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Dynamic Allocation of Responsibility Between Operators With Different Models of System Information Using Computer-Mediated Communication

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ABSTRACT

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The focus of this research was to determine the effectiveness of using two operators to control a process dynamically. Control and failure detection responsibilities were shared between the operators using computer-mediated communication. Different computer representations of system information were used to portray different mental models of the process. A primary and support operator each were provided with either a graphic/integral system representation, an alphanumeric/separable representation, or both representations. The following five team-display configurations were used: primary operator with graphic display, support operator with alphanumeric (GRAL); primary operator with alphanumeric display, support operator with graphic display (ALGR); both operators with alphanumeric display (BOAL); both operators with graphic display (BOGR); and both operators with both displays (BOTH).

The results demonstrated a positive relationship between the ability of the teams to control the process and the amount of communication they exchanged. Communication dropped significantly during the session where system

failures were present. The drop in communication was indicative of the increased workload of diagnosing failures. When failures were present the performance of the teams in optimizing the system, and minimizing system takeovers, was degraded significantly. While communication may have been effective for controlling the system during normal conditions, when failures were present, the team did not appear to work as well together. Several primary operators commented that they did not utilize the support operator as much during the failure condition as during normal operations.

Although there were no differences in the ability of the teams to control the process or detect failures, the way in which they utilized information varied as function of their display configuration. This utilization of information was significantly better for the ALGR. Also, the response sensitivities of these teams were significantly higher. It appeared that the ALGR team was able to better use the resources of their partners or the screen displays for obtaining information, rather than querying the system.

Comparisons were made with similar research which used individuals rather than teams (Coury & Pietras, 1986). These comparisons revealed that the teams in the present study were not as effective in optimizing the process or in detecting failures. These differences may be attributed either to population differences, workload requirements of team communication and coordination, or actual differences in the performance of teams versus individuals.

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CHAPTER ONE

Introduction

Background of the Research Problem

Automation technology is beginning to make an important contribution to the revitalization of current systems and the design of future systems. Designers of systems, such as those involved in air traffic control, aircraft piloting, and nuclear power plant operations, are striving to incorporate automated system features into designs to decrease human operator error. Issues concerning such automation have evolved from questions about whether a function **can** be automated to questions concerning whether a function **should** be automated (Wiener & Curry, 1980). There is also a growing concern about the impact of automation on the functioning of human operators in these systems. Specifically, researchers are concerned with issues related to how automation will affect human failure detection, manual override capabilities, skill maintenance, and communication effectiveness. Increasing automation has created a need for establishing new system requirements for users, designers, and instructors. Decisions concerning the selection of equipment, the design of computer interfaces, or the levels of automation must be based on whether the change will enhance the performance of human operators, or merely serve to impede their performance.

The successful automation of system functions usually produces higher overall system reliability. However, while machine reliability is being increased, the percentage of accidents attributed to "human error" is also increasing (Chambers & Nagel, 1985). Higher system reliability and automation reduces the need for active human intervention, but they also create a requirement for more passive monitoring of the system. Removal of the human from active involvement in the operating loop does not guarantee that human errors or system failures will not occur. Removing the human from the loop merely shifts the responsibilities of human operators from active control to intermittent intervention (Rasmussen & Rouse, 1981), which can create new and distinct problems for human operators (Ephrath and Young, 1981).

The changing role of the human operator is evident when human errors are studied at different levels of automation. The primary role of aircraft pilots has changed because of the increasing use of automation in the cockpit (Chambers & Nagel, 1985). Pilots have become supervisors of systems, primarily responsible for monitoring the automated equipment. Early studies of pilot errors associated with manual control (Fitts & Jones, 1947) listed pilot errors which were associated mainly with misreading or misinterpreting information. More recently, studies in highly automated aircraft (the Boeing 767 and McDonnell-

Douglas MD-80) have pointed to new types of pilot errors; namely, those involving setting up equipment or entering data (Curry, 1985; Wiener, 1985, 1985).

Reducing the number or complexity of manual tasks performed by operators may enhance their performance in complex systems (Ephrath & Curry, 1977; Ephrath & Young, 1981; Wickens & Kessel, 1979). Operators are more likely to miss equipment failures in complex operations while they are engaged in the manual control of systems (Ephrath & Curry, 1977; Ephrath & Young, 1981). The heavier workload of complex tasks increases the time necessary to detect failures. Reducing operator workload by automating system functions helps to minimize human errors in complex systems. However, this may only remain true as long as operators remain involved with the system dynamics during long periods of monitoring. Long periods of nonintervention make it necessary for operators to make a conscious effort to learn the status and fluctuations of the systems continuously (Norros & Sammatti, 1986).

During the intervals when operators are monitoring automated systems, failures might be missed or ignored because the operator is out of the direct control loop. Furthermore, significant performance problems might be encountered when an operator is required to switch from passive monitoring to active system control. Switching participatory modes might require a period of adaptation, which could become critical during a system failure. Wiener and Curry (1980) have documented incidents related to human detection of failures in automatic aircraft equipment. They found that these incidents occurred primarily when pilots ignored equipment malfunctions or deferred action until a situation had reached or exceeded a critical point. They also found that, in certain circumstances, operators who remained actively involved with system operations actually detected malfunctions faster than operators who assumed a passive monitoring role.

Research and development in human-machine systems must strive to bring the human back into the operating loop (Wiener, 1985), at least in terms of the operator's conscious involvement with the status of the system. This does not suggest ignoring advances in technology. Rather it suggests that monitoring should become a more active and interactive function with the system. Research is needed to develop innovative approaches for keeping operators aware of system information while enabling them to maintain optimal workload levels. Regardless of the extent of automation within a system, no dynamic system is completely predictable; system reliability is ultimately determined by the human element. The knowledge and flexibility of human problem-solving continue to be vital to most systems. The design of such systems must integrate the cognitive requirements of human operators. An optimal balance between workload reduction and operator involvement is a challenging objective for human factors research.

The research presented in this paper studied the role of operators as supervisors in complex systems. Specifically, the study focused on the performance of operators who were required to monitor and detect failures in a dynamic system. It explored the use of dynamic allocation of problem-solving responsibilities between two operators as a way to enhance human performance. The way in which these responsibilities are communicated and the way in which dynamic system information is represented were specifically investigated. Each of these topics is explored in the following sections.

The Role of Operators in Dynamic Process Control

As the role of the system operators changes so that they become more supervisors than controllers, performance requirements also change so as to place greater emphasis on cognitive resources rather than manual force. This evolution in role places new demands on operators, that are certain to affect system performance. This section examines the role of the operator as supervisor in a dynamic system. The dynamic system associated with process control is emphasized.

Process control systems involve the interaction and transformation of material and energy. Most modern process control systems are complex systems with many interacting variables (Wickens, 1984). The control and regulation of the processes are relatively slow. The effects of certain changes are not evident for several seconds or minutes after control input. Because of the complexity and the hazardous and toxic nature of the process control environment, there is an increasing tendency to use more automation in the design of these systems (Wickens, 1984).

As these systems become more automated, the demands on human performance shift from manual control to cognitive processing. The human operator becomes less of a controller and more of a monitor or supervisor (Sheridan, 1976). Sheridan (1984, 1988) describes this situation as one in which the human operator controls a process by supervising or managing automated or semi-automated equipment. The computer controls the physical processes through the command of artificial sensors and actuators. It also controls and monitors a variety of subsystems, while the human supervises these activities (Greenstein, Williges, & Williges, 1981). The operator receives information intermittently from the computer, and in turn, the operator enters instructions into the computer.

Along with the management of equipment, the operator also makes adjustments, minimizes the effects of breakdowns, and controls the start-up and shut-down of the process (Kragt & Landeweerd, 1974). The functions of the human operator include planning, teaching, monitoring, intervening, and learning (Sheridan, 1976, 1984, 1988).

Planning includes determining the tasks to be performed, allocating necessary resources, setting goals, and making decisions. It might involve deciding among alternative actions such as maintaining normal operations versus shutting down a system in order to isolate a problem (Rouse & Rouse, 1983). This function mainly involves information processing and decision-making.

The operator also teaches or instructs the computer in the proper objectives for performance and the steps to take to maintain these objectives (Sheridan, 1984, 1988). This involves programming the computer to execute the determined sequence of actions.

Monitoring the system includes the detection and diagnosis of abnormal events. Typically this involves processing information presented on various computer displays to detect abnormal fluctuations in the system. Performance involved in the detection of system failures might be as simple as monitoring for obvious warning signals or as sophisticated as detecting subtle changes in the state of the system (Wickens, 1984).

When system failures are detected, it often is necessary for operators to regain manual control of the system by overriding the automated functions, or by entering instructions into the computer. It is likely that operators actively interact with an automated process only during these system malfunctions (Kessel & Wickens, 1982).

Finally, another role for the operator in supervisory systems is learning from experience. Because of the flexibility of human problem-solving (Jordan, 1963), it is not necessary to plan for the recovery of control of simple systems. But as systems grow in complexity, so do the demands for complex human problem-solving. In more complex systems, the smooth and timely recovery of control by the human operator becomes more critical and more complicated. The adaptability of human operators in handling abnormal events, and their ability to learn from past experiences, are critical to this process.

This new role of operators in complex systems needs to be studied in order to determine the effects of the new demands on system performance. The functions of interest in the current research were monitoring and intervening.

The Role of System Knowledge in Operator Performance

The control of automated systems requires operators to perform on the basis of different types of knowledge requirements. Rasmussen (1983) defines internal knowledge representations in terms of three levels of performance requirements: skill-, rule-, and knowledge-based performance. The task used in the current study required operator performance at all three levels.

Skill-based behaviors are not consciously controlled; they are smooth and virtually automatic. They are typically represented by sensorimotor performances. Skill-based behaviors relate to automatic search and detection functioning as defined by Schneider and Shiffrin (1977). Automatic detection places relatively little demand on attentional capacity and is a well learned behavior in long-term memory.

Rule-based behaviors are controlled by specific how-to-do-it procedures for familiar tasks. Performance in a rule-based situation is guided by an explicitly stated set of rules. The operator does not have to infer correct actions, but relies on past experiences and procedures for guidance.

Knowledge-based performance is required in unfamiliar situations in which no set of rules is known. The operator cannot depend on past experience for guidance. The goal controls the operator's performance at a higher conceptual level; the goal is explicitly formulated from an analysis of the environment; and a conceptual plan for action is formulated. Routine tasks and some familiar tasks are executed by skill-based behavior, while other familiar and preplanned tasks are executed by rule-based behavior, and new situations requiring problem-solving are executed by knowledge-based behavior (Goodstein, 1981).

Operators' ability to cope with the complexity of the process environment is related to their ability to utilize various internal models and to shift to different levels of abstraction and reasoning as needed (Rasmussen, 1986). The function of monitoring is a semi-continuous, well-learned and largely perceptual motor skill. It is generally conducted at the skill level. Teaching and intervening appear to be rule-based. Planning and learning involve much greater attention to goals and to problem formulation; it is seen as knowledge-based behavior (Sheridan, 1984, 1988). In many systems, alternative plans are readily available in terms of formal procedures for dealing with particular situations. Further, training may prescribe the specific course of action to be taken. When unexpected situations arise that were not anticipated in the design of the procedures, or are unfamiliar because they were not considered in training, operators can be required to pursue planning and commitment. In such situations, human decision-making and problem-solving abilities, as well as experience, are likely to be crucial (Rouse & Rouse, 1983).

Rasmussen's knowledge-based level of performance is also called "model-based", since the internal structure of the system is assumed to be explicitly represented by a "mental model". It is assumed that operators of complex systems develop a dynamic mental model of the system, and that they use this understanding of the situation to guide their performance in operating the system (Morris & Rouse, 1983). Some operators in process control may base decisions on procedures and past experience, while others might use their own mental models of the system to guide them (Crossman, 1974). The mental model enables the operator to infer proper actions when past experience or training does not directly apply. Such models have been depicted as a simulation language for thinking about the process that the operator is controlling (Bainbridge, 1969).

An internal model is assumed to include a knowledge of the system, the principles on which it is operated, and its relationship with the environment (Morris & Rouse, 1985). It must also contain knowledge and understanding of the dynamic physical relationships of the system. It is conceivable that the component of mental models that contributes most to operator performance is a representation of the dynamics of the system (Baune & Trollip, 1982). This advanced level of thinking has been described as "theoretical system thinking" (Norros & Sammatti, 1986). It involves an understanding of the system's internal structures and processes - the "how-it-works knowledge." (Kieras & Bovair, 1983, 1984).

Some researchers have argued that operator performance is enhanced by knowledge of the system and its processes. On the other hand, others claim that it is sufficient to give the operator a basic level of knowledge which informs the operator what to do. Rasmussen (1983) reviews this relationship between system knowledge and performance in terms of routine and unfamiliar conditions. In familiar circumstances, human behavior is oriented toward the system goal and is controlled by a set of previously validated rules. In such conditions, an internal model of the system contributes little to the operator's performance. However, when an operator is required to perform in an unfamiliar situation (where there is no set of rules or novice conditions), behavior is goal-controlled and the operator experiments though the use of internal models of the system. In these situations, performance depends on an accessible internal representation of the system and its environment.

Major research issues concerning mental models are related to the manner in which they are formed, and the way they are "run" and updated in the system environment (Zhang & Wickens, 1987). The formation of a mental model is achieved through the use of instructions and operator training. A research question in this area has been concerned with the efficacy of theoretical training as compared to procedural training. The extent to which mental models are updated during the monitoring and controlling of a process is affected by the particular system representation that is used by the operator in controlling the system. The design of the displays can be manipulated to affect the mental model of the operator. Both of these issues are discussed below.

Formation of Mental Models Through Instructions and Training

Skill-based and knowledge-based information and operator performance have been studied by Rouse and his associates in a simulation of a dynamic production process, known as the Production Levels and Network Troubleshooting (PLANT) task (Morris & Rouse, 1985). Morris and Rouse (1985) manipulated operator knowledge of the system via instructions. Subjects were presented system-relevant knowledge in one of four sets of written instructions: 1) minimal 2) procedures, 3) principles, or 4) relationships between principles and procedures. All subjects received the first set of introductory instructions, which was concerned with the goals of the operation and command options which were available. The procedural instructions included rule-based information which provided specific, sequential control actions. The instructions concerning principles were theoretically-based, interpretive knowledge about the principles that guided the operator of the PLANT task. The last set contained both the procedures and their principles.

Morris and Rouse (1985) expected that the procedural information would guide subjects' behavior in familiar and ordinary circumstances. In unusual situations, where the procedures did not apply, they hypothesized that those subjects with the principles would be the ones better equipped to handle events. The authors found support for their first hypothesis; namely, subjects who received instructions concerning the procedures (with or without the principles) generally controlled the processes more consistently. However, their second hypothesis was not supported. In unfamiliar circumstances, there was no advantage for subjects who received instructions based on principles. Based on this result, the authors concluded that their principles might have been so general they could not be used directly for troubleshooting a specific component.

The role of mental models in operator performance was also studied by Kieras and Bovair (1984). They required two groups of subjects to learn a set of procedures for operating a control panel device in normal situations and during malfunctions. The procedures that the subjects learned were not, in all cases, the most efficient ones. Subjects could formulate their own, more effective procedures. In addition to learning the procedures, one of the groups, the device model group, learned "how-it-works" knowledge (which the authors called a "device model"). Knowledge of the internal components and processes was presented to them in the form of a description of the device based on the television series **Star Trek**. The device model was based on a block diagram of the major internal components of the system, their relationships to each other and to the controls and indicators, and the flow of "energy" between the components. To ensure that they understood the model, subjects were required to pass a test before learning the procedures for operating the device. The second group of subjects learned the procedures only. As the authors hypothesized, the device model group executed the procedures faster, remembered the procedures more accurately, and used more efficient procedures more often than the other group.

Kieras and Bovair (1984) conducted a follow-up to this study by testing whether the instructed device model was beneficial in situations where subjects were not given procedures, but were asked to infer them. While both groups executed the optimal procedures, the device model group successfully inferred these procedures with fewer attempts. They seemed to rely on the device model rather than trial and error. The authors also found that the effectiveness of the device model was due to the information concerning system topology that related the controls to the components and to the possible paths of power flow. It was not due to motivational effects related to the fantasy context of the description, to the information provided about the system components, or to the general principles underlying the system. They concluded that the value of the device model is contingent upon whether the user actually needs to infer the procedures for operation and needs the information in the model in order to be able to infer the procedures.

Halasz and Moran (1983) found similar effects of procedures and theory on performance with a hand calculator. In routine calculations there was no difference between a group trained with procedures and another group trained with procedures and an explicit model of a stack calculator. However, in unfamiliar calculations requiring invention (search through a problem space), the performance of the group with the explicit model was superior.

There are several differences between the studies reported above. First, in the study by Kieras and Bovair (1984) subjects were required to pass a multiple choice test for knowledge of the model before proceeding to the training. Morris and Rouse (1985) tested subjects on minimal knowledge (Test 1), and on minimal knowledge, procedural knowledge, and principle knowledge (Test 2). Test 2 was administered at the end of the experiment and was not used as a criterion to retrain subjects (as in Kieras and Bovair, 1984). The information offered by the model might not have been as well learned as it was in the study by Kieras and Bovair (1984)

A second difference is related to the knowledge-based information in the study by Morris and Rouse (1985). This information was not related to system topology. System topology information focuses on the pattern of connections between the internal components and the operating controls and indicators (Kieras, 1984). The model in the PLANT study

(Morris & Rouse, 1985) explained components and general principles. Kieras (1984) claimed that information about the overall function of the system and the principles that the system is based on are not important. These authors examined correlations on the tests and performance on the process control task. Morris and Rouse (1985) found low correlations between Test 2 scores and performance measures, thus reinforcing their suspicions that the principles might not have been in a form that was directly usable by the subjects. The principles alone might not have made a difference in the performance of the subjects. The principles and a topology of system dynamics might have been more effective.

