the crew to reach a consensus as to the ranking of the usefulness of the supplies and provided the locations of the supplies.

During the second flight segment, the crew received further instructions about the specifics of their mission. Operations informed the crew that they had time to pick up four supplies and deliver them to one disaster site. They were to fly the designated airways only; if they flew over a supply check point, a supply must be obtained. The crew was instructed to identify their first supply check point and inform Operations of their decision two miles prior to their present check point (i.e., Midway). After the crew reported their first supply check point, they were instructed to fly to a specific supply check point (i.e., Lewis) to pick up a supply after reaching Midway. The crew received this instruction regardless of the first supply check point the crew had chosen.

During the third flight segment, the crew was informed which supplies were specifically needed at each disaster site and the usefulness of the supplies in terms of the supply's point value for that site. Based on this information, the crews were instructed to develop a flight plan to pick up three additional supplies and deliver them to a disaster site. Additionally, they were to maximize the number of points acquired, thus ensuring that the most useful supplies would be delivered.

During the remaining two flight segments, four and five, the crew was required to fly to the next two supply check points that they had chosen and obtain the second and third supply. After they reached the third supply check point in segment five, the scenario ended. The crew was informed that environmental conditions would preclude them from continuing further and that the current supply point was their final destination. Appendix D presents an outline of the script used by the experimenter for the tornado disaster in the high difficulty condition.

Practice scenario composition. Preliminary data indicated that one hour of practice in the flight simulator was sufficient for the aircrews to become familiar with the flight simulator, interactions with the control centers, and the flight performance requirements. The crew first received a 15-minute introduction to the simulator instrument panel and the controls required to fly the simulator. A list of crew responsibilities and checklist procedures were provided to the crew (see Appendices E and F). The crew then flew a practice scenario, similar to the experimental scenario, except for the requirement to obtain and deliver supplies. That is, during the practice scenario, the crew flew from check point to check point, maintaining an altitude of 4000 feet above ground level, and calculating airspeeds needed to reach each destination on schedule; however, the flight route was predetermined for them and the need to make decisions about the course of flight was not introduced. The crew was instructed to work as a team by assisting each other when possible.

Procedures

All flight data were collected over a period of 7 weeks. Typically, two crews were observed each day, one crew during a morning session and one during an afternoon session. Participants were assigned a crew mate randomly; however, the participants who indicated that they wished to perform as a crew were so assigned.

Experimental sessions. After completing an informed consent form, each participant completed a demographic information sheet (see Appendix G). Participants were then randomly assigned either the role of the pilot or the copilot. Following the completion of the practice scenario, participants flew the first experimental flight scenario. After completion of the first scenario, participants completed a subjective assessment of workload, the National Aeronautics and Space Administration Task Load Index (NASA TLX) developed by Hart and Staveland (1988). After a ten minute rest break, the participants flew the second experimental flight scenario and again completed the workload assessment. Finally, the participants responded to a post-experimental questionnaire (see Appendix H) and were debriefed by the experimenter.

Flight Performance

Summary values for each of the flight performance measures were computed for each crew.

Altitude deviation. The crews were instructed to maintain an altitude of 4000 feet throughout the scenario. The root mean square error (RMSE) for altitude deviation from designated altitude was calculated in feet for intervals of 15 seconds for each crew.

Course deviation. The crews were required to remain on the designated airways as closely as possible throughout each scenario. The RMSE for the deviation from designated course was calculated in tenths of a mile for each 15 second interval.

Time deviation. The crews were instructed to reach each airfield check point at a specific time as determined by Center. Each ETA to the next check point was calculated by adding a predetermined time in seconds to the time that the crew actually passed over the airfield (ATA). The measure of performance was derived by calculating the absolute difference between the crew's ETA and ATA. The unit of measurement was seconds.

Problem Solving Performance

Crews were instructed to obtain the most supply points possible by flying over four supply airfields, using only the airways shown on the map, and then delivering them to one disaster site. They could not fly over an airfield more than once. The total points possible for obtaining four disaster supplies ranged from 0 to 17 and was dependent upon the disaster site chosen.

Scores for problem solving performance were calculated by summing the points assigned to the flight path chosen. Higher points were indicative of better flight paths chosen in terms of the usefulness of the supplies at a specific disaster site.

Subjective Workload

The NASA TLX is the multidimensional rating scale that was employed as the measure of subjective workload. A weighted average of ratings on six subscales provides an overall workload rating. These subscales are: Mental

Demand, Physical Demand, Temporal Demand, Own Performance, Effort, and Frustration. The participants rated their perceived exertion on five of these subscales (except Own Performance) on a graded scale from "Low" to "High". The Own Performance scale ranges from "Good" to "Poor". The TLX was completed by each participant after each experimental scenario.

Crew Coordination

An adaptation of the Aircrew Coordination Observation and Evaluation (ACOE) scale (Franz et al., 1991) was used to measure the frequency and quality of crew coordination behaviors that were exhibited by crews. The scale comprises seven dimensions: leadership, mission analysis, situation awareness, assertiveness, adaptability/flexibility, and communication.

As previously discussed, the development of the original scales has been documented by several authors (e.g., Prince, Salas, & Franz, 1990). The original ACOE scale consisted of two forms: (1) a checklist on which the frequency of observed behaviors for each dimension and crew position are noted, and (2) a form on which the quality of the observed coordination behaviors for each dimension and crew position is evaluated. The rating scale anchors ranged from 0 (not observed) to 5 (excellent).

Development of revised ACOE forms.

The format of both the observation checklist and the dimension rating form were revised (see Appendices I and J). Changes made to the checklist were mainly cosmetic ones introduced for ease of administration. Only one behavior was eliminated from the original ACOE checklist (i.e., "conveys information concisely") because the behavior proved difficult to operationalize in the experimental setting.

In an effort to assist raters in the assessment of quality of crew coordination behaviors, behavioral indicators of the skill levels were developed for each dimension of crew coordination. The behavioral indicators were developed from specific behaviors observed during the experiment and an examination of the dimension definitions and knowledge, skills, and abilities required by the dimensions (McCuish & Morgan, in preparation). In addition, discussions were held with personnel familiar with coordination issues, including three pilots who participated in pre-tests of the scenarios. The pilots provided specific feedback on effective and ineffective crew coordination behaviors. Two of the pilots reviewed and provided additional feedback on the behavioral indicators and the examples constructed. Scores for quality of crew coordination skill level for each dimension ranged from 1 to 5. Behaviors were anchored at 1, 3, and 5 as indicators of hardly any, adequate, and complete skill, respectively, in the particular dimension.

Rater training. Two raters received 13 hours of training related to the experimental scenario and the ACOE forms. Videotapes of three crews were used as training aids. Two of the crews had been excluded from the experiment because of missing data; the third crew performed only in the pilot-test. The crews exhibited a full range of skill levels in crew coordination.

Both raters had previous experience flying the simulator. Rater training began with the raters receiving instruction on the simulator instrument panel and the controls required to fly the simulator. The raters then participated as a crew for one scenario. Afterward, they and the experimenter reviewed crew responsibilities, mission goals, and the critical events that could be expected to occur during each segment of flight.

The seven dimensions of crew coordination were introduced through a presentation of dimension definitions, corresponding behaviors, and specific behavioral examples. Examples of behaviors were then tied to critical events. The behavioral observation form was introduced by first explaining the procedure to note the frequency of behaviors. The raters then recorded behaviors observed during each flight segment of a videotaped scenario presented in 20 second intervals. The experimenter provided feedback and the behaviors were discussed for each time interval.

The experimenter introduced the crew coordination rating scale by reviewing the dimension definitions and then explaining the procedure to rate the quality of crew coordination exhibited. Behavioral indicators of each dimension and related behavioral examples were presented and discussed (see Appendix K). The raters individually rated each crew member position on each dimension for the scenario previously shown. After the raters discussed their initial ratings with the experimenter, they made a final rating for each crew member on each dimension. The remainder of the training involved practice in observation of crew coordination behaviors and rating the behaviors observed in the flight scenarios of the two remaining crews.

Rating procedures. The two raters recorded the frequency of crew coordination behaviors on the checklist while observing the videotaped scenarios. The raters then used the behavioral summary scales to evaluate the quality of the crew coordination behaviors exhibited by each crew member for each dimension. As in training, these procedures led to initial ratings of crew coordination by each individual rater and then to final ratings of crew coordination as a result of rater discussion.

III. RESULTS

Overview

The interrater reliability of the crew coordination measures are presented first. The second and third sections present the analysis of the performance for flight tasks and the problems solving task. The analysis of subjective workload is presented in the fourth section, followed by the analysis of crew coordination in the fifth section. The final section presents the analyses for the relationship of performance and crew coordination.

Interrater Reliability of Crew Coordination Measures

The interrater reliabilities of the ACOE behavioral observation checklist and the behavioral summary ratings of crew coordination were calculated using the Pearson *r* correlation. Correlations were computed at the dimension level (e.g., mission analysis, leadership) for each crew position.

Observational checklist. Interrater reliabilties for frequency of behavioral observations of crew coordination were computed for each crew position and dimension of crew coordination. The Pearson *r* values ranged from .917 to .993 (see Table 1).

Behavioral summary scales. Interrater reliabilties for the behavioral summary scales were computed for both initial and final ratings for each dimension of crew coordination and crew position. Interrater reliabilities of the initial ratings ranged from .540 to .851. Interrater reliabilities of the final ratings ranged from .912 to .991 (see Table 2).

Table 1

Interrater Reliability of Frequency of Behavioral Observations for the Seven Dimensions of Crew Coordination

Dimension	Pilot	Copilot
Mission Analysis	.986	.978
Situational Awareness	.950	.978
Decision Making	.974	.917
Leadership	.981	.963
Assertiveness	.959	.946
Adaptability/Flexibility	.943	.981
Communication	.984	.993

Flight Performance

Flight performance data were collected and analyzed for each crew by levels of task difficulty and automation. Analyses of variance (ANOVA) with Tukey post hoc tests were utilized for these analyses. The data are summarized below by flight task.

Course Deviation. The crews were required to remain on the designated airways as closely as possible throughout each scenario. A 2 x 2 (Task Difficulty by Automation) mixed-design ANOVA was performed on the course deviation data. No effects were observed (see Table 3).

Table 2

Interrater Reliability of Behavioral Summary Ratings for the Seven Dimensions of Crew Coordination

Dimension	Pilot	Copilot
Mission Analysis		
Initial	.830	.851
Final	.960	.958
Situational Awareness		
Initial	.724	.730
Final	.980	.978
Decision Making		
Initial	.762	.682
Final	.991	.962
Leadership		
Initial	.753	.613
Final	.983	.960
Assertiveness		
Initial	.782	.610
Final	.971	.951
Adaptability/Flexibility		
Initial	.540	.574
Final	.912	.920
Communication		
Initial	.776	.719
Final	.980	.942

Table 3

Summary of the Analysis of Variance for Course Deviation

Source of Variation	df	Mean Square	F	Eta Square
Task Difficulty (D)	1	0.0008	0.00	
Automation (A)	1	0.2748	0.89	
A x D	1	0.1156	0.37	
Subject (D) [S(D)]	34	0.3370	NT	
A x S(D)	34	0.3105	NT	

NT = no test.

Altitude Deviation. A 2 x 2 (Task Difficulty by Automation) mixed-design ANOVA was performed on the altitude data. The analysis yielded a main effect for task difficulty, $F(1,33) = 5.30$, $p < .05$ (see Table 4). Altitude deviation in the high task difficulty condition ($M = 368.34$) was significantly greater than in the low task difficulty condition ($M = 333.95$).

A main effect was also indicated for automation, $F(1,33) = 17.21$, $p < .01$. The mean RMS error for altitude deviation in the manual condition ($M = 371.46$) was significantly greater than in the automated condition ($M = 327.88$). No other difference was found.

Table 4

Summary of the Analysis of Variance for Altitude Deviation

Source of Variation	*df*	Mean Square	*F*	Eta Square
Task Difficulty (D)	1	102702.8846	5.30*	0.00
Automation (A)	1	169756.6829	17.21**	0.00
A x D	1	4750.7226	0.48	
Subject (D) [S(D)]	33	19394.2138	NT	
A x S(D)	33	9861.4351	NT	

* p < .05. ** p < .01; NT = no test.

Time Deviation. A 2 x 2 (Task Difficulty x Automation) mixed-design ANOVA was performed on the time deviation data. The data set tended to be positively skewed; transformations by log, reciprocal, and square root failed to provide any increase in normality and power. Therefore, the analysis was conducted on the raw data. No significant difference was noted (see Table 5).

Table 5

Summary of the Analysis of Variance for Time Deviation

Source of Variation	df	Mean Square	F	Eta Square
Task Difficulty (D)	1	344.0118	0.07	
Automation (A)	1	2.3059	0.00	
A x D	1	2424.8941	1.08	
Subject (D) [S(D)]	32	5291.6669	NT	
A x S(D)	32	2247.2750	NT	

Problem Solving Performance

A 2 x 2 (Task Difficulty by Automation) mixed-design ANOVA was performed on the flight path problem solution data. These data were calculated by summing the points assigned to the flight path that was chosen. Higher points were indicative of better flight paths chosen in terms of the usefulness of the supplies that could be delivered. Because of the high negative skew in the supply solution data, these data were transformed using a reflect and inverse equation (Tabachnick & Fidell, 1989). The transformation increased the normality of the distribution, but did not affect the significance of the results; therefore, the original data are reported.

