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The Effects of Interface Management Tasks On Crew Performance and Safety in Complex, Computer-Based Systems

Detailed Analysis

Brookhaven National Laboratory

U.S. Nuclear Regulatory Commission
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Washington, DC 20555-0001

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The Effects of Interface Management Tasks On Crew Performance and Safety in Complex, Computer-Based Systems

Detailed Analysis

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ABSTRACT

The primary tasks performed by nuclear power plant operators are process monitoring and control. To perform these tasks in a computer-based system, operators must perform secondary tasks such as retrieving information and configuring workstation displays. These are called "interface management tasks." Demands associated with interface management tasks may be excessive under some circumstances and potentially affect plant safety. The objective of this research was to evaluate the effects of interface management tasks on crew performance and safety using published literature, discussions with subject-matter experts, site visits, and simulator studies. We found evidence of two forms of negative effects: (1) primary task performance declines because operator attention is directed toward the interface management task, and (2) under high workload, operators minimize their performance of interface management tasks, thus failing to retrieve potentially important information for their primary tasks. Further, these effects were found to have potential negative effect on safety. The results of this study are reported in two volumes. Volume 1 provides an overview of the major findings. Volume 2 describes the detailed analyses that were performed. The results form the technical basis for human factors engineering guidelines for the review the interface management aspects of human-system interface designs, to help ensure that they do not compromise safety.

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PREFACE

This report was prepared by Brookhaven National Laboratory (BNL) for the Division of Systems Analysis and Regulatory Effectiveness of the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research. It is submitted as part of the requirements of the project *The Development of Human-System Interface Design Review Guidance for NUREG-0700, Revision 2* (JCN W6546), specifically for Task 6, Develop and Evaluate New Design Review Guidance for Selected Topics. The NRC Project Manager is Paul Lewis (301 415-6767; PML1@nrc.gov) and the BNL Principal Investigator is John O'Hara (631 344-3638; ohara@bnl.gov).

ACRONYMS

ABB-CE	ASEA-Brown Boveri Combustion Engineering
ABWR	advanced boiling water reactor
BNL	Brookhaven National Laboratory
COSS	computerized operator support systems
CPPF	channel power peaking factor
CPS	cycles per second
CR	control rooms
CRT	cathode ray tube
CSF	critical safety function
CSDV	condenser steam discharge valves
DoD	Department of Defense
EdF	Electricite de France
EOP	emergency operating procedure
EPRI	Electric Power Research Institute
FINCH	fully instrumented channel
GOMS	goals, operators, methods, and selection rules
HFE	human factors engineering
HSI	human-system interface
I&C	instrumentation and control
ISLOCA	interfacing system loss of coolant accident
LTM	long-term memory
MTLX	modified task load index
NPP	nuclear power plants
NRC	Nuclear Regulatory Commission (U.S.)
OP	output
P&ID	piping and instrumentation diagram
PHT	primary heat transport system
POC	performance operating characteristic
PV	process value
SAR	safety analysis report
SDT	signal detection theory
SME	subject matter experts
SP	setpoint
SPDS	safety parameter display system
TEM	text-editing method
TLAP	timeline analysis and prediction
USQ	unreviewed safety question
VDU	video display units
W/INDEX	workload index
WM	working memory

1 INTRODUCTION

1.1 Background

The *Human-System Interface Design Review Guidelines*, NUREG-0700, Rev. 2, (NRC, 2002) provides the U.S. Nuclear Regulatory Commission (NRC) with review guidance on the human factors engineering (HFE) aspect of human-system interfaces (HSIs). The NRC reviews the HFE aspects of control rooms to ensure that they are designed using HFE principles. These reviews help protect public health and safety by ensuring that operator performance and reliability are appropriately supported.

The NRC staff uses NUREG-0700 for (1) reviewing the submittals of HSI design prepared by licensees or applicants for a license or design certification of a commercial nuclear power plant (NPP), and (2) conducting reviews of HSIs that might be part of an inspection or other type of regulatory review involving HSI design or incidents involving human performance. It describes those aspects of the HSI design review that are important to identifying and resolving discrepancies in human engineering that could adversely affect plant safety. NUREG-0700 also details HFE guidelines for assessing implementations of HSI design.

Several topics were identified as gaps because there was an insufficient technical basis upon which to develop guidance (O'Hara, 1994; O'Hara, Brown, and Nasta, 1996). One such topic was interface management. Interface management may be defined as actions performed by the operator to interact with the HSI rather than with the plant. When the HSIs are computer-based, interface management tasks include workstation configuration, display navigation, and window manipulation. As operational experience with these computer-based HSIs develops, there is increasing concern that, when compared with more conventional interfaces, the interface management demands may be excessive under some circumstances. This additional workload may interfere with the operators' ability to monitor and control the plant and it may detract from their ability to handle process disturbances. Thus, interface management tasks have the potential to affect plant safety. The issue also was identified by the NRC's Office of Nuclear Reactor Regulation in a Human Factors User Need titled "Effects of Advanced Control-Display Interfaces on Crew Workload" (Memorandum from W. Russell to D. Morrison titled "Status of Human Factors User Needs" dated March 25, 1996).

There has been a steady increase in the use of computer-based displays and controls in NPPs. Advanced plant designs, such as the General Electric Advanced Boiling Water Reactor, the Westinghouse AP600, and the Electricite de France (EdF) N4, make extensive use of computer-based HSIs. However, computer-based HSI technology is not solely in the domain of advanced plants. Currently, computer-based HSI technology is being integrated into existing plants as part of modernization programs that upgrade control rooms (CRs), remote shutdown facilities, and local panels (O'Hara, Stubler, and Higgins, 1996).

CRs designed with conventional HSIs consist of very large workspaces with spatially dedicated displays and controls. The displays typically provide indication of single parameters, and the controls are generally for single components, such as pumps and valves. Integration and interpretation are performed by the operators based on crew coordination, communication, training, and experience. Operators "walk the boards" to monitor information and perform plant control operations from a standing position.

By contrast, CRs with computer-based HSIs are considerably more compact, with information and controls presented on video display units (VDUs) in computer-driven, workstation-like consoles for seated operators. O'Hara, Stubler, and Higgins (1996) generally characterize advanced plant HSIs by:

- Alarms systems that use computer-based methods to analyze, process, and reduce alarms. This includes HSI facilities to interface with these systems to sort alarms, view suppressed alarms, query alarm logic, modify setpoints, and establish temporary alarms.

- Information and display systems that use graphic formats and may have hundreds (or thousands) of displays of which only a small number may be viewed at any one time at VDU-based workstations. To supplement and partially compensate this limited display, large screen group-view displays may be provided.

- Control of plant systems and components through soft controls such as on-screen software defined buttons and icons that are activated through input devices. Higher automation of plant control functions for complex tasks, including plant startup and feedwater control.

- Computer-based procedure systems that access and display plant data referenced by procedure steps and resolve the logic of individual steps, such as "If pressurizer level is above x, then do Y."

- Computerized operator support systems (COSSs) which are decision aids for operator cognitive functions such as situation assessment.

With these technology changes, the ways operators perform interface management tasks has changed dramatically. These changes have led to the concerns expressed. To address them, the NRC undertook research at Brookhaven National Laboratory (BNL) to (1) better define the effects of interface management on personnel performance and plant safety, and (2) develop guidance on HFE to support safety reviews. This report communicates the results of the first part of this research by addressing the effects of interface management on personnel performance and plant safety.

The results of this study formed the technical basis for establishing HFE review guidelines for interface management. The use of this information for guidance development is discussed elsewhere (O'Hara and Brown, 2001). The guidance was integrated into NUREG-0700 and will be used to provide the NRC staff with the technical basis to ensure that HSI designs do not compromise safety. Thus, the results of this project will contribute to satisfying the NRC's goals of maintaining safety, increasing public confidence, increasing regulatory efficiency and effectiveness, and reducing unnecessary burden.

1.2 Organization of This Report

To address the potential concerns regarding interface management, the NRC undertook research to better define the effects of interface management on personnel performance and plant safety. The results are described in two report volumes. Volume 1 provides an overview of the major findings of the study and their implications. Volume 2 (this volume) is the basis for this overview and describes the detailed analyses and evaluations the were performed. Chapter 2 presents the objectives of the study. Chapter 3 addresses the effects of interface management on task performance. Chapter 4 addresses the effects of interface management on plant safety. Chapter 5 discusses the human performance issues associated with interface management. References are given in Chapter 6.

2 OBJECTIVES

The objective of this study was to assess the effects of interface management on personnel performance and plant safety. To support this objective, the following tasks were undertaken:

- model the potential effects of interface management based on a cognitive analysis of their demands, potential impacts on primary task performance, and their relationship to human error
- determine whether there is support for the interface management effects in complex, real-world, computer-based systems
- identify the effects of HSI design features on the performance of interface management tasks
- determine the potential relationship between interface management task effects and plant safety.

3 THE EFFECTS OF INTERFACE MANAGEMENT ON TASK PERFORMANCE

3.1 Methodology

The potential effects of interface management were modeled based on a cognitive analysis of their demands, potential impacts on crew primary task performance, and the relationship to human error. An analysis of interface management task performance was considered within the framework of current theory and research on human information processing and cognition. This analysis gave both the cognitive basis to understand why interface management might be a concern. The analysis led to the identification of interface management effects.

Once cognitive effects were identified, information related to them was examined. Information was obtained from the following sources of information (1) literature analysis, (2) interviews with subject matter experts from many industrial domains, (3) sitevisits to perform walkdowns of scenarios in seven process control facilities, and (4) two simulator studies focused on HSI issues. The role of each is discussed below.

3.1.1 Analysis of Literature

The basic literature (mainly papers from research journals and technical conferences) provides a theoretical basis for understanding human performance concerns related to complex human-machine systems. It also provides general theory for human-machine interaction relevant to user interface design, human error, and usability.