Finally, there were differences in the context in which the models were used. Kieras and Bovair (1984) defined a useful device model as the "knowledge about the internal workings of the system that allows the user to infer exactly how to operate the device." They also suggested several principles for the selection of device model information. First, the information must support inferences about the exact and specific control actions. General principles, metaphors, or analogies are of little value. Second, it is not necessary for the information to be complete in order for the user to infer the procedures. Third, the device model will not always be useful; this will depend on whether the user is required to infer the procedures and whether additional information is needed. In simple systems, where procedures are easily learned or practiced, device models might not be required. Finally, device models do not always improve performance but might actually degrade it. This could occur if the user fails to learn the device model correctly and, thereby, draws incorrect conclusions. It is essential that the operator develop a useful and accurate model that is directly applicable to performance. The advantage of the model in helping an operator learn how to control a device is more clearly defined in the absence of explicit instructions (Kieras, 1984).

Although theoretical knowledge or experience can influence the behavior of operators, this effect may not always be noticeable in performance (Mann & Hammer, 1986). Other studies also have failed to support the hypothesis of theoretical training as a contributor to performance (Brigham & Laios, 1975; Kragt & Landeweerd, 1974; Shepard, Marshall, Turner, & Duncan, 1977). Mann and Hammer (1986) claim that the important distinction in determining if such knowledge affects performance is whether or not it is actually used by operators. With respect to the design of theoretical training, they suggest the following:

(1) Theoretical training should be integrated with the procedures for operation. This enables operators to see the theoretical reasons behind the applied principles.

(2) Operators should be taught to use the theoretical

knowledge in unfamiliar situations (for which no procedures are available).

(3) Operators should be trained to discriminate between routine and novel failures, and then to diagnose these failures based on their theoretical training.

In other words, Mann & Hammer (1986) argue that operators should be taught the difference between rule-based reasoning, (procedures) and knowledge-based reasoning (theory; Rasmussen, 1983). They suggest that it might also be important to provide operators with the physical representation of how the components interact, as well as the theoretical knowledge, "how-it-works," information.

Improving Operator Performance Through Screen Design

Although the terms "mental model" and "conceptual model" often are used synonymously, they are distinguished by their degree of tangibility. Norman (1983) defines a mental model as a non-observable concept in the mind of the user. A conceptual model is the model that is given to the operator by the experimenter or designer as an explanation for the system. It is the basis for designing the interface between the operator and the system. The operator views the image of that system in order to form a mental model of the system. Displays which are compatible with the way the operator views the system should minimize workload; in turn, this should result in more accurate detection and diagnosis performance (Casey, 1986).

The comparison of different visual displays which represent complex systems implies comparisons of the effectiveness of different mental models of the system (Sanderson, 1986). The design or selection of a particular representation of system information must incorporate the relation between the statistical properties of the task and the physical format of the display (B.G. Coury, personal communication, December 1987). Some of the statistical properties of the task which have been researched involve the dimensions of system information related to orthogonality (Carswell & Wickens, 1986; Wickens, 1984), degree of uncertainty (Coury, Boulette, Zubritzky, & Fisher, 1986; Coury & Boulette, 1987) and time constraints (Boulette, Coury, & Bezar, 1987).

Statistical properties have been studied with respect to integral and separable display formats. Integrative displays present information graphically as a holistic representation, which might be useful for developing a high fidelity internal model (Wickens, 1984). A holistic image enables operators to perceive several attributes in rapid, parallel processing (Carswell & Wickens, 1987). The integral display simplifies the operator's task of classifying the state of the system by mapping unique display configurations to system state categories (Coury et al., 1986).

In integral displays, the operator attends to the shape or configuration of the object to determine the system's status. A study by Carswell and Wickens (1987) using a triangle display showed superior performance when the subject had to integrate two pieces of quantitative information. It is most beneficial when the operator requires information concerning the overall status of correlated variables rather than detailed information attributes. Integral displays do not enhance performance when the stimulus dimensions vary independently (Wickens, 1984). In these cases, parallel processing of information is not useful.

When operator requirements demand more explicit information, the separable display is useful. Separable displays, in both alphanumeric and tabular formats, demand attention to individual data and variables; thus, a sequential processing of information is involved (Coury & Boulette, 1987). A separable display is desirable when a single variable must be selectively read or attended to and the operator must ignore other dimensions of the display (Wickens, 1984).

Woods, Wise, and Hanes (1981) designed the Safety Parameter Display System (SPDS) in order to provide operators with an overall representation of nuclear power plant parameters. They utilized both an iconic or polar-graphic display format and a traditional display which represented each parameter separately. In the integral display, each spoke in the figure represented the value for a particular parameter. The integral display was found to be related to equal or better performance as compared to the separable display.

Casey (1986) presented subjects with a task which required them to observe the overall pattern of correlation between variables. It was expected that failure detection and diagnosis performance would improve with display integrality. What Casey actually found was that the integral displays were related to poorer diagnosis performance. She explained the conflict of her results with the results of previous research (Carswell & Wickens, 1984) by distinguishing the complexity of the mapping of displayed information to system state. Carswell and Wickens (1984) required diagnostic performance that involved the consideration of more than one variable. In this case the integral display enhanced performance. Casey (1986) referred to her study as requiring a one-to-one mapping between variable and diagnostic state. The focus was on a single variable rather than an integration of variables. Thus, the separable display enabled more precise diagnosis.

Casey (1987) followed her study by attempting to determine whether the benefits of an integral or separable display in fault detection and diagnosis are a function of the relationship between the system components. She differentiated two systems based on correlational and causal relationships. Diagnosis of correlational components required pinpointing which system variable was responsible for the failure. On the other hand, in a causal relationship, the integration of related information was required to determine what kind of failure had occurred. Casey (1987) found that the integral display degraded performance in either case. Once again, differences from previous research were pointed out. Carswell and Wickens (1984) required subjects only to detect failures; they were not required to determine the specific reason for the failures. Therefore, focus was not on the particular components of the system. Because Casey (1987) required subjects to detect and diagnose the system, the emphasis was on finding the responsible component. She concluded that for tasks demanding a specific focus of attention, a separable display was the choice, even when system components were correlated.

Coury and his colleagues (Coury, Boulette, Zubritzky, & Fisher, 1986; Coury and Boulette, 1987) have investigated the relationship between uncertainty in system state and the preference for integral and separable representations. If the state of the system is not clear to the operator, and the display must be separated into individual variables, the integral display might degrade performance. Both studies (1986; 1987) found the integral display produced better performance during learning and when a system state could be classified without any uncertainty. When uncertainty was high the separable display, with its more precise representation of the system, was necessary. Once the task was well learned then the difference between the displays was nullified. Coury (Coury et al., 1986) cautioned against the conclusion that the advantages of integral display might merely be an effect which is negated by practice. In situations which require integration of information over time, such as might be required in the performance of dynamic tasks, the integral display might be better.

In more complex situations, both the integral and the separable types of representations might be necessary (Coury & Boulette, 1987). It might be advantageous to display, or at least make available, separate representations of system variables, even when the integral representation is presented (Wickens, 1984). In the study reported below, Coury and Pietras (1986) found that both optimization of system performance and failure diagnosis were better when integral and separable displays were presented concurrently.

Coury and Pietras (1986) used theories of mental models in the design of different representations of system information. They looked at the merits of graphic and alphanumeric displays for representing process-plant data and information in a dynamic process monitoring and control environment. Their simulation was a derivative of the PLANT task used by Morris and Rouse (1985). The device topography model of deKleer and Brown (1983) provided input to their graphic display. Their graphic display provided an overall, physical representation of the structure of a fluid processing plant. This display did not describe how components function in the device, but how they are organized. They predicted that this screen would enhance system optimization. Coury and Pietras also designed an alphanumeric display which included the specific values of process variables, the relation between process data and components, and some knowledge of the impact that a change in a particular process variable might have on other components in the system. This display provided more detailed knowledge of the underlying relationships between the function of components and the concomitant changes in attribute values and was hypothesized to be better suited for failure diagnosis compared to the graphic display. This alphanumeric display presents the knowledge of system function depicted by deKleer and Brown's (1983) attribute values and component models. When both displays were presented, the operator was given a more complete representation of the system, a representation most closely resembling deKleer and Brown's (1983) attribute topography.

This is also similar to Kieras and Bovair's (1984) device model, where subjects both learned "how-it-works" information about a device and saw a physical representation of the device. Operators are given both the theoretical principles of the system and a device topography of its physical representation.

Coury and Pietras (1986) predicted that the graphic display would produce better system optimization performance under normal conditions, while the alphanumeric display would provide a better interface for the detection and location of failures. They further hypothesized that the overall performance of both tasks would be superior if both representations were available. The researchers found that operators optimized system performance best when using both displays. Optimization of performance was the poorest with the graphic display alone. The percentage of failures detected and the number of iterations required to detect those failures were also measured. The failure detection task used in this study required the specification of the location of the failed components. They found no significant relationship between the type of display and the percentage of failures detected. However, the number of iterations required to detect a failure was related significantly to the type of display used by an operator; the use of both displays resulted in shorter detection times. The graphic display required significantly more iterations to detect failures than with both displays or the alphanumeric display alone.

The current research studied system representation as it affected the operator's mental model of the system. The integral/graphic and separable/alphanumeric displays of Coury and Pietras (1986) were used to influence the mental model of operators as they controlled the task. The team display configuration was expected to influence performance. In complex environments, the combinations of the integral and separable representations should be most effective. This study sought to determine whether this was true as a team functioned together using their own representation of the system.

The Allocation of Problem-Solving Functions

Operator control of automated systems involves the interaction of the human with the computer, not directly with the process itself (Greenstein et al., 1981). Therefore, increases in system effectiveness are often related to the issues of the interaction of humans and computers. The manner in which problem-solving functions are allocated in complex systems is an important variable in determining operator workload and involvement with system status. Functions can be allocated according to strategies which optimize workload yet encourage conscious involvement with the dynamics of the system. The goal of task allocation should not be to take responsibility from the human operator, or to minimize workload, but to optimize workload and responsibility. The current research utilized allocation of problem-solving as a dynamic function and this function was shared between two operators.

Decisions concerning the allocation of functions and responsibility within complex systems have previously been approached using lists of capabilities (Chapanis, 1965; Fitts, 1951). Researchers determined which tasks humans perform better than machines, or vice versa, in order to make allocation decisions. Humans are generally more capable of setting goals, formulating hypotheses, determining criteria, and evaluating results (Licklider, 1960). Computations and implementations are more efficiently computer- or machine-driven. Edwards and Lees (1974) provide an extensive summary of the advantages and disadvantages of task allocation on the basis of such lists of abilities.

Methodologies which rely on lists for allocation of functions are based on several misconceptions about human abilities and the measurement of these abilities. First of all, these methodologies assume that it is possible to predict human performance and then make comparisons with engineering data on machine performance. The belief that a large, quantified, and complete human performance database exists is simply not true (Price, 1985). The available human performance data are not generalizable to new, complex systems and the multiple human and machine variables within these systems. Expert judgment and empirical research are needed in order to compile such data.

A second misconception surrounding the use of task allocation lists is related to their applications. It has been assumed that the methodologies that are successful for allocating psychomotor behaviors can be applied to the cognitive content of performance (Price, 1985). This is not an appropriate generalization. Price (1985) has suggested that the cognitive models of Rasmussen (1976) be incorporated in systems design in order to describe covert, information-processing behavior.

Task allocation lists are not fully adequate when they are used to make comparisons between the abilities of human and machine. Attempts are made to describe human functions in mathematical terms similar to machine functions (Jordan, 1963). Technology progresses and machine capability continues to increase, but human capability essentially remains stable. In this situation, whenever possible, the goal is to give responsibility to these advanced machines in order to reduce the likelihood of human error.

Finally, lists of capability criteria are also limited in use because of the assumption that functions are to be performed by only the machine or the human (Price, Maisano, & Van Cott, 1982). Allocation lists distribute functions between humans and machines according to a predetermined division of labor. While some tasks clearly are performed better by a machine, and others better by a human, the best division for many tasks is not as clear cut, or the task may be completed equally well by both.

The use of these lists of abilities constitutes a static approach to the allocation of functions (Turner & Karasek, 1984). Static methods of task allocation do not allow for the adaptability of roles permitted by computers. Task allocation could be enhanced through the use of an approach that treats humans and machines as complementary components of a human-machine symbiotic relationship (Jordan, 1963). A task allocation strategy based on this rationale constitutes a dynamic allocation of functions.

A dynamic allocation approach adjusts allocation to the human's processing load (Rouse, 1976, 1981). Tasks may be allocated to the decision-maker or controller (human or computer) that has available resources at the moment. When a decision-maker recognizes the need for action, action might be taken, unless the other decision-maker has already responded (Rouse, 1977). Rouse and Chu (Rouse 1975, Rouse, 1976, Rouse, 1977; Chu and Rouse, 1979) have reviewed some of the potential advantages of adaptive decision-making. Two of these advantages, more consistent operator workload and improved system knowledge, are vital to the detection and diagnosis of system failures (Rouse, 1977).

The advantages of the dynamic allocation of functions might also be evident when applied to situations with more than one operator. Many problems require the synthesis of more than one specialist, each contributing a different point of view (Woods, Roth, & Bennett, 1987). This effective "joint cognitive system" (Woods, Roth, & Bennett, 1987) consists of two elements, such as two humans, with partial and overlapping expertise. The domains of expertise of two operators can be integrated for better overall performance.

The value of two operators working as a team has long been recognized by the military. In recent years, the civilian sector also has become aware of the importance of the total team to performance. Typically, the behavior of pilots has been studied from the perspective of individual performance. Attempts to reduce human error in aircraft systems have been synonymous with providing the pilot with redundant information (Foushee, 1982). However, many problems and mishaps in this environment seem to be more dependent on the communication and coordination of the crew, rather than individual performance. In fact, the lack of adequate coordination of crews and poor resource management have been connected to several aircraft disasters in the past two decades (Chambers & Nagel, 1985). In the nuclear arena, during reviews for requalification, initial examination, emergency operating procedures, or training audits and inspections, the Nuclear Regulatory Commission evaluates a licensee's team performance as well as individual performance. However, as of yet, no formal evaluation techniques exist to serve this purpose.

In dynamic process control systems, decisions and control actions of operators affect the future state of the system (Coury & Pietras, 1986). Dynamic allocation is particularly applicable to the control of these systems (Greenstein & Lam, 1985). It is predictable that the dynamic allocation of function between two operators in these systems will result in cooperative task sharing based on adaptive criteria. The flexibility of this allocation strategy would allow problem-solving to be based on criteria that require the operator with the expertise and available resources to handle specific transients as they arise. The ability to distribute the allocation of problem-solving between two operators has the potential to maximize performance and optimize the workload of human operators. The current research required operators to share problem-solving in a dynamic, process control environment.

Communication and Coordination of Shared Tasks

Communication issues in dynamic systems pertain to the ways that operators and computers keep each other informed of the status of the system and of their own completed or "intended" actions (Rouse, 1984). In a situation where problem-solving has been allocated dynamically, the communication between operators is vital to effective performance.

The division of problem-solving functions between a computer and an operator can be initiated by either the operator or the computer using explicit or implicit means of communication (Lam & Greenstein, 1985). An ideal dynamic allocation would require no conscious effort from the operator (Kantowitz & Sorkin, 1987). The system would automatically relieve the operator of responsibility when operator workload reached a given point, or when another controller was better informed of system knowledge. The system would maintain an optimal workload that neither overloaded nor underloaded operators, and which kept both operators and computers informed of system information. This method of communication, implicit communication, is based on inferences drawn from direct observation, indirect measurements, or inference with the use of models (Rouse, 1984). It does not involve a conscious awareness of the communication process (Rouse & Rouse, 1983); therefore, it does not add to the operator's existing workload. It may also be used to observe information that the operator is unable to communicate.

In contrast, if a dialogue to determine the appropriate allocation strategy occurs, then the communication is classified as explicit (Greenstein & Revesman, 1981).

Explicit communication involves the transmission of information through traditional devices such as specific displays and controls, structured dialogues via keyboards or voice, or natural language via keyboards or voice. Explicit communication is useful for avoiding conflict between decision-makers, but it is costly in terms of time to enter information and of operator workload to give and receive messages.

Lam and Greenstein (1985) studied different explicit strategies for allocating responsibilities between a human and a computer aid. Using four explicit dialogues and a control condition, they investigated differences in performance measures in a multi-task, air-traffic controller scenario. Assignment of planes to the computer aid was based on one of the following strategies: 1) identification numbers of the planes (Designation), 2) location of the planes on the CRT screen (Spatial), 3) time frame (Temporal), or 4) emergency basis (Contingency-based). Their strategies were distinct in terms of different dimensions of cognitive processing, levels of abstraction, degree of specificity, flexibility, power to allocate planes, and control over decisions. The poorest performance occurred in the control condition, when computer aiding was not available. Three of the strategies (Designation, Spatial, Contingency-based) resulted in higher overall system performance, while the temporal assignment strategy yielded the smallest increase in performance. It was concluded that the temporal strategy added additional workload to the operator in the form of keeping track of the tasks assigned to the computer.

The degree to which communication should be explicit or implicit is an important research issue in human-computer communication (Rouse & Rouse, 1983), particularly as it relates to the development of a flexible and dynamic task allocation system. To a certain extent, this variable may depend on situational circumstances, such as the appropriate combinations of medium, mode, style, and strategy for a given human-computer system and task environment (Greenstein & Lam, 1985). The degree to which communication should be explicit or implicit between two humans might also be contingent upon the situational circumstances. In the present research, operators shared problem-solving functions from different locations. Although explicit communication might increase the workload of the operators, it was the most viable option for avoiding conflicts between the operators in this situation. This study examined the relationship of the communication to the measures of system control and failure detection.

The effects of computer communication on the nature of work have been studied, not only it relates to the performance of an individual operator tool, but also as a tool to enhance performance on shared tasks (Curtis &

Malone, 1987-1988). The emphasis in this type of environment is on the computer as an agent to support communication and coordination of problem-solving and decision-making.

Chapanis and associates (Chapanis, Parrish, Oschman, & Weeks, 1977) used human-human communication as an analogy to the ideal human-computer interaction. One person was designated as the source of information and the other as the seeker of information. The source is analogous to the ideal computer. The seeker is analogous to the user of the computer. Human-computer communication was accomplished in a manner that is similar to human-human communication. The seeker was given a problem with incomplete information. The source had the remainder of the information needed to solve the problem. The source and the seeker had to communicate information; neither one could solve the problem alone.