No main effect was found; however, there was a significant interaction of automation by task difficulty,

$F(1,46) = 5.67$, $p < .05$. A test for simple effects revealed that in the high task difficulty condition, the flight paths chosen in the manual condition ($M = 15.89$) were significantly better than those chosen in the automated condition ($M = 13.77$), $F(1,46) = 4.53$, $p < .05$. The mean problem solving scores and the source of variation are presented in Tables 6 and 7.

Table 6

Summary of the Analysis of Variance for the Problem Solving Task

Source of Variation	df	Mean Square	F	Eta Square
Task Difficulty (D)	1	1.2178	0.07	
Automation (A)	1	8.8741	0.92	
A x D	1	54.8470	5.67*	0.04
Subject (D) [S(D)]	46	17.3442	NT	
A x S(D)	46	9.6675	NT	

* $p < .05$; NT = no test.

Table 7

Mean Problem Solving Score by Automation and Task Difficulty

	Task Difficulty	
Automation[a]	High	Low
Automated	13.77 (4.38)	15.06 (3.55)
Manual	15.89 (2.44)	14.15 (4.04)

Note. Standard deviations appear in parentheses.

[a] $n = 48$.

Subjective Workload

A 2 x 2 x 2 (Task Difficulty by Position by Automation) mixed-design ANOVA was performed on the subjective workload data. The analysis indicated a main effect of automation, $F(1,86) = 8.09$, $p < .01$) and no significant interactions (see Table 8). Subjective workload, as measured by the NASA TLX, was significantly higher in the manual condition ($M = 58.41$) than in the automated condition ($M = 52.75$).

Table 8

Summary of the Analysis of Variance for Subjective Workload

Source of Variation	df	Mean Square	F	Eta Square
Task Difficulty (D)	1	0.2634	0.00	
Position (P)	1	40.2596	0.09	
D x P	1	20.4540	0.05	
Automation (A)	1	1444.6307	8.09**	0.03
A x D	1	8.3313	0.05	
A x P	1	514.0214	2.88	
A x D x P	1	97.6909	0.55	
Subject (D X P) [S(D x P)]	86	447.3665	NT	
A x S(D x P)	86	178.6422	NT	

** $p < .01$.

Subscale analyses. The subjective workload data were analyzed further by conducting a 2 x 2 x 2 (Task Difficulty by Position by Automation) mixed-design ANOVA on each of the six TLX subscales. Significant differences were found within two workload subscales, physical demand and effort.

The analysis of the physical demand workload subscale revealed two main effects of automation and position, $F(1, 87) = 16.56$, $p < .05$, and $F(1,87) = 33.23$, $p < .05$, respectively. The mean physical demand workload in the manual condition ($M = 54.07$) was significantly greater than the automated condition ($M = 39.12$). The mean physical demand workload of the pilot ($M = 55.49$) was significantly greater than the copilot's mean workload ($M = 37.42$).

The analysis of the physical demand subscale also revealed a significant interaction of automation and position, $F(1,87) = 25.48$, $p < .05$. A test for simple effects indicated significant differences in physical demand workload for position in the manual condition, $F(1,140) = 58.47$, $p < .05$. The physical demand of the pilots ($M = 69.46$) was significantly greater than the copilots ($M = 38.35$) in the manual condition. Also, physical demand for the pilot differed significantly between the two levels of automation, $F(1,87) = 58.48$, $p < .05$. The mean physical demand workload was greater for the pilot in the manual condition than in the automated condition ($M = 41.52$).

The analysis for the effort subscale revealed a significant main effect of automation, F(1,87) = 7.11, p < .05. The perception of effort as a source of workload was greater in the manual condition (M = 69.94) than in the automated condition (M = 62.86). The sources of variation for the two workload subscales that were significant are presented in Table 9.

Table 9

Summary of the Analyses of Variance for the Workload Subscales of Physical Demand and Effort

Source of Variation	df	Mean Square	F	Eta Square
Physical Demand				
Task Difficulty (D)	1	1464.5071	1.63	
Position (P)	1	14844.3312	16.56**	0.11
P x D	1	67.4626	0.08	
Automation (A)	1	10089.2773	33.23**	0.07
A x D	1	776.8933	2.56	
A x P	1	7735.2225	25.48**	0.06
A x D x P	1	818.2953	2.70	
Subject (D x P) [S(D x P)]	87	896.4413	NT	
A x S(D x P)	87	303.5854	NT	

** p < .01.

Table 9 (continued)

Summary of the Analyses of Variance for the Workload Subscales of Physical Demand and Effort

Source of Variation	df	Mean Square	F	Eta Square
Effort				
Task Difficulty (D)	1	0.0025	0.00	
Position (P)	1	89.8657	0.13	
P x D	1	0.4666	0.00	
Automation (A)	1	2265.6351	7.11*	0.02
A x D	1	44.1891	0.14	
A x P	1	311.2873	0.98	
A x D x P	1	33.8081	0.11	
Subject (D x P) [S(D x P)]	87	706.7816	NT	
A x S(D x P)	87	318.5257	NT	

* $p < .05$.

Crew Coordination

The crew coordination behaviors were analyzed in terms of two measures: the frequency per minute of observed crew coordination behaviors and the behavioral ratings of the quality of crew coordination exhibited.

Frequency per minute of crew coordination behaviors. A 2 x 2 (Automation by Task Difficulty) mixed-design ANOVA was conducted to identify differences in the length of the scenarios among conditions. A significant main effect was revealed for task difficulty, $F(1,43) = 14.14$, $p < .01$. The length of flight in seconds in the high difficulty condition ($M = 3530.02$) was significantly longer than in the low difficulty condition ($M = 3270.59$) (approximately 4 minutes 19 seconds longer). For this reason, the frequency data were converted to a measure of frequency of crew coordination behaviors per minute to overcome differences in the opportunity to display coordination behaviors.

First, frequency data were obtained from the ACOE behavioral observation checklist. The frequency of behaviors for each crew position was calculated by summing the individual crew coordination behaviors within each dimension for the entire scenario.

The frequency per minute was determined by summing the frequency of behaviors occurring within each dimension and dividing by the duration of scenario. Frequency per minute was calculated for pilot and copilot. These data were then submitted to the following analyses to identify differences in the frequency per minute of coordination behaviors among levels of automation and task difficulty and between crew positions for each dimension.

A 2 x 2 x 2 (Automation by Task Difficulty by Position) mixed-design ANOVA was conducted for each of the seven crew coordination dimensions. A significant main effect for automation was revealed for mission analysis, $F(1, 92) = 10.56$, $p < .01$. Mission analysis behaviors occurred more frequently in the automated condition ($M = .052$ per minute) than in the manual condition ($M = .040$ per minute). No other difference was found for mission analysis.

A significant main effect for automation was also found for decision making $F(1, 92) = 4.19$, $p < .05$. More decision making behaviors were exhibited during the automated condition ($M = .019$ per minute) than during the manual condition ($M = .016$ per minute). No other difference was found.

A significant main effect for position was revealed for situation awareness, $F(1, 92) = 20.31$, $p < .01$. The copilot displayed more situation awareness coordination behaviors ($M = .082$ per minute) than the pilot ($M = .041$ per minute). No other difference was noted for situation awareness.

The analysis for the leadership dimension revealed significant main effects of position, $F(1,92) = 11.86$, $p < .01$, automation, $F(1,92) = 19.43$, $p < .01$. The pilot exhibited more leadership behaviors ($M = .119$ per minute) than the copilot ($M = .065$ per minute). Significantly more leadership behaviors were exhibited in the automated condition ($M = .105$ per minute) than in the manual condition ($M = .079$ per minute). A significant interaction of position by automation was also indicated, $F(1,92) = 24.79$, $p < .01$. A test for simple effects indicated that the pilot displayed significantly more leadership behaviors in the automated condition ($M = .148$ per minute) than in the manual condition ($M = .091$ per minute), $F(1,92) = 24.92$, $p < .01$. Additionally, the pilot displayed significantly more leadership behaviors in the automated condition than the copilot ($M = .063$ per minute), $F(1,118) = 44.14$, $p < .01$. No other difference was observed for the leadership dimension.

The analysis for frequency per minute of assertiveness behaviors revealed a significant effect of position, $F(1, 92) = 24.56$, $p < .01$, and automation, $F(1,92) = 6.59$, $p < .01$. The pilot exhibited more assertiveness behaviors ($M = .142$ per minute) than the copilot ($M = .078$ per minute). Coordination behaviors for the assertiveness dimension occurred significantly more frequently in the automated condition ($M = .117$ per minute) than in the manual condition ($M = .102$ per minute). A test for simple effects indicated that the pilot displayed significantly more assertiveness behaviors in the automated condition, ($M = .142$ per minute) than the copilot ($M = .092$ per minute), $F(1,128) = 12.57$, $p < .01$. The pilot also displayed significantly more assertiveness behaviors ($M = .141$ per minute) than the copilot ($M = .064$ per minute) in the manual condition, $F(1,128) = 30.20$, $p < .01$. In addition, the copilot displayed significantly more assertiveness behaviors during the automated condition than in the manual condition, $F(1,92) = 12.20$, $p < .01$.

A significant main effect of position was revealed for the communication dimension, $\underline{F}(1,92) = 11.94$, $\underline{p} < .01$. The copilot displayed significantly more communication behaviors ($\underline{M} = .486$ per minute) than the pilot ($\underline{M} = .347$ per minute). An additional main effect, automation, was revealed for communication behaviors, $\underline{F}(1,92) = 6.86$, $\underline{p} < .01$. Significantly more communication behaviors occurred in the automated condition ($\underline{M} = .436$ per minute) than in the manual condition ($\underline{M} = .396$ per minute). No other significant difference was found for the communication dimension. Finally, the analysis for the adaptability/flexibility dimension at the position level revealed no significant differences. The sources of variation for frequency per minute of the seven dimensions of crew coordination are presented in Table 10.

Table 10

Summary of the Analyses of Variance for Frequency Per Minute by Dimension of Crew Coordination

Source of Variation	*df*	Mean Square[1]	*F*	Eta Square
Mission Analysis				
Task Difficulty (D)	1	0.58	0.50	
Position (P)	1	1.83	1.58	
P x D	1	0.59	0.51	
Automation (A)	1	6.67	10.56**	0.10
A x D	1	1.05	1.66	
A x P	1	0.61	0.96	
A x D x P	1	0.00	0.01	
Subject (D x P) [S(D x P)]	92	1.16	NT	
A x S(D x P)	92	0.63	NT	

** $p < .01$.

[1] Mean Square x 1000.

Table 10 (continued)

Source of Variation	df	Mean Square[1]	_F_	Eta Square
Situational Awareness				
Task Difficulty (D)	1	0.06	0.01	
Position (P)	1	81.73	20.31**	0.15
P x D	1	0.08	0.02	
Automation (A)	1	0.02	0.02	
A x D	1	0.08	0.09	
A x P	1	1.49	1.58	
A x D x P	1	0.29	0.31	
Subject (D x P) [S(D x P)]	92	4.02	NT	
A x S(D x P)	92	0.94	NT	

** $p < .01$.

[1] Mean Square x 1000.

Table 10 (continued)

Source of Variation	df	Mean Square[1]	F	Eta Square
Decision Making				
Task Difficulty (D)	1	0.00	0.00	
Position (P)	1	0.98	3.35	
P x D	1	0.25	0.85	
Automation (A)	1	0.55	4.19*	0.01
A x D	1	0.01	0.11	
A x P	1	0.27	2.05	
A x D x P	1	0.02	0.12	
Subject (D x P) [S(D x P)]	92	0.29	NT	
A x S(D x P)	92	0.13	NT	

* $p < .05$.

[1] Mean Square x 1000.

Table 10 (continued)

Source of Variation	df	Mean Square[1]	*F*	Eta Square
Leadership				
Task Difficulty (D)	1	3.16	0.26	
Position (P)	1	141.82	11.86**	0.10
P x D	1	7.29	0.61	
Automation (A)	1	33.61	19.43**	0.02
A x D	1	0.27	0.15	
A x P	1	42.87	24.79**	0.03
A x D x P	1	0.50	0.29	
Subject (D x P) [S(D x P)]	92	11.96	NT	
A x S(D x P)	92	1.73	NT	

** $p < .01$.

[1] Mean Square x 1000.

Table 10 (continued)

Source of Variation	df	Mean Square[1]	_F_	Eta Square
<u>Assertiveness</u>				
Task Difficulty (D)	1	0.24	0.03	
Position (P)	1	193.43	24.56**	0.18
P x D	1	3.43	0.44	
Automation (A)	1	10.52	6.59**	0.01
A x D	1	0.49	0.31	
A x P	1	9.05	5.67*	0.01
A x D x P	1	0.37	0.23	
Subject (D x P) [S(D x P)]	92	7.87	NT	
A x S(D x P)	92	1.60	NT	

* $p < .05$. ** $p < .01$.

[1] Mean Square x 1000.

Table 10 (continued)

Source of Variation	df	Mean Square[1]	F	Eta Square
Adaptability/Flexibility				
Task Difficulty (D)	1	0.05	0.27	
Position (P)	1	0.08	0.42	
P x D	1	0.12	0.62	
Automation (A)	1	0.16	3.31	
A x D	1	0.12	2.44	
A x P	1	0.16	3.27	
A x D x P	1	0.01	0.17	
Subject (D x P) [S(D x P)]	92	0.20	NT	
A x S(D x P)	92	0.05	NT	

[1] Mean Square x 1000.