The literature was used to address two aspects of performance that are significant to understanding interface management effects (1) the effect of interface management task performance on the operator's primary tasks, and (2) the effects of HSI design characteristics on the operator's performance of those interface management tasks. While our main focus was on commercial NPPs, information from non-nuclear human-machine systems also was obtained. In many cases, the general demands placed on personnel for monitoring and detection, situation assessment, response planning, and response execution are quite similar. Thus, even though specific operator tasks may be different, operating experience from non-nuclear human-machine systems can offer useful information. Furthermore, in the U.S., many non-nuclear industries have been more aggressive in the implementation of computer-based HSI technologies and, therefore, have greater and more diverse experience.

A focused review of HFE literature pertaining to HSI technologies and associated human performance effects was performed. This literature included technology descriptions, empirical studies, and studies of operating experience from the following domains: nuclear power, fossil power, process control, medical systems, aviation, and general HFE research literature. The information from nuclear power industry sources included research reports and technical publications describing HFE trends and human performance concerns related to the introduction of technology into complex systems.

Guidance based on basic literature requires engineering judgement to generalize from the unique aspects of individual experiments and studies to actual applications in the workplace. This is because individual experiments have unique constraints that limit their generalizability (such as their unique participants, types of tasks performed, and types of equipment used). For example, laboratory experiments often do not involve tasks of the complexity of NPP operations, and most experiments do not examine tasks under the same performance shaping factors (such as rotating shifts, stress, and fatigue) that exist in a work environment. While information from research is a valuable part of developing guidance, it usually cannot be adopted blindly. Thus, the results must be interpreted in the context of real-world tasks and systems, which involves judgement based on professional and operational experience.

3.1.2 SME Interviews

Interviews were conducted with engineering, training, and human factors personnel involved in designing computer-based HSIs, including:

- One human factors engineer from each of the following NPP vendors:
  - ASEA-Brown Boveri Combustion Engineering (ABB-CE)
  - Atomic Energy of Canada, Ltd.
  - Westinghouse Electric Corporation
- An instructor from a foreign NPP
- A human factors researcher from a foreign consulting agency that addresses NPPs
- A human factors researcher from a manufacturer of computer-based HSIs for process industries,
- An HSI design engineer from a chemical plant,
- A human factors consultant for the chemical industry
- An anesthesiologist with extensive experience in human factors
- A manager of a user interface design organization for a financial institution

Where there was insufficient information to provide a technical basis upon which to develop guidance, an issue is defined.

3.1.3 Site Visit Walkdowns

BNL researchers visited a variety of sites that featured computer-based HSIs. The purpose of these visits was to develop a better understanding of the following topics:

- The effects of interface management tasks on operator performance of primary work tasks
- HSI technologies and features that are used for interface management
- The types of interface management tasks that are imposed on operators by HSI technologies and features
- Operator strategies for dealing with interface management
- The differential effects of operator experience with the HSI upon performance of interface management tasks and strategies used for such

The three sites selected were representative of the types of HSI technologies and tasks that may be encountered in computer-based HSIs of NPPs. Two selection criteria were considered: (1) the site is a NPP or other process control plant in which interface management is an important part of the operators' activities when interacting with plant control systems, alarm systems, or other systems important to plant safety; and (2) the site has an HSI that includes computer-based technologies relevant to new or modernized NPP control rooms, such as visual display units, information structures (e.g., menu-based display systems), and input devices (e.g., keyboards and pointing devices). Also, the site should be willing to participate. Based on these criteria, three sites were chosen:

Nuclear Power Plant 1 - This plant, located outside the U.S., had been operating for approximately 10 years. The control room was a hybrid design featuring a mixture of computer-based technologies (e.g., VDUs and light pens) and more traditional hardwired control and display devices. The tests were conducted at a full-scale control room simulator.

Nuclear Power Plant 2 - This plant, also located abroad, had a control room with compact computer-based consoles from which operators access information and perform control actions. The HSI design provided multiple means of operator-system interaction. Visits were made to a training simulator and to the actual plant, which was in hot testing mode.

Chemical Manufacturing Facility - This facility, located in the U.S., contained three plants with distributed control systems based on digital instrumentation and control technologies. The HSIs for these plants are approximately 2-, 5-, and 10-years old, respectively. The control rooms contain many of the types of technologies proposed for advanced NPPs. Operators work at computer-based consoles and almost all control actions are performed using soft controls. Operators interact with computer-based alarms and safety interlock systems.

Information was gathered at these visits through the following methods: (1) interviews with operations, training, and design personnel, and (2) walk-through exercises which showed important features of the HSI and how they are used. In addition, operations personnel were informally observed carrying out their normal responsibilities using the HSI. Each is described below.

Before each site visit, BNL coordinated with personnel from the sites to characterize the HSI, identify relevant HSI components, and identify operator tasks that include challenging but realistic interface management demands. A detailed plan for each site visit was developed that described the procedures to be used for each site visit. Before the interviews and walk-through exercises at each site, the procedures were reviewed with an on-site facilitator, usually a trainer, design engineer, or human factors engineer, who hosted the visit. In addition, participants were informed of the purpose of this study and how results would be used. The general approach to interviews and walk-through exercises is described below. The specific details of each varied across the sites.

The interviews were conducted with operators, supervisors, and instructors who were knowledgeable of interface management technologies and tasks using a structured set of questions. The questions focused on interface management tasks that occur during an operating shift.

Such tasks impose demands for the operator's effort and attention. The questions covered the effects of these demands upon primary task performance (e.g., ability to operate the plant), and also upon the performance of interface management tasks (e.g., time and errors involved in accessing information).

The interviews addressed strategies used by operators for minimizing or managing the interface management demands including:

- Task tailoring - Adjusting primary tasks to accommodate limitations of the HSI (e.g., interrupting low priority tasks to retrieve displays that will be needed for high-priority tasks), and

- Device tailoring - Adjusting the user interface to reduce demands (e.g., arranging displays spatially so they are easier to find and identify in the future).

In addition, the use of specific interface management features such as navigation aids and controls were addressed. BNL interviewers looked for evidence of these strategies in the responses of participants. In addition, interviewers attempted to differentiate the interface management strategies of experienced operators and operators learning to use the HSI.

The walk-throughs were designed to observe interface management tasks, identify strategies used by operators to accomplish them, and to develop a better understanding of their effects on operator and plant performance. Walk-through scenarios were identified in coordination with trainers and HSI designers. Operators were instructed to perform particular actions that required using the HSI. They described the details of their actions either while performing the tasks or after each task was completed. Two types of scenarios were used: interface management and operational scenarios. Each is described below.

Interface Management Scenarios - Interface management scenarios provided the opportunity to observe the detailed task demands and strategies for dealing with common interface management tasks. For example, participants were asked to retrieve specific displays or controls from the display system as they would in response to a specific alarm, a request from a crew member, or a procedure step. These exercises started from predefined positions in the information structure. Once that target item was retrieved, the operator was instructed to access another starting from the last location. Several targets were retrieved in total. Two types of information structures were navigated:

- The display system (e.g., finding displays in the hierarchical organization)

- Large display pages (e.g., mimics, tables)

For those target items that resided in more than one location in the information structure (e.g., they were included in multiple displays), two separate sets of trials were conducted:

- Directed - The particular displays to be retrieved were specified.

- Exploratory - Participants described decision making associated with selecting a display.

The scenarios imposed varying degrees of difficulty with respect to interface management demands. Difficulty factors included the length and familiarity of the navigation paths required to reach the requested target. An example of a low-difficulty task was to retrieve a display that was directly below the top-level display. A high-difficulty task was to start at a bottom-level display in one branch of the display structure, and to move to a bottom-level display in another branch. Investigators noted how the tasks were performed in terms of the use of HSI features and interface management strategies.

Operational Scenarios - While interface management scenarios enabled task demands to be observed, they did not examine the relationship and integration of these tasks with primary tasks. The latter is necessary to understand the potential negative impacts of interface management tasks on primary task performance and plant operation. Thus, the purpose of these scenarios was to observe interface management tasks and strategies within the context of realistic tasks in order to provide a better understanding of the consequences of display system navigation errors upon the completion of operational tasks.

Operators were asked to perform operational tasks that required a series of interface management actions, such as monitoring displays or operating controls. The following types of scenarios were addressed:

- General plant status assessment - Participants were asked to scan the HSI to determine the overall status of the plant as they would during shift turnover or routine monitoring. This task addressed strategies used to conduct a broad-scope review of plant status.

- Disturbance analysis and situation assessment - Participants were asked to describe how they would respond to various process disturbances. The interface management tasks included locating and reviewing information in response to alarms and other indications of process disturbances that varied in scope. For example, a "trouble" alarm, which indicated that a plant system was operating unusually but did not identify the troublesome plant variable, was used to address interface management strategies used to narrow the search to a specific plant system and then identify an anomaly within that system. A multiple alarm condition was used to address interface management strategies used by operators during fault diagnosis, including detecting, prioritizing, and responding to multiple alarms and navigating to and integrating numerous process displays.

- Process control tasks - Participants were asked to perform control operations, such as aligning a piping system or changing a group of control setpoints. The scenarios incorporated various levels of difficulty with respect to interface management demands such as the number, order, and timing of control actions, the amount of navigation required, and operator's familiarity with the action. This task revealed strategies used to access display and controls and then coordinate their use.

3.1.4 Simulator Studies

Two studies were conducted in the course of addressing other HSI topics that provided information relevant to interface management:

- An experimental investigation of alarm system display, processing, and availability characteristics (O'Hara, Brown, Hallbert, Skråning, Wachtel, and Persensky, 2000).

- A simulator-based observational study of CBPs, computer-based alarms, and interface management (Roth and O'Hara, 1998).