Coombs and Atly (1980) found that successful human-human interactions between two partial experts (an experienced computer user with a domain task to be accomplished and a specialist in the local computer system) involved cooperation in the problem-solving process. Less successful interactions occurred between an expert advisor and a user. In this case, the user gave the expert the information and in return was given a solution with little participation in the problem-solving process (Alty & Coombs, 1980; Coombs & Alty (1980). Thus, in successful human-human interactions, control is shared by identifying the important facts and using them to better define the problem. Either operator might step out of a specific domain in order to solve the problem at hand (Woods, Roth, & Bennett, 1987).

The modality, or the form of communication, is an important variable in the effectiveness of communication between operators. This has been determined to be relevant to the coordination among the crew members of the space station. In fact, it has been suggested (Cook, 1987), that on space missions, the modality of communication might play a role in affecting morale, efficiency, productivity, potential for conflict, the exercise of authority and control, and, ultimately, in mission success. On space missions, cost dictates a heavy reliance upon computer-mediated communication as the primary modality for the transmission of information.

Comparisons have been made (Week & Chapanis, 1976; Williams, 1977) of different communication modalities. Voice communication (face-to-face, audio, and audio-video) and written communication (teletype and remote handwriting) were compared for problem-solving and information transmission tasks. It was found that voice communication resulted in faster solutions, although more messages were necessary. Specifically, there tended to be many more messages, words, and unique words in the voice modes than in the written mode (Chapanis, Parrish, Ochsman, & Weeks, 1977). The faster solution times in the voice modes might be attributable to the fact that people are able to engage in another activity, such as searching for information, while speaking. This is not true for writing.

More recently, computer-mediated communication has been studied with respect to group decision-making (Kiesler, Siegal, & McGuire, 1984; Siegal, Dubrovsky, Kiesler & McGuire, 1986). Siegal and associates (Siegal et al., 1986) used three-member groups to compare computer-mediated communication with face-to-face communication. They defined communication efficiency as "the ability of members of the group to communicate data, ideas, opinions, and feelings among themselves in the least wasteful way." Their measures of efficiency included the number of remarks exchanged by group members, the number of task-oriented remarks as a fraction of total remarks, and the number of decision proposals as a fraction of total remarks. The computer group took more time to reach a decision and they exchanged fewer remarks. However, the longer decision intervals for computer-mediated communication seemed to have resulted from factors other than the time required for typing the input (Kiesler et al. 1984). The amount of task-oriented remarks was generally the same for groups using computer-mediated or face-to-face communication. The computer-mediated communicators made more decision proposals as a fraction of the total remarks made. The authors determined that the lack of nonverbal and auditory cues characteristic of computer-mediated communication might interfere with information exchanges such as intentions and feedback.

It is interesting to note the internal group hierarchy and structure that usually emerge in face-to-face meetings do not emerge so clearly in written and computer-mediated communication. Participation in group processes is usually divided based on social status and the expertise of individuals (Siegal, et al., 1986). In his review, Williams (1977) noted that participation, in terms of number of messages, was essentially equal for the computer-mediated and teletypewriter groups. Computer-mediated communication also yields a more equal participation among group members than face-to-face communication (Siegal, et al., 1986). This modality of communication might be associated with increased feelings of control which focus users' attention to the task. Also, the lack of non-verbal cues might force the users' attention on the actual information communicated rather than the individual who is doing the communicating.

The authors (Kiesler et al., 1984) offer the following reasons for the fact that it is more difficult to coordinate communication among group members and to reach a decision when using computer-mediated communication. First, the absence of informational feedback makes it difficult to realize when one's point of view is accepted or understood. Users believed that they had to exert more effort to be understood. Second, because of a more equal distribution among people, no one person is coordinating and controlling activities. This lack of a centralized effort makes coordination difficult.

Although computer-mediated communication might contribute to less efficient, more wordy interactions between operators, it is a practical device for the dynamic allocation of problem-solving. When two operators cooperate on a task, it is expected that equal participation would contribute to better performance (assuming equal expertise and availability of resources). A "joint cognitive system" (Woods, et al., 1987) should be better able to pool the system resources to perform the task. Communication efficiency is not necessarily desirable in this situation. The operators must communicate to share responsibilities. It was expected that the amount of communication would be related positively to system performance. In the current study, the amount and distribution of communication was expected to vary as a function of the team display configuration.

Present Research

The goal of the present research was to study dynamically shared problem-solving between teams in a complex system. This study addressed the relationship among system representations, communication, and the performance of teams.

Each of the subjects in the current research served as a team member with independent access to a computer display of different representations of system information. Subjects were provided with a computer representation that presented the system either in an integral/graphic format, a separable/alphanumeric format, or both. Members of the same team either had the same or different displays.

Operators in this study were required to share problem-solving in order to optimize the flow of fluid through a simulated system (Coury & Pietras, 1986) and to monitor and diagnose failed components. One subject served as the primary operator, responsible for actually finalizing and implementing decisions. A second support operator served as an advisor, recommending plans to the primary operator. The operators communicated via explicit, computer-mediated communication.

Hypotheses

The following questions and hypotheses were examined:

(1) Does the mental model of the team have an effect on the ability of the team to control the process? It was hypothesized that <u>there would be a difference in the process control</u>

performance of teams based on the type of system representation they employed.

(2) Does the mental model of the team affect the ability of the team to detect failures? It was hypothesized that there would be a difference in failure detection based on the system representation of the teams.

(3) Does the mental model of the team affect the ability of the team to utilize the displayed information? It was hypothesized that the ability of the teams to utilize the displayed information would differ according to team display type.

(4) Does the mental model of the team affect the communication efficiency between the operators? It was hypothesized that there would be a difference in the amount of communication based on the display type of the teams.

(5) Does the mental model of the team affect the distribution of communication between the operators of a team? It was hypothesized that communication distribution would vary as a function of display type.

(6) Is there a relationship between communication efficiency and system performance? It was

hypothesized that there would be a positive relationship between the amount of communication and the dependent measures of system performance.

(7) Is there a relationship between the distribution of communication and system performance? It was hypothesized that there would be a relationship between communication distribution and the dependent measures of system performance.

CHAPTER TWO

Method

Subjects

Fifty Navy and Marine Reservists from the Navy and Marine Reserve Center in Knoxville, Tennessee served as subjects for this study. Of the 50, two were female. Ages of the subjects ranged from 21 to 59, with an average age of 34 years. Subjects were selected by the respective commanding officers of the reserve center from among reservists who were making up a previously missed drill weekend. Twenty-five teams of two subjects each were tested.

Design

Subjects were scheduled for the experiment in groups of two. They were randomly assigned as either the primary operator or as the support operator. The teams were then randomly assigned to one of five conditions: (1) primary and support operator with graphic representation (BOGR), (2) primary and support operator with alphanumeric representation (BOAL), (3) primary and support operator with both representations (BOTH), (4) primary operator with graphic representation and support operator with alphanumeric (GRAL), or (5) primary operator with alphanumeric representation and support operator with graphic representation (ALGR). See Figure 1 for a overview of assignment of teams to display types.

A mixed 5 x 2 factorial design was used with two independent variables: (a) the Display Type (BOGR, BOAL, BOTH, GRAL, ALGR), and (b) the Failure Condition (No Failure, Failure).

Apparatus

A DEC PRO 380 microcomputer with two high resolution color monitors and two DEC VT 100 terminals was used to produce the simulation and to record subjects' responses. The DEC PRO computer uses a P/OS operating system, and a PRO Tool Kit environment. The code of the simulation task runs on this computer in Protool Kit Pascal. Two IBM XT's were used for communication between the two operators. The IBM terminals were connected by cable and the communications package ProComm was used (See Figure 2 for a layout of the configuration).

ProComm splits the computer screen into a local window and a remote window. The local window displays up to four lines of text that the operator has written or sent. The remote window displays up to 20 lines of messages that have been received from the other operator. Each window scrolls independently. Messages are sent automatically after the operator presses the enter key.

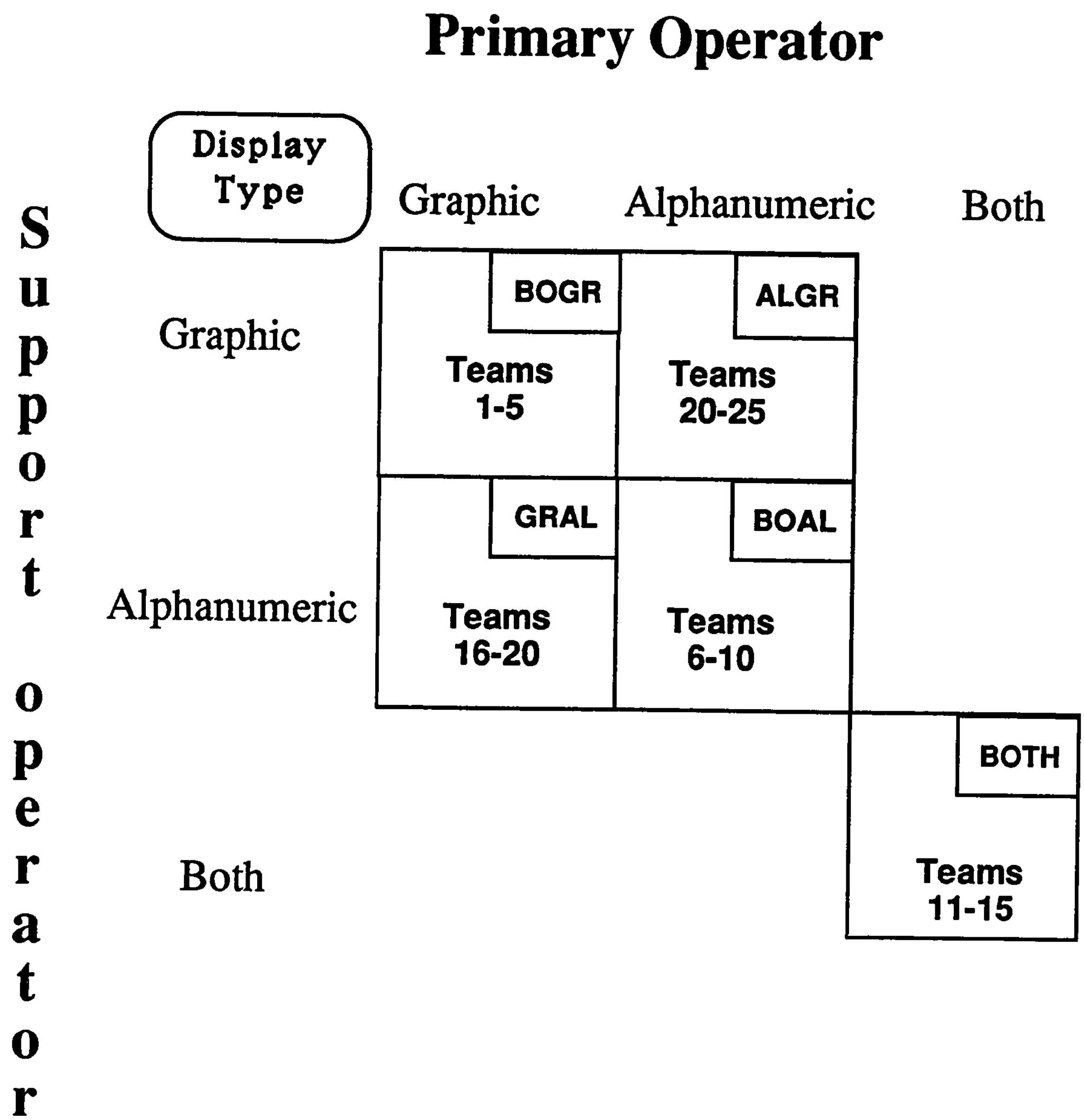


Figure 1. Assignment of Teams to Groups

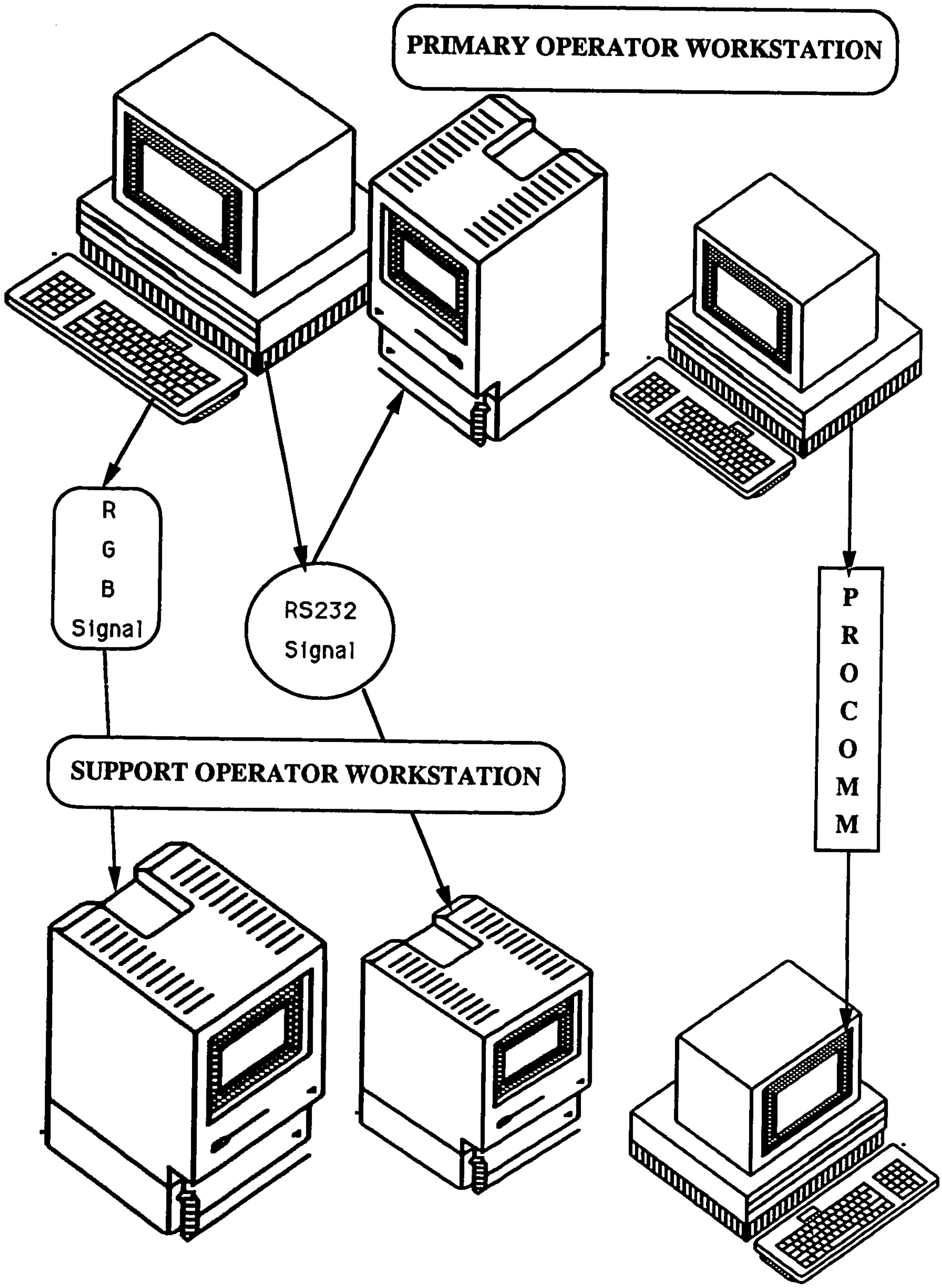


Figure 2. Primary and Support Workstations

Task

A computer-simulated dynamic task was used for this research. The task is a generic, dynamic production process, known as SARPI (Simulation for Assessing Representation of Process Information), developed by Bruce Coury and his associates at the University of Massachusetts (Coury and Pietras, 1986). SARPI is a version of Production Levels and Network Troubleshooting (PLANT) software, a computer-based process control task (Morris, Rouse, & Fath, 1985). SARPI was developed in order to study optimization of system performance and diagnosis of system failures. It has a graphic display and an alphanumeric display which present similar system information in two different formats. The graphic display uses a 13 inch color monitor, the alphanumeric display uses the thirteen inch monochrome VT 100 terminal. The simulation was developed to be used by one operator using either the graphic, alphanumeric, or both screens. For the present study, a configuration was utilized which enabled two operators to view the simulation via the graphic, alphanumeric, or both screens, from separate workstations (a picture of the two screens is presented in Figure 3). Only one operator, the primary operator, was able to control the process.

As represented by the simulation, fluid enters the system through three tanks on the left (tanks 1, 2, and 3), flows from left to right though the three middle tanks (4,

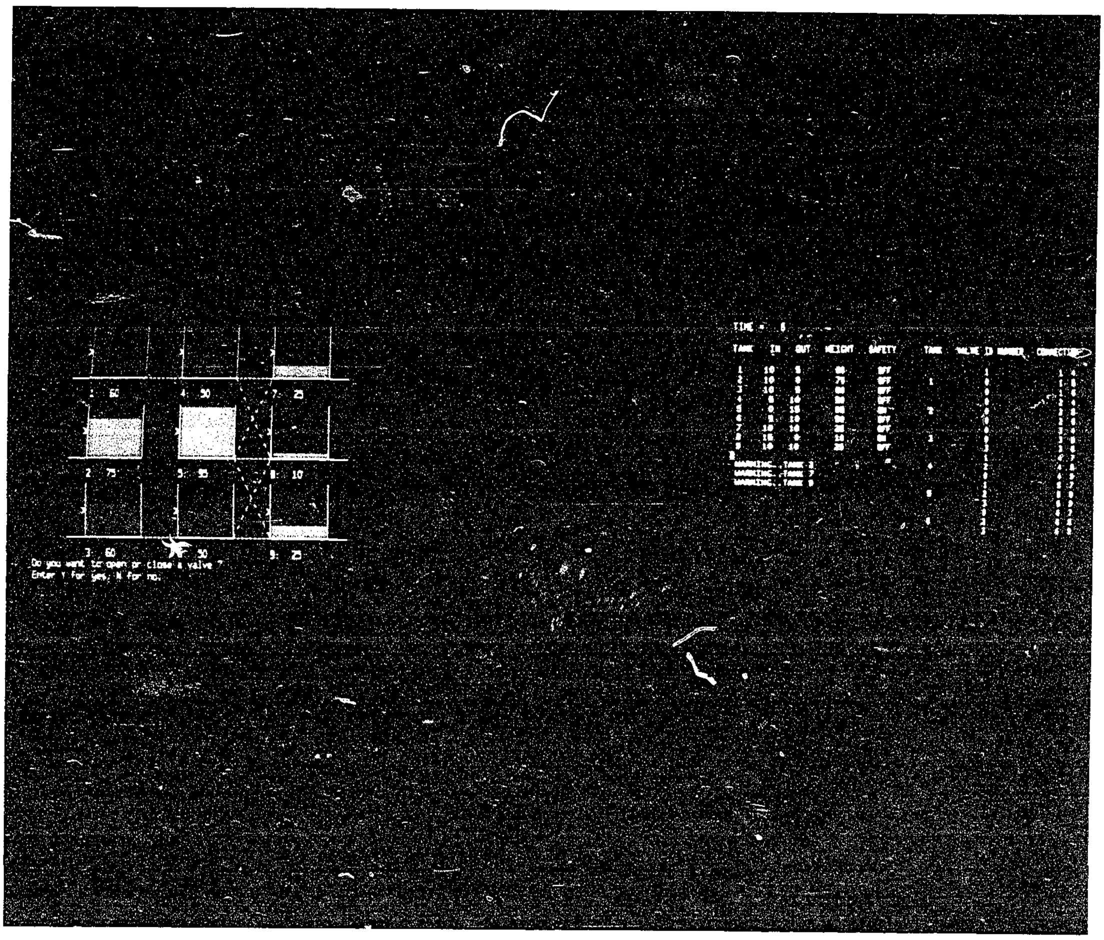


Figure 3. Graphic and Alphanumeric screens.