Table 10 (concluded)

Source of Variation	df	Mean Square[1]	F	Eta Square
Communication				
Task Difficulty (D)	1	296.89	3.87	
Position (P)	1	916.86	11.94**	0.10
P x D	1	6.34	0.08	
Automation (A)	1	77.12	6.86**	0.01
A x D	1	0.27	0.02	
A x P	1	34.88	3.10	
A x D x P	1	0.44	0.04	
Subject (D x P) [S(D x P)]	92	76.77	NT	
A x S(D x P)	92	11.25	NT	

** $p < .01$.

[1] Mean Square x 1000.

Behavioral ratings of crew coordination dimensions and overall crew coordination. Ratings for the seven dimensions of crew coordination were calculated by averaging the final behavioral summary ratings of the raters for both pilot and copilot separately. These data were submitted to the following analyses to identify differences between ratings of crew coordination quality among levels of automation and task difficulty and between crew position.

A 2 x 2 x 2 (Automation by Task Difficulty by Position) mixed-design ANOVA was conducted for each of the seven crew coordination dimensions. A significant main effect for position was revealed for mission analysis, $\underline{F}(1, 92) = 4.77$, $\underline{p} < .03$. The mission analysis behaviors of the copilot was rated significantly higher ($\underline{M} = 2.92$) than the pilot's rating ($\underline{M} = 2.60$). No other difference was found for mission analysis.

A significant main effect of position was also revealed for situation awareness, $\underline{F}(1, 92) = 6.86$, $\underline{p} < .01$. Again, situation awareness of the copilot was rated significantly better ($\underline{M} = 2.98$) than the pilot's rating ($\underline{M} = 2.64$). No other difference was noted for situation awareness.

A significant main effect of position for communication was revealed, $\underline{F}(1,92) = 6.54$, $\underline{p} < .01$. As with mission analysis and situation awareness, the communication of the copilot was rated significantly higher ($\underline{M} = 3.16$) than the pilot's rating ($\underline{M} = 2.80$). An additional main effect, automation, was revealed for communication, $\underline{F}(1, 92) = 5.73$, $\underline{p} < .02$. Coordination behaviors for the communication dimension were rated higher in the automated condition ($\underline{M} = 3.04$) than in the manual condition ($\underline{M} = 2.92$).

A significant main effect of automation for decision making was revealed, $\underline{F}(1,92) = 8.22$, $\underline{p} < .01$. Coordination behaviors for the decision making dimension received higher ratings in the automated condition ($\underline{M} = 2.80$) than in the manual condition (M = 2.65). No other significant difference was found for decision making.

The analysis for the leadership dimension revealed a significant interaction of position by automation, F(1,92) = 7.87, $p < .01$. A test for simple effects indicated that the quality of pilot leadership was rated significantly higher in the automated condition (M = 2.69) than in the manual condition (M = 2.46), F(1,92) = 7.99, $p < .01$. No other difference was observed.

The analysis for the assertiveness dimension of crew coordination revealed a significant effect of automation, F(1, 92) = 5.51, $p < .02$. Coordination behaviors for the assertiveness dimension were rated significantly higher in the automated condition (M = 3.05) than in the manual condition (M = 2.94). No other difference was revealed for assertiveness. Finally, the analysis of the adaptability/flexibility dimension revealed no significant difference. The sources of variation for ratings of crew coordination are presented in Table 11.

Table 11

Summary of the Analyses of Variance for Dimension Ratings of Crew Coordination Quality

Source of Variation	df	Mean Square	F	Eta Square
Mission Analysis				
Task Difficulty (D)	1	0.0208	0.02	
Position (P)	1	5.0052	4.77*	0.04
P x D	1	0.1302	0.12	
Automation (A)	1	0.3333	1.56	
A x D	1	0.1875	0.87	
A x P	1	0.2552	1.19	
A x P x D	1	0.2552	1.19	
Subject (D x P) [S(D x P)]	92	1.0497	NT	
A x S(D x P)	92	0.2143	NT	

* $p < .05$.

Table 11 (continued)

Source of Variation	df	Mean Square	F	Eta Square
Situational Awareness				
Task Difficulty (D)	1	0.0469	0.06	
Position (P)	1	5.6719	6.86**	0.06
P x D	1	0.1302	0.16	
Automation (A)	1	0.0469	0.28	
A x D	1	0.1302	0.79	
A x P	1	0.6302	3.82	
A x D x P	1	0.0052	0.03	
Subject (D x P) [S(D x P)]	92	0.8263	NT	
A x S(D x P)	92	0.1651	NT	

** $p < .01$.

Table 11 (continued)

Source of Variation	df	Mean Square	F	Eta Square
Decision Making				
Task Difficulty (D)	1	0.2552	0.30	
Position (P)	1	1.6875	1.97	
P x D	1	0.1875	0.22	
Automation (A)	1	1.1719	8.22**	0.01
A x P	1	0.1875	1.32	
A x D	1	0.0052	0.04	
A x D x P	1	0.0208	0.15	
Subject (D x P) [S(D x P)]	92	0.8559	NT	
A x S(D x P)	92	0.1426	NT	

** $p < .01$.

Table 11 (continued)

Source of Variation	df	Mean Square	*F*	Eta Square
<u>Leadership</u>				
Task Difficulty (D)	1	0.8138	0.95	
Position (P)	1	0.0117	0.01	
P x D	1	0.0117	0.01	
Automation (A)	1	0.2200	1.38	
A x P	1	1.2513	7.87**	0.01
A x D	1	0.0326	0.20	
A x D x P	1	0.0013	0.01	
Subject (D x P) [S(D x P)]	92	0.8537	NT	
A x S(D x P)	92	0.1589	NT	

** $p < .01$.

Table 11 (continued)

Source of Variation	df	Mean Square	_F_	Eta Square
<u>Assertiveness</u>				
Task Difficulty (D)	1	0.3333	0.50	
Position (P)	1	0.0052	0.01	
P x D	1	0.0833	0.12	
Automation (A)	1	0.5208	5.51*	0.02
A x P	1	0.1875	1.98	
A x D	1	0.0469	0.50	
A x D x P	1	0.0469	0.50	
Subject (D x P) [S(D x P)]	92	0.6693	NT	
A x S(D x P)	92	0.0945	NT	

* $p < .05$.

Table 11 (continued)

Source of Variation	df	Mean Square	*F*	Eta Square
Adaptability/Flexibility				
Task Difficulty (D)	1	0.1576	0.29	
Position (P)	1	0.9492	1.75	
P x D	1	0.2930	0.54	
Automation (A)	1	0.0013	0.01	
A x P	1	0.0638	0.56	
A x D	1	0.1055	0.93	
A x D x P	1	0.0326	0.29	
Subject (D x P) [S(D x P)]	92	0.5422	NT	
A x S(D x P)	92	0.1133	NT	

Table 11 (concluded)

Source of Variation	df	Mean Square	F	Eta Square
Communication				
Task Difficulty (D)	1	1.1719	1.27	
Position (P)	1	6.0208	6.54**	0.06
P x D	1	0.0469	0.05	
Automation (A)	1	0.7500	5.73*	0.01
A x D	1	0.0052	0.04	
A x P	1	0.1875	1.43	
A x D x P	1	0.0052	0.04	
Subject (D x P) [S(D x P)]	92	0.9204	NT	
A x S(D x P)	92	0.1310	NT	

* $p < .05$. ** $p < .01$.

Overall Rating of Crew Coordination Quality

Overall ratings of crew coordination quality for each crew position were calculated by averaging the behavioral summary ratings across the seven dimensions of crew coordination. A 2 x 2 x 2 (Position by Automation by Task Difficulty) mixed-design ANOVA was conducted on the quality of crew coordination ratings. The analysis revealed a significant main effect of automation, $F(1,92) = 5.80$, $p < .05$ (see Table 12). The overall rating of crew coordination was higher in the automated condition ($\underline{M}$ = 2.85) than in the manual condition ($\underline{M}$ = 2.77).

A significant interaction of automation by position was also found $\underline{F}(1,92) = 5.80$, $\underline{p} < .05$. A test for simple effects indicated that the overall crew coordination ratings for the pilots were rated higher in the automated condition ($\underline{M}$ = 2.80) than in the manual condition ($\underline{M}$ = 2.63), $\underline{F}(1,92) = 5.82$, $\underline{p} < .02$. There were no significant differences between the copilot ratings nor between the pilot and the copilot.

Table 12

Summary of the Analysis of Variance for Overall Rating of Crew Coordination Quality

Source of Variation	df	Mean Square	F	Eta Square
Task Difficulty (D)	1	0.2552	0.47	
Position (P)	1	1.8520	3.39	
P x D	1	0.0086	0.02	
Automation (A)	1	0.3215	5.80*	0.01
A x P	1	0.3215	5.80*	0.01
A x D	1	0.0038	0.07	
A x D x P	1	0.0004	0.01	
Subject (D x P) [S(D x P)]	92	0.5460	NT	
A x S(D x P)	92	0.0554	NT	

* $p < .05$.

Task Performance and Crew Coordination

Two series of stepwise multiple regression analyses were conducted using the measures of flight performance and problem solving as the dependent variables. The first analyses investigated the relationship of the performance measures with the observed frequencies of the seven crew coordination dimensions for pilot and copilot. The second series investigated the relationship of the performance measures with the behavioral summary ratings of the seven crew coordination dimensions. These analyses were conducted for both levels of automation.

Relationship of task performance and frequency of crew coordination behaviors. The frequencies of two crew coordination dimensions were predictive of altitude deviation (see Table 13). The frequency of the copilot's situation awareness behaviors accounted for 15% of the altitude deviation variance in the manual condition. As the frequency of the copilot's situation awareness behaviors increased, mean altitude deviation increased. In the automated condition, the frequency of the assertiveness behaviors of the copilot predicted 10% of the variance. As the frequency of the copilot's assertiveness behaviors increased, mean altitude deviation increased.

Analysis of mean course deviation in the manual condition indicated a main effect for the frequency of the pilot's situation awareness behaviors. As the number of the pilot's situation awareness behaviors increased, mean course deviation increased. No effect for frequency was found for course deviation in the automated condition. The regression analysis for mean time deviation indicated no main effect in either condition.

Analysis of the final dependent variable, problem solving, indicated a significant main effect for the frequency of the decision making behaviors of the copilot in automated flight. As the frequency of the copilot's decision making behaviors decreased, the problem solving scores improved. Table 13 provides a summary of the significant effects of the regression analyses for frequency of crew coordination behaviors.

Table 13

Stepwise Multiple Regression Analyses for Frequency Using Mean Altitude Deviation, Course Deviation, and Problem Solving as the Dependent Variables

	Step	Multiple R^2	Final Beta	F	df
Altitude Deviation					
			Manual		
Situation Awareness - Copilot	1	.152	.389	8.22	1,46
			Automated		
Assertiveness - Copilot	1	.102	.319	5.23	1,46
Course Deviation					
			Automated		
Situation Awareness - Pilot	1	.126	.356	6.66	1,46
Problem Solving					
			Automated		
Decision Making - Copilot	1	.095	-.308	4.81	1,46

Relationship of task performance and ratings of crew coordination quality. The variance of mean time deviation was accounted for by ratings of crew coordination quality during both levels of automation (see Table 14). Ratings of the pilot's mission analysis and leadership, and the copilot's communication explained 25% of the variance for time deviation in the manual condition. Mean time deviation increased in relation to increases in the ratings of the pilot's mission analysis behaviors and to decreases in the ratings of the copilot's communication and the pilot's leadership behaviors. Similarily in the automated condition, ratings of the pilot's leadership and assertiveness, and the copilot's communication explained 29% of the variance for time deviation. Again, mean time deviation increased in relation to decreases in the ratings of the copilot's communication and the pilot's leadership behaviors; however, as the ratings of the pilot's assertiveness behaviors increased, mean time deviation increased likewise.

Altitude deviation was explained by ratings of the pilots's situation awareness in the manual condition. Better ratings of the pilot's situation awareness were related to less mean altitude deviation. No dimension of crew coordination was predictive of altitude deviation in the automated condition.

Course deviation in the manual condition was explained by ratings of the copilots's mission analysis (20%); however, in the automated condition two dimensions of crew coordination for the pilot explained 18% of the variance: mission analysis and situation awareness. In the manual condition, increases in mean course deviation were associated with poorer mission analysis behaviors of the copilot. In the automated condition, increases in mean course deviation were associated with better mission analysis behaviors of the pilot, and better ratings of situation awareness for the pilot.

Finally, ratings of two crew coordination dimensions for the copilot were predictive of problem solving: the copilot's situation awareness in the manual condition and mission analysis in the automated condition. In the manual condition, better ratings of situation awareness for the copilot were associated with better problem solving performance. In the automated condition, better problem solving performance was associated with higher ratings of mission analysis for the copilot. These results are summarized in Table 14.