3.2 Findings

The findings are organized largely based on the type of information used:

- a cognitive analysis of interface management task effects on primary task performance in order to identify a plausible model to describe their potential effects (Chapter 3.2.1)

- an evaluation of interface management effects on crew primary task performance in complex systems based on existing literature, including studies performed by the NRC (Chapter 3.2.2)

- an evaluation of the effects of HSI design characteristics on interface management tasks based on existing literature (Chapter 3.2.3)

- an evaluation of interface management problems and issues based on data collected during site visits and interviews with subject matter experts (SMEs) (Chapter 3.2.4)

- an evaluation of interface management problems and issues based on data collected durıng interviews with subject matter experts (Chapter 3.2.5)

3.2.1 Cognitive Analysis of Interface Management Effects on Primary Task Performance

This chapter describes a cognitive analysis of interface management task effects on primary task performance in order to identify plausible a model to describe their potential effects. Operators contribute to the plant's defense-in-depth approach to safety, serving a vital function in ensuring its safe operation. NPP operators are supervisory controllers. Plant performance is the result of the interaction of human and automatic control. Reason (1990) called this a complex multiple-dynamic configuration and in such systems decision making can be difficult when things go wrong.

The operators' impact on the plant's functions, processes, systems, and components is mediated by a causal chain from their physiological and cognitive processes, to task performance, and ultimately, to plant performance through the operators' manipulation of the HSI (see Figure 3.1). HSI design, including its procedures, affects plant performance through personnel tasks that support operations.

Within the context of NUREG-0700, the operator's tasks are divided into two broad categories: primary tasks and secondary tasks. Primary tasks involve several generic cognitive tasks, i.e., situation assessment, monitoring and detection, response planning, and response implementation (see Figure 3.2).

Secondary tasks are those performed that are not directly related to the primary tasks. One class of secondary task is interface management, e.g., navigating through an information system, arranging the way that information is presented, and manipulating windows on a VDU. NUREG-0700 uses the term secondary task to refer to this type of task because, while necessary, interface management tasks are secondary to the operator's primary tasks. They result from the design of the interfaces used to support the primary and secondary tasks. There are other secondary tasks that are not interface management tasks, such as mentally calculating a value based on parameters presented in a display.

NUREG-0700 provides high-level design review principles to support task design and secondary task control. However, more detailed guidance is needed, especially for control or interface management tasks.

In this chapter, the distinction between these two classes of tasks is analyzed in greater detail.

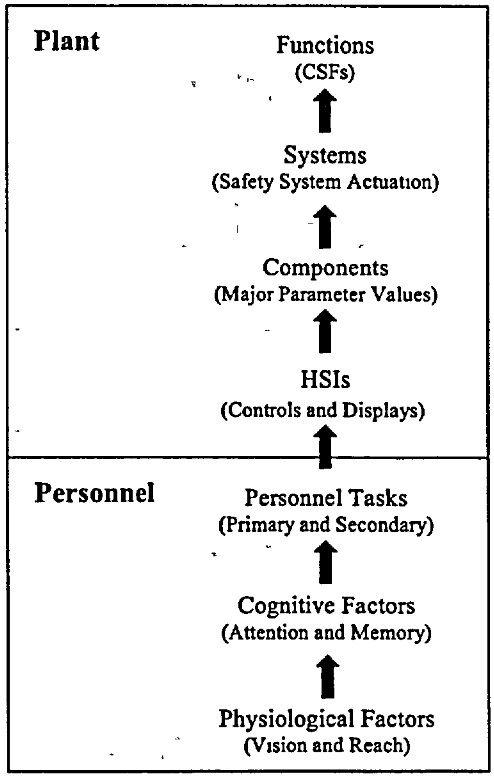

Figure 3.1 Hierarchical influence of human activity on plant performance

3.2.1.1 Primary Tasks

When addressing primary tasks, the generic cognitive tasks shown in Figure 3.2 are discussed rather than the detailed specific tasks, such as monitoring steam flow, starting pumps, and aligning valves. To adequately perform their tasks, operators utilize their information processing resources such as attention, reasoning, and memory. A simplified model of human information processing is presented in Figure 3.3. The model is adapted from Wickens (1984) and was used in the development of NUREG-0700 (see O'Hara, 1994). The model borrows features that are common to many models of human cognition that have considerable empirical support. While it is depicted showing the flow of information through the system from left to right, the interaction between cognitive elements is more complex; the figure is a simplification. The role of these cognitive processes in performing primary tasks is discussed below. The objective of the discussion is to develop a picture of the complexity and cognitive demands of the operators' primary tasks so that the demands of interface management tasks can be understood within the context of these primary task demands.

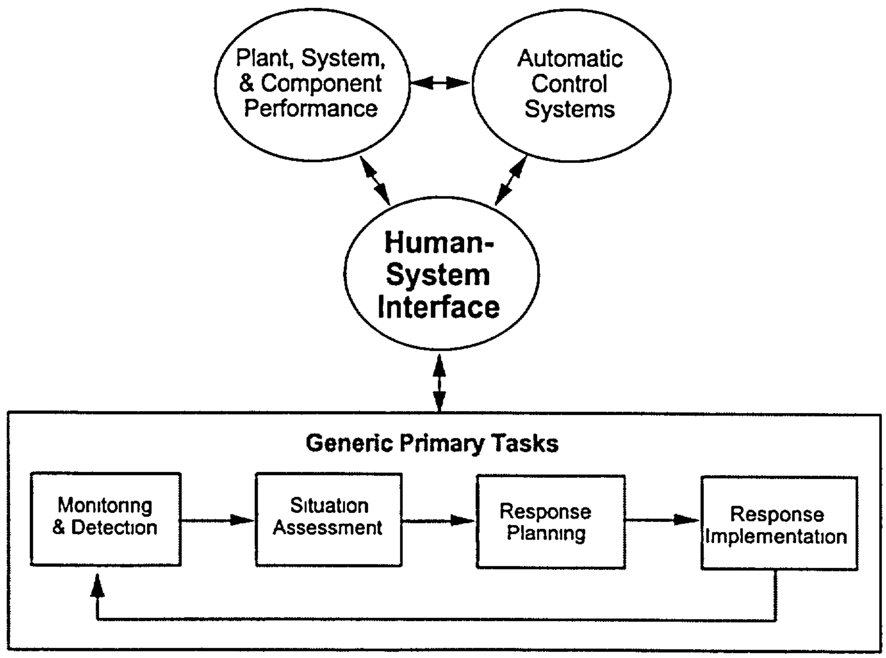

Figure 3.2 Generic primary tasks of a supervisory controller

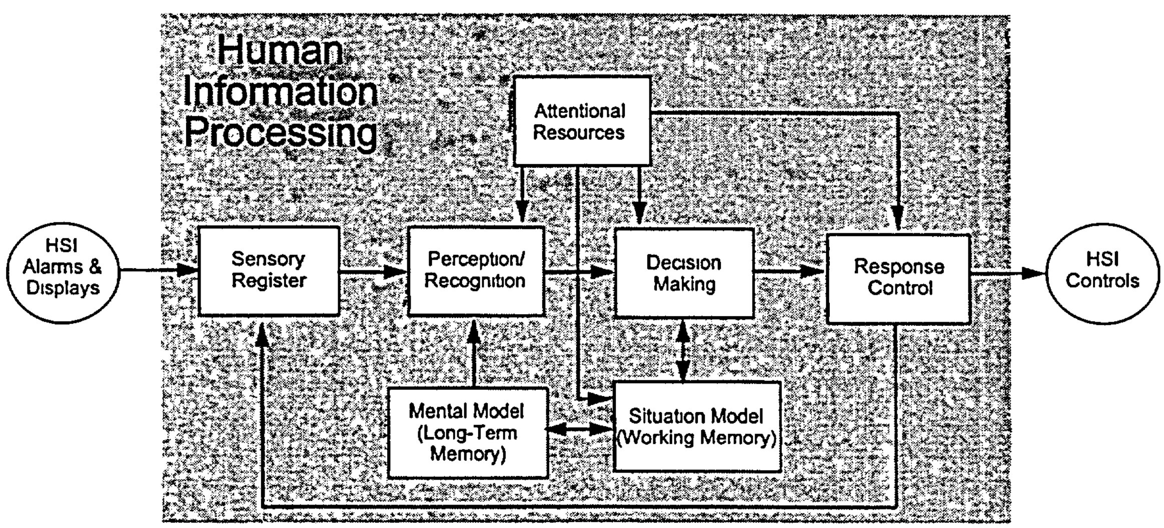

Figure 3.3 Simplified supervisory control information processing model
(adapted from Wickens, 1984)

Situation Assessment

When faced with an abnormal occurrence, operators actively try to construct a coherent, logical explanation to account for their observations. This cognitive activity, situation assessment, involves two related concepts: the situation model and the mental model. Operators develop and update a mental representation of the factors known, or hypothesized, to be affecting the plant's state at a given point in time. The mental representation resulting from situation assessment may be referred to as a *situation model*, the person's understanding of the specific current situation. The situation model is constantly updated as new information is received. (See O'Hara, Higgins, Stubler, and Kramer, 2000, for a discussion of situation assessment and response planning during the use of symptom-based procedures).

To construct a situation model, operators use their general knowledge and understanding about the plant and how it operates to interpret the information they observe and understand its implications. Limitations in knowledge may result in incomplete or inaccurate situation models. The general knowledge governing the performance of highly experienced individuals may be referred to as a *mental model,* which constitutes the operator's internal representation of the physical and functional characteristics of the system and its operation. Mental models may not always be fully accurate or complete (Woods et al., 1994). The mental model is built up through formal education, system-specific training, and operational experience. It is represented in the knowledge bases of long-term memory (LTM). The knowledge base in LTM is relatively permanent, has a large capacity, and can process information in parallel.