5, and 6) and exits from three right-most tanks (tanks 7, 8, and 9). Each tank has a pump which forces fluid out of the tanks. The fluid can flow from each of the tanks in the two left columns through up to three valves connected to the three tanks in the neighboring column. An operator can open or close any or all of these valves to control the fluid process. Operators cannot open valves between tanks in the same column, can open only one valve between any two tanks, and can open only valves between 2 tanks in columns immediately next to each other. The objectives are to keep fluid levels in each tank between the range of 0-99 and as close as possible to an optimum level of 50.

At the beginning of each production run, the fluid level in each tank is set at 50, and all horizontal valves are open. Total system input and output, as well as the flow rate for connections, are set by the experimenter when the production run is initialized. Input to the system (set at 30 for this experiment) is evenly divided among the first three tanks (1, 2, and 3). Total output (set at 30 for this experiment) flows from the last three tanks (7, 8, and 9). The flow rate (set at 5 for this experiment) is the amount of fluid that flows out of each open valve to the next tank as the system is updated at the completion of each iteration An iteration (described below) is one complete cycle in which the operator adjusts valves and diagnoses failures.

During production runs in which failures are present, the experimenter sets the type and percentage of randomly occurring system failures (either valve, pump, or simultaneous pump and valve). Each of these failures was set at 7%. For the purpose of this experiment, system parameters were set so that approximately 7% of the iterations contained valve failures, 7% contained pump failures, and 7% contained both types of failures. Thus, a total of six failures, two of each type, occurred during each production run. For each of the failures there was a difference between the actual and expected tank heights. If the operator suspects a failure, the pump or valve can be checked (system check). If there is no failure in that pump or valve, the system informs the operator that no failure was detected. The operator can continue to check for failures or end the iteration and update the system. If the operator finds a failure, the "repair team" is automatically sent out to the valve or pump. There is one repair team available. The operator continues to control the process, but the repair team is unavailable until the pump or valve is repaired. Pump "repairs" require three iterations, while valve "repairs" require two iterations.

An automatic safety system assumes control if the fluid in any tank equals or exceeds a height of 90 or equals or drops below a height of 10. Valves into a critical tank are either opened or closed by the system in order to correct the deviation. During a safety system takeover, if the operator tries to open a valve into a critical tank, a message is displayed which indicates that the connection is not valid. The safety system functions to prevent damage to the system and to keep the system under control.

Prompts to the operator are displayed on the bottom of the graphics display. These prompts query operators about whether they wish to open or close a valve, repair a valve, or repair a pump. SARPI is a subject-paced simulation; the system updates the displays after operators have responded to these prompts. The time between successive system updates constitutes one iteration. The experimenter determines the number of iterations (with a maximum of 500) at the beginning of a production run. In this experiment, the number of iterations was set at 30 for each type of production runs (No Failure and Failure).

The graphic display presents the fluid flow process as a nine tank matrix (see Figure 4). Each tank is labelled with a number from 1 to 9. The fluid level in each tank is shown as the colored area within the tank. The height is also represented by a number below the tank. When the fluid is maintained at an acceptable level the fluid in the tank is blue. If the fluid level approaches an unacceptable level (80 and above, or 20 and below), the fluid turns green. If the level enters the critical range (90 and above, or 10 and below), the fluid turns red and the safety systems takes

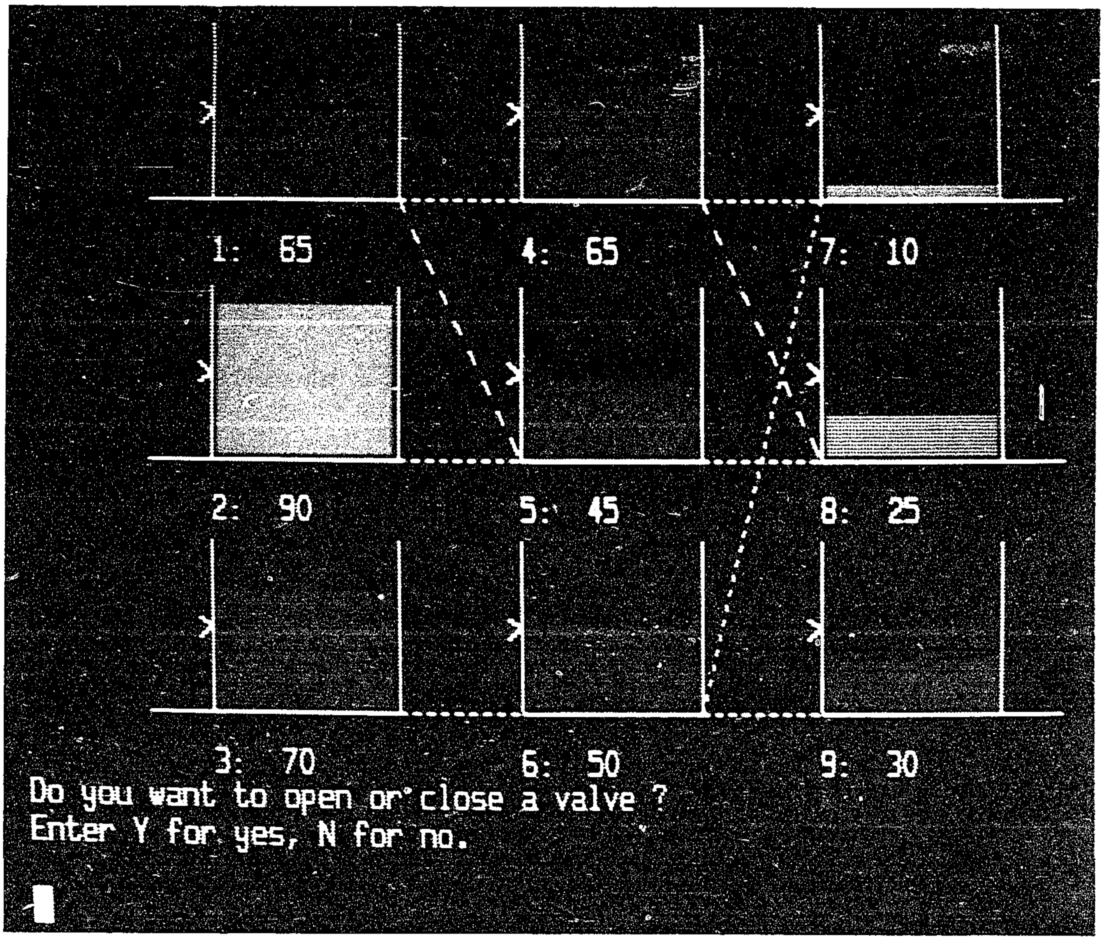


Figure 4. Graphic Screen

over. Open valves between tanks are portrayed as dotted-lines between the tanks. The subject must count the number of connections between tanks to determine the input and output flow rates. If the safety system assumes control over a tank, the connections are automatically adjusted between the tanks to show the corrections the system has made.

The alphanumeric display provides basically the same information about the system variables in two tables (see Figure 5). A "time" value is displayed on the upper left side of the monitor. This indicates the number of times the system has been updated, or the number of iterations completed. The table on the left of the monitor lists each tank's number, its input and output flow, fluid height, and safety system status. The table on the right of the monitor also displays each tank number, its three possible connections, and each connections' corresponding valve identification number. A valve identification number equal to "0" signifies that the valve is closed. An identification number of "1" indicates an open connection between that tank and the first tank in the next column. A "2" indicates an open connection between that tank and the second tank in the next column, and a "3" indicates a connection with the third tank in the next column. When the height in a tank approaches an unacceptable level (80 and above, or 20 and below) a warning is displayed below the

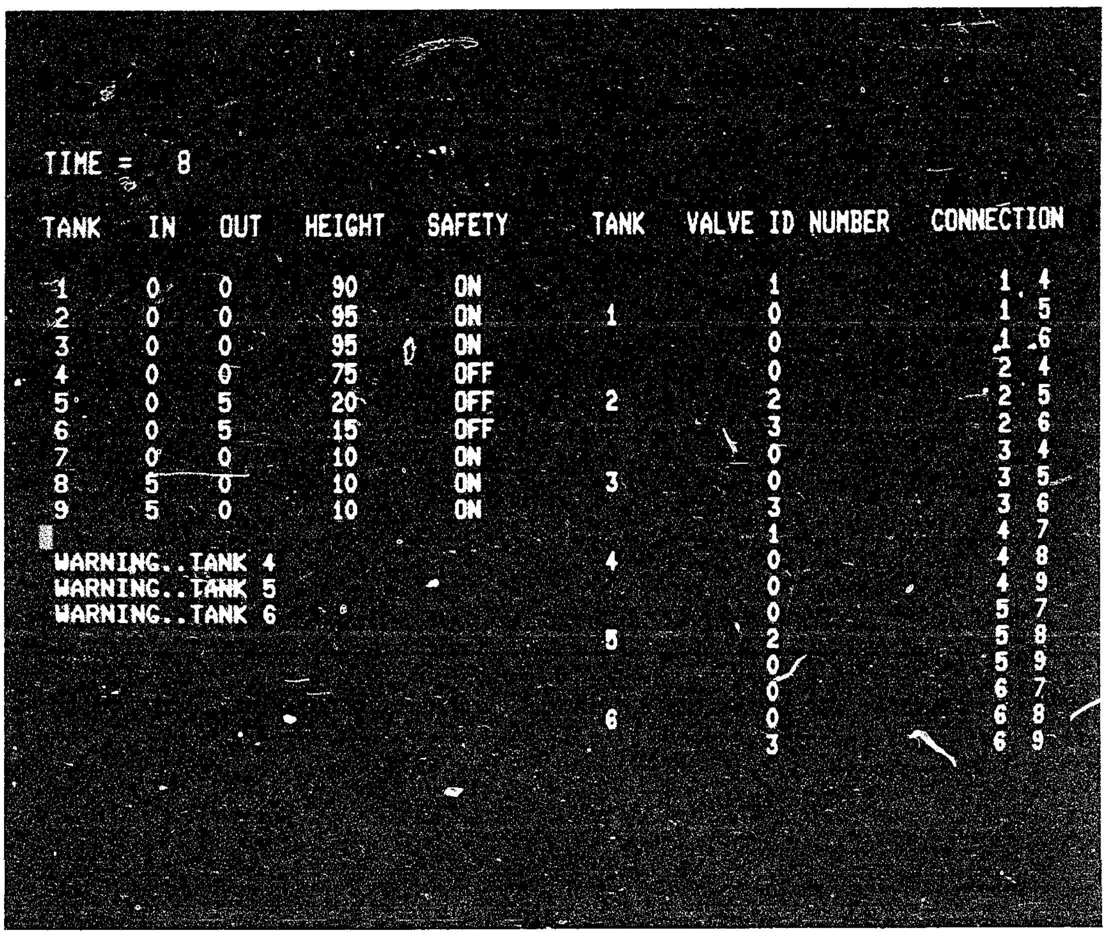


Figure 5. Alphanumeric screen.

left table. If the tank height becomes critical (90 and above, or 10 and below) the safety system shows an 'on' status for that tank.

Subjects are required to operate SARPI so as to optimize system performance and to diagnose system failures (Coury & Pietras, 1986). In order to optimize system performance the operator must be capable of controlling the fluid movement when no failures are present. This requires maintaining the height of the fluid in each tank in the desired range, close to the 50 setpoint, while meeting overall flow requirements. The operator can optimize system performance by determining the set of connections between tanks necessary for maintaining optimum fluid heights in each tank.

To diagnose system failures, the operator must determine that a fault exists, then correctly locate the fault. When the correct location of a valve or pump failure is identified, the system automatically sends out the repair team to correct the problem. Since failures disrupt the flow of fluid, operators must accommodate the disruption in fluid flow by adjusting connections between tanks. As a result, optimizing system performance becomes secondary to minimizing the adverse effects of failures. In this situation, the displayed status of specific components becomes the most relevant source of information (Coury & Pietras, 1986).

Procedure

Permission for this study was obtained through the Human Subjects Committee at Old Dominion University. The experimental procedure met all of the requirements of the American Psychological Association (APA) ethical guidelines for the use of human subjects (APA, 1988). Subjects were informed of their rights as participants and asked to sign a human subjects consent form.

After the subjects were greeted, they each were presented with an overview of the experiment, then required to read a set of written instructions describing the task. There was a separate set of instructions for the primary operator (Appendix A) and for the support operator (Appendix B). Following this, five practice iterations of the simulation were run as the experimenter answered questions and pointed out important features of the system. Both the graphic and the alphanumeric displays were used during the demonstration run. Subjects were instructed to maintain tank levels as close as possible to the preset 50-unit level while monitoring the system for the occurrence of failures. Problem-solving and decision-making were shared by both operators. The teams determined actions to be taken via computer-mediated communication, and then the primary operator informed the system of their decisions. After the practice session, subjects filled out a demographic data questionnaire (Appendix C).

Subjects completed one 30-iteration session with no failures present and one 30-iteration session with failures present. The presentation order of these conditions was counterbalanced. Testing time averaged about 3 hours for each team of subjects.

Dependent Measures

Three sets of dependent measures were used to measure system performance and two sets were used to measure communication in the system.

System Performance

Three categories of dependent measures were chosen to reflect the performance of the teams on the simulation: process control, failure detection, and information utilization strategies.

Process Control. Operators were instructed to control the system by maintaining tank heights as close to 50 units as possible. This performance was measured by the mean deviation ($d = \Sigma \mid x - \mu \mid$) from the tank setpoint height of 50 for the 9 tanks averaged over the 30 iterations. This measure was computed for the session of 30 iterations without failures and for the session of 30 iterations with failures. Other dependent measures of process control were the number of system warnings and safety system takeovers that occurred during the No Failure condition and during the Failure condition.

Failure Detection. Measures of failure detection were assessed during the 30 iterations of the failure session. Failure detection was measured by sensitivity to the signal (d'), response criterion (β), the percent of failures detected, the average number of iterations between the occurrence of a failure and its detection by the operator, and the number of times an operator checked the operation of a pump or valve.

Information Utilization. Utilization of information measures how well the operators used the information presented on the screens (Coury and Pietras, 1986). This measure was assessed only during the 30 iterations of the session where failures were present. Information utilization (IU) is computed as the ratio of the number of connections made between tanks in relation to the number of system checks. The number of tank connections reflects the ability of the operator to control the system. The ratio indicates the number of connections made before checking the status of a component. Large IU ratio operators are characterized as effective information users. These operators do not query the system about the status of the various subsystems, do not send out the repair team unless a failure is detected, and make a relatively large number of fluid flow connections. They effectively use the displayed information to control the system and to diagnose system failures.

Communication

Two dependent measures were chosen to analyze the communication that occurred during the simulation: **communication efficiency** and **communication distribution**.

Communication Efficiency. The efficiency of communication was estimated with the following measures: the number of remarks of the primary operator, the number of remarks of the support operator, and the number of remarks combined. The greater the number of comments, the more the operators communicated.

Communication Distribution. Communication distribution is related to the social equalization measures of communication defined by Siegal et al. (1986). It is a measure of how communication is partitioned between the operators of the team. This measure is determined as the ratio between the number of communication remarks for the primary operator and the support operator. Equal distribution of communication is equal to one. A distribution higher than one is indicative of more communication on the part of the primary operator, and a distribution less than one indicates that the support operator communicated more.

CHAPTER THREE

Results

All analyses were computed using SPSS PC+ and SAS for Personal Computers. As noted above, the total number of teams was 25. The data from the No Failure condition of one BOTH team were lost due to a computer error.

System Performance

Process Control.

A 5 X 6 X 2 multivariate analysis of variance (MANOVA) was performed with three dependent measures of process control: mean deviation from the setpoint of 50, number of system warnings, and number of system takeovers. The variables were measured for the No Failure condition and for the Failure condition. The grouping factors were team Display Type (BOGR, BOAL, BOTH, GRAL, ALGR), Blocks of Iterations (in groups of 5: Block 1, Block 2, Block 3, Block 4, Block 5, Block 6), and the levels of the Failure condition (No Failure, Failure). Blocks of Iterations and Failure conditions were both within-subjects factors. Display Type was a between-subject variable (Winer, 1971). A summary of these data collapsed across Blocks of Iterations is presented in Table 1.