Table 14

Stepwise Multiple Regression Analyses for Rating Using Problem Score, Mean Time, Altitude, and Course Deviation as the Dependent Variables

	Step	Multiple R^2	Final Beta	F	df
Time Deviation					
			Manual		
Communication - Copilot	1	.098	-.425	4.89	1,45
Mission Analysis - Pilot	2	.177	.574	4.74	2,44
Leadership - Pilot	3	.248	-.380	4.72	3,43
			Automated		
Communication - Copilot	1	.119	-.470	6.24	1,46
Assertiveness - Pilot	2	.198	.653	5.57	2,45
Leadership - Pilot	3	.293	-.466	6.07	3,44
Altitude Deviation					
			Manual		
Situation Awareness - Pilot	1	.162	-.402	8.86	1,46

Table 14 (concluded)

	Step	Multiple R^2	Final Beta	F	df
<u>Course Deviation</u>					
			Manual		
Mission Analysis - Copilot	1	.203	-.450	11.70	1,46
			Automated		
Mission Analysis - Pilot	1	.088	.712	4.43	1,46
Situation Awareness - Pilot	2	.183	.518	5.03	2,45
<u>Problem Solving</u>					
			Manual		
Situation Awareness - Copilot	1	.239	.489	14.48	1,46
			Automated		
Mission Analysis - Copilot	1	.274	.524	17.38	1,46

Post-Experimental Questionnaire

A questionnaire administered at the end of the experiment solicited the participants' opinions about the experiment and their experience with cockpit resourse management (CRM) training. The participants indicated that they felt the scenarios were moderately to very representative of how aircraft might be used in response to emergency situations (M = 5.23). Both the flight performance and the decision making requirements of the scenarios were felt to reflect very accurately issues important in aviation, (M = 6.14 and M = 6.05, respectively). Additionally, the participants indicated that the practice received during the training scenario was very adequate (M = 5.87).

A related samples t-test was conducted between the responses to Questions 5 and 6. These questions asked about the extent to which the participant became complacent during the automated and manual conditions. The participants indicated that they were significantly more complacent (t = 8.09, $p < .05$) in the automated condition (M = 4.02, "moderately complacent") than in the manual condition (M = 2.18, "somewhat complacent"). No difference was noted between pilot and copilot in either condition.

The final two questions concerned the amount of CRM training the participant had experienced previously. Only 47% of the participants indicated they had received any previous training. Chi-square tests for independence revealed no relationship between CRM training for either pilots or copilots and levels of task difficulty, $\chi^2 = .49$, $\chi^2 = .06$, df = 1, respectively, nor any difference between crew position, $\chi^2 = 1.58$, df = 1.

Summary

This investigation revealed an interesting, but complex array of results. The following sections provide a global summary of the findings.

Interrater reliability. Interrater reliabilities were within acceptable levels for both the crew coordination observation and behavioral summary scales. Reliabilities ranged from .917 to .993 for the observation scales and from .912 to .971 for the final rating made on the behavioral summary scales.

Crew coordination. ANOVA results for the frequency per minute of crew coordination behaviors indicated significant effects as follows: (1) a crew position effect for the dimensions of situation awareness, leadership, assertiveness, and communication, (2) an automation effect for the dimensions of mission analysis, decision making, leadership, assertiveness, and communication, and (3) an automation by position effect for leadership and assertiveness. ANOVA results for the behavioral summary ratings of crew coordination quality revealed the following: (1) a crew position effect for mission analysis, situation awareness, and communication, (2) an automation effect for decision making, assertiveness, communication, and overall crew coordination.

The results of the regression analyses indicated that several dimensions of the frequency of behavioral observations and ratings of crew coordination behaviors were predictive of task performance, although the dimensions varied according to level of automation; however, the behavioral ratings indicated a stronger effect than frequency. Altitude deviation was predicted by the frequency of situation awareness of the copilot in the manual condition and the assertiveness of the copilot in the automated condition. In the automated condition, course deviation was predicted by the frequency of situation awareness behaviors of the pilot; problem solving performance by the frequency of decision making of the copilot.

The relationship of task performance and the behavioral summary ratings for crew coordination is summarized below. Time deviation was predicted by ratings of the communication of the copilot, and mission analysis and leadership of the pilot in the manual condition, and by the communication of the copilot, and leadership and assertiveness of the pilot in the automated condition. Altitude deviation was predicted by ratings of the situation awareness of the pilot. Course deviation was predicted by ratings of the mission analysis of the copilot in the manual condition and by the mission analysis and situation awareness of the pilot in the automated condition. Problem solving performance was predicted by the situation awareness in the manual condition and mission analysis of the copilot in the automated condition.

Task performance. The only flight performance measure affected by level of automation was altitude deviation. Altitude deviation was greater in the manual condition, and also in the high difficulty condition. Problem solving performance was better in the manual high difficulty condition than in the automated high difficulty condition.

Subjective workload. The subjective workload reported by the crews was lower in the automated condition. In addition, pilots reported higher physical demand workload in the automated condition, and both crew members reported greater effort as a source of workload in the automated condition.

Opinion and experience data. The participants indicated a general level of satisfaction with the representativeness of the scenarios, performance requirements, and adequacy of the training. They indicated that they felt more complacent during automated flight. No differences was found in the amount of CRM training previously received by the participants.

IV. DISCUSSION

The purposes of this research were two-fold: (1) to assess the reliability and utility of the ACOE scales in decribing the crew coordination behaviors displayed during flight and (2) to examine the effects automation and task difficulty on crew coordination, workload, and performance. Two levels of automation were investigated: an autopilot that featured an attitude, altitude, and navigation hold and no autopilot. It was hypothesized that in the automated condition, performance would be better, subjective workload lower, differences in the frequency of crew coordination behaviors would occur, and no differences would appear in relation to the quality of coordination performance exhibited. Additionally, two levels of task difficulty were investigated: the presence of wind and turbulence and the absence of environmental influences. It was hypothesized that performance would be better and workload would be lower in the low task difficulty condition, differences in frequency of crew coordination behaviors would transpire, and no difference would appear in relation to the quality of coordination performance exhibited.

Overview

An interesting pattern of results emerged from this low fidelity investigation of automation. The participants reported less workload in the automated mode of flight. Yet, flight performance, for all intents and purposes was not enhanced to any great extent. In addition, the flight paths developed for the problem solving task were significantly worse in the automated, high difficulty condition than in the manual, high difficulty condition. During the automated condition, crew coordination behaviors occurred more frequently. Also, crew coordination performance was better for four of the seven dimensions and for the overall rating of crew coordination. Finally, support for a relationship between performance and quality of crew coordination behaviors was evidenced. The following discussion will examine these results in detail and interpret them within the context of the hypotheses previously generated and related research findings.

Flight Performance

Contrary to hypothesis and the past findings of Wickens et al. (1989), with the exception of altitude deviation, automation had little effect on the three flight performance measures. Although the flight performance measures of altitude, course, and time deviation were realistic in relation to the specific requirements of the mission, the latter two measures were perhaps too gross for a difference in performance to be detected. In addition, staying on course and arriving on time appear to be more influenced by factors outside of the direct control of the autopilot. For example, the autopilot has no direct link to the speed of the plane, speed being under the control of the pilot;

however, it could be argued that the use of the autopilot could allow the crew members to pay more attention to the calculation and adjustment of airspeed. Likewise, although the navigation feature of the autopilot enabled the aircraft to lock on to the selected VOR, the observation of the experimenter suggested that the benefit of this feature appeared to be more governed by the method of its utilization by the crews than was altitude.

It is also possible that the use of a higher level of automation or several additional levels of automation, as Sheridan's taxonomy of computer aiding (1991) outlines, would have further delineated any effects of automation. The use of other levels of automation, such as the system offering advice but performing no actions, in addition to a wider range of performance measures, (e.g., severity of errors, timeliness and accuracy of radio calls), may have indicated performance differences not highlighted by the current measures.

As found with the automation manipulation, altitude deviation was also the only one of the three measures of flight performance affected by task difficulty. The wind and turbulence present in the high difficulty scenario appeared to increase altitude deviation over that present in the low difficulty scenario. This finding was anticipated in light of the effects of turbulence on aircraft handling in general. However, the lack of a significant effect on course and time deviations may be related to the participants' general aviation skill training.

Subjective Workload

The results of the NASA TLX analyses indicate that subjective workload was perceived to be lower in the scenarios in which automation was available. A closer examination of the workload subscales revealed that the sources of workload affected by level of automation were physical demand and effort. The pilots reported more physical demand when flying without the autopilot. A contrast between pilot and copilot responsibilities was shown by the higher rating of physical demand made by the pilots than the copilots in the manual condition. These results indicate that the autopilot achieved some of its designed intent; that is, automation provided at least subjective relief from some of the demands of the mission.

Individual participants, regardless of crew position, indicated that their own effort, as a source of workload, was lower in the automated condition. This finding suggests that even though the bulk of the physical demand fell on the pilot, both crew members felt that they had to work harder mentally and physically to accomplish their own level of performance in the manual condition.

Analyses of the remaining workload subscales (i.e., temporal demand, mental demand, performance, and frustration revealed no difference between level of automation for either crew position. The absence of differences among these subscales suggests again that the primary end of the autopilot was a reduction in the physical demand placed on the pilot and perhaps an overall reduction in the general level of effort exerted by the crew.

No difference in subjective workload was found in relation to task difficulty. As with the measures of flight performance, it appears that the wind and turbulence did not sufficiently tax the skills of the crew members (pilots in particular) to produce significant reports of workload inequality between levels of task difficulty.

The automation effect on workload supports the stated research hypothesis and the findings reported by Wickens et al. (1989). Wiener et al. (1991), however, found the opposite; that is, in a simulator study comparing a traditional DC-9 and the glass cockpit of the MD-88, the first officers, rather than the captains, reported more workload. In addition, the advanced technology crews reported higher physical demand for the first officer and higher frustration for both crew members. The disparity in results may be explained in part by the differences in the amount of experience in the aircraft. DC-9 crews had significantly more time (i.e., both months and hours) in their aircraft than did the crews in the advanced aircraft (30.4 months vs 9.5). The difference in the crews' familiarity with flight systems and possibly in new task requirements placed on the first officer in the advanced system suggest a possible bias on the basis of experience in favor of the traditional cockpit.

Problem Solving

Automation did not produce better decisions about the optimal flight path to take in either level of task difficulty. In fact, when wind and turbulence were present, more optimal flight paths were developed during manual rather than automated flight. The failure of automation to improve the flight path chosen is somewhat surprising, especially in the higher difficulty setting where automation, at first glance, would logically seem to be most helpful. Given the reported advantages of automation and reduced reports of workload, this finding is intuitively perplexing. Because the crews experienced less workload in the automated condition, one might hypothesize that more of their "resources" would have been available for other activities, such as planning and problem resolution.

This hypothesis is supported by the increased number of mission analysis and decision making behaviors exhibited during automated flight. However, the occurrence of more coordination behaviors did not produce better flight path solutions. And as previously noted, mental demand, such as that might have been created by the need to develop a flight plan to obtain and deliver the optimal supplies, showed no apparent decrease in the automated condition.

One viable explanation involves the notion of complacency, which has been described as an attitude that "modulates our probabilities in responding" (Wiener, 1981, p. 118). Complacency, defined as an attitude, is not measured easily, does not necessarily produce observable negative results, and therefore is most likely to be measured only subjectively. Wiener suggested that complacency be viewed as "a conscious or subconscious relaxation of one's usual standards in exercising judgement, in selecting strategies, and in making decisions" p. 118.

Give consideration, then, to the automated condition in which the aircraft generally required much less active flying. During this condition the workload derived specifically from physical demand and overall effort was decreased; in addition, the crews reported a higher degree of complacency. The resultant complacency, particularly that which occurred in the high task difficulty condition as the autopilot handled a more difficult environmental condition for the crew, may have placed the crews at risk to accept less than optimal flight path solutions in spite of an increased number of coordination behaviors. (The frequency of crew coordination behaviors is discussed in more detail in the next section).

Anecdotal support for the complacency rationale is frequently cited by researchers and pilots alike. The primary theme of complacency involves an individual or crew feeling familiar and perhaps overly comfortable with a situation, sometimes to the detriment of the situation. The analysis of the problem solving task, in conjunction with reports of lower workload and higher complacency, provide additional evidence of the potentially debilitating effects of complacency.

Crew Coordination

Many have contended that the nature of coordination may differ among increasingly automated flight systems because of the changes that automation impose on flight tasks, and eventually on the roles and interactions of the crew members. This contention is supported by one of the more notable findings of this investigation that demonstrates a difference in the frequency per minute of coordination behaviors observed between levels of automation. Crews during automated flight exhibited a higher frequency of coordination behaviors of mission analysis, decision making, leadership, and communication. Apparently energy (i.e., resources) not spent in direct control of the aircraft was directed to more overt interaction between crew members. In contrast, crews in manual flight displayed almost no decrease in overall flight performance, but significantly less coordination behaviors.

Kleinman and Serfaty (1989) reported similar results when examining adaptive team coordination strategies. Under low to moderate levels of workload, team members coordinated their actions and resource sharing in an explicit manner. However as workload increased, performance was maintained, but the coordination strategy changed to an implicit one in which crew members responded to unsolicited requests for assistance and communication was greatly reduced.

The lack of performance differences in light of the increased coordination behaviors may be partially explained by the conclusions of Williges, Johnston, & Briggs (1966). After noting divergent effects of communication on team performance, they suggested that when a task does not require, but rather allows communication, then crew communication may seem "little more than an unnecessary and rather tempting luxury that has relatively little impact on teamwork" p. 477. Similarly, if automated flight permitted the opportunity for more coordination behaviors that were not essential for the maintenance of safety and performance standards, the increase in coordination behaviors may have been superfluous. It is conceivable that the level of automation present in this investigation permitted more explicit coordination behaviors, when possibly only implicit behaviors were needed.