An accurate mental model is generally considered a defining characteristic of expert performance (e.g., Wickens, 1984; Bainbridge, 1986; Moray et al., 1986; Rasmussen, 1983; Sheridan, 1976) and is extremely important to many aspects of processing information. The mental model is thought to drive skill-based processing, control rule-based activity through the mediation of the operator's conscious effort in working memory, and provide the substantive capability to reason and predict future plant states which is required of knowledge-based processing (Rasmussen, 1983).

The distinctions between the mental and situation models reflect their cognitive underpinnings in long-term and working memory. The mental model is relatively permanent. By contrast, an operator's situation model is the current interpretation of the plant's status, and, therefore, can be rapidly changed.

When the operator's situation model is an accurate reflection of the plant's actual state, an operator is said to have good situation awareness Thus, the accuracy of situation awareness is a function of the degree of correlation between the operator's situation model and the actual plant conditions at any given time. An operator can have a good mental model (e.g., knowledge of how the plant functions), but poor situation awareness because the situation model does not match the current plant conditions. The process of situation assessment has been identified as the single-most important factor in improving effectiveness of the crew in complex systems (Endsley, 1988).

For an experienced, well-trained operator, when the HSI can provide information that readily maps to knowledge in the operator's mental model, an accurate situation model is easily developed. Situation assessment under these circumstances can occur using "automatic" information processing with little effort. Automatic processing means the behavior comes under the direct control of well-learned behavioral patterns in LTM and, therefore, has the appearance of being automatic and requiring almost no conscious effort (Atkinson and Shiffrin, 1968; Schneider and Shiffrin, 1977; Schneider and Fisk, 1983; Gopher and Donchin, 1986). Automatic processing is fast and parallel with little demand on working memory (WM) and attention. When processing information automatically, it is not necessary for the operator to maintain in working memory each detail of the situation.

To the extent that an easy match cannot be made between plant information and the situations defined in the mental model, information processing becomes more "controlled" and situation assessment requires more working memory and attention (Endsley, 1993a, 1995b; Fraker, 1988). Cognitive workload will be high. However, in addition to supporting situation assessment, working memory also must support other activities, such as the selection and implementation of operator actions. Accordingly, if other tasks place high demands on working memory, situation awareness may suffer.

Situation awareness and cognitive workload may vary inversely under complex, somewhat ambiguous situations. For example, under unfamiliar or otherwise difficult conditions, high cognitive workload may be associated with decreased situation awareness This may be due to a lack of available attentional resources for analyzing the situation. However, as Endsley (1993b) points out, situation awareness and cognitive workload, while interrelated, may vary independently. For example, a task may be intensive, but readily recognizable. Situation assessment requires the expenditure of cognitive resources that contribute to workload, but it is not the only cognitive activity requiring such resources.

Thus, mental models enable operators to engage in situation assessment and to establish situation models. Endsley (1995b) distinguishes three levels of situation awareness. Good situation models include a knowledge of the important elements of the current situation, and a comprehension of how they interrelate to reflect the overall situation. These two aspects of good situation models correspond to Endsley's (1995b) Level 1 (Perception of Elements) and Level 2 (Comprehension of Situation) situation awareness.

Mental models enable operators to make predictions and form expectations; projection of future states corresponds to Endsley's (1995b) Level 3 situation awareness. These expectations guide monitoring and affect how information is interpreted. This is a general characteristic of information processing; it is a synthesis of "bottom-up" processing (what an operator perceives from the environment) and "top-down" processing (what an operator expects) (Neisser, 1976). An example of bottom-up processing occurs during a disturbance when an operator monitors the HSI and processes data from the interface to determine what is wrong. Simultaneously, these data are used to formulate hypotheses or expectations about the plant's status that structure the perceptual process and data gathering at lower levels. This is top-down processing. Both contribute to the operator's interpretation of the situation.

The ability to make predictions using a mental model that is based on the current situation model enables the operator's performance to become more "open-loop" (Moray, 1986). "Open-loop" in this context means that behavior becomes less driven by feedback and more governed by the operator's prediction of future system behavior and the desired goal state. A NPP mental model includes such knowledge as the physical interconnections among plant systems to predict flow paths (e.g., considering piping and valve interconnections to figure out how water from one system could get into another) and knowledge of mass and energy changes in one system to predict the effect on a second system (e.g., predicting the effect that changes in levels of secondary side steam generators and temperatures will have on the primary system's cooldown). While mental models provide the principles upon which predictions can be made, the situation model provides the starting point and becomes the basis from which expectations are developed about events that should be happening at the same time, how events should evolve over time, and effects that may occur in the future.

The operator's expectations of the near-term future state of the plant is used to guide the sampling of indicators to confirm the prediction (Bainbridge, 1974). Expectations are used to search for evidence to confirm the current situation model and to explain observed symptoms. If a new symptom is observed that is consistent with operator expectations, a ready explanation for the finding will be developed, yielding greater confidence in the situation model.

While the mental model allows prediction and expectancy to guide control responses, expectancy also can make detecting subtle system failures difficult (Wickens and Kessel, 1981). When a new symptom is inconsistent with an operator's expectation, the operator may discount or misinterpret it to make it consistent with the expectations derived from the current situation model. For example, an operator may fail to detect key signals, or detect them but misinterpret or discount them, because of an inappropriate understanding of the situation and the expectations derived from that understanding. That is, operators tend to ignore or discount symptoms that are not consistent with their situation model. However, if the new symptom is recognized as an unexpected plant behavior, the need to revise the situation model will become apparent. In that case, the symptom may trigger situation assessment activity to search for a better explanation of the current observations. In turn, situation assessment may involve developing a hypothesis for what might be occurring, and then searching for confirmatory evidence in the environment. Thus, situation assessment activities can result in detecting abnormal plant behavior that might not otherwise have been observed, detecting plant symptoms and alarms that may have otherwise been missed, and identifying problems, such as sensor failures or plant malfunctions.

The situation model is constantly updated as new information is received and a person's understanding of a situation changes. In NPP applications, maintaining and updating a situation model entails keeping track of the changing factors that influence plant processes, including faults, operator actions, and automatic system responses.

The importance of mental and situation models, and the expectations that are based on them, cannot be overemphasized. They not only govern situation assessment, but also play an important role in guiding monitoring, using procedures and formulating response plans, and implementing responses.

Monitoring and Detection

Monitoring and detection refer to the activities involved in extracting information from the environment. Information about the plant is made available to the operator through the HSI and through communications via the operator's sensory organs. Some of this information is perceived, which implies that (1) a stimulus pattern was associated with a meaningful pattern based on information stored in the knowledge base or long-term memory (LTM) (see path from LTM to perception in Figure 3.3), or (2) the stimulus was perceptually intense (such as very loud noise or a very bright flash).

Monitoring is checking the state of the plant to determine whether the systems are operating correctly, including checking parameters indicated on the CR panels, monitoring parameters displayed by the process computer, obtaining verbal reports from operators in the plant areas, and sending operators to areas of the plant to check on equipment. Detection is the operator's recognition that something is not operating correctly and that an abnormality exists.

In a highly automated plant, much of what supervisory controllers do involves monitoring. For example, operators must monitor normal conditions to determine that what is expected to happen does, results of actions (feedback), normal and safety indications for changes or disturbances, performance of automated systems, problematic equipment, and activities of coworkers (test and maintenance).

Monitoring and detection are influenced by two factors: the characteristics of the environment and the operator's knowledge and expectations. These factors lead to two types of monitoring: data-driven and model-driven. Monitoring that is driven by characteristics of the environment is often referred to as data-driven monitoring. It is affected by the salience of the information's presentation (e.g., size, color, and loudness). For example, alarm systems are basically automated monitors that are designed to influence data-driven monitoring by using aspects of physical salience to direct attention. Auditory alerts, flashing, and color coding are examples of physical characteristics that enable operators to quickly identify an important new alarm. Data-driven monitoring also is influenced by the behavior of the information being monitored such as the bandwidth and rate of change of the information signal. For example, observers more frequently monitor a signal that is rapidly changing.

Monitoring also can be model-driven, i.e., initiated by operators based on their knowledge and expectations about the most important sources of information. This type of monitoring also is referred to as knowledge-driven monitoring. It can be viewed as active monitoring in that the operator is not merely responding to characteristics of the environment that "shout out" like an alarm system does, but is deliberately directing attention to areas of the environment that are expected to provide specific information.

Model-driven monitoring may be initiated by several factors. First, it may be guided by operating procedures or standard practice (e.g., control panel walk-downs that accompany shift turnovers). Second, it can be triggered by situation assessment or response planning activities, and therefore, is strongly influenced by a person's current situation model. The situation model allows the operator to direct attention and focus monitoring effectively. However, such a monitoring strategy also can lead operators to miss important information. For example, an incorrect situation model may lead an operator to focus attention in the wrong place, to fail to observe a critical finding, or to misinterpret or discount an indication.

An operator is faced with an environment containing more variables than can be realistically monitored. The real monitoring challenge comes from the fact that there are a large number of potentially relevant things to attend to at any point in time and that the operator must determine what information is worth pursuing within a constantly changing environment (Vicente et al., 1997). In this situation, monitoring requires the operator to decide what to monitor and when to shift attention elsewhere. These decisions are strongly influenced by an operator's current situation model which guides the allocation of attentional resources to sampling data from the environment based on its statistical properties; i.e., expected probability and correlation. The operator's ability to develop and effectively use knowledge to guide monitoring relies on the ability to understand the current state of the process. As cognitive workload increases, monitoring strategies become less thorough and the capability to detect particular failures decreases (Ephrath and Young, 1981).

As discussed above, under normal conditions, situation assessment is accomplished by mapping the information obtained in monitoring to elements in the situation model. For experienced operators, this comparison is relatively effortless and requires little attention. During unfamiliar conditions, however, the process is considerably more complex. The first step in realizing that the current plant conditions are not consistent with the situation model is to detect a discrepancy between information representing the current situation and information detected from monitoring. This process is facilitated by the alarm system, which helps to direct the attention of a plant operator to an off-normal situation.