There was a significant multivariate effect for Blocks of Iterations (F (15,271) = 9.32, $p < .05$), by the Wilks' Lamda Criterion. The examination of the univariate F tests showed the Blocks of Iterations effect to be significant for

Table 1

Fluid Deviation Means for Process Control

Display Type	Mean Deviation		System Warnings		System Takeovers	
	No Failures	Failures	No Failures	Failures	No Failures	Failures
BOGR	11.6	20.8	9.4	22.0	5.2	12.8
BOAL	9.7	22.5	6.4	22.8	0.6	23.0
BOTH	11.4	21.1	9.7	20.2	3.0	23.0
ALGR	8.7	19.3	4.0	18.8	1.2	9.8
GRAL	11.0	19.4	8.8	19.0	3.2	11.8
Means	10.42	20.53	7.58	20.56	2.62	16.08
Standard Deviations	5.04	4.90	8.08	6.48	4.98	12.80

the mean deviations ($F(5,100) = 35.08$, $p < .05$) and system takeovers ($F(5,100) = 8.17$, $p < .05$). The MANOVA showed that the main effect for Failure was also significant ($F(3,17) = 51.42$, $p < .05$). All three of the dependent variables contributed significantly to this effect ($F(1,19) = 154.19$ (mean deviations), 113.40 (system warnings), 38.97 (system takeovers). The multivariate effect for Display Type was not significant ($p > .05$).

Among the two-way interactions, Failure by Blocks was significant ($F(15,257) = 4.62$, $p < .05$). The univariate tests showed that both mean deviation ($F(5,95) = 12.99$, $p < .05$) and system takeovers ($F(5,95) = 6.02$, $p < .05$) contributed to this effect. The interactions of Display Type by Failure, Display Type by Blocks, and the three-way interaction of Display by Failure by Blocks were not significant ($p > .05$).

The mean deviation data for the effects of Blocks of Iterations and Failure conditions are presented in Figure 6. In the graph, the data are averaged across Display Type. The Newman Keuls multiple comparisons procedure was computed on the significant main effect of Blocks of Iterations for the dependent variable of mean deviation. These means are presented in the last column of Table 2. With respect to the Blocks of Iterations, the first block of iterations (Block 1) was found to be significantly different from the last four blocks (Block 3, Block 4, Block 5, Block 6) ($p <$

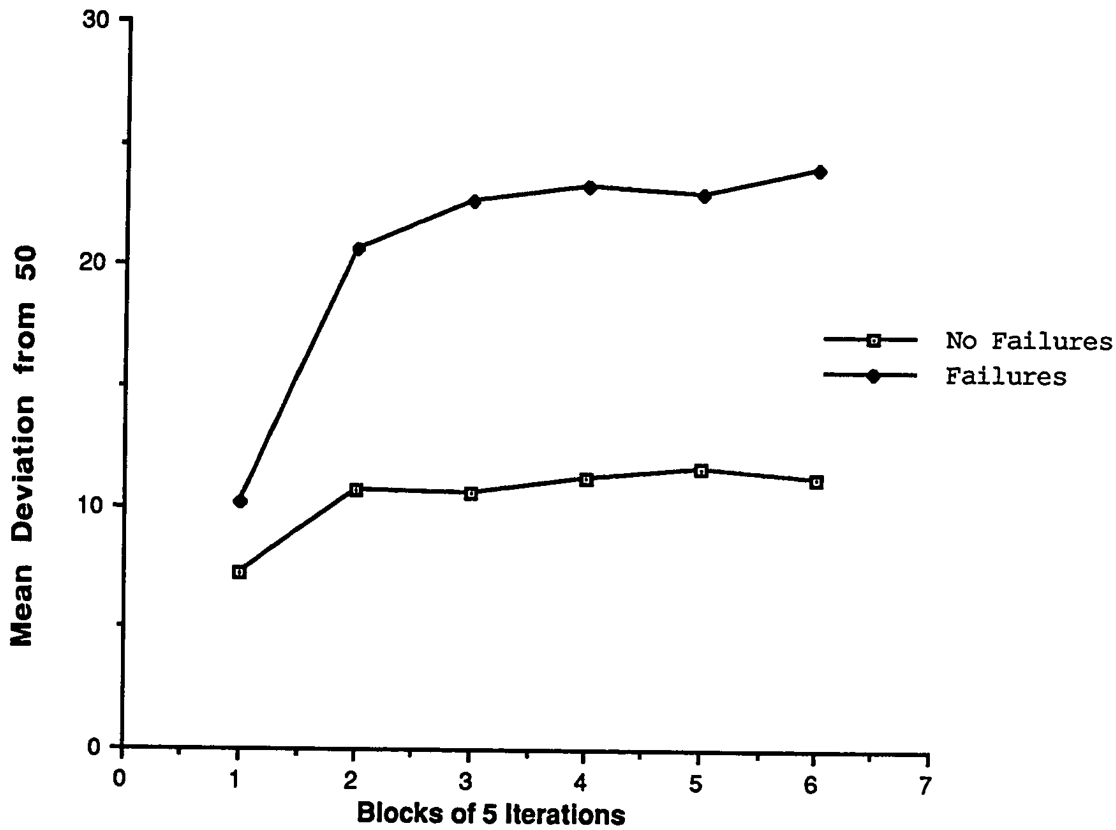


Figure 6. Mean Fluid Deviation from Setpoint: All Teams Combined

Table 2

Fluid Deviation Means For Blocks of Five Iterations

Condition		No Failure	Failure	Means
BLOCKS	1	7.24	10.17 * (F2, F3, F4, F5, F6)	8.73 (BL2, BL3, BL4, BL5, BL6)
	2	10.73	20.68 (F5, F6)	15.80 (BL4, BL5, BL6)
	3	10.55	22.67	16.73
	4	11.20	23.27	17.36
	5	11.63	23.00	17.43
	6	11.24	24.03	17.64

*Alphanumerics indicate the blocks from which the current block is significantly different ($p < .05$)

.05), and Block 2 was significantly different from Blocks 4, 5, and 6. This indicates that the process was more difficult to control in the last three blocks as compared to the first two blocks. Teams stabilized performance at 16-17 deviation units from the optimal setpoint.

The interaction of Blocks of Iterations by Failure was broken down for the mean deviations using the Newman Keuls procedure. These means are presented in the first two columns of Table 2. None of the blocks of iterations in the No Failure condition differed significantly. In the Failure condition, the last five blocks of iterations were significantly higher than the first block of iterations, and the last two blocks of iterations were significantly higher than the first two blocks of iterations. This indicates a significant decrease in the ability of the team to control the fluid deviation over the last 20 iterations.

The Newman Keuls procedure also was computed on the dependent variable of system takeovers for the Blocks of Iterations effect and the interaction of Blocks of Iterations by Failure condition. These data were collapsed across Display Type and are presented in Figure 7. The means for the effects of Blocks are presented in the last column of Table 3. The numbers of system takeovers in Block 1 were significantly lower than those in Block 2, Block 3, Block 4, Block 5, Block 6. The means for Blocks by Failure conditions are presented in the first two columns of Table

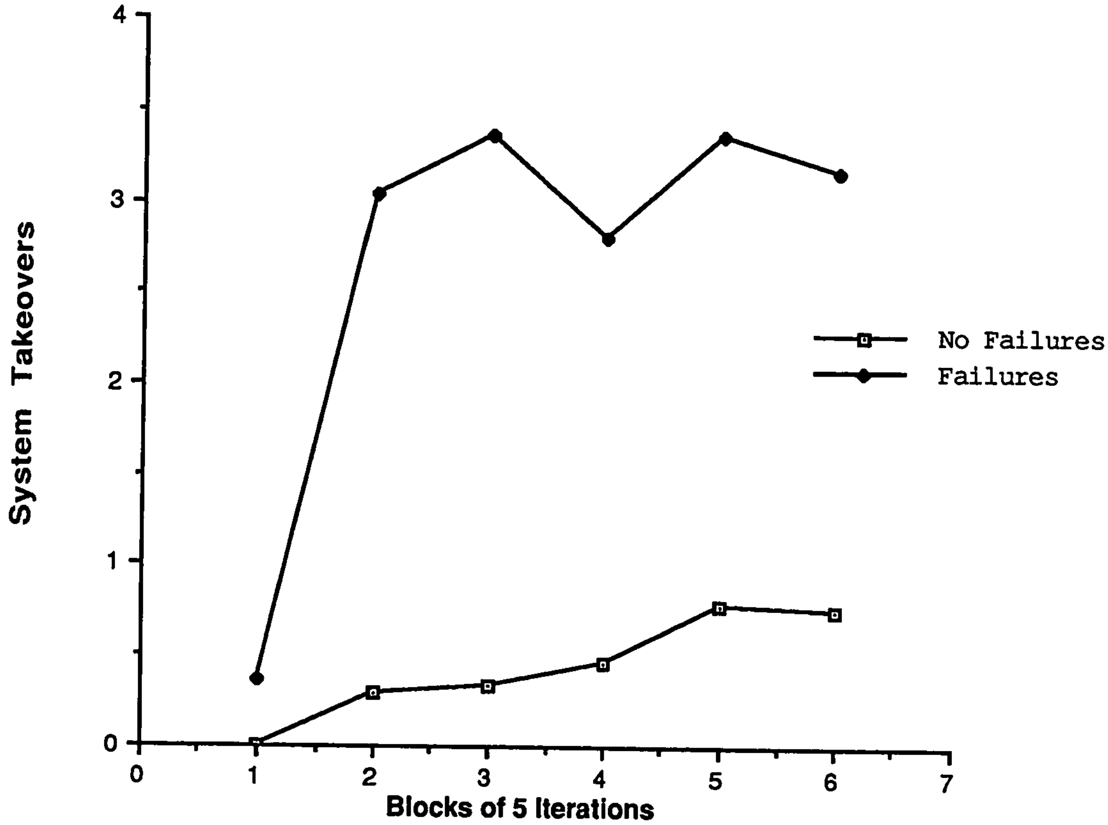


Figure 7. System Takeovers: All Teams

Table 3

System Takeover Means For Blocks of Five Iterations

Condition		No Failure	Failure	Means
BLOCKS	1	0.00	0.36 * (F2, F3, F4, F5, F6)	0.18 (BL2, BL3, BL4, BL5, BL6)
	2	0.29	3.04	1.66
	3	0.33	3.36	1.84
	4	0.46	2.80	1.63
	5	0.79	3.36	2.07
	6	0.75	3.16	1.95

*Alphanumerics indicate the blocks from which the current block is significantly different ($p < .05$)

3. There was no significant difference between the number of system takeovers during the No Failure condition. During the Failure condition, the numbers of system takeovers in the last five blocks of iterations were significantly higher than those in the first block of iterations.

Failure Detection. Two analyses were performed on the failure detection data using measures from the theory of signal detectability (TSD). TSD analyses (Tanner & Swets, 1954) are applicable when there are two discrete states that cannot be easily discriminated (Wickens, 1984). The theory was applied in the present study to the subjects' task of monitoring for failures. The frequency of "hits" was computed as the number of times the teams detected a failure. "Misses" were recorded as the number of failures which went undetected by the team. "False alarms" were recorded as the number of times the teams checked the system when no failures actually existed. "Correct rejections" were recorded as the number of times the teams did not check the system when no failures existed. The response outcome probabilities for each of the display types are shown in Tables 4 through 8.

TSD enables a separate estimate of subjects' sensitivity to the signal (d') and their response criterion (β). The estimate of d' is independent of signal probability, as well

Table 4

Stimulus Response Matrix for BOGR Display Type

State of the System

RESPONSE	Failures Present		No Failures Present	
	HIT		FALSE ALARM	
YES	TEAM			TEAM
	1	.50	.35	1
	2	.62	.74	2
	3	.50	.62	3
	4	.38	.86	4
	5	.75	.25	5
	MISS		Correct Rejection	
NO	TEAM			TEAM
	1	.50	.65	1
	2	.38	.26	2
	3	.50	.38	3
	4	.62	.14	4
	5	.25	.75	5

TEAM	d'	β
1	0.40	1.07
2	-0.30	1.16
3	-0.30	1.05
4	-1.40	1.69
5	1.35	1.00

Table 5

Stimulus Response Matrix for BOAL Display Type

State of the System

RESPONSE	TEAM	Failures Present	No Failures Present
YES		HIT	FALSE ALARM
	1	.38	.36
	2	.50	.36
	3	.38	.21
	4	.25	.58
	5	.43	.39
NO		MISS	Correct Rejection
	1	.62	.64
	2	.50	.64
	3	.62	.79
	4	.75	.42
	5	.57	.61

TEAM	d'	β
1	0.05	1.02
2	0.40	1.07
3	0.50	1.33
4	-0.90	0.82
5	0.10	1.02

Table 6

Stimulus Response Matrix for ALGR Display Type

State of the System

RESPONSE	Failures Present		No Failures Present	
	HIT		FALSE ALARM	
YES	TEAM			TEAM
	1	.38	.62	1
	2	.25	.00	2
	3	.50	.07	3
	4	.50	.00	4
	5	.62	.17	5
	MISS		Correct Rejection	
NO	TEAM			TEAM
	1	.62	.38	1
	2	.75	1.00	2
	3	.50	.93	3
	4	.50	1.00	4
	5	.38	.83	5

TEAM	d'	β
1	-0.65	1.00
2	3.25	>10.00*
3	1.50	2.97
4	3.95	>10.00*
5	1.30	1.53

*These were capped off at 10.00

Table 7

Stimulus Response Matrix for GRAL Display Type

State of the System

RESPONSE	TEAM	Failures Present	No Failures Present
YES		HIT	FALSE ALARM
	1	.62	.55
	2	.50	.19
	3	.50	.66
	4	.50	.63
	5	.38	.78
NO		MISS	Correct Rejection
	1	.38	.45
	2	.50	.81
	3	.50	.34
	4	.50	.37
	5	.62	.22

TEAM	d'	β
1	0.20	0.96
2	0.90	1.47
3	-0.40	1.10
4	-0.30	1.05
5	-1.10	1.28

Table 8

Stimulus Response Matrix for BOTH Display Type

State of the System

RESPONSE	TEAM	Failures Present	No Failures Present
YES		HIT	FALSE ALARM
	1	.75	.44
	2	.50	.44
	3	.57	.63
	4	.50	.42
	5	.60	.84
NO		MISS	Correct Rejection
	1	.25	.56
	2	.50	.56
	3	.43	.37
	4	.50	.58
	5	.40	.16

TEAM	d'	β
1	-0.85	0.81
2	0.20	1.02
3	-0.15	1.03
4	0.25	1.02
5	-0.95	1.61

as response bias and costs of correct answers (Elliot, 1964). It enables the researcher to compare sensitivities and, therefore, to evaluate the quality of performance among conditions (Wickens, 1984). Both the d′ and β were computed using a program written in BASIC (Coates, 1988) which computed each of these values. These are also displayed in Tables 4-9. A one-way ANOVA was computed on these data with Display Type as the grouping factor. The difference among the groups for d′ was significant ($F(4,20) = 3.26$, $p < .05$. The Newman Keuls procedure showed a significant difference between the d′ means for the ALGR teams (1.87) and each of the other teams (GRAL, -.14, BOGR, -.05, BOAL, .03, and BOTH .04).

The response criterion value used by the observer is known as β. It is computed from the ratio of the ordinate for the probability of hits to the ordinate for the probability of false alarms. These are also reported in Tables 4-8. In order to determine whether the operators adjusted β as a function of Display Type, the β values were submitted to a one-way ANOVA with Display Type as the grouping factor. This ANOVA was not significant at the .05 level.

A single factor MANOVA was computed with Display Type as the grouping factor and the following failure detection variables: the percentage of failures detected, the number of iterations between the occurrence of a failure and its detection, and the average number of times the team checked the system for failures. The multivariate test revealed no significant effect ($p > .05$). The means for these data are presented in Table 9.

As can be seen in Table 9, the teams with two alphanumeric screens (BOAL) detected the lowest percentage of failures (38.6). ALGR teams required fewer iterations to detect a failure. ALGR also had the fewest system checks; BOTH and GRAL had the most.

Information Utilization (IU). A one-way Analysis of Variance (ANOVA) was computed on the IU ratio (Number of Tank Connections/Number of System Checks) with Display Type as the grouping factor (BOGR, BOAL, ALGR, GRAL, BOTH). This analysis yielded a significant difference across the groups on IU, $F(4,20) = 3.24$, $p < .05$. The means for the groups are displayed in Table 9. Recall that the larger this ratio, the better the team used the information displayed. The Newman Keuls test revealed a significantly higher mean for the ALGR team (5.3) and the mean for each of the other teams ($p < .05$).

<u>**Communication**</u>

Communication Efficiency. A two-factor repeated-measures MANOVA was computed for measures of communication efficiency with Display Type (BOGR, BOAL, ALGR, GRAL, BOTH) and Failure

Table 9

Means for Failure Detection, Information Utilization, and Errors

Display Type	Percentage of Failures Detected	Number of Iterations to Detect	Number of System Checks	Number of Tank Connections	Information Utilization (IU)
BOGR	55.0	4.3	13.8	27.6	2.3
BOAL	38.6	5.6	11.8	22.6	2.1
BOTH	56.4	4.7	19.6	30.2	1.7
ALGR	45.0	3.6	7.6	27.0	5.3 *
GRAL	50.0	5.3	19.6	26.0	2.1

*Mean is significantly different from all other means ($p < .05$)

condition (No Failure, Failure) as the grouping factors. The dependent variables were the number of remarks communicated by the primary operator and the number of remarks communicated by the support operator. There was a significant multivariate effect for Failure condition ($F(2,19) = 6.38$, $p < .05$) by the Wilks' Lamda Criterion, with both of the dependent variables contributing significantly to a drop in communication during the Failure condition ($p < .05$). The multivariate effect for Display was not significant ($p > .05$), nor was the Display by Failure interaction effect ($p > .05$). The means for communication efficiency are presented in Table 10.

Communication Distribution. Another two-factor repeated-measures MANOVA was computed for measures of communication distribution. The dependent variable was the ratio of the number of remarks communicated by the primary and the support operators. The larger the deviation of this ratio from 1, the more unequitable the distribution is. None of the multivariate effects were significant: Display ($p > .05$), Failure ($p > .05$), Display by Failure interaction effect ($p > .05$).

The means for communication distribution are presented in Table 10. The table illustrates a close distribution between the No Failure (.7757) and the Failure condition (.6429). The decimal numbers indicate that in every case,

Table 10

Means for Communication Efficiency and Distribution

Display Type	Efficiency		Distribution	
	NO FAILURES	FAILURES	NO FAILURES	FAILURES
BOGR	113.0	92.4	.59	.54
BOAL	109.0	79.0	.80	.88
BOTH	141.0	90.8	.76	.54
ALGR	168.0	84.2	.79	.65
GRAL	147.4	68.6	.91	.59
Means	135.84	83.00	.776	.643
Standard Deviations	66.88	37.05	.449	.545

the support operator communicated more than the primary operator.