Brown, Boff, and Swierenga (1991) bring a slightly different perspective to the explanation for increased coordination behaviors in the automated condition. They suggest that if automated systems reduce control actions (e.g., pushing or pulling), the implicit communication of a crew member's present knowledge and intent to other crew members may also be reduced. Therefore, it may be hypothesized that more explicit coordination behaviors may be needed in increasingly advanced cockpits to convey the information that was previously conveyed by a push, pull, or a look.

Other differences in the distribution of coordination behaviors occurred in relation to crew members. In support of Norman & Orlady's (1988a) proposal concerning changes in the role of pilots, the pilots in this investigation assumed more of a managerial role as shown by increased leadership behaviors (i.e., directing, organizing, and supporting) in the automated condition. Additionally, copilots became more assertive, taking a more active role in offering unsolicited opinions and admitting uncertainty during automated flight.

Differences between the ratings of crew coordination quality were also observed, although none was hypothesized. When differences were noted, the ratings favored the automated condition. Coordination behaviors displayed during automated flight were rated higher for the dimensions of decision making, assertiveness, and communication. The overall rating of crew coordination quality also revealed a higher rating in automated condition; however, only the pilots received significantly higher overall ratings.

These results are somewhat contrary to the report of Wiener et al. (1991) who found that overall CRM performance was either the same or slightly higher (dependent on the rater) in the traditional aircraft. Again, differences in time in aircraft may have biased those findings. In contrast, Clothier (1991) found that CRM performance was better in advanced technology aircraft when LOFt scenarios were used.

Although differences between the coordination behaviors of the two crew members were not hypothesized, the analysis of the frequency per minute and rating of crew coordination behaviors indicated differences in the responsibilities of the individual crew members. Regardless of the level of automation, the copilot displayed more situation awareness and communication behaviors than did the pilot, and the pilot exhibited more assertiveness behaviors. In the automated condition only, the pilot displayed more leadership behaviors than the copilot. Surprisingly, the copilot received higher coordination ratings than the pilot for situation awareness, mission analysis, and communication behaviors across conditions. These results suggest that some of the responsibilities of the crew members may remain stable and the copilot may be in a better position to display overt coordination actions regardless of automation level.

Performance and Crew Coordination

The analysis of the relationship between frequency of crew coordination behaviors and task performance indicated that the frequency with which crew coordination behaviors occurred explained small, but significant amounts of variance in the performance measures. Three coordination dimensions (e.g, the number of the copilot's situation awareness behaviors) were significantly predictive, explaining 10 to 15% of the variance of three of the four performance measures. However, in this investigation it appears that the increased frequency of situation awareness and assertiveness behaviors were indicative of deviations in flight performance and thus perhaps were performance-driven behaviors, as Straus & Cooper (1989) suggested in their analysis of communication frequency. Likewise, the negative relationship of the frequency of decision making behaviors of the copilot and problem solving scores suggests that the decision making behaviors may have been symptomatic of difficulties in determining the most optimal flight path.

The analysis of the ratings of crew coordination indicated a stronger effect on task performance than did frequency. Quality ratings of coordination accounted for 16 to 29% of the variance in performance. Unfortunately, explanations for the direction of the relationships are not intuitive. For example, task performance was typically negatively associated with ratings of crew coordination behaviors for the pilot, but was positively associated with ratings for the copilot.

In the manual condition, the crew coordination performance of the copilot was positively associated with task performance; that is, better communication and mission analysis with improved flight performance and better situation awareness with improved problem solving performance. It appears that if the copilot was able to keep abreast of mission and flight status and provide timely information to the pilot, both flight and problem solving performance were enhanced. In contrast, only leadership ratings for the pilot were positively associated with flight performance in the manual condition; ratings of mission analysis and situation awareness behaviors for the pilot were negatively associated. The exhibition of mission analysis and situation awareness behaviors on the part of the pilot may actually have been in response to deviations in flight performance rather than preventative behaviors. Another explanation for the negative relationship of pilot ratings and flight performance may be related to the burden of the physical demand placed on the pilot in manual flight. The extra efforts made by the pilot, other than to provide directive behaviors, may have contributed to deteriorated flight performance by overtaxing the resources available to the pilot.

In the automated condition, flight performance was positively associated again with ratings of the copilot's communication, and problem solving performance with ratings of the copilot's mission analysis. Flight performance was negatively associated with ratings of the pilot's mission analysis, situation awareness, and also assertiveness. The results in automated flight suggest that the higher ratings that the pilot received were related to an awareness of flight deviations rather than an overload.

These results provide some evidence of the changing structure of the flight task across levels of automation as hypothesized by Norman & Orlady (1989a). During the manual condition, the crew dealt essentially with two tasks: controlling the aircraft and planning an optimal route of flight. In this mode of flight, the primary responsibility of the pilot was to keep the aircraft aloft. Planning a route of flight to obtain and deliver supplies was typically a task relegated to the copilot in light of the physical demand placed on the pilot.

In contrast during automated flight, tasks were reallocated among the crew members and the system. The autopilot assumed the moment-to-moment control of the aircraft, freeing the pilot to perform other tasks as less attention was focused on the direct control of flight. Although problem solving was a task that was generally handled by the copilot in the manual condition, the pilot was more available to share in the development of the flight plan in automated flight. Unfortunately, this reallocation of tasks did not produce better problem solutions in the automated condition, perhaps because of the diffusion of responsibility noted earlier by Farrell (1987). In this situation, a lack of clearly defined duties may have obscured the potential benefits of automation.

Summary

The results of the present investigation add to a complex pattern of results found in the aviation literature. Although automation generally is assumed to reduce the workload of crews, a reduction that was accomplished in this investigation, the decreased workload that was associated with automatic flight did not consistently improve performance on flight tasks or in the development of an optimal flight path to obtain and deliver supplies. In addition, the manipulation of task difficulty produced fewer effects than hypothesized. It may be that the benefits of automatic systems are apparent only in the case of more extreme workload levels in which manual control is more difficult to maintain over time. These results are consistent with the mixed results of previous research findings derived from higher fidelity flight simulations (Wickens et al., 1989; Wiener et al., 1991) and other experimental data (Ephrath & Curry, 1977; Fuld, Liu, & Wickens, 1987; Young, 1969).

The hypotheses concerning crew coordination received some support. The hypothesis regarding the distribution of crew coordination behaviors was partially confirmed in that several dimensions of crew coordination behaviors occurred more frequently in relation to the level of automation. The most remarkable difference between the two conditions is the increased frequency of coordination behaviors observed in the automated condition. It appears that any "saved" processing resources afforded by the automatic flight condition may have been invested in more frequent communications. Also, in support of the findings of Clothier (1991), crew coordination performance was also better in the automated condition. It may be that the automated condition provided more of an opportunity or perhaps a requirement for the crew members to coordinate.

Efforts to identify the coordination behaviors that were associated with task performance met with limited success. The frequency of coordination behaviors predicted a few small, yet significant amount of variance in the performance measures. However, the ratings of crew coordination performance demonstrated more predictive power than did frequency.

In summary, the results of the present investigation demonstrate the complex relationship between automation, workload, performance, and coordination. Several additional conclusions that may be drawn from this study are discussed below.

First, the utility of the ACOE to discriminate between coordination behaviors was shown; that is, interrater reliability for the observations and ratings of crew coordination behaviors were demonstrated. Because the nature of aviation tasks may change even more as a function of increasing advanced technology systems, it is possible that advanced aviation systems may require special behaviors not assessed by current crew coordination measurement instruments. Efforts should be made to identify other behaviors more specific to advanced cockpits.

Second, the results of the present investigation converge to illustrate the utility of low fidelity simulation to assess the effects of automation on crew coordination. The use of a low fidelity simulation produced results comparable with higher level simulations; however, the generalizabilty of the findings to more advanced technology aircraft is unknown. It must be noted that these data are derived from a simulation that employed only one automatic system. Advanced aircraft currently employ increasing levels of flight control, in addition to integrated data displays and intelligent systems. It is necessary then to replicate these results in either higher fidelity simulations or actual aircraft to assess their generalizabilty. Additionally, it is unclear whether results obtained with one type of automatic system generalize across levels of automation. The investigation of a range of automated systems would provide more information.

Third, a related concern is the measurement of flight performance in advanced systems. Traditional performance measures (e.g., course deviation) may be less useful in the study of advanced technology aircraft. Performance parameters must be identified and validated to allow researchers to differentiate between effective and ineffective or acceptable and unacceptable performance in these systems.

Fifth, the manipulation of task difficulty in this investigation was an environmental one because of the limitations of the software. Other characteristics of the flight task may need to be altered to investigate the effects of automation more closely. Kantowitz and Casper (1988) have suggested comparisons of regular vs irregular operations. The introduction of system failures or abnormal conditions (e.g., snow closing an airport) would provide additional situations in which to assess performance and coordination in aircraft with higher levels of automation.

Sixth, manipulations of the reliability of the automation may shed additional light on the interactions among crew members and system. Parasuraman, Bahri, Molloy, and Singh (1991) reported that complacency and its performance consequences in system monitoring were related to the reliability and consistency of the automation. Such a manipulation in the investigation of advanced aircraft systems may identify guidelines for system reliability as well as for crew training to deal with unreliability.

Finally, a thorough analysis of the interface between pilot and system is recommended before comparing automated aircraft in relation to reduction of workload and improvement of performance, or even crew coordination. Reports of the mixed consequences of automation may be related to poorly designed system interfaces. A closer examination of the interfaces may clarify performance differences.

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APPENDIX A:

PREMISSION BRIEFING FOR THE TORNADO DISASTER, HIGH DIFFICULTY SCENARIO

Premission Briefing

OVERVIEW

During this flight scenario, you will be performing as two off-duty military officers responding to a civilian disaster. You will by flying a Cessna 182RG. While serving as an emergency rescue and supply aircrew, your mission is to pick up and deliver supplies to a disaster site. Your aircraft is currently located at the end of runway 27 at the O'Hare airport. During your mission you will be interacting with 3 controlling agencies: the tower, center, and operations. The frequency for the tower is 119.1. Center frequency is 132.5, and Operations is 119.25. Operations will provide you with specific information regarding the disaster.

To be prepared for this mission, you should have the aircraft's checklists, the area map, a flight plan log, a flight computer, a mission log, and pen or pencil. Do not advance in the mission log until you have been instructed by Operations.

DISASTER SUMMARY

Initial reports indicate that a tornado has touched down at three locations in your flight area. These sites are Spring Brook, Kankakee, and Fair Oak. A state of emergency has been declared for each locality. Several hundred civilians have been affected. No fatalities have occurred, but some injuries have been reported. As an emergency rescue and supply aircrew, your mission is to pick up and deliver supplies to one of the three disaster sites. Current reports indicated that airports located near these sites are open and unaffected.

There are eleven airfields between Midway and the disaster sites. Each airfield has one specific supply. You will be notified of what supply is located at each airport.

PROCEDURES

A supply is picked up from a supply point or delivered to a disaster site by flying through the box located over the airfield. This box is 1000′ square and the center of it is located at 4000′ MSL. You cannot fly over an airfield without picking up a supply. Furthermore, you may only fly the airways depicted on the map. For example, you cannot fly directly from O′Hare to Frankfort without flying over other airfields. Since time is critical, Center will provide you with specific times your are to arrive at each supply site. Unfortunately, because of time and aircraft limitations, it is unlikely that all supplies can be picked up. To ensure that the most valuable supplies reach a disaster site, it is important that you give consideration to the usefulness of the supplies before departure. Upon arrival in the cockpit, call Operations for further instructions.

WEATHER

Flight service reports weather south of Midway to be clear with moderate turbulence at 4000’. Winds at 4000’ are 210 at 20. O’Hare altimeter is 30.01.