When determining whether or not a signal is significant and worth further investigation, operators examine the signal in the context of their current situation model. They must judge whether the anomaly indicates a real abnormality or an instrumentation failure. They then will assess the likely cause of the abnormality and evaluate the importance of the signal in determining their next action.

Monitoring and detection have been described in terms of signal detection theory (SDT) (Green and Swets, 1988). Process control operators are in a monitoring environment that was described in SDT terms as an alerted-monitor system (Sorkin et al., 1985 and 1988). Such a system is composed of an automated monitor and a human monitor, an operator. The automated monitor is the alarm system, which monitors the system to detect off-normal conditions. When a plant parameter exceeds the criterion of the automated monitor, the operator is alerted and must then detect, analyze, and interpret the signal as a false alarm, or a true indication of a plant upset. The operator also can assess plant parameters independently of the automated monitor (the alarm system). Both the operator and alarm system have their own specific, signal-detection parameter values for sensitivity (d') and response criterion. The response criterion refers to the amount of evidence that is needed before an operator will conclude that a signaled event is actually present; this is sometimes referred to as response bias since it describes an operator's degree of conservatism. Sensitivity refers to the resolution of the system, which determines the ease with which signals (represented as a statistical distribution) can be distinguished from signals and noise (also represented as a distribution).

SDT research has many implications for understanding how operators process information during a disturbance. First, the response criterion is affected by expectancy, i.e., the expected probability that an event will occur and the payoff structure (rewards and penalties for making correct and incorrect detections, respectively). While alarms can occur frequently, significant off-normal events in NPPs typically have a low probability of occurring. Therefore, operators have low expectancy about their actual occurrence, which creates a conflict between the cost to productivity for falsely taking an action that shuts down the reactor versus the cost for failing to take a warranted action. In the real-world system, since disturbances have a low probability, operators must access and consider redundant and supplemental information to confirm the alarmed condition. Upon verification of several confirmatory indicators, the operator can accept the alarm information as indicating an actual off-normal condition (compared with a spurious condition).

There are two types of anomalies: (1) deviations from desired system function, referred to as abnormal findings, and (2) deviations from the operator's situation model, referred to as unexpected findings. The different kinds of anomalies lead to different follow-up reasoning and monitoring behavior:

- Abnormal findings lead to information processing about how to cope with the disturbance (response planning) and to monitoring behavior to see if responses to coping occurred as expected, and whether they are having the desired effect.

- Unexpected findings or process behavior lead to situation assessment activity and knowledge-driven monitoring to explain the finding.

Failures in monitoring can include failing to observe parameters, misunderstanding their significance, or failing to obtain needed information about the plant. Failures in detection can include failing to recognize an abnormality despite appropriate monitoring. An error in monitoring or detection can lead to the operator's failure to respond to the event or, at least, failure to respond within the required period.

Response Planning

Response planning refers to deciding upon a course of action to address an event. Response planning can be as simple as selecting an alarm response or Emergency Operating Procedure (EOP), or it may involve more thoroughly developing a plan in circumstances where existing procedures have proved incomplete or ineffective.

In general, response planning involves the operators using their situation model of the current plant state to identify goals and the transformations required to achieve them. The goal may be varied, such as to identify the proper procedure, assess the status of back-up systems, or diagnose a problem (Rasmussen, 1981). To achieve the goals, operators generate alternative response plans, evaluate them, and select the most appropriate one that is relevant to the current situation model.

While this is the basic sequence of cognitive activities associated with response planning, one or more of these steps may be skipped or modified based on the operator's assessment in a particular situation. When procedures are available and judged appropriate to the current situation, the need to generate a response plan in real time may be eliminated. However, even when written procedures are available, some aspects of response planning will be done. For example, operators still need to (1) identify appropriate goals based on their own situation awareness, (2) select the appropriate procedure, (3) evaluate whether the procedure-defined actions are sufficient to achieve those goals, and (4) adapt the procedure to the situation, if necessary.

The decision making involved in situation assessment and response planning, especially in ambiguous situations, such as when available procedures do not suffice, can be a large cognitive burden and draw heavily upon working memory, long-term memory, and attentional resources. In such situations, information is consciously manipulated in working memory, and the ability to do so is a direct function of the attentional resources available. Working memory has limited capacity, and without sustained attentional resources (or transfer of the information to long-term memory), information decays rapidly. Information can be lost due to (1) insufficient attentional resources to keep it active, (2) overload of the working memory capacity, and (3) interference from other information in working memory. To increase the capacity of working memory, operators use memory heuristics, such as chunking, that enable them to organize various bits of information into higher-level, meaningful units. A heuristic, as used in this report, means a shortcut for information processing developed through experience and trial-and-error rather than systematic, formal analysis. Once this is accomplished, the higher-level units, not the individual elements, are stored in working memory.

Operators need to maintain a supervisory role even when responses are largely dictated by EOPs (O'Hara et al., 2000; Roth and O'Hara, 1998; Roth, Mumaw, and Lewis, 1994). Roth et al. (1994) investigated how operators handle cognitively demanding emergencies. Their objective was to examine the role of situation assessment and response planning on guiding the crew's performance in situations where EOPs were being used. NPP operators from two different utilities performed interfacing system loss of coolant accident (ISLOCA) and loss of heat sink scenarios on training simulators where complexities made it difficult to simply follow the appropriate procedure. The results showed the importance of high-level cognitive functions during the use of EOPs. The operators developed an understanding of the plant state and confirmed their situation assessment. They also attempted to understand the plant's performance that was not expected based on their current situation model. These cognitive activities enabled them to evaluate the appropriateness of the EOP for the high-level goal dictated by the situation assessment. Roth et al. (1994) showed the importance of the crew's interaction and communication to these high-level cognitive functions. This was partly because of the need to obtain information from many HSIs in different locations. In addition, communication helped operators overcome the fact that EOPs do not address all the important information about the current plant's state. Roth et al. showed that these cognitive activities made it possible for crews to evaluate the ability of a procedure to achieve its high-level goal in the context of the current plant condition. When a specific procedure failed to meet the high-level goal, operators would alter its path to better address the situation.

Thus, Roth et al. (1994) demonstrated the importance of understanding the basis of the procedure and the higher-level goals it is intended to achieve. The need to formulate modifications to pathways of the procedure also means that operators may not simply proceed linearly through a procedure. They may need to consider future steps, reexamine previous steps and other procedures to verify that their current activities are correct and will meet the high-level goals of the procedure.

Response Implementation

Response implementation is the actual performance of the actions identified in response planning. This can be as simple as selecting and operating a control by a single operator, or it can involve communications and coordination with teams of operators in different locations of the plant, who each then select and operate appropriate equipment controls in a centrally coordinated manner. The actions may be discrete (e.g., flipping a switch) or they may involve continuous control (e.g., controlling steam generator level).

The results of actions are monitored through feedback loops. Two aspects of NPPs can make implementing responses difficult: response time and indirect observation. Time and feedback delays are disruptive to the performance of response implementation because they make it difficult to determine whether control actions are having their intended effect. In such a situation, the operator's ability to predict future states using mental models can be more important in controlling responses than feedback. Further, since plant processes cannot be directly observed, their status is inferred through indications. Thus, errors in the cognitive process can disrupt performance.

Conclusion

The performance of the operator's primary tasks places high demands on the operator's information processing facilities. As was illustrated above, even relatively straightforward activities such as interpreting alarms, monitoring plant states, and using well-defined response plans require operators to use their cognitive resources to ensure the accuracy and appropriateness of the information. We will next consider the requirement for operators to perform interface management tasks and the cognitive demands involved.

3.2.1.2 Secondary Tasks

Interface management tasks are performed in both conventional as well as computer-based CRs. CRs with conventional HSIs typically consist of very large workplaces with spatially-dedicated displays and controls where operators physically navigate to plant information by walking the boards to perform monitoring and plant control operations. Operators must visually search the boards to find the specific information they need. Sometimes the monitoring and search process is difficult because, even in conventional CRs, information can be physically hidden from view (Barber, 1996), such as by tags (as happened during the Three-Mile Island event) or by its very location away from the main CR, such as on back panels. One of the major values of the detailed CR design reviews of the 1980's was making the search process easier (Van Cott, 1997). Improvements that facilitated interface management task performance and reduced the chance for error were evident in NUREG-0700-based modifications. These included better organization of indicators and controls, improved labeling, and improved demarcation of the relationships between indicators and controls through the use of board mimics. However, there is little actual manipulation of the interface: what Vicente, Mumaw, and Roth (1997) referred to as "HSI degrees of freedom." The CR information and controls were fixed and spatially dedicated in the way the HSI designer felt was most appropriate.

Interface management demands are significantly different and greater in computer-based CRs. The characteristics of computer-based HSIs that change the nature of interface management tasks include: information volume, virtual workspaces, and HSI flexibility. Computer-based CRs coupled with digital I&C systems typically provide much more real-time information than is found in conventional CRs. While the volume of information increases considerably, it is available through a limited viewing area provided by workstation VDUs. In more advanced plants, VDU displays may be augmented with group-view displays, such as wall panel display units that can be seen from anywhere in the CR (Stubler and O'Hara, 1996). The characteristic of limited viewing area sometimes has been referred to as the "keyhole effect," an analogy to the limited view of a room that is provided by a physical keyhole (Woods et al., 1990, 1994). The consequence of the keyhole effect is that at any given time most of the information is hidden from view in a virtual workspace, i.e., the operator has only a glimpse of the current plant information through the display devices. Therefore, operators must know what information and controls are available in the "virtual information space," where they are, and how to navigate and retrieve them. If insufficient viewing area is available for operators to perform their tasks, they may have to frequently repeat navigation tasks. A problem related to the keyhole effect is that access to controls and displays tends to be serial, e.g., only a few controls can be accessed at one time. This is in contrast to the parallel presentation of controls and displays in conventional CRs. The displays and controls of conventional CRs are predominantly spatially dedicated and have fixed locations that cannot be changed in form or function. By contrast, computer-based HSIs are flexible. They can be configured and can function in various operating modes. Thus, these interfaces have a considerable number of degrees of freedom.