Relationship of Communication to Measures of Process Control, Failure Detection and IU.

Correlations were computed in order to determine whether the measures of communication were related to process control, failure detection, or IU. These correlations are presented in Table 11. For the failure conditions combined, three measures of communication efficiency (number of remarks communicated by the primary operator, the number of remarks communicated by the support operator, and the total number of remarks) and one measure of communication distribution were correlated with the three measures of process control (mean deviation, system warnings, and system takeovers).

As displayed in Table 11 the total number of remarks was correlated negatively with mean deviation (-.44). The smaller the mean deviation, the greater the number of remarks exchanged between the support and the primary operator. The total number of remarks was correlated negatively with system warnings (-.29) and system takeovers (-.44). Communication distribution was not correlated significantly with any of the process control measures.

Correlations were also computed in order to examine the relationship between the measures of failure detection

Table 11

Relationship Between Communication and System Performance

Process Control	Efficiency Primary	Efficiency Support	Efficiency Both	Distribution Ratio of Primary/Support
Deviations	-.46*	-.43*	-.44*	-.08
Warnings	-.30	-.41*	-.29*	.03
Takeovers	-.38*	-.45*	-.44*	-.01
Failure Detection				
d'	.08	.01	.07	.05
β	-.15	-.28	-.27	.06
% Detect	-.21	.07	-.16	-.21
Iterations	-.01	-.12	-.08	.04
Checks	-.09	-.20	-.18	-.01
Information Utilization				
IU	.16	.16	.20	.07

*p<.05

(percent of failures detected, average number of iterations to detection, average number of checks, d′, and β) and the indices of communication efficiency and communication distribution. As Table 11 displays, none of the failure measures were correlated significantly with the measures of communication, and the measures of IU were not related significantly to the communication measures.

CHAPTER FOUR

Discussion

The results of this study suggest that the problems encountered by operators of complex systems are not automatically solved by the use of teams. Individuals monitoring complex systems might miss or ignore failures, but the teams in the present research were subject to these errors also.

In order to compare the performance of the teams in the present study to the performance of individuals, the data from this study were compared to those reported in Coury and Pietras (1986). The process control data of the two studies are presented in Table 12. As the table illustrates, the overall mean deviation for the teams in the current research (15.5) is larger than the mean deviation obtained from individual operators (10.6) by Coury and Pietras (1986). The exception to this was Coury's Graphic display group, with a mean deviation during the Failure condition of 20.3. This was higher than the ALGR and GRAL teams in the current study. It is interesting to note that both studies resulted in an approximately 10-point difference between the means in No Failure condition and the means in the Failure condition.

The comparisons of the blocked data from the two studies are presented in Table 13. Consistent with the

Table 12

Comparison of Fluid Deviation with Coury and Pietras (1986)

	CONDITION	NO FAILURES	FAILURES	MEANS
DISPLAY TYPE	BOGR	11.6	20.8	16.2
	BOAL	9.7	22.5	16.1
	BOTH	11.4	21.1	16.0
	ALGR	8.7	19.3	14.0
	GRAL	11.0	19.4	15.2
	MEANS	10.5	20.6	15.5
		Coury and Pietras (1986)		
	BOTH	2.0	9.9	6.0
	NUMERIC	5.9	16.9	11.5
	GRAPHIC	8.4	20.3	14.3
	MEANS	5.5	15.7	10.6

Table 13

Comparison of Fluid Deviation with Coury and Pietras (1986) by blocks

Condition		No Failure		Failure	
			Coury et al.		Coury et al.
B	1	7.24	4.5	10.17	6.7
L	2	10.73	5.8	20.68	13.5
O	3	10.55	5.8	22.67	16.0
C	4	11.20	5.6	23.27	17.2
K	5	11.63	5.4	23.00	19.0
S	6	11.24	5.6	24.03	21.0

results of the current study, Coury and Pietras (1986) found an increase in mean deviation during the Failure condition across blocks of iterations. In their No Failure condition, the mean deviation stabilized around 4-6 units from the setpoint of 50; in the current study, the mean deviation stabilized around 10-12 units from the setpoint of 50. This might indicate that the teams either had a more difficult time stabilizing the system, or merely selected a higher criterion for stabilizing the system. Coury and Pietras (1986) also found a significant Failure by Blocks of Iterations interaction.

The failure detection data are compared to the individual operator data of Coury and Pietras (1986) in Table 14. The teams did not detect as many failures (49.00) as the individuals (58.03) and took more iterations (4.7) to detect them than did the individual operators (3.2). However, the teams did not check the system (14.48) nearly as much as the individual operators did (23.00). On the other hand, the overall mean for IU was lower for the team data than for the individual operators. The exception to this was the ALGR team. They had a higher mean IU than both Coury and Pietras' Graphic groups and Alphanumeric groups.

These comparisons indicate that the subjects in the present study were not as effective in optimizing the process. Also, the teams detected fewer failures, required more iterations to detect them, and made fewer tank

Table 14

Comparison of Failure Detection Data and Information Utilization Ratio to Coury and Pietras (1986)

Display Type	Percentage of Failures Detected	Number of Iterations to Detect	Number of System Checks	Number of Tank Connections	Information Utilization (IU)
BOGR	55.0	4.3	13.8	27.6	2.3
BOAL	38.6	5.6	11.8	22.6	2.1
BOTH	56.4	4.7	19.6	30.2	1.7
ALGR	45.0	3.6	7.6	27.0	5.3
GRAL	50.0	5.3	19.6	26.0	2.1
Means	49.00	4.70	14.48	26.68	2.70
	Coury and Pietras (1986)				
BOTH	54.5	2.4	26.0	47.0	6.7
NUMERIC	58.2	3.0	20.0	42.0	3.0
GRAPHIC	61.4	4.2	23.0	43.0	2.6
Means	58.03	3.20	23.00	44.00	4.10

connections. On the other hand, the teams did not make as many system checks as Coury and Pietras' (1986) individuals. Unnecessary systems checks can be avoided if operators can detect failures from information displayed on the screen. Although, on the whole, the teams did not utilize information as effectively as the individuals, the ALGR team was an exception.

The differences between this study and Coury and Pietras (1986) should be considered from several aspects. First of all, population differences must be regarded. Coury and Pietras (1986) employed industrial engineering college students. The current study used subjects from the general population serving in a military installation.

Secondly, the communication and coordination efforts of the teams in this study contributed to higher workloads. In a study of pilot workload, Hart and associates (Hart, Hauser, & Lester, 1984) found that communication contributed to a significant proportion of the rating of workload. Also, the nature of the communication medium in the current study might have increased the subjects' workloads. Beith (1987) compared the subjective workload demands of individuals performing a complex cognitive task with another person under varying conditions of time stress and team communication. Under conditions of free communication, team workload levels remained stable, even under time stress. However, under restricted communication, workload increased almost 50%. Hart et al. (1984) decided that communication might serve as an objective indicator of the level of pilot workload. The present study can actually be described in terms of a dual task scenario. The subjects were performing the primary task of controlling the system and secondary tasks of communication and coordination activities.

The differences between the teams in this study and individuals in Coury and Pietras (1986) could have been due to actual differences in the performance of teams versus individuals. Team performance could be less effective in this dynamic situation. This might be due to teams having more difficultly in coordinating activities in order to stabilize the system. Some team members concentrated on trying to help their teammate rather than optimizing system performance. One subject responded that, because his partner did not understand the system very well, he spent a lot of time communicating help rather than controlling the system. At certain times the communication took precedence over the control of the system.

Finally, perhaps the lower team performance may be explained by a tendency for teams to select different criteria for reporting failures and optimizing performance than individuals. This might be due to a psychological diffusion of responsibility when there is more than one controller (Foushee, 1982). One team member might assume that the other one is attending to certain functions of the process.

The current research was based on the premise that dynamic allocation of problem-solving responsibilities between human operators would be more effective than individual operators. The research showed that the performance of these teams may only be as effective as their communication. It appears that the amount of communication that the teams exchanged was related to the optimization of fluid flow. Communication or interaction processes among members of a group might serve to prevent errors that occur in individual performance (Fousee, 1982; Hackman & Morris, 1975). In fact, in flight crews it has been observed that there is a tendency for poorer performing crews to communicate less (Foushee & Manos, 1981).

In the current study the amount of communication was not related to failure detection. In fact there was a significant drop in the amount of communication when failures were present. One subject in this study commented that the communication was effective for the No Failure condition but was ineffective for the Failure condition. The workload of communication may have been too much to handle when the additional workload of failures was added to the task.

The way in which teams share their own unique contributions of information is a critical factor in performance (Hackman & Morris, 1975). Members may either hold back information or contribute freely on cue from the other team member. Performance is best when information is offered (Lanzetta & Roby, 1960). Communication measures have been shown to predict group performance better than measures such as individual knowledge or skill (Lanzetta & Roby, 1960). It may not be only the amount of communication, but the manner in which the resources are utilized that contributes to optimal performance.

The presence of failures significantly degraded the performance of the teams in controlling the flow process. This was true for the all the measures of process control: the optimization of flow around the setpoint, the number of system warnings, and the number of takeovers that the teams incurred. The Failure condition placed additional workload on the teams. This also indicates that the process control measures were in fact, sensitive enough to pick up differences in the performance of the teams if appreciable differences had occurred.

The ability of the teams to optimize flow decreased as a function of time. The process was more difficult for the teams to control as the number of iterations progressed. Increases in iterations usually mean more valve connections and more flow through the system. In the Failure condition, unless failures were recognized immediately, this decrease might also result from failures disrupting the system.

While optimization performance did stabilize, it remained at a relatively large deviation from the setpoint. This appears to be a function of the increase in failures in the system, since performance remained fairly stable when failures were absent.

Although there was no difference among the teams on the three measures of failure detection, their sensitivities did vary as a function of Display Type. Detectability was the strongest for teams where the primary operator had the Alphanumeric representation and the support operator had the Graphic representation (ALGR). There was no difference in the response criterion, or the willingness to report a failure, by the display types. Since β is sensitive to changes in the probability of a stimulus, and the probability of the stimulus was consistent across teams, it would be expected that β would not change as a function of Display Type. The small values that were obtained for β might also be expected because of the frequency of the failures occurring. The subjects expected many signals. With signals that occur frequently, the observer accepts weak sensations as indications of the signal, therefore increasing the proportions of false alarms.

The way in which the teams utilized the information they were provided did vary as a function of team Display Type. The IU ratio was significantly higher for the ALGR. It would appear from these results that these teams were able to employ the displayed information and the information obtained from each other more efficiently.

The results of this study only partially supported the hypotheses concerning the particular mental model of the teams. While the mental model of the teams did not affect their ability to control the process or to detect failures, it did affect the detectability of the signal for the ALGR team. In studying cooperation, or lack thereof, between human and computers, Rouse (1976) found that not all actions are planned in response to what the other controller is doing. Rouse (1976) termed this "competitive intelligence". Controllers compete with each other to complete the task. Its effects on performance are severe. The military setting of this study might have facilitated competitive intelligence. The subjects were motivated highly throughout the experiment, and every subject displayed enthusiasm to participate in the research. This might have contributed to an ambitious effort rather than a cooperative one between team members. The hypotheses concerning the relationship between the utilization of information and the mental model of the team was partially supported. The mental model of the ALGR team did enable them to utilize the displayed information better. As discussed above, they were also more sensitive to the detection of failures.

In the current study, there was no difference among the team Display Types for communication efficiency or communication distribution. In previous research (Cook, 1987), equality of participation in computer-mediated communication has been shown to be practical for tasks requiring creative solutions, or during brainstorming. This equality in participation might not be functional during task-oriented or dynamic performance such as in the present study. In a dynamic, although subject-paced, system such as SARPI, answers to system questions were needed relatively quickly. A more "unequitable" form of communication, where the primary or the support operator took more control and facilitated the communication process, might have contributed to better results. In complex problem-solving tasks, especially under time constraints, face-to-face communication might be more effective (Cook, 1987). In the present study, when questioned about the effectiveness of the computer communication, most of the respondents felt that it was effective. However, two subjects felt that a more direct form of communication such as word of mouth would have improved performance on the task.

When asked about their support operator, several primary operators in the current study commented that they did not utilize the support operator as much during the Failure condition as during normal operations. Other research has reported (Foushee, 1982) that if a potentially dangerous situation occurs during an aircraft flight, many pilots tend to take over control from co-pilots. In the aircraft, it might actually be best for the captain to resign control to the co-pilot. This would free the resources of the captain to make decisions and delegate responsibility, while the co-pilot carries out the decisions. The configuration of the current study did not allow for the support operator to take control of the system. Only the primary operator could input decisions into the system. In future research it would be interesting to allow the actual control of the system to be dynamic, as well as the problem-solving.

Summary and Conclusions

Removing the human from the operating loop of systems does not always improve overall system reliability. Regardless of the extent of automation, no system can be completely predictable. Taking the human out of the loop only serves to shift human intervention from an active mode to an intermittent one. The knowledge and flexibility of human operators continue to be vital to the success of most systems. However, higher levels of automation create new and distinct problems for human operators. Operators take on more monitoring and supervisory functions, and their interaction is mainly with the computers controlling the system. The human role in systems with higher levels of automation must be supported by an interface design that optimizes human abilities. Future studies of human performance must strive to prepare and assist operators in communicating and interpreting system information, while balancing workload levels. The current study of the use of teams to share problem-solving functions, represents a move in that direction.

In many complex systems it is desirable to include the resources of more than one specialist. The dynamic allocation of functions between human operators may be an effective means to control systems as they grow in complexity. However, to a certain extent, the results of this study have shown degraded performance when teams controlled a dynamic complex system, as compared to individuals in previous research (Coury & Pietras, 1986). While population variables and experimental control might have played a role in these differences, the workload of communication also took its toll. By its nature, computer-mediated and explicit communication add to the workload of the task. Also, team members who used the communication medium to help instruct the other team member might have distracted attention away from the system task. Also, teams might select different, and more stringent, criteria than individuals to report problems. This phenomenon would be especially dangerous in systems with automation. Systems which include automation tend to perpetrate a psychological sense of diffusion of responsibility (Foushee, 1982).

Operators are not as likely to take control when a disaster is eminent, or even to interpret a potentially dangerous situation as a threat. One might expect that this effect would be magnified when teams are a part of the automated system.

Today's complex systems place increased emphasis on the use of teams. More research is needed in order to understand how teams can be used to their greatest potential. This study demonstrated that communication was related to effective control of the system. The way in which teams coordinate and communicate dynamic problem-solving is an important area for future research. The study of the problems and mishaps in complex systems should not neglect the communication and coordination of operators working together.

The knowledge-based behaviors demanded by complex systems require computer interfaces that enhance the operator's mental model of the system. The importance of this model is critical when the operator is required to rely on internal resources to guide performance. Different computer representations of system information affect the operator's model of that system. The design or selection of a particular representation of system information must incorporate the properties of the tasks with the physical format of the display. This study attempted to determine the best configuration for teams working together to control a process. The results are inconclusive.

Much attention has been focused on the individuals in systems, especially in those systems where system performance is contingent on the human operator. Although many aids and improvements for individual operators have been built into systems, human errors are still evident. In many complex systems it might be advantageous to use more than one human operator or decision-maker to share the load. The design of computer interfaces to be used by separate members of a team is an area of investigation which might help to facilitate effective performance between operators. More research is needed in order to understand how to develop optimal coordination and communication between human operators in complex systems. Explicit computer-mediated communication, increases workload, and suffers when task workload increases. However, this communication is related to better control of the system. This study demonstrated that communication is vital to the performance of teams when problem-solving is being shared dynamically.

References

American Psychological Association. (1988). Publication manual of the American Psychological Association. Washington, DC: American Psychological Association.

Bainbridge, L. (1969). The nature of the mental model in process control. In Proceedings of the IEEE International Conference on Man-Machine Systems. Piscataway, NJ: IEEE.

Beith, B.H. (1987). Subjective workload under individual and team performance conditions. In Proceedings of the Human Factors Society 27th Annual Meeting (pp. 67-71). Santa Monica, CA: Human Factors Society.

Brigham, F.R. and Laios, L. (1975). Operator performance in the control of a laboratory process plant. Ergonomics, 18, 53-66.

Boulette, M.D., Coury, B.G., and Bezar, N. A. (1987). Classification of multidimensional data under time constraints: Evaluating digital and configural display representations. In Proceedings of the Human Factors Society 31th Annual Meeting (pp. 116-120). Santa Monica, CA: Human Factors Society.

Carswell, C.M. and Wickens, C.D. (1984). Stimulus integrality in displays of system input-output relationships: A failure detection study. In Proceedings of the Human Factors Society 28th Annual Meeting (pp. 534-537). Santa Monica, CA: Human Factors Society.

Carswell, C.M. and Wickens, C.D. (1987). Information integration and the object display: An interaction of task demands and display superiority. Ergonomics, 30, 511-527.

Casey, E.J. (1986). Visual display representations of multidimensional systems: The effect of information correlation and display integrality. In Proceedings of the Human Factors Society 30th Annual Meeting (pp. 430-434). Santa Monica, CA: Human Factors Society.

Casey, E.J. (1987). Visual display representations of multidimensional systems: The effect of system structures and display integrality. In Proceedings of the Human Factors Society 31st Annual Meeting (pp. 112-115). Santa Monica, CA: Human Factors Society.

Chambers, A.B. and Nagel, D.C. (1985). Pilots of the future: Human or computer? Communications of the ACM, 28, 1187-1199.

Chapanis, A. (1965). On the allocation of functions between men and machines. Occupational Psychology, 39, 1-11.

Chapanis, A., Parrish, R.N., Oschman, R.B., and Weeks, G.D. (1977). Studies in Interactive Communication: II. The effects of four communication modes on the linguistic performance of teams during cooperative problem solving. Human Factors, 19, 101-126.

Chu, Y. and Rouse, W., (1979). Adaptive allocation of decision making responsibility between human and computer in multi-task situations. I.E.E.E. Transactions on Systems, Man and Cybernetics, 12, 769-778.

Coates, G.D. (1988). TSD PLOT [Computer Program]. Norfolk, Virginia: Old Dominion University, Psychology Department.