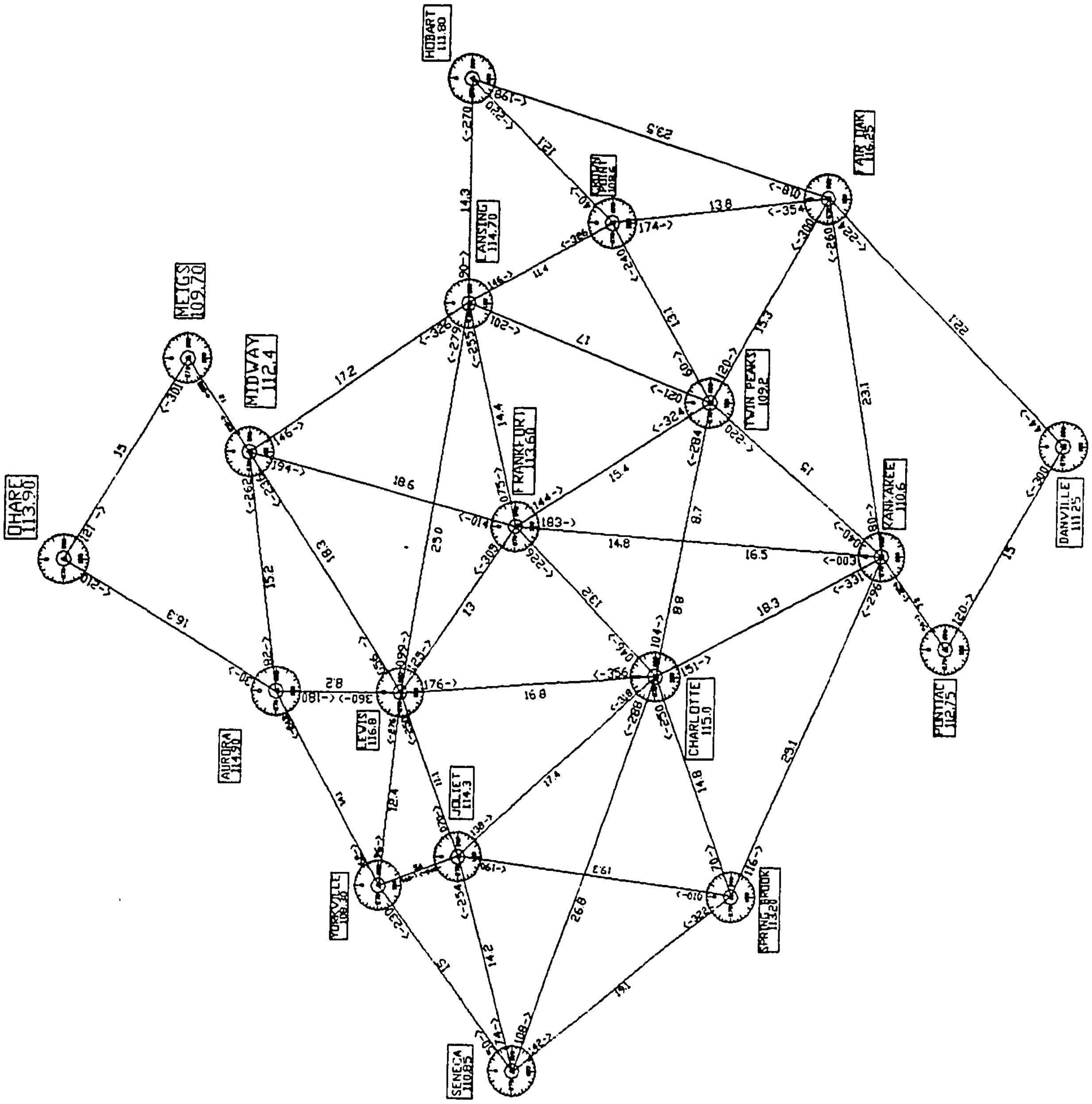
PERFORMANCE

Your crew’s performance will be assessed by determining how well you maintained 4000’, followed the airways shown, and reached your points at assigned times. Performance will also be assessed by determining the utility of the supplies you delivered.

Do not advance in the mission log until instructed by Operations. Your actual flight planning will be done in the cockpit. Contact Operations on 119.25 for further information as soon as you arrive in the cockpit. If you have any questions, please ask them now.

APPENDIX B:

MAP OF THE TORNADO SCENARIO


HOBART 111.80
AIR OAK 116.25
LANSING 114.70
MEIGS 109.70
MIDWAY 112.4
OHARE 113.90
FRANKFURT 113.60
TWIN PEAKS 109.2
KANKAKEE 110.6
DANVILLE 111.25
PONTIAC 112.75
CHARLOTTE 115.0
AURORA 114.90
LEWIS 116.8
JOLIET 114.3
YORKVILLE
SPRING BROOK 113.20
SENECA 110.85

APPENDIX C:

MISSION LOG

FLIGHT PLAN

DESTINATION	DISTANCE	SPEED	ETA	ATA

Individual Supply Ranking

Record supplies in order of their usefulness.
(1 = least useful; 11 = most useful)

	Supply	Rank
1.	first aid kits	____
2.	water	____
3.	flashlights	____
4.	food	____
5.	blankets	____
6.	power generators	____
7.	drugs	____
8.	tents	____
9.	chainsaws	____
10.	water purifiers	____
11.	ropes	____

DO NOT TURN PAGE UNTIL INSTRUCTED

Aircrew Supply Ranking

Record ranks according to aircrew agreement.
(1 = least useful; 11 = most useful)

	Supply	Rank
1.	first aid kits	____
2.	water	____
3.	flashlights	____
4.	food	____
5.	blankets	____
6.	power generators	____
7.	drugs	____
8.	tents	____
9.	chainsaws	____
10.	water purifiers	____
11.	ropes	____

	Supply	
1.	first aid kit	Frankfort
2.	water	Crown Point
3.	flashlights	Lewis
4.	food	Hobart
5.	blankets	Aurora
6.	power generators	Yorkville
7.	drugs	Lansing
8.	tents	Seneca
9.	chainsaws	Twin Peaks
10.	water purifiers	Joilet
11.	ropes	Charlotte

DO NOT TURN PAGE UNTIL INSTRUCTED

REMEMBER

- Airfields between Midway and the disaster sites have only one supply.
- Supplies are picked up by flying through the box over the airfield.
- Only 4 supplies can be picked up for delivery to a disaster site.
- You may only fly the airways indicated on the map.
- If you fly over a supply airfield, you have picked up a supply.
- Report next destination to Operations 2 miles prior to Midway. Then contact Center for clearance.

DO NOT TURN PAGE UNTIL INSTRUCTED

SUPPLIES USEFUL AT EACH DISASTER SITE

**** The number beside each supply denotes the point value of that supply for a particular disaster site.

	Fair Oak		Kankakee		Spring Brook
6	drugs	6	ropes	6	drugs
5	first aid kits	5	blankets	5	first aid kits
4	blankets	4	chainsaws	4	blankets
3	flashlights	3	drugs	3	flashlights
2	water	2	first aid kits	2	tents
1	food	1	flashlights	1	water

REMEMBER

- Deliver 4 supplies to one disaster site.
- Higher the number, the more useful the supply (0 - 17 points possible).
- If equal supply points, choose shorter flight path.
- Report next destination to Operations 2 miles prior to Lewis. Then contact Center for clearance.

APPENDIX D:

SCRIPT FOR THE TORNADO DISASTER, HIGH DIFFICULTY SCENARIO

Script for Controlling Agencies for Tornado Disaster, High Difficulty Scenario

Operations We have sketchy information about the disasters at this time. Bad weather is currently dictating the first 2 legs of your mission so that it's important that you get off the ground soon and be heading in the general direction of the supplies and disasters. First, fly from OHare to Meigs and then on to Midway. Maintain 4000 feet and remain on the designated airways as closely as possible. After completing the initial route, you'll be responsible for determining which supplies you pick up and developing a flight plan to deliver them. We'll provide you with additional information as we receive it. The flight plan attached to your mission log should be completed for each destination throughout your mission. Now, take a few minutes to begin individually ranking these supplies in order of their usefulness in providing disaster relief. These supplies are listed on page 1 of your mission log. A rank of 1 is most useful; a rank of 11 is least useful. Your time is limited so do not discuss your rankings with your crew mate at this time. You'll be provided with an opportunity to do so after departure. Complete your checklists and expect departure in six minutes at - approximately _____. Do not miss your departure time. Contact Tower for clearance at that time.

Tower 1FS, O'Hare Tower, **winds 210 at 20**, altimeter, 30.01. Upon departure, climb runway heading to 1500'. Cleared for takeoff. Begin secondary task by pressing any key on the keypad.

SEGMENT 1 - OHARE TO MEIGS

Tower (1200 ft) 1FS, Tower. Remember, this is a **MANUAL** (OR **AUTOPILOT)** FLIGHT. Contact Midland center 132.5, Good Day.

Center 1FS, Midland Center, Radar contact, resume own navigation. Climb and maintain 4000'. Your expected arrival time at Meigs is _________. Contact Operations on 119.25. Report back on.

Operations 1FS, Operations. We have an update for your mission on page (2) of your mission log. Because you aren't going to be able to carry all the supplies needed for this mission, both of you must decide which supplies are most useful. After reaching an agreement, record your crew's ranking in the mission log. Also shown is a listing of the locations where the supplies are located. We'll contact you as soon as we have more information as to the status of the disaster areas. Monitor Center frequency for expected time to MIDWAY.

SEGMENT 2 - MEIGS TO MIDWAY

Center 1FS, Center. Your expected arrival time at MIDWAY is _____. Operations is requesting you contact them for a mission update. Report back on.

Operations 1FS, Operations. Looks like you only have enough time to pick up 4 supplies. Therefore, you must develop a flight plan to pick up and deliver 4 supplies to any one of the sites. Remember, your mission involves acquiring and delivering the most useful supplies as possible, in addition to reaching each airfield at the appropriate time. However, you may only fly the airways shown on the map. Furthermore, you may not fly over an airfield without picking up a supply. Report your next destination to us 2 miles before reaching MIDWAY. Repeat, 2 miles prior to MIDWAY. Then monitor Center for time to your next destination. If you need a review of these instructions, Page 3 of your mission log provides one.

[After call about destination]

Operations 1FS, Operations. We're currently receiving reports about the severity of the damages at each disaster site and the supplies actually needed. After reaching Midway, proceed to LEWIS for a pick up of FLASHLIGHTS. We'll provide additional information to you as we receive it. Contact Center with Lewis destination.

SEGMENT 3 - MIDWAY TO LEWIS

Center 1FS, Center. Understand destination ______. Your expected arrival time at LEWIS is _________. Contact Operations for mission update. Report back on.

Operations 1FS, Operations. We've just received a list of priority supplies needed at each individual disaster site. Page 4 in your mission log indicates each disaster site and the usefulness of the supplies needed in terms of point values. The higher the number, the more useful the supply at that site. If a supply isn't listed, that indicates the supply is of no value at that site. Given this information, your mission is to deliver a group of four supplies to a disaster site and obtain the most points possible. Acquiring the higher point values ensures that the supplies that arrive can be used. The sum of obtainable points range from 0 to 16. In the event that you are able to obtain an equal number of supply points from two flight paths, you should choose the shorter route. Inform us of your next destination two miles before you reach LEWIS. Then contact Center for the expected time to your next destination.

Operations 1FS, Operations. Understand destination ______. Contact Center with next destination.

SEGMENT 4 - LEWIS TO 2ND SUPPLY

Center 1FS, Center. Understand destination ______. Your expected arrival time is __________. Confirm with Operations next destination 2 miles prior _____. Report back on.

Operations 1FS, Operations. Understand destination - ________. Contact Center with next destination.

SEGMENT 5 - 2nd SUPPLY TO 3RD SUPPLY

Center 1FS, Center. Understand destination _________. Your expected arrival time is __________. Confirm with Operations next destination 2 miles prior _____. Report back on.

Operations 1FS, Operations. Understand destination - _______. Contact Center with next destination.

APPENDIX E:

CHECKLIST PROCEDURES

CHECKLIST PROCEDURES   CESSNA - MODEL R182

BEFORE STARTING ENGINE

1. Brakes -- TEST.
2. Landing Gear Lever -- DOWN.
3. Autopilot (if installed) -- OFF.

STARTING ENGINE

1. Carburetor Heat -- COLD.
2. Radios -- ON.
3. Mags -- SWITCH to start.

BEFORE TAKEOFF

1. Flight controls -- FREE and CORRECT.
2. Fuel Quantity -- CHECK.
3. Elevator Trim -- SET for takeoff.
4. Electric Trim (if installed) -- PREFLIGHT TEST.
5. Radios and Avionics -- SET.
10. Autopilot -- OFF.

TAKEOFF

1. Wing Flaps -- 0°
2. Carburetor Heat -- OFF.
3. Power -- FULL THROTTLE and 2400 RPM.
4. Elevator Control -- LIFT NOSE WHEEL AT 70 KIAS.
5. Climb Speed -- 80 KIAS (flaps UP).
6. Brakes -- APPLY momentarily when airborne.
7. Landing Gear -- RETRACT in climb out.

ENROUTE CLIMB

1. Airspeed -- 80-100 KIAS.

CRUISE

1. Power -- 2100-2400 RPM.

2. Elevator Trim -- ADJUST.

AUTOPILOT - PILOT'S OPERATING SUPPLEMENT

SECTION 1 General

The Flight Simulator Autopilot is a two axis automatic flight control system that governs the position of the ailerons and elevators to provide automatic roll and pitch stability. The system also provides for tracking of VOR radials selected by the OBS and NAV 1 radio.

The major components in the Flight Simulator system consist of a single control unit mounted below the artificial horizon and the directional gyro. The autopilot is turned ON and OFF by moving the mouse arrow into the AUTOPILOT indicator box and clicking.

SECTION 2 Limitations

The following autopilot limitations must be followed during airplane operation.

1. Autopilot must be OFF for takeoff and landing.
2. Autopilot altitude is preselected at 4000' MSL

SECTION 3 Emergency Procedures

IN CASE OF AUTOPILOT MALFUNCTION

1. Airplane control stick - - OPERATE as required to manually override the autopilot
2. AUTOPILOT Indicator to OFF to disconnect autopilot system.

SECTION 4 Normal Procedures

BEFORE TAKEOFF AND LANDING:

1. AUTOPILOT indicator --- Ensure OFF

IN-FLIGHT OPERATIONS:

1. The autopilot is configured to climb at a rate of 500 FPM only.
2. The autopilot is preconfigured to an altitude of 4000 MSL.

DESCENT:

1. AUTOPILOT indicator to OFF

VOR COUPLING:

1. The autopilot is configured to track VOR radials based upon information in the OBS and the NAV 1 radio.
2. The airplane will automatically intercept and then track the selected VOR course. The AUTOPILOT must be turned OFF when the selected VOR course is changed, and then turned ON again.
3. The desired course must be within 90 degrees of current heading for the AUTOPILOT to work effectively.