Based on a consideration of a variety of computer-based HSIs, the following generic interface management tasks are defined: Configuring, navigating, arranging, interrogating, and automating. These tasks can be performed "off-line" (at the same time as primary tasks) or "on-line" (such as before a shift). It should be noted that the extent to which any of these tasks can be performed, and the manner in which they are performed, is dependent on the specific details of the HSI design.

Configuring

Configuring refers to setting up the HSIs in a desired arrangement. Configuration can occur at several levels, such as workstations, individual displays, and individual functions, such as mode adjustment.

In computer-based CRs, the individual workstations may be able to be assigned general configurations that provide a unique organization of displays and controls, such as for a reactor operator or a turbine operator. Workstations may be assigned control authority or may be designated as monitoring stations only. They can be assigned an operations or test/maintenance function. Similarly, if large group-view displays are provided in the CR, the information to be portrayed may be configurable.

Individual workstations can be configured with respect to the types of displays and their layout by assigning them to individual VDUs. Individual displays may be configured to portray, for example, the specific variables to be plotted in a trend graph.

Also, individual functions may be configurable, such as assigning the soft functions on a multifunction display.

Navigating

Navigating refers to the access and retrieval of a specific aspect of the HSI, such as a display or control. This may involve developing and following a path to the desired item based on an understanding of one's current location or the location of the desired item within the information system. Navigation can also refer to accessing a specific item from within a display page; for example, scrolling a piping and instrumentation diagram (P&ID) display to locate a specific component.

Navigation may be supported by HSI-search functions to assist operators in locating and retrieving information when they are unsure of a specific navigation path.

Arranging

Arranging refers to adjustments made to the operator's view of the information. It can occur at several levels, across and within displays. For example, once a specific display is retrieved and placed on a display screen, the information may have to be rearranged to place it in a desired order to support an ongoing task or reduce clutter. The arrangement and coordination of multiple windows within a display screen is an example of this. In addition, the operators may arrange items within a display page or window, such as by suppressing (decluttering) display items or by freezing displays that are updating.

Interrogating

Interrogating refers to tasks associated with questioning the HSI to determine information regarding its status, such as the relationship of the current display to the rest of the display network or the latest file date. Also included in this category is the use of help systems. Such systems can support the user in identifying and executing interface management tasks, especially when the user interface is complex or the desired interface management operation is not very familiar to the user. Brown (1997) identified a help system as important to the implementation of a new windows-based safety parameter display system (SPDS).

Automating

Automating in this context refers to setting up shortcuts to make interface management tasks easier. For example, operators may assign a particular display to a function key to minimize display retrieval time and effort. Another example is using macro functions to reduce keystrokes for frequently performed activities. These shortcuts may be applied to any of the other interface management tasks (i.e., configuring, navigating, arranging, and interrogating).

While interface management tasks may be demanding, it is important to determine whether they draw on the same cognitive resources as primary tasks. Wickens (1984 and 1987) has defined dimensions along which task demands for cognitive resources can be compared. The dimensions include (1) Processing Stage, i.e., perceptual and central processes require different resources than response processes; (2) Input Modality, i.e., visual information processing requires different resources than auditory information processing; and (3) Information Code Type, i.e., spatial and analog mental representations require different resources than linguistic information.

When considered within this framework, the cognitive demands of primary tasks and interface management are quite similar. They both draw largely upon resources for:

- Visual modality (both process and HSI information presented on VDUs)
- Mix of spatial codes (physical layouts and relationships between plant components, systems, and functions) and verbal codes (linguistic information)
- Predominantly manual response (using commands entered via many of the same computer input devices).

Simplistically viewed, interface management tasks involve situation assessment; for example, computer-based HSIs often have modes of operation and operators must be aware of the mode to properly understand information and operate the HSI. To retrieve information, operators use their mental model of the information system to determine the location of a display in a display network (sometimes with few clues). When navigating through displays, operators plan a path, execute the plan, and monitor performance. In fact, many of the same HSI components are used for both primary and secondary tasks. For example, an operator may click a pump icon with a mouse-driven cursor to start a pump or to navigate through the display system. These tasks, and the types of interface management tasks that are described above, require controlled information processing because of the lack of spatial dedication, which is highly compatible with automatic processing and places high demand on working memory and attentional resources.

Thus, the two classes of tasks, primary tasks and interface management tasks, draw on the same cognitive resources. The next chapter addresses how the competition for cognitive resources could affect primary task performance.

3.2.1.3 Interface Management and Primary Task Performance

The relationship between cognitive resources demanded by a task and its performance is illustrated in Figure 3.4. As task resource demands increase, primary task performance is maintained at a fairly high level until the task approaches the point at which maximum resources are demanded. Beyond that point, primary task performance demands more resources than are available, and primary task performance begins to decline rapidly. Norman and Bobrow (1975), in their classic paper on performance operating characteristics, observed that:

> Resources are always limited... In general, it is this property that leads to the principal of graceful degradation. However, if there is some critical amount of a resource which is required for the results of a process to be successful, then when the resources available to that process is decreased enough, the gradual degradation will become an observed catastrophic failure in performance. (p. 45)

Thus, as illustrated in Figure 3.4, performance can be limited when resource demands exceed the available supply. In this situation, performance is "resource limited." Performance also can be limited by a lack of information, i.e., no matter how many additional resources are applied, performance cannot improve because there is a lack of information. Norman and Bobrow (1975) described this as "data-limited performance."

The relationship between the performance and resource supply can get more complicated than the simple relationship illustrated in Figure 3.4. For example, consider the hypothetical performance-resource function in Figure 3.5. The function indicates that a certain amount of resources are necessary in order to initiate performance (see R_{min} in Figure 3.5). At this point, some level of task performance is immediately achieved. After that point, performance increases monotonically as resources are increasingly devoted to the task. Although for some tasks the performance-resource function may be monotonically increasing, for others, there may be points in the function where performance levels off as the resource demands increase considerably (see the flat portion of the function within the resource-limited region of Figure 3.5). Once sufficient resources are applied, task performance increases once again.

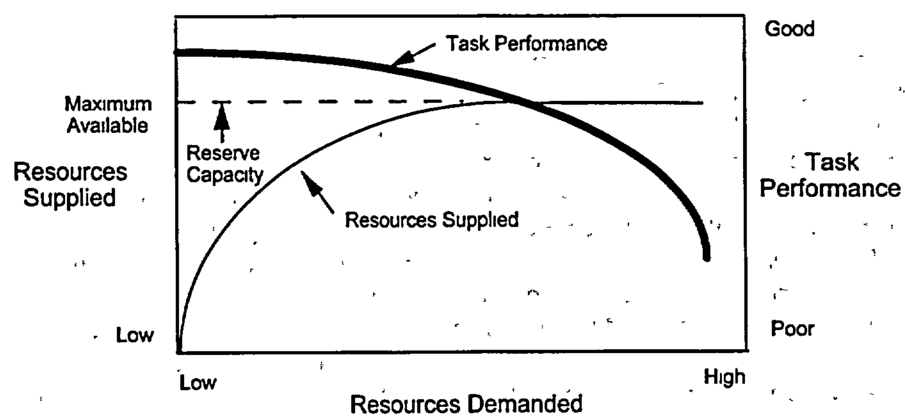

Figure 3.4 Resource demand and performance
(adapted from Wickens, 1984)

In some cases, there may be a point at which increasing cognitive resources has no effect on task performance and the level of performance reaches an asymptote (see R_{dl} in Figure 3.5). That is the point at which performance becomes limited, not because of a lack of resources, but a lack of data. That is, regardless of how much additional resources could be devoted to the task, performance will not improve because there is no additional information from the task environment that can be processed to improve performance.

In some cases the relationship between cognitive resources and task performance can be described by this function (i.e., tasks have both resource-limited and data-limited regions), although its form will change depending on the specific task demands. The next question that arises is what happens when a second task (or class of tasks) must be performed concurrently with the primary task.

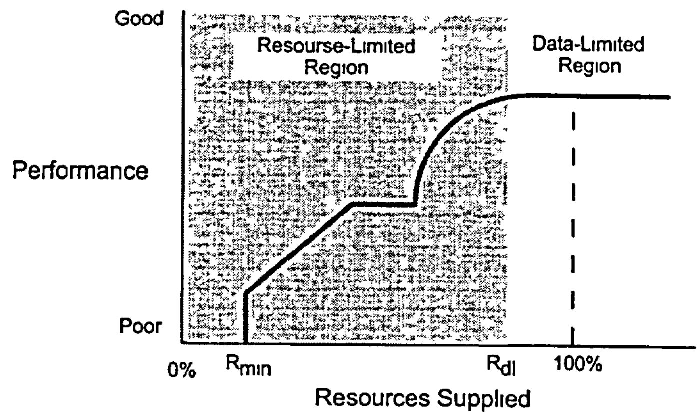

Figure 3.5 Performance resource function
(adapted from Norman and Bobrow, 1975)

This has been studied in dual-task research using the "secondary-task" paradigm, especially in the context of workload measurement. In order to determine the amount of cognitive workload that is associated with a primary task, such as driving a car, a person is given a concurrent secondary task, such as a memory search. The person is instructed to perform this secondary task while maintaining performance on the primary task. Thus, as the performance of the primary task is maintained, the secondary task is performed with the spare processing resource capacity. The logic of the secondary task approach is simple. If it is assumed that the total resource capacity is equal to one, and the primary task utilizes "x" resources, then 1-x is left in reserve to be used for the secondary task. The performance on the secondary task, therefore, is assumed to have an inverse relationship with the level of workload associated with the primary task. If primary task performance is the same under conditions A and B, but the secondary task performance was better in condition A, the conclusion is that condition A was less cognitively demanding than condition B.