Cook, K.S. (1987). Social stress, computer-mediated communication systems, and human productivity in space stations: A research agenda. In T.B. Sheridan, D.S. Kruser, and S. Deutsch (Eds.) Human factors in automated and robotic space systems (329-355). Washington, D.C.: National Research Council.

Coury, B.G. and Pietras, C.M. (1986). Alphanumeric and graphic displays for dynamic process monitoring and control. Unpublished manuscript, University of Massachusetts, Amherst, Massachusetts.

Coury, B.G. and Boulette, M.D. (1987). The impact of uncertainty on classification of multidimensional data: A comparison of integral and separable displays (Tech Report #BGC1-1987). University of Massachusetts, Amherst, MA: Human Performance Laboratory.

Coury, B.G., Boulette, M.D., Zubritzky, M.C., and Fisher, D. (1986). Classification of multidimensional data: Evaluating displays to aid identification of system state. In Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics (pp. 1503-1508). Piscataway, NJ: IEEE.

Crossman, E.R.F.W. (1974). Automation and skill. In E. Edwards and F.P. Lees (Eds.) The human operator in process control. London: Taylor and Francis Ltd.

Curtis, B. and Malone, T. (1987-88). Introduction to this special issue on computer-supported cooperative work. Human Computer Interaction, 3, 1-2.

deKleer, J. and Brown, J.S. (1983). Assumptions and ambiguities in mechanistic mental models. In D. Gentner and A.L. Stevens (Eds.) Mental models. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Edwards, E. and Lees, F.P. (1974). The influence of the process characteristics on the role of the human operator in process control. Applied Ergonomics, 5.1, 21-25.

Elliot, P.B. (1964) Appendix - Tables of d'. In J.A. Swets (Ed.) Human observers: Contemporary readings. New York: John Wiley.

Ephrath, A.R. and Curry, R.E. (1977). Detection by pilots of system failures during instrument landings. IEEE Transactions on System, Man, and Cybernetics, SMC-7, 841-848.

Ephrath, A.R. and Young, L.R. (1981). Monitoring vs. man-in-the-loop detection of aircraft control failures. In J. Rasmussen and W.B. Rouse (Eds.). Human detection and diagnosis of system failure. New York: Plenum Press.

Fisk, A.D., Derrick, W.L., and Schneider, W. (1983). The assessment of workload: Dual task methodology. In

Proceedings of the Human Factors Society 27th Annual Meeting (pp. 229-233). Santa Monica, CA: Human Factors Society.

Foushee, H.C. (1982). The role of communications, social-psychological, and personality factors in the maintenance of crew coordination. Aviation, Space, and Environmental Medicine, 53, 1062-1066.

Foushee, H.C. and Manos, K.L. (1981). Information transfer within the cockpit: Problems in intracockpit communications. In C.E. Billings and E.S. Cheaney (Eds.) Information transfer problems in the aviation system. (Tech. Report NASA TP-1875). Washington, D.C.: National Aeronautics and Space Administration.

Goodstein, L.P. (1981). Discriminative display support for process operators. In J. Rasmussen and W.B. Rouse (Eds.). Human detection and diagnosis of system failure. New York: Plenum Press.

Gopher, D. (1980). On the training of time sharing skills: An attention viewpoint. In Proceedings of the Human Factors Society, 24th Annual Meeting (pp.259-263). Santa Monica, Ca: Human Factors Society.

Greenstein, J.S. and Lam, S.T. (1985). An experimental study of dialogue-based communication for dynamic human-computer task allocation. International Journal of Man-Machine Studies, 23, 605-621.

Greenstein, J.S. and Revesman, M.E. (1981). A Monte-Carlo simulation investigating means of human-computer communication for dynamic task allocation. In Proceedings of the IEEE International Conference on Cybernetics and Society (pp. 488-494). Piscataway, NJ: IEEE.

Greenstein, J.S, Williges, R.C., and Williges, B.H. (1981). Human-computer dialogue design: Hardware and software. In Proceedings of the Fall Industrial Engineering Conference (89-98). Washington, D.C.: American Institute of Industrial Engineers.

Hackman, J.R. and Morris, C.G. (1975). Group tasks, group interaction process, and group performance effectiveness: A review and proposed integration. In L. Berkowitz (Ed.) Advances in experimental social psychology (45-99). New York: Academic Press.

Harris, R.J. (1985) A Primer of Multivariate Statistics. Orlando, Florida: Academic Press.

Harris, S.D. and Helander, M.G. (1984). Machine intelligence in real systems: Some ergonomic issues. In G. Salvendy (Ed.). Human-computer interaction, Amsterdam: Elsevier Science Publishers B.V.

Hart, S.G, Hauser, J.R., and Lester, P.T. (1984). Inflight evaluation of four measures of pilot workload. In Proceedings of the Human Factors Society 27th Annual

Meeting (pp. 945-949). Santa Monica, CA: Human Factors Society.

Jordan, N. (1963). Allocation of functions between man and Machines in automated systems. Journal of Applied Psychology, 47, 161-165.

Kantowitz, B.H. and Sorkin, R.D. (1987). Allocation of functions. In G. Salvendy (Ed.) Handbook of human factors. New York: John Wiley.

Kessel, C.J. and Wickens, C.D. (1982). The transfer of failure-detection skills between monitoring and controlling dynamic systems. Human Factors, 24, 49-60.

Kieras, D.E. (1984). A simulation model for procedure inference from a mental model for a simple device Tech. Report UARZ/DP/TR-84/ONR-15). Washington, D.C.: Office of Naval Research.

Kieras, D.E. (1987). What mental model should be taught: Choosing instructional content for complex engineered systems. Tech. Report TR-87/ONR-24). Washington, D.C.: Office of Naval Research.

Kieras, D.E. and Bovair, S. (1983). The role of a mental model in learning to operate a device Tech Report UARZ/DP/TR-83/ONR-13). Washington, D.C.: Office of Naval Research.

Kieras, D.E. and Bovair, S. (1984). The role of a mental model in learning to operate a device. Cognitive Science, 8, 255-273.

Kiesler, S., Siegal, J, and McGuire, T.W. (1984). Social psychological aspects of computer-mediated communication. American Psychologist, 39, 1123-1134.

Kling, J.W. and Riggs, L.A. (1971). Experimental Psychology. New York: Holt, Rinehart, and Winston, Inc.

Kragt, H. and Landeweerd, J.A. (1974). Mental skills in process control. In Edwards and F.P. Lees (Eds.) The human operator in process control. London: Taylor and Francis Ltd.

Lam, S.T. and Greenstein, J.S. (1985). The effects of input medium and task allocation strategy on performance of a human-computer system. In B. Shackel (Ed.). Human computer interaction - INTERACT '84. North Holland: Elsevier Science Publishers B.V.

Lanzetta, J.T. and Roby, T.B. (1960). The relationship between certain group process variables and group problem-solving efficiency. The Journal of Social Psychology, 52, 135-148.

Lee, A.T. and Roske-Hofstrand, R. (1986). Effects of operator experience and training on the representation of system topology in memory. In Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics (pp. 588-591). Piscataway, NJ: IEEE.

Licklider, J.C.R. (1960). Man-computer symbiosis. I.E.E.E. Transactions on Human Factors in Electronics, HFE-1, 4-11.

Mann, T.L. and Hammer, J.M. (1986). Analysis of user procedural compliance in controlling a simulated process. I.E.E.E. Transactions on Systems, Man, and Cybernetics, SMC-16, 505-509.

Morris, N.M. (1983). Human problem solving in process control. (Report 83-2). Atlanta: Georgia Institute of Technology, Center for Man-Machine Systems Research.

Morris, N.M. and Rouse, W.B. (1983). The effects of level of knowledge upon human problem solving in a process control task. In Proceedings of the 27th Annual Human Factors Society Meeting (pp. 690-694). Santa Monica, CA: Human Factors Society.

Morris, N.M. and Rouse, W.B. (1985). The effects of type of knowledge upon human problem solving in a process control task. IEEE Transactions on Systems, Man, and Cybernetics, SMC-13, 698-707.

Morris, N.M. and Rouse, W.B. (1985). An experimental approach to validating a theory of human error in complex systems. In Proceedings of the 29th Annual Human Factors Society Meeting (pp. 333-337). Santa Monica, CA: Human Factors Society.

Morris, N.M., Rouse, W.B., and Fath, J.L. (1985). PLANT: An experimental task for the study of human problem solving in a process control task. IEEE Transactions on Systems, Man, and Cybernetics, SMC-15, 792-798.

Norman, D.A. (1983). Some observations on mental models. In D. Gentner and A.L. Stevens (Eds.). _Mental models_ (pp. 7-14). Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Norros, L. and Sammatti, P. (1986). _Nuclear power plant operator errors during simulator training_ (Tech. Report 446). Finland: Valtion Teknillinen Tutkimuskeskus.

Price, H.E. (1985). The allocation of functions in systems. _Human Factors_, _27_, 33-45.

Price, H.E. and Tabachnick, B.J. (1968). _A descriptive model for determining optimal human performance in systems: Vol. III, An approach for determining the optimal role of man and allocation of functions in an aerospace system_ (Tech. Report NASA CR-878). Chatsworth, CA: Serendipity Associates.

Price, H.E., Maisano, R.E. and Van Cott, H.P. (1982). _The allocation of functions in man-machine systems: A perspective and literature review_ (Tech. Report NUREG/CR-2623). Washington, D.C.: U.S. Nuclear Regulatory Commission.

Rasmussen, J. (1976). Outlines of a hybrid model of the process plant operator. In T.B. Sheridan and G. Johannsen (Eds.). _Monitoring behavior and supervisory control_. New York: Plenum Press.

Rasmussen, J. (1981). Models of mental strategies in process plant diagnosis. In J. Rasmussen and W.B. Rouse (Eds.).

Human detection and diagnosis of system failure (pp. 241-258). New York: Plenum Press.

Rasmussen, J. (1983). Skills, rules, and knowledge; Signals, signs, and symbols, and other distinctions in human performance models. I.E.E.E. Transactions on Systems, Man, and Cybernetics, SMC-13, 257-266.

Rasmussen, J. (1986). A framework for cognitive task analysis in system design. In E. Hollnagel, G. Mancini, and D. Woods, (Eds.). Intelligent Decision Support in Process Environments. Heidelberg: Springer Verlag.

Rasmussen, J. and Rouse, W.B. (1981). Introduction. In J. Rasmussen and W.B. Rouse (Eds.). Human detection and diagnosis of system failure (pp. 1-6). New York: Plenum Press.

Rouse, W.B. (1976). Adaptive allocation of decision making responsibility between supervisor and computer. In T.B. Sheridan and G. Johannsen (Eds.). Monitoring behavior and supervisory control. New York: Plenum Press.

Rouse, W.B. (1977). Human-computer interaction in multi-task situation. I.E.E.E. Transactions on Systems, Man, and Cybernetics, SMC-7, 384-392.

Rouse, W.B. (1981). Human-computer interaction in the control of dynamic systems. ACM Computing Survey, 13, 71-99.

Rouse, W.B. (1984). Design and evaluation of computer-based support systems. In G. Salvendy (Ed.). Human-computer interaction. Elsevier Science Publishers B.V.: Amsterdam.

Rouse, W.B. (1984) Dynamic process control: Cognitive requirements and expert systems. In G. Salvendy (Ed.) Human-computer interaction (pp. 229-246). Amsterdam: Elsevier Science Publishers.

Rouse, W.B. and Rouse, S.H. (1983). A Framework for Research on Adaptive Decision Aids. AFAMRL-TR-83-082.

Sanderson, P. (1986). Designing 'Mental Models' for complex worlds. In Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics (pp. 267-271). Piscataway, NJ: IEEE.

Schneider, W. and Shiffrin, R. (1977). Control and automatic human information processing. I. Detection, search, and attention. Psychological Bulletin, 84, 1-66.

Sheperd, A., Marshall, E.L., Turner, A., and Duncan, K.D. (1977). Diagnosis of plant failures from a control panel: A comparison of three training methods. Ergonomics, 20.

Sheridan, T.B. (1976). Preview of the human monitor/supervisor. In T.B. Sheridan and G. Johannsen (Eds.). Monitoring behavior and supervisory control. New York: Plenum Press.

Sheridan, T.B. (1984). Supervisory control of remote manipulator, vehicles, and dynamic processes: Experiments in command and display aiding. In W.B. Rouse (Ed.)

Advances in man-machine systems research. Greenwich, Connecticut: JAI Press, Inc.

Sheridan, T.B. (1988). Human and computer roles in supervisory control and telerobotics: Musings about function, language and hierarchy. In L.P. Goodstein, H.B. Anderson, and S.E. Olsen (Eds.) Tasks, errors and mental models. London: Taylor & Francis.

Siegal, J., Dubrovsky, V., Kiesler, S., and McGuire, T. (1986). Group processes in computer-mediated communication. Organizational Behavior and Human Decision Processes, 37, 157-187.

Tabachnick, B.G. and Fidell, L.S. (1983). Using multivariate statistics. Harper & Row: New York.

Turner, J.A. and Karasek, R.A. (1984). Software ergonomics: Effects of computer application design parameters on operator task performance and health. Ergonomics, 27, 663-690.

Weeks, G.D. and Chapanis, Alphonse (1976). Cooperative versus conflictive problem solving in three telecommunication modes. Perceptual and Motor SKills, 42, 897-917.

Wickens, C.D. (1984). Engineering psychology and human performance. Columbus, Ohio: Merrill Publishing Company.

Wickens, C.D. and Gopher, D. (1977). Control theory measures of tracking as indices of attention allocation strategies. Human Factors, 19, 349-365.

Wickens, C.D. and Kessel, C. (1979). The effects of participatory mode and task workload on the detection of dynamic system failures. IEEE Transactions on Systems, Man, and Cybernetics, SMC-13, 24-34.

Wickens, C.D. and Kessel, C. (1981). Failure Detection in Dynamic Systems. In J. Rasmussen and W.B. Rouse (Eds.). Human detection and diagnosis of system failure (pp. 155-170). New York: Plenum Press.

Wiener, E.L. (1985). Beyond the sterile cockpit. Human Factors, 27, 75-90.

Williams, E. (1977). Experimental comparisons of face-to-face and mediated communication: A review. Psychological Bulletin, 84, 963-976.

Winer, B.J. (1962). Statistical principles in experimental design. New York: McGraw-Hill, Inc.

Woods, D.D., Wise, J.A., and Hanes, L.F. (1981). An evaluation of nuclear power plant safety parameter display systems.In Proceedings of the Human Factors Society 25th Annual Meeting (pp. 110-114). Santa Monica, CA: Human Factors Society.

Woods, D.D., Roth, E.M., and Bennett, K. (in press). Explorations in joint human-machine cognitive systems. In W. Zachary and S. Robertson (Eds.). Cognition, computing and cooperation. Norwood, N.J.: Ablex.

Zhang, K. and Wickens, C.D. (1987). A study of the mental model of a complex dynamic system: The effect of display aiding and contextual system training. In *Proceedings of the Human Factors Society 31th Annual Meeting* (pp. 102-106). Santa Monica, CA: Human Factors Society.

APPENDIX A

Operating Instructions - Primary Operator

This is a process shared by two operators: a primary operator and a support operator. Completely at random, you have been assigned as the primary operator. The computer stations for both operators will be at different locations. You will be working with and communicating with the support operator through a computer terminal. As the primary operator you will have the final decision and will be responsible for inputting this decision to the computer.

The operation you will be controlling is a fluid process. You are to control fluids as they enter the system and flow through a series of tanks. As the fluid flows through the system you control the route they take by opening or closing valves between tanks.

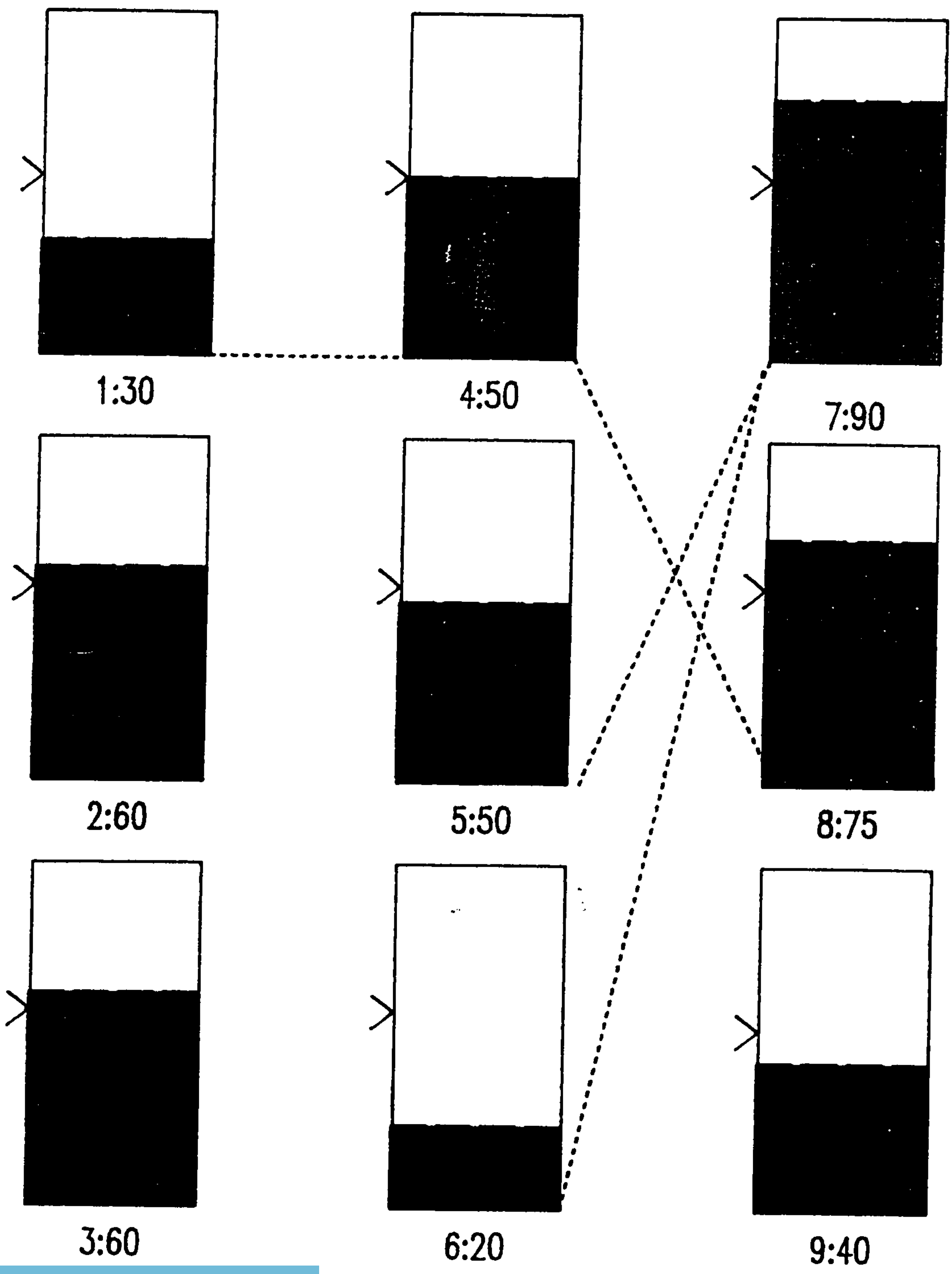
There are several features of the production system which are important for you to know:

1. Computer displays. This system has a graphics display and an alphanumeric display which present the same information in different forms. A sample of the graphic computer display is shown in Figure 1. There are nine tanks in this process, identified 1 through 9. Fluid enters the system through the three tanks on the left, flows from left to right though the three middle tanks, and exits from the three right tanks.