APPENDIX F:

RESPONSIBILITIES OF THE CREW MEMBERS

Pilot Responsibilities

Assume ultimate responsibility for flight safety and mission effectiveness.

Control aircraft flight.

Copilot Responsibilities

Navigate.

Assume duties as assigned.

Aircrew Responsibilities

Monitor status of instruments and controls.

Arrive at destinations on schedule.

Communicate effectively with crew member.

Communicate effectively with ATC and operations.

Record information in mission log as required.

Provide assistance to each other.

Complete checklist procedures.

APPENDIX G:

PILOT DEMOGRAPHIC FORM

Pilot Demographics

Crew Number: __________ Condition Order: (A,M) (M,A)
Date: __________ Scenario Order: (G,T) (T,G)
(H) (L)

Crew Position: (Pilot) (Copilot)

Please take a moment to complete the following questions. Remember all information will remain confidential.

1. Age: _______

2. Gender: (Male) (Female) (circle one)

3. Ratings: (Circle ratings that apply)
   - Student
   - Private
   - Instrument
   - Commercial
   - CFI
   - CFII
   - ATP

4. What are your total flight hours? _________________

5. Have you flown MicroSoft Flight Simulator before? (Yes) (No)

6. If you responded "Yes" to question 5, how many hours have you flown Microsoft Flight Simulator? ____________

7. Have you flown any other airplane flight simulators for training purposes? (Yes) (No)

8. If you responded "Yes" to question 7, how many hours have you flown in other airplane flight simulators? ____

9. Do you play video/computer games? (Yes) (No)

10. If you responded "Yes" to question 9, how many hours per week do you engage video/computer games? (This does not include Microsoft Flight Simulator) ______________

11. How long have you known your crew mate? ____ (months)

12. Have you flown with your crew mate before today? (Yes) (No)

APPENDIX H:

POST-EXPERIMENTAL QUESTIONNAIRE

Post-experimental Questionnaire

Crew:______ Position: (Pilot) (Copilot)

We are interested in your opinions concerning the experiment in which you just completed. Please take a moment to complete the following questions. Your responses will aid our effort in developing future research. Respond to each question by circling the number which best represents your experience.

1. The experimental scenarios flown were representative of how aircraft may be used in response to emergency situations.

0	1	2	3	4	5	6	7	8
not at all		somewhat		moderately representative		very		extremely representative

2. The flight performance requirements (maintaining altitude, course, and time requirements) of the scenarios accurately reflected issues important in aviation.

0	1	2	3	4	5	6	7	8
not at all		somewhat		moderately accurate		very		extremely accurate

3. The decision making requirements of the scenarios accurately reflected issues important in aviation.

0	1	2	3	4	5	6	7	8
not at all		somewhat		moderately accurate		very		extremely accurate

4. The training flight scenario provided adequate practice for the experimental scenarios.

0	1	2	3	4	5	6	7	8
not at all		somewhat		moderately adequate		very		extremely adequate

5. To what extent did you become complacent during the experimental scenario in which the autopilot **WAS** used ?

0	1	2	3	4	5	6	7	8
not at all		somewhat		moderately complacent		very		extremely complacent

6. To what extent did you become complacent during the experimental scenario in which the autopilot was **NOT** used?

0	1	2	3	4	5	6	7	8
not at all		somewhat		moderately complacent		very		extremely complacent

7. Have you received any cockpit resource management training?

(Yes) (No)

8. How many hours classroom time? __________

9. COMMENTS:

APPENDIX I:

CREW COORDINATION BEHAVIORAL OBSERVATION SCALE

Rater: ________ Crew: ______ Time: _____ Leg:______
Start/Stop: ____________
Stmt:____________________

DIMENSION	CREW COORDINATION BEHAVIORS PER DIMENSION		
MISSION ANALYSIS	C	P	MISSION ANALYSIS
	______	______	Define tasks based on mission requirements.
	______	______	Question data/ideas re: mission accomplishments.
	______	______	Devise long/short term plans.
	______	______	Id potential impact of unplanned events on mission.
	______	______	Structure tasks, plans, & objectives.
	______	______	Critique existing plans.
SITUATIONAL AWARENESS	C	P	SITUATIONAL AWARENESS
	______	______	Note deviations.
	______	______	Provide information in advance.
	______	______	Demonstrate awareness of task performance of self/others.
	______	______	Identify problems/potential problems.
	______	______	Recognize need for action.
	______	______	Demonstrate ongoing awareness of mission status.
DECISION MAKING	C	P	DECISION MAKING
	______	______	Gather information before making decision..
	______	______	Cross check information sources.
	______	______	Identify alternatives & contingencies.
	______	______	Anticipate consequences of decisions.
	______	______	Provide rationale for decision.
LEADERSHIP	C	P	LEADERSHIP
	______	______	Determine tasks to be assigned.
	______	______	Ask for input, discussed problem.
	______	______	Focus crew attention to task.
	______	______	Told crew member what to do.
	______	______	Inform crew member of mission progress.
	______	______	Provide a legitimate avenue of dissent.
	______	______	Provide feedback to crew on performance.
ASSERTIVENESS	C	P	ASSERTIVENESS
	______	______	Ask questions when uncertain.
	______	______	Make suggestions.
	______	______	State opinions on decisions/procedures.
	______	______	Confront ambiguities and conflicts.
	______	______	Advocate a specific course of action.
ADAPTABIL./ FLEXIBITY	C	P	ADAPTABILITY/FLEXIBILITY
	______	______	Alter behaviors to meet situational demands.
	______	______	Receptive to other's ideas.
	______	______	Step in and help others.
	______	______	Alter flight plans to meet situational demands.
COMMUNICATION	C	P	COMMUNICATION
	______	______	Made no response.
	______	______	Acknowledge communication.
	______	______	Repeat information as required.
	______	______	Ask for clarification of a communication.
	______	______	Used standard terminology.
	______	______	Provide information as required.
	______	______	Provide information when asked.
	______	______	Verbalize plans for procedures/maneuvers.

APPENDIX J:

CREW COORDINATION BEHAVIORAL SUMMARY SCALES

Crew:______
Time:______
Rater:_____

MISSION ANALYSIS

Mission analysis involves the organization and assessment of the information that pertains to the crew's assignment (i.e., mission).

Behavioral Indicators of Skill Level

5 Complete skill	Crew members identify and prioritize the tasks that must be performed to accomplish the mission; anticipate the consequences of unexpected changes in mission requirements; review their plan of action to ensure that the plan maximizes the resources.
4 Very much skill	
3 Adequate skill	Crew members make short term plans, but ususally do not anticipate future events; outline the immediate tasks required for the mission.
2 Some skill	
1 Hardly any skill	Crew members are unable or unwilling to determine what is important or relevant to the accomplishment of the mission; assume the first plan to accomplish the mission is the best without considering alternatives.

	Crew	**Copilot**	**Pilot**
Initial:	_____	_____	_____
Final:	_____	_____	_____

Comments:

Crew:______
Time:______
Rater:_____

SITUATIONAL AWARENESS

Situational awareness refers to the maintenance of an accurate perception of the environment, both internal and external to the aircraft. The crew is oriented to mission activities, flight status, and alternative courses of action. This awareness may enchance the ability of the crew members to take appropriate actions.

Behavioral Indicators of Skill Level

5 Complete skill	Crew members note inappropriate trends in gauges before deviations occur; anticipate the need for information and provide it in advance; monitor the actions of themselves and others for satisfactory performance; are sensitive to changes in other crew members' needs; are consistently aware of their position and heading relative to ground navigation aids.
4 Very much skill	
3 Adequate skill	Crew members are sometimes aware of the performance of other crew members; detect deviations from normal readings, procedures or tasks before gross deviations occur; generally know the status of their mission accomplishments; have a general idea of aircraft position.
2 Some skill	
1 Hardly any	Crew members fail to check their own or other's actions to ensure that tasks are properly executed; show confusion as to their progress in accomplishing the mission; typically provide information after an action should have been taken; fails to detect significant deviations from desired parameters; are not aware of aircraft position.

	Crew	**Copilot**	**Pilot**
Initial:	_____	_____	_____
Final:	_____	_____	_____

Comments: ____
____

Crew:______
Time:______
Rater:_____

DECISION MAKING

Decision making refers to the processes by which logical and sound judgements are made based on the information available. This involves the method by which data is collected and integrated into a strategy for task performance.

Behavioral Indicators of Skill Level

5 Complete skill	Crew members anticipate the consequences of decisions and related consequences in order to prepare to take alternative actions; consistently consider several factors before making a decision; verify information by cross checking sources before making a final decision.
4 Very much skill	
3 Adequate skill	Crew members generally acquire all critical information needed for immediate decision making; typically are prepared for immediate actions that must be taken.
2 Some skill	
1 Hardly any skill	Crew members are rarely prepared to make immediate decisions when unanticipated events occur; fail to seek information that may enhance decisions; fail to consider the consequences of their decisions.

	Crew	**Copilot**	**Pilot**
Initial:	_____	_____	_____
Final:	_____	_____	_____

Comments: ____

Crew:______
Time:______
Rater:_____

LEADERSHIP

Leadership involves the direction, organization, and support of other crew members. It can be shown by crew members other than individuals with formal authority.

Behavioral Indicators of Skill Level

5 Complete skill	Crew members quickly assess a situation when the crew appears overwhelmed and structure the activities of others by assigning tasks or by focusing attention to a task to be performed; identify and delay non-critical duties until low workload periods; facilitate crew performance by giving feedback without creating conflict.
4 Very much skill	
3 Adequate skill	Crew members provide direction only when a problem occurs; inform other members that they are performing a task poorly rather than providing specific guidance; provide task oriented focus only when responding to a deviation.
2 Some skill	
1 Hardly any skill	Crew members leave others to govern their own behaviors by providing little feedback when the correct course of action is unclear; create an atmosphere in which disagreements are not tolerated or confronted; discount the ideas of other crew members.

	Crew	Copilot	Pilot
Initial:	_____	_____	_____
Final:	_____	_____	_____

Comments: ____

Crew:______
Time:______
Rater:_____

ASSERTIVENESS

Assertiveness involves the offer of opinions or beliefs to other crew members, particularily when the the situation is unclear or the offer is unsolicited. This may also refer to an admission of uncertainity on the part of a crew member.

	Behavioral Indicators of Skill Level
5 Complete skill	Crew members present information essential to proper execution of tasks, even when conflict is present; speak up when they believe a particular course of action is best; display a willingness to seek assistance rather than struggle and make mistakes; directly confront differences of opinion in a positive manner.
4 Very much skill	
3 Adequate skill	Crew members admit they need help when their need is obvious; provides nonjudgemental prompts in response to deviations from desired flight parameters.
2 Some skill	
1 Hardly any skill	Crew members fail to offer suggestions or assistance when the situation is unclear; are unwilling to ask for help even when it is available; withhold critical pieces of information from other crew members; make extraneous sarcastic remarks when deviations from desired performance are noted.

	Crew	Copilot	Pilot
Initial:	_____	_____	_____
Final:	_____	_____	_____

Comments: ____
____
____
____

Crew:______
Time:______
Rater:_____

ADAPTABILITY/FLEXIBILITY

Adaptability/flexibility refers to the willingness of crew members to change their behaviors or plans to accommodate the situation.

	Behavioral Indicators of Skill Level
5 Complete skill	Crew members assist others that are having difficulty by redistributing workload when possible; easily adjust to changes based on new information or demands; anticipate if a crew member will need help prior to an event.
4 Very much skill	
3 Adequate skill	Crew members do not provide help until they are asked; provide assistance in accordance with their assigned duties.
2 Some skill	
1 Hardly any skill	As time constraints increase, crew members are unwilling to concede a position; display an unwillingness to attempt to eliminate overload conditions for others; are reluctant to alter plans based new instructions or information.

	Crew	**Copilot**	**Pilot**
Initial:	_____	_____	_____
Final:	_____	_____	_____

Comments: ____
____
____
____

Crew:______
Time:______
Rater:_____

COMMUNICATION

Communication involves the exchange of information between crew members in a manner that enhances performance. Frequently the purpose of communication is to prevent misunderstandings by clarifying or acknowledging critical information.

Behavioral Indicators of Skill Level

5 Complete skill	Crew members ensure that messages are understood by requesting clarification when confused or by repeating information; keep each other informed of the current status of tasks and of their future intentions; utilize standard language and provide redundancy cues to reduce the likelihood of errors.
4 Very much skill	
3 Adequate skill	Crew members acknowledge decisions made; provide information when requested; convey information essential to effective task performance.
2 Some skill	
1 Hardly any skill	Crew members rarely acknowledge information offered or requested; fail to request clarification of an unclear message; typically take actions or make decisions without informing other crew members.

	Crew	**Copilot**	**Pilot**
Initial:	_____	_____	_____
Final:	_____	_____	_____

Comments: ____
____
____
____

APPENDIX K:

GUIDELINES FOR THE CREW COORDINATION BEHAVIORAL SUMMARY SCALES

Mission Analysis Guidelines

Behavioral Summary of "Complete Skill" in Mission Analysis

Crew members identify and prioritize the tasks that must be performed to accomplish the mission; anticipate the consequences of unexpected changes in mission requirements; review their plan of action to ensure that the plan maximizes the resources.

Behavioral examples of "Complete Skill" in Mission Analysis:

After receiving mission instructions from Operations during the first leg of the mission, the copilot indicates that they should first assess the usefulness of the supplies, determine their location, and then plan a flight path.