There has been an extensive amount of research examining the division of attentional resources between dual tasks. Wickens concludes from this research that the greater the extent that two tasks require separate resources, the more effectively they can be timeshared. That is, changes in difficulty of one task will be less likely to affect the other. Thus, two tasks competing for the same resources will be performed less well than if they require separate resources (Moray, 1986; Wickens, 1987). As a simple example, it is easier to drive a car and talk with a passenger than it is to drive and manually tune an analog radio. While both involve two simultaneous tasks, the former situation involves less competition for common processing resources than the latter because it is mainly an auditory task. Tuning the radio requires resources for visual processing of information and, thus, may compete with resources required for processing visual information from the road.

Based on the multiple resource model, it can be assumed that operator performance will be impaired when concurrent primary tasks and interface management tasks will impose demands on the same cognitive resources. Conversely, it is assumed that operator performance will be enhanced by an HSI design that produces a good allocation (i.e., the competition for cognitive resources between the supervisory control and interface management tasks is minimized). When applying the multiple resource model, it is important to know which of the structural dichotomies produce effects that are of practical significance in multiple task environments and which produce effects that are only of theoretical importance. This is important both for the assessment of HSI features for interface management and for the selection of measures and criteria for testing HSI designs.

A study of the relationship between the cognitive resources and multiple task performance was conducted by Sarno and Wickens (1992, 1995). The study investigated three workload models that have different assumptions regarding cognitive resources, and then determined the degree to which each model accounted for task performance data that had been collected in a previous aviation simulator study. The purpose was to determine which models provided the best predictions of operator performance. The concurrent tasks were a continuous two-axis tracking task with first-order dynamics, a continuous visual monitoring task, and a discrete decision task. The continuous visual monitoring task required the participants to monitor two analog (edge meter) indicators located at the periphery of the tracking task display. The participants were required to push a button if either indicator exceeded its normal operating range. The decision task had 16 variations, which were created by combining the following factors: input modality (visual versus auditory), processing code (spatial versus verbal decision tasks), difficulty (two levels), and response modality (spoken versus keyed response).

The three workload models evaluated in this study were Timeline Analysis and Prediction (TLAP), the VACP workload model, and the Workload Index (W/INDEX). Each of these models is based on the concept of multiple workload components (i.e., different mental resources capable of performing different types of processing on different types of information). Each model assumes parallel processing of information and provides predictions regarding interference between concurrent tasks. The models differ in their assumptions regarding five considerations related to timesharing of mental resources: the nature of workload components, coding of cognitive processing, classification of voice response, coding of task demands, and the use of overload red-lines (i.e., the point at which participants are incapable of maintaining optimum performance).

All three provided predictions substantially correlated with overall performance. The TLAP model provided the best prediction, accounting for 77% of the variance. W/INDEX accounted for 65% and VACP accounted for 61%. For completeness, a simple single-channel workload model (i.e, one that does not assume multiple resources) was also tested. Its predictions were negatively correlated with performance ($r = -0.25$).

Next, hybrid workload models were developed by the investigators by manipulating the assumptions for the five timesharing considerations. The best hybrid model accounted for 85% of the variance. Its assumptions were that (1) workload components overlapped (i.e., interference between tasks was computed via a conflict matrix), (2) spatial and verbal cognitive processing were not distinguished as separate workload components, and (3) voice response was classified as a separate workload component. In this analysis, no theoretical overload red-line was used. In addition, task demands were coded two ways: quantitatively on a scale from 0 to 7 and dichotomously as either 0 or 1.

Their findings have implications for assessing the effects of interface management on primary tasks. First, the results provide further evidence that the multiple workload component approach is valid for describing workload and predicting performance in multiple task environments. Thus, it is meaningful to describe workload demands imposed by interface management tasks in terms of the information code required, cognitive processing stages, and response execution. However, it also provided some evidence that the workload components (i.e., visual perception, auditory perception, cognition, and psychomotor response) are not entirely independent, but instead can interact and interfere with each other. This finding implies that interference between cognitive resources cannot be completely avoided by designing the HSI so that different cognitive resources are loaded by the supervisory and interface management tasks. Even if these tasks impose demands on different resources, some interference may still exist.

Second, their results provided additional evidence that voice response was different from other types of psychomotor response. This suggests that speech output may be a useful way to off-load response execution tasks that are primarily performed using psychomotor activities, such as tasks requiring the operation of keys and mice.

The potential benefit of using voice input or voice output to off-load other cognitive resources should be considered in light of other verbal activities performed in the work setting. For example, an important part of an operator's role is to hear and process verbal instructions or information from other crew members and then provide a verbal response. HSI technologies that use voice input or output for interface management tasks may reduce the demands on cognitive resources used for some primary tasks, such as operating controls. However, the use of these technologies may also interfere with other primary tasks that already involve verbal input or output or the processing of linguistic information. Thus, the use of voice in a control room would have to be carefully evaluated for these tradeoffs.

In the dual-task situation, operators are not always able to performance of the primary task at a constant level. The secondary task may slow primary task performance (as the two tasks are timeshared - performed serially), performance may degrade (as greater variation in the primary task is created because it is not monitored/performed as carefully), or performance may be interrupted (as the secondary task distracts the operator from the primary task and the operator loses track of the primary task).

In a multiple-task environment personnel process information from more than one source and perform more than one task at a time (Wickens and Carswell, 1997). A NPP CR is an example of a multiple-task environment in which operators encounter competing task demands. When discussing these tradeoffs for a multiple-task environment, two points should be recognized. First, interface management tasks are often, although not always, an integral part of supervisory control tasks. For example, before a specific supervisory control action can be executed, the operator must first perform the interface management tasks necessary to access the required control or display. Second, operators often concurrently perform multiple supervisory control tasks. Thus, human performance in a multiple-task environment may entail the allocation of cognitive resources among *multiple* primary and secondary tasks.

Wickens and Carswell identify three different modes of multiple-task behavior (1) *perfect parallel* processing, in which tasks are performed concurrently at the same levels as when each is performed separately, (2) *degraded concurrent* processing, in which tasks are performed concurrently, but one or more suffers relative to its single-task level, and (3) *strict serial* processing, during which operators perform only one task at a time. These three modes occur under different conditions (different loadings of cognitive resources) and have somewhat different implications for HSI design. In addition, operators adopt strategies to cope with changing task demands. The first set of strategies includes shifts in work objectives and methods during periods of escalating task load. The second set includes strategies for modifying the HSI to be more compatible with task demands and cognitive capabilities. An understanding of these topics is needed to understand the effects of interface management tasks on primary task performance.

Tasks may be performed serially for two reasons. First, tasks may be sequentially constrained such that the second task cannot be performed until the first is accomplished (e.g., one cannot turn the ignition key in an automobile until it has been inserted in the keyhole). Second, tasks may be performed serially because they draw on the same pool of cognitive resources and the resources are not sufficient to support both tasks concurrently. Performing tasks in serial mode becomes a human factors concern when the performance of one task delays the other tasks to an undesirable extent (Wickens and Carswell, 1997). For example, plant safety may be challenged if an operator fails to check an important plant parameter because he is attending to another task.

Human factors investigations have focused on the process by which the operator chooses to perform one task and, by necessity, neglects another at a given time. This choice process involves managing tasks based on their perceived priorities. It is often modeled mathematically, such as via queuing theory. Models of optimal behavior describe (1) when a task should be performed, as a function of the task's importance (e.g., the cost of not performing it), and (2) the frequency with which it should be carried out to achieve an optimal level of performance of the human-machine system. When actual human performance is compared to these models, operator performance appears to be reasonably optimal, with the following limitation. When personnel are prone to forgetting the last monitored value, they tend to sample the variable more frequently than an "optimal" performer who has perfect memory (Sheridan, 1980). Models of optimal behavior are important for the development of HFE guidance for interface management because they identify dimensions that may be used when describing actual performance and provide a framework for comparing actual performance to theoretically optimal levels of performance. The following describes some key studies in this area.

In his investigations of supervisory control, Sheridan (1980) developed a mathematical model of monitoring behavior for automated systems. This model describes how a cognitive resource for monitoring is allocated in time to address multiple tasks. The tasks are modeled as occurring at random time intervals, remaining for varying periods of time, and providing varying levels of reward to the user for servicing them. The model provides insights into the frequency with which automatic systems should be monitored. It prescribes that, when an information channel is being monitored or supervised to detect an important event, the optimal amount of time that attention should be diverted away from that channel (i.e., to attend to a competing task) is:

- Inversely related to the bandwidth of the channel (i.e., the frequency with which events occur)
- Inversely related to the cost of missing events on that channel
- Directly proportional to the benefits of performing the competing task
- Directly proportional to the reliability of the operator's memory of the state of the channel when last sampled.

Thus, as the channel bandwidth increases and the criticality of detecting an important event increases (i.e., the cost of missing an event), the operator should monitor the channel more frequently. This assumption was derived from earlier studies in aviation that indicated that, for a set of similar instruments displaying signals outside of an indicated tolerance range with different bandwidths, pilots tend to visually sample each instrument at rates proportional to their bandwidth (Sheridan, 1980). Conversely, as the benefits of performing a competing task increase, the operator should spend more time away from the channel (i.e., monitor it less frequently). Finally, to the degree that the operator's memory is unreliable, the operator should monitor the channel more frequently. Thus, the optimal sampling rate derived from these considerations maximizes the expected payoff of the monitoring behavior. The predictions of this model were validated in laboratory studies (Wickens and Seidler, 1997).