2. Opening and closing valves. Each tank of the 9 tanks have a pump which pushes the fluid between tanks. Fluid flows out of each tank through valves. You control the fluid flow by opening and closing valves. An open valve between tanks is shown by a dotted-line in the graphics display. In Figure 1 the valve between tanks 1 and 4 is open, as are the valves between tanks 4 and 8, and between 6 and 7. At the beginning of each production run, all horizontal valves are open. You may open or close any valve you wish in order to control the production process. There are some important things to keep in mind:

    1) Each of the tanks in the 2 left columns has 3 valves.
    2) You can open only valves between tanks in next column.
    3) Valves leading from tanks in the last column are controlled automatically by the computer.

Figure 1



4) You can not open valves between tanks in the same column (e.g. between tanks 1 and 2).
5) There is only one valve between any two tanks.
6) Fluid flow is to the right.

The system will prompt you for your decisions concerning opening and closing valves and repairing pumps and tanks. When it does, discuss the next move with the support operator. You as the primary operator will input the decision. After all the questions have been answered, the system uses your information and updates the computer displays. This is one complete cycle. During one cycle the system will prompt for the following information:

1) Whether you wish to open or close a valve.
2) Whether you wish to repair a valve.
3) Whether you wish to repair a pump.

When you answer yes to any of the prompts, the system will ask you for additional information. For example, if you indicated that you wanted to open a valve, the system would ask you for information concerning the specific valve you wished to open. **The system will not update the displays until you have completed the entire cycle.** The first production run will be a practice run of 5 cycles. After you feel comfortable with the system, you will go on to complete 2 more production runs with 20 cycles each.

3. Fluid levels in tanks. The numbers below each tank represent the levels of fluid in the tank. In Figure 1 the level of fluid in tank number 8 is currently at 70. At the beginning of each production run the fluid level in each tank is set at 50. Your goal is to keep fluid levels in each of the nine tanks between 10-90. The fluid level in each tank is shown as a shaded area within the tank. If fluid is at an acceptable level (above 25 and below 75) the shaded area in the tank is blue. If the fluid level approaches an unacceptable level (25 and below or 75 and above), the fluid turns green. This is a warning. If the level enters the critical range (10 and below or 90 and above) the fluid turns red.

The amount of fluid entering the system, the input, controls the number of units of fluid pumped into each tanks per cycle. For example, an input rate set at 60 would mean that 20 units of fluid are pumped into each of the three input tanks (1,2, & 3) per cycle. System output controls the units of fluids pumped out of the system per cycle. For example, an output rate of 30 indicates that 10 units of fluid are pumped out of each of the three output tanks (7, 8, & 9). The system throughput is the amount of fluid moving out of each tank through open valves. If throughput is set at 20, then 20 units of fluid are pumped through each open valve per cycle. Input, output, and throughput are set at the beginning of the production run by the experimenter.

4. <u>Systems failures</u>. Sometimes failures occur in the components of the system. There are three types of failures: valve, pump, or both pump and valve at the same time.
   1) When a valve fails, it closes and fluid cannot flow through it. However, the valve will still appear as though it is open. In the graphic display the dotted line indicating the valve was opened remain, even though the valve has failed and is actually closed.
   2) If a pump fails, fluid is not pushed from the tank.

   In order for you to detect that one or both of these failures have occurred, you must be alert to differences between what you expect the level of a tank to be and what it actually is. Since failures disrupt the flow of fluid, you must accommodate the disruption in fluid flow by adjusting connections between tanks. The first production run of 20 cycles will not have failures; the second one of 20 cycles will.

   The production system has a computer repair team available for correcting these failures. If you think there is a failure, you can send the repair team to the suspected valve or pump. If the team finds no failure, you will receive notice of this. If the team finds a failure, it is automatically repaired. While the repair team works on the failure, you continue to control the fluid flow process, but the repair team is unavailable until the pump or valve is repaired. Pump failures require three cycles to fix, while valves failures require two cycles.

5. <u>Automatic safety system</u>. The production system is equipped with an automatic safety system. The purpose of the safety system is to prevent damage to the system and to help you to keep the process under control. If the fluid in any tank equals or goes above a level of 90, or equals or goes below a level of 10, an automatic safety system takes over the control of fluid in and out of that tank. The safety system automatically opens or closes valves to correct the problem. If the safety system takes

over, the dotted-lines are automatically drawn or erased between the tanks to show the corrections the system has made. If you try to open a valve that the safety system has closed, a message will be displayed saying that the connection is not valid.

6. <u>Alphanumeric display</u>. There is a second type of display, an alphanumeric display, which provides basically the same information about the system as the graphics display but in a different format (see Figure 2). The time is actually the number of cycles that have been completed in the production run. The table on the left of the display has the tank numbers, the amount of fluid flowing in and out of each tank, the level of fluid in each tank, and whether the safety system is off or on for each tank. In Figure 2 you can determine that tank 3 has 10 units of fluid flowing into it and 0 flowing out. There are either no valves opened leading from this tank or there is a failure. The other table, on the right of the display, provides the tank numbers, a valve identification number, and the three possible connections for each tank. A valve identification number greater than zero indicates that the valve is open between the two tanks in the connection column. For example, the connection between tanks 1 and 4 has a valve ID number of 1, therefore, this valve is opened. The connection between tanks 1 and 5 is closed (the ID number is 0). When the level of a tank approaches an unacceptable level (25 and below, or 75 and above) a warning is displayed in the left column. If the tank level becomes critical (10 and below or 90 and above) the safety system shows an 'on' status for that tank.

Figure 2

Time = 4

TANK	IN	OUT	HEIGHT	SAFETY
1	10	30	30	OFF
2	10	0	60	OFF
3	10	0	60	OFF
4	30	30	50	OFF
5	0	30	50	OFF
6	0	30	20	OFF
7	60	10	90	ON
8	30	10	75	OFF
9	0	10	40	OFF

TANK	VALVE ID NUMBER	CONNECTION
	1	1 4
1	0	1 5
	0	1 6
	0	2 4
2	0	2 5
	0	2 6
	0	3 4
3	0	3 5
	0	3 6
	0	4 7
4	2	4 8
	0	4 9
	1	5 7
5	0	5 8
	0	5 9
	1	6 7
6	0	6 8
	0	6 9

Warning..Tank 8

Your job as a team member is to monitor and control the process in order to keep fluid levels as close as possible to the preset 50 unit level and to monitor for failures. Completely at random you have been assigned to work with either the graphic display, the alphanumeric display, or both. If you have both displays, try and use the information from both of them to make your decisions. You are to communicate with the support operator in order to make decisions about the system. The final decision rests with you as the primary operator. If you do not agree with the support operator's decision or cannot come to a decision with the support operator, then the responsibility is yours. You are responsible for communicating decisions to the production system. Work as fast but as accurately as you can.

APPENDIX B

Operating Instructions - Support Operator

This is a process shared by two operators: a primary operator and a support operator. Completely at random, you have been assigned as the support operator. The computer stations for both operators will be at different locations. You will be working with and communicating with the primary operator through a computer terminal. As the support operator you will have the role of advising and communicating with the primary operator. The primary operator will input the final decision to the computer.

The operation you will be controlling is a fluid process. You are to control fluids as they enter the system and flow through a series of tanks. As the fluid flows through the system you control the route they take by opening or closing valves between tanks.

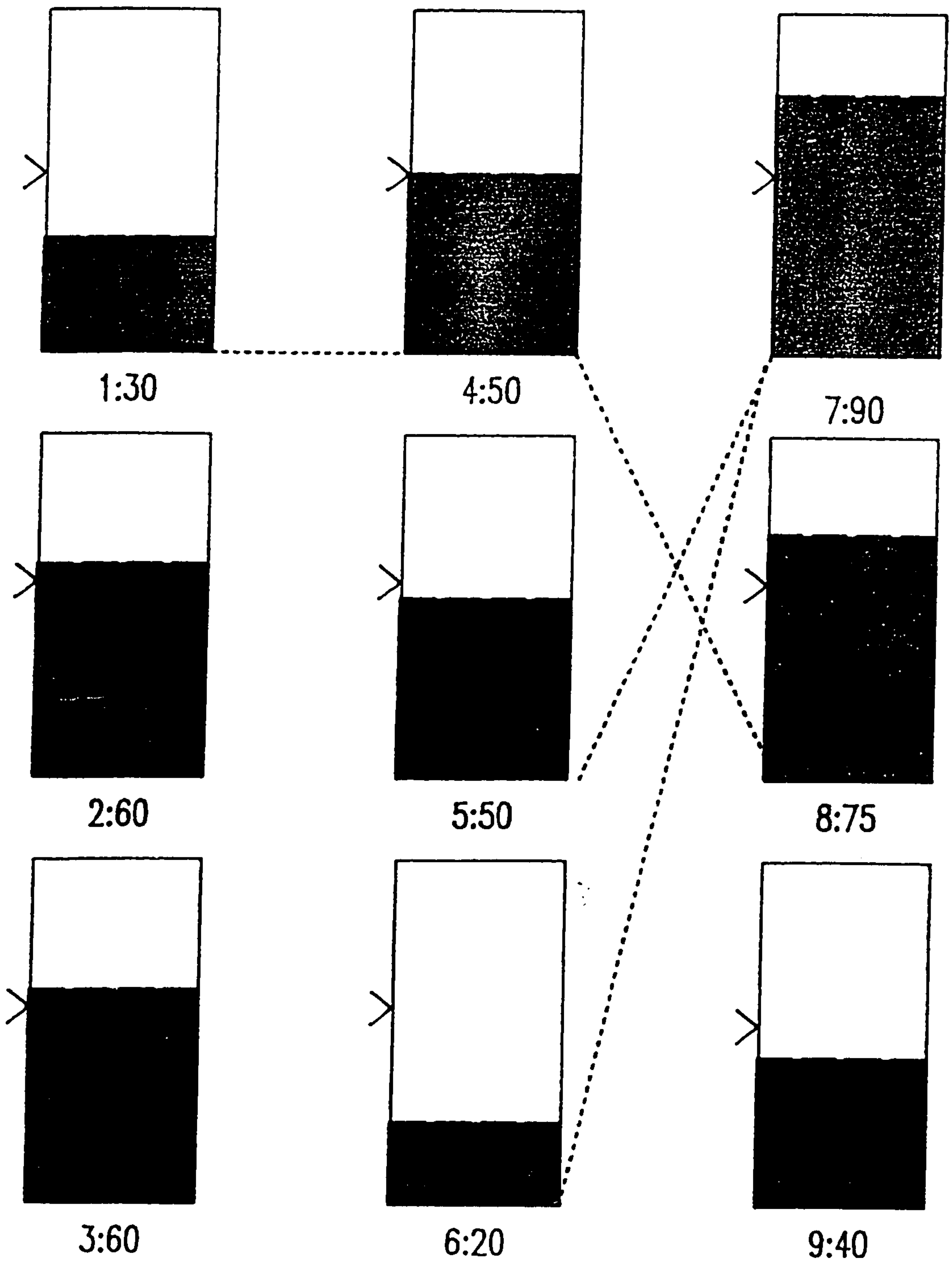
There are several features of the production system which are important for you to know:

1. **Computer displays**. This system has a graphics display and an alphanumeric display which present the same information in different forms. A sample of the graphic computer display is shown in Figure 1. There are nine tanks in this process, identified 1 through 9. Fluid enters the system through the 3 tanks on the left, flows from left to right though the three middle tanks, and exits from the three right tanks.

2. **Opening and closing valves**. Each tank of the 9 tanks have a pump which pushes the fluid between tanks. Fluid flows out of each tank through valves. You control the fluid flow by opening and closing valves. An open valve between tanks is shown by a dotted-line in the graphics display. In Figure 1 the valve between tanks 1 and 4 is open, as are the valves between tanks 4 and 8, and between 6 and 7. At the beginning of each production run, all horizontal valves are open. You may open or close any valve you wish in order to control the production process. There are some important things to keep in mind:

   1) Each of the tanks in the 2 left columns has three valves.
   2) You can open only valves between tanks in next column.
   3) Valves leading from tanks in the last column are controlled automatically by the computer.

Figure 1



4) You can not open valves between tanks in the same column (e.g. between tanks 1 and 2).
5) There is only one valve between any two tanks.
6) Fluid flow is to the right.

The system will prompt you for your decisions concerning opening and closing valves and repairing pumps and tanks. When it does, discuss the next move with the primary operator. The primary operator will input the decision. After all the questions have been answered, the system uses this information and updates the computer displays. This is one complete cycle. During one cycle the system will prompt for the following information:

1) Whether you wish to open or close a valve.
2) Whether you wish to repair a valve.
3) Whether you wish to repair a pump.

When you answer yes to any of the prompts, the system will ask you for additional information. For example, if you indicated that you wanted to open a valve, the system would ask you for information concerning the specific valve you wished to open. **The system will not update the displays until you have completed the entire cycle.** The first production run will be a practice run of 5 cycles. After you feel comfortable with the system, you will go on to complete 2 more production runs with 20 cycles each.

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Time = 4

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2	10	0	60	OFF
3	10	0	60	OFF
4	30	30	50	OFF
5	0	30	50	OFF
6	0	30	20	OFF
7	60	10	90	ON
8	30	10	75	OFF
9	0	10	40	OFF

Warning..Tank 8

TANK	VALVE ID NUMBER	CONNECTION
	1	1 4
1	0	1 5
	0	1 6
	0	2 4
2	0	2 5
	0	2 6
	0	3 4
3	0	3 5
	0	3 6
	0	4 7
4	2	4 8
	0	4 9
	1	5 7
5	0	5 8
	0	5 9
	1	6 7
6	0	6 8
	0	6 9

Your job as a team member is to monitor and control the process in order to keep fluid levels as close as possible to the preset 50 unit level and to monitor for failures. Completely at random you have been assigned to work with either the graphic display, the alphanumeric display, or both. If you have both displays, try and use the information from both of them to make your decisions. You are to communicate with the primary operator in order to make decisions about the system. The final decision rests with the primary operator. Work as fast but as accurately as you can.

APPENDIX C

Participant Information

Please answer the following questions about yourself. Remember, you are not being identified individually on this questionnaire.

1. Age:______________ 2. Sex: M F

2. Check all the following that you have obtained:

____ High School or GED
____ Technical or Trade School in ________________
____ Some College Coursework
____ Associates Degree in ____________
____ Bachelor's Degree in ____________
____ Master's Degree in ______________
____ Ph.D. Degree in _________________
Other_____________________________________

____

3. List all college engineering courses that you have taken.

____

____

____

____

4. List any math courses that you have taken.

____

____

____

____

5. List any science courses that you have taken.

_______________________________________ _________________

____

____

____

6. Do you have any experience in regulating and controlling chemical, energy, or thermal processes?
No Yes

If yes, describe this experience. When was this? For how long?

____

____

____

8. Do you use a computer? No Yes

If yes, for what type of work?
_____ Word Processing
_____ Data Processing
_____ Statistical Analyses
_____ Programming
_____ Other (such as balancing checkbook, etc) Please describe ____________________________________
____

How long have you been using a computer?
____

How often do you use a computer as part of your work?

____Never ____Seldom ____Sometimes ____Generally ____Always

9. Do you wear glasses or contact lenses? No Yes

10. Do you have normal color vision? No Yes

11. Are you right or left handed? right left

12. How many years have you been in the military?______

12a. Does your work in the military require you to work as a team member? No Yes

If yes, describe____

____

____

13. How many years have you been in the Navy reserves?______

14. In your civilian job, do you do any work which must be done while another person watches, another person helps, or another person operates equipment with you? No Yes

If yes, describe____

____

____

15. Do you, or have you, supervised people?

If yes, how many people? _______

AUTOBIOGRAPHICAL STATEMENT

Michele Terranova was born April 23, 1959, in Whitestone, New York. She was enrolled at The City University of New York in Queens in 1977 before transferring to the State University of New York at Stony Brook in 1979. She received the B.A. degree in psychology from Stony Brook. In 1981, Michele graduated with highest honors and as a member of Phi Beta Kappa.

Michele began attending Old Dominion University in 1981, where she worked towards the Ph.D. in Industrial/Organizational Psychology. She was a graduate teaching assistant for the Psychology Department from 1981 to 1983. After completing her masters degree in 1981 under the direction of Dr. Ben B. Morgan, Jr. she chose to specialize in Engineering and Systems Psychology and minor in Personnel Psychology. In 1983 she worked on an Air Force contract for the Center for Applied Psychological Studies (CAPS) in the role of data analyst. For six months in 1985 she completed her internship with IBM in Boulder Colorado. After returning to Old Dominion in the summer of 1985, she held a position as an instructor of Psychology for undergraduate statistics courses. In September of 1986, Michele took a position at the Oak Ridge National Laboratory, in Oak Ridge Tennessee. While working under the direction of Dr. Raymond Kirby, Michele completed her Ph.D. in Psychology from Old Dominion University in December 1988.

Her interests include user-system interface, mental models, and communication systems. She is a member of the Human Factors Society, the Institute of Electrical and Electronic Engineers, and the American Psychological Association.