The crew notes that if Operations reroutes their flight course again they may need to reassess their supply priorities.

After deciding on a flight path to obtain the supplies, the crew scrutinizes the plan to confirm that the most supply points will be obtained.

Behavioral Summary of "Adequate Skill" in Mission Analysis

Crew members make short term plans, but ususally do not anticipate future events; outline the immediate tasks required for the mission

Behavioral examples of "Adequate Skill" in Mission Analysis:

During the first leg of their mission, the crew identifies the usefulness of the supplies and plans to obtain the top 5 or 6; however, they do not consider that the location of the supplies may affect their ability to obtain them quickly.

The copilot indicates that the crew must fly from Meigs to Midway because of poor weather in addition to developing a crew ranking of supply usefulness.

Behavioral Summary of "Hardly Any Skill" in Mission Analysis

Crew members are unable or unwilling to determine what is important or relevant to the accomplishment of the mission; assume the first plan to accomplish the mission is the best without considering alternatives.

Behavioral examples of "Hardly Any Skill" in Mission Analysis:

Throughout the mission the crew does not attempt to clarify their confusion about the requirements to accomplish the mission successfully.

The crew develops only one flight plan to deliver supplies; they never examine alternative routes.

Situational Awareness Guidelines

Behavioral Summary of "Complete Skill" in Situational Awareness

Crew members note inappropriate trends in gauges before deviations occur; anticipate the need for information and provide it in advance; monitor the actions of themselves and others for satisfactory performance; are sensitive to changes in other crew members' needs; are consistently aware of their position and heading relative to ground navigation aids.

Behavioral examples of "Complete Skill" in Situational Awareness:

The pilot indicates that the altitude is beginning to drop very slightly in relation to the use of the autopilot at slow speeds.

Two to three miles before passing over the VOR, the copilot informs the pilot what the next heading will be.

The copilot notes that they will be reach the next station crossing 2 minutes early unless the pilot decreases airspeed to 100 knots.

Because the copilot is aware the pilot is having difficulty maintaining altitude, the copilot does not attempt to question her about her ranking of the supplies until the altitude is established.

Behavioral Summary of "Adequate Skill" in Situational Awareness

Crew members are sometimes aware of the performance of other crew members; detect deviations from normal readings, procedures or tasks before gross deviations occur; generally know the status of their mission accomplishments; have a general idea of aircraft position.

Behavioral examples of "Adequate Skill" in Situational Awareness:

The pilot notices when the copilot has input an incorrect frequency, especially if she needs to make the radio call immediately.

The crew notes that they haven't put the landing gear up before they reach 1500 feet.

After a moments consideration, the copilot indicates that they have only picked up two supplies because no supplies were located at their first two station crossings.

Behavioral Summary of "Hardly Any Skill" in Situational Awareness

Crew members fail to check their own or other's actions to ensure that tasks are properly executed; show confusion as to their progress in accomplishing the mission; typically provide information after an action should have been taken; fail to detect significant deviations from desired parameters; are not aware of aircraft position.

Behavioral examples of "Hardly Any Skill" in Situation Awareness:

The crew engages in several games of "tic-tac-toe" and fail to notice that they have lost 2000 feet in altitude.

The crew spends five minutes attempting to determine how many more supplies they should obtain.

After the aircraft passes over the VOR and in response to a query from the pilot, the copilot tells the pilot what the new heading should be.

The crew notices that they have flown several miles in the wrong direction.

The copilot consistently asks the pilot where they are on the map.

Decision Making Guidelines

Behavioral Summary of "Complete Skill" in Decision Making

Crew members anticipate the consequences of decisions and related consequences in order to prepare to take alternative actions; consistently consider several factors before making a decision; verify information by cross checking sources before making a final decision.

Behavioral examples of "Complete Skill" in Decision Making:

The crew realizes that if they fly a 360 degree circle to slow their arrival time, they may actually arrive later than the designated time.

Before deciding between two flight routes of equal value, the crew considers the distance in addition to the usefulness of the supplies.

The crew compares their individual supply rankings before finalizing their crew ranking.

Behavioral Summary of "Adequate Skill" in Decision Making

Crew members generally acquire all critical information needed for immediate decision making; typically are prepared for immediate actions that must be taken.

Behavioral examples of "Adequate Skill" in Decision Making:

The pilot attempts to identify why the distance is increasing on the DME by first asking the copilot if the correct NAV radio is on, then asking if the correct TO-FROM indication is shown on the OBI and if the appropriate NAV frequency has been input.

When the stall warning sounds as the aircraft approaches the station, the pilot immediately increases the throttle and after verifying a safe airspeed, the copilot brings the flaps up.

Behavioral Summary of "Hardly Any Skill" in Decision Making

Crew members are rarely prepared to make immediate decisions when unanticipated events occur; fail to seek information that may enhance decisions; fail to consider the consequences of their decisions.

Behavioral examples of "Hardly Any Skill" in Decision Making:

After the crew is reminded that they may not fly over the same airfield twice, they have difficulty identifying another supply point; they do not reach a decision until they have flown several minutes past their immediate destination.

The crew declares the autopilot completely inoperative without reviewing the supplemental autopilot procedure checklist. Also, when forced with a location incongruity, the crew choses to disregard other information sources that may validate their position (e.g., call to Center, use of alternate NAVAIDS).

The crew does not discuss how their decision to maintain the cruise speed indicated on the checklist will compromise their ability to reach each station crossing at the appropriate time.

Assertiveness Guidelines

Behavioral Summary of "Complete Skill" in Assertiveness

Crew members present information essential to proper execution of tasks, even when conflict is present; speak up when they believe a particular course of action is best; display a willingness to seek assistance rather than struggle and make mistakes; directly confront differences of opinion in a positive manner.

> Behavioral examples of "Complete Skill" in Assertiveness:
>
> After reaching their first station crossing three minutes early, the pilot reminds the copilot that one of their goals is to reach check points at the designated time, even if it means that the cruise speed indicated on the checklist cannot be maintained.
>
> The copilot recommends that they gain better control of the aircraft before they begin to decide on the crew ranking of disaster supplies.
>
> The pilot admits that he doesn't understand the instructions for obtaining the supplies and requests the copilot explain them.
>
> The copilot notes that their idea of supply usefulness appears to be totally opposite and suggests they discuss their rationale.

Behavioral Summary of "Adequate Skill" in Assertiveness

Crew members admit they need help when their need is obvious; provides nonjudgemental prompts in response to deviations from desired flight parameters.

> Behavioral examples of "Adequate Skill" in Assertiveness:
>
> After repeated attempts to calculate the needed airspeed, the copilot indicates that he's forgotten how to perform that task.
>
> After the pilot makes several unsuccessful attempts to fly over the VOR, the copilot recommends that she regain altitude before making another attempt.

Behavioral Summary of "Hardly Any Skill" in Assertiveness

Crew members fail to offer suggestions or assistance when the situation is unclear; are unwilling to ask for help even when it is available; withhold critical pieces of information from other crew members; make extraneous sarcastic remarks when deviations from desired performance are noted.

Behavioral examples of "Hardly Any Skill" in Assertiveness:

The copilot sits silently and makes no suggestions while he waits for the pilot to determine their route of flight.

The copilot has forgotten how to calculate airspeeds, but does not ask for assistance.

The copilot refuses to switch the DME to distance at the request of the pilot.

After noting that the copilot is having difficulty computing ground speed, the pilot comments that "a monkey can compute required ground speed faster than you can".

Leadership Guidelines

Behavioral summary of "Complete Skill" in Leadership

Crew members quickly assess a situation when the crew appears overwhelmed and structure the activities of others by assigning tasks or by focusing attention to a task to be performed; identify and delay non-critical duties until low workload periods; facilitate crew performance by giving feedback without creating conflict.

Behavioral examples of "Complete Skill" in Leadership:

When the copilot appears overwhelmed with new supply delivery instructions, the pilot recommends that they calm down first, ensure they are on the correct heading, and then worry about what supplies to deliver.

The copilot suggests that they wait to develop a flight plan until after the pilot has the aircraft stabilized.

The pilot explains that although the copilot is consistently inputting the correct frequencies for radio calls, the pilot needs to know when that action has been completed.

Behavioral Summary of "Adequate Skill" in Leadership

Crew members provide direction only when a problem occurs; inform other members that they are performing a task poorly rather than providing specific guidance; provides task oriented focus only when responding to a deviation.

Behavioral examples of "Adequate Skill" in Leadership:

The pilot announces that because of the high workload present at that time, all nonessential tasks will be disregarded.

The pilot indicates that the airspeeds the copilot has calculated typically make the crew late to their next destination.

The copilot notes that they are 500 feet below assigned altitude and directs the pilot to increase altitude back to 4000 feet.

Behavioral Summary of "Hardly Any Skill" in Leadership

Crew members leave others to govern their own behaviors by providing little feedback when the correct course of action is unclear; create an atmosphere in which disagreements are not tolerated or confronted; discount the ideas of others.

Behavioral examples of "Hardly Any Skill" in Leadership:

Although stall warnings keep sounding and the pilot is obviously having difficulty, the copilot does not offer any suggestions as to how to maintain altitude.

Throughout the flight, the pilot repeatedly states that he is the pilot and therefore makes the decisions.

The pilot ignores any suggestions about aircraft handling that the copilot makes.

Adaptability/Flexibility Guidelines

Behavioral Summary of "Complete Skill" in Adaptability/Flexibility

Crew members assist others that are having difficulty by redistributing workload when possible; easily adjust to changes based on new information or demands; anticipate if a crew member will need help prior to an event.

Behavioral examples of "Complete Skill" in Adaptability/ Flexibility:

The pilot begins making the radio calls after he notices the copilot is preoccupied with other duties.

After planning a route to pick up supplies, Operations instructs the crew to fly to a different supply point; the copilot quickly identifies the new heading and VOR frequency, thereby enabling the pilot to modify his flight path.

Because the autopilot is unreliable at speeds below 80 knots, the copilot begins to monitor the altitude more closely when the aircraft is flying below 85 knots.

Behavioral Summary of "Adequate Skill" in Adaptability/Flexibility

Crew members do not provide help until they are asked; provide assistance in accordance with their assigned duties.

Behavioral examples of "Adequate Skill" in Adaptability/ Flexibility:

The copilot is aware the pilot is having difficulty trimming the aircraft, but helps him adjust it only after the pilot requests help.

The copilot calculates the needed airspeed and informs the pilot.

Behavioral Summary of "Hardly Any Skill" in Adaptability/Flexibility

As time constraints increase, crew members are unwilling to concede a position; display an unwillingness to attempt to eliminate overload conditions for others; are reluctant to alter plans based new instructions or information.

Behavioral examples of "Hardly Any Skill" in Adaptability/ Flexibility:

The crew must inform Operations of their newly developed flight plan before reaching Midway; however, they continue to argue about the best course of action and are late in calling Operations with the new plan.

The pilot merely laughs as he comments that the copilot seems to be having difficulty completing his duties.

The pilot first instructs the copilot to dial up Operations and then changes his instruction to Center. The copilot grumbles about having to change what is already dialed in. The pilot has to direct the copilot a second time before the copilot acts.

Communication Guidelines

Behavioral Summary of "Complete Skill" in Communication

Crew members ensure that messages are understood by requesting clarification when confused or by repeating information; keep each other informed of the current status of tasks and of their future intentions; utilize standard language and provide redundancy cues to reduce the likelihood of errors.

Behavioral examples of "Complete Skill" in Communication:

When the copilot tells the pilot to turn to a specific heading to get back on course, the pilot repeats the heading and then requests the copilot confirm the heading.

The copilot informs the pilot that he's input the correct nav frequency and will change the heading prior to the VOR.

When providing heading information, the copilot also provides the necessary direction of turn (e.g., "Left turn to a heading of 236 degrees").

Behavioral Summary of "Adequate Skill" in Communication

Crew members acknowledge decisions made; provide information when requested; convey information essential to effective task performance.

Behavioral examples of "Adequate Skill" in Communication:

After the copilot indicates that he is turning off the autopilot, the pilot replies "roger".

After Center reports the crew's expected time to the next VOR, the copilot informs the pilot of the correct airspeed to fly in order to arrive on time.

Behavioral Summary of "Hardly Any Skill" in Communication

Crew members rarely acknowledge information offered or requested; fail to request clarification of an unclear message; typically take actions or make decisions without informing other crew members.

Behavioral examples of "Hardly Any" in Communication:

Although the copilot provides numerous directions as to heading and airspeed, the pilot does not acknowledge his instructions.

The pilot issues an incomplete command regarding the communication frequency; the copilot does not ask him to repeat the message.

After determining that the speed of the aircraft should be changed, the copilot adjusts the throttle without notifying the pilot.

Ruth Coleen Thornton was born in Newport News, Virginia in 1953. She received a B.S. in psychology (industrial concentration) in 1978, a M.S. in psychology in 1987, and a Ph.D. in Industrial/Organizational Psychology (engineering and systems psychology) in 1992 from Old Dominion University. She is currently a human factors engineer in the Advanced Design Division of Lockheed Aeronautical Systems Company, Marietta, Georgia. She previously worked for Anacapa Sciences, Inc. in the area of Army helicopter aviation, taught undergraduate statistics and human factors, and conducted research in the area of training. She has held positions in regional and university chapters of the Human Factors Society and received a University Fellowship in 1985 and 1986.