Tulga and Sheridan (1980) extended the supervisory sampling model by developing an optimal attention-allocation algorithm to address the situation in which multiple task demands appear randomly and with varying deadlines (after which no gain can be had from servicing the task) and tasks occurred more frequently than could be performed one at a time. The model predicts that when the task load exceeds the ability of operators to service all of the tasks, the operators maximize their gain by choosing to service those tasks that have the highest expected payoff. Tulga and Sheridan evaluated this model by conducting empirical tests in which participants performing a monitoring task at a computer-based graphical display. The results indicated a "reasonable fit, under various model parameters and task conditions" (Tulga and Sheridan, 1980, p. 217). They found that the model behaved much as the participants did with regard to which tasks were conducted and which were ignored. However, the participants and the model differed with regard to the order in which some tasks were performed. Tulga and Sheridan concluded by proposing that after workload becomes excessive and the operator adopts the optimal strategy of directing attention to the task with the best immediate payoff, the operator's subjective assessment of workload will decrease. They state that this decrease will occur despite an increase in the actual external task load. This is apparently because the operator is focusing attention on a smaller portion of the situation rather than on the total problem. Thus, when this strategy is adopted, increases in the external task load become less relevant to the operator.

This model has implications for interface management tasks under very high workload conditions. One interpretation is that during such conditions when the operator is focused on a task that has a high payoff, he or she many disregard other tasks considered to be of lower importance at the moment. For example, an operator who is concentrating on a particular, highly important monitoring or control task may temporarily discontinue general monitoring of overall plant condition because he or she feels that the benefit of attending to the current task outweighs the potential problems of monitoring for other problem conditions. However, if this strategy is chosen, the operator stands a chance of losing awareness of other possibly higher priority situations that may be developing. In this case, the interface management task is avoided, not so much because the cognitive demands associated with the interface management actions are high, but because the task of updating situation assessment is expected by the operator to provide less benefit than continuing with the primary task at hand. In effect, the operator chooses to not perform the interface management task.

When tasks are performed serially, scheduling is important. Traditionally, workload for serial tasks has been modeled as an open-loop system - tasks vary with respect to the demands they impose and performance depends on the operator's aptitude for dealing with these demands. Thus, scheduling was conceived as the operator choosing among currently available choices without much consideration of the implications of those choices on future workload levels. Hart and Wickens (1990) proposed an alternative, closed-loop model in which the operator uses, at times, different available resources to mediate task demands. The model assumes a proactive rather than reactive operator who plans for possible demands, allocates resources to different tasks, sets priorities, evaluates the time to accomplish a task, and finally establishes schedules. Thus, the optimum operator has a clearly defined task priority. As workload becomes excessive, tasks at the bottom of a hierarchy are postponed or canceled. In this regard, the model is consistent with the findings of Sperandio (1978), who observed that air traffic controllers changed their work objectives and methods as the external task load increased. Hart and Wickens state that plans for operator actions are first generated on the basis of the initial conditions of the situation. However, these plans are modified by operators in response to changing conditions, the time available to finish the task, and the operator's level of performance (e.g., speed, accuracy) on the task.

Raby and Wickens (1990) conducted an experiment to test issues related to the Hart and Wickens model. This simulator study addressed pilot performance in landing a twin engine aircraft. Three landing approach speed conditions were tested. The higher approach speeds represent higher levels of external task loading. During each flight, the pilot performed tasks that experimenters had previously categorized according to three levels of priority: "must" (highest), "should" (medium), and "could" (lowest). The study examined (1) the optimality in rescheduling or 'shedding' tasks according to their priority as workload increases, and, (2) the accuracy with which pilots forecasted the time required to carry out specific events. The increased workload conditions affected both the overall flight performance and the planning and scheduling of the tasks. Changes in the amount of time spent on these tasks was consistent with the model. That is, when workload increased, pilots spent more time performing the "must" tasks, less time performing the "should tasks," and put aside tasks from the "could" category in order to complete the approach safely. In addition, the pilots performed a separate subjective rating of these tasks. Their assessments of priority were consistent with the categories that previously were established by the experimenters, based on assessments by flight instructors. The study also found that participants were not highly sophisticated in scheduling tasks optimally on the basis of anticipated demands or current workload conditions. However, while they tended to assign the correct priority to tasks, they also tended to underestimate the amount of time required to complete them.

Raby and Wickens (1994) state that cognitive resources are required to determine how to optimally schedule and manage tasks in multiple task environments. They conclude that these resources may become unavailable during high-workload conditions, resulting in sub-optimal scheduling and management of tasks. This finding is relevant to interface management tasks performed in NPPs. It suggests that when supervisory control tasks become very demanding, operators may lack the cognitive resources needed to plan interface management tasks well.

Segal and Wickens (1990) conducted a test of scheduling strategies used by pilots for managing their workload level, including the use of knowledge of situations that would be encountered. Pilots were divided into four groups defined by (1) the presence or absence of information regarding the type and stage of difficulties that would be imposed during the flight, and (2) the presence or absence of the capability to control the schedule of some tasks during the flight. The information about future conditions identified the category of problem, but did not identify the problem in detail, and the stage of the mission in which the problem was to occur. The focus of this study was on three factors (1) the level of difficulty of scenarios, (2) the degree of control that pilots had over task scheduling, and (3) the pilots' knowledge of flight difficulties that awaited ahead. The results indicated that having access to information about future conditions supported pilot strategies that yielded significantly higher levels of performance. However, control over task scheduling seemed to have no impact on performance. On all performance measures, the average scores achieved by the two groups of pilots who received the advanced information were higher than those achieved by the groups that had no such prior knowledge.

The benefits of this information was attributed to two possible effects. First, it may allow tasks to be scheduled so they may be performed at the easiest time. Second, it could indirectly benefit tasks that cannot be rescheduled by possibly reducing the need to anticipate or worry about future events. Segal and Wickens (1990, pp. 69) state

> The operator who knows with certainty that things will not get worse in the future can now devote himself fully to activities in the present, without worrying about monitoring for possible changes in conditions. By the same token, knowing with certainty that conditions will deteriorate, the [operator] can prepare to deal with the now certain increase in workload when it does occur, with much less disruption.

It was concluded that having information on future conditions allowed better global planning of task distribution. With this information available, pilots prepared for future conditions. However, when this information was not available, participants did not invest resources in preparing for worse case conditions. Instead, they anticipated and prepared for *typical* conditions. They then reacted to worsening conditions as they occurred. These findings indicate the importance of HSI features, such as alarms and displays, that allow operators to anticipate future conditions. HSI characteristics, such as reduced access to displays due to the keyhole effect, can restrict operator access to information that supports global planning.

Norman and Bobrow (1975) examined the role of expectation and distraction in human performance. It was found that when participants focused their attention on a stimulus, they appeared to perform equally well on tests involving responses to both newly learned and well-learned patterns. However, performance on newly learned patterns deteriorated if the patterns were presented to the participants unexpectedly. The interpretation by Norman and Bobrow was that when only a single, expected task is tested, then both well-learned and newly learned recognition processes will be in the data-limited range and, hence, both will produce equal performance. However, under distraction conditions, the newly learned process may be driven to the resources-limited region, but the well-learned process will tend to stay in the data-limited region. As a result, the well-learned task will be affected less by distractions. In addition, Norman and Bobrow suggest that even well-learned processes can be forced into the resource-limited region and diminish performance if severe attentional distraction is encountered. Thus, task performance can be enhanced by HSI features that present task information in ways that support planning and prioritization while avoiding distractions that impose unnecessary demands on attention.

Based on their review of empirical research, Wickens and Carswell (1997) identify three factors for improving operator performance in multiple-task environments in which tasks are serially processed. The focus is on addressing situations in which personnel fail to perform important tasks within the necessary time. These factors have implications for the design of HSI features that support interface management tasks, and are discussed in light of the findings described above.

First, visible or auditory reminders tend to increase the likelihood that a particular task will be performed, compared to situations in which task initiation must be based on prospective memory alone. For example, an operator who is focusing attention on one task may forget to periodically attend to other tasks. Checklists support personnel in performing actions at required times (Wickens and Carswell, 1997).

The concept of reminders described by Wickens and Carswell addresses tasks that are known to the operator and can be held in prospective memory. However, the argument for the benefits of reminders can also be extended to warnings and alerts, which address new conditions that may not be known to the

operator. For example, an operator who is focusing attention on one task may forget to monitor the other indications to detect new problems. Warnings and alerts can direct operator attention to these new conditions and provide information that can be used for anticipating future tasks and prioritizing and planning actions. Such advanced notification may improve the prioritization and planning of tasks, and improve the utilization of cognitive resources, as described by Raby and Wickens (1990). Some examples of HSI features that can provide advanced warnings and indications include: checklists and computer-
based aids that allow the operator to look ahead at future activities (e.g., computer-based procedures that show upcoming steps), trend and predictor displays, and alarms and displays that provide early warnings of a developing conditions.

As mentioned earlier, this information should be presented in ways that reduce distraction, since distracting stimuli can impose high demands on attentional resources. This may drive the usage of cognitive resources into the resource-limited region, thereby diminishing overall task performance. Where distracting stimuli cannot be avoided, the future benefit of improved planning should be weighed against the near-term costs of the immediate distraction. For example, advanced warnings may not be appropriate if they impair the performance of on-going tasks.

Personnel training was the second factor identified by Wickens and Carswell. A high workload associated with one task may lead an operator to neglect other tasks or fail to return to another task when necessary. This deficiency may be addressed by operator training that is directed toward interface management and workload management.

The third factor noted by Wickens and Carswell was the pronounced differences between individuals with respect to the kind and effectiveness of task management strategies they employ. Wickens and Carswell state that these differences should be considered for personnel training and qualification.

The ability to perform multiple tasks at the same time, whether in perfect parallel or degraded concurrent mode, depends upon the information-processing characteristics of the tasks and the cognitive resources required for this processing. This contrasts with the serial tasks, which depend more upon the ability of the operator to prioritize and schedule tasks. Wickens and Carswell (1997) identify three factors that support concurrent processing: task demands, task similarity, and task structure. Each is described below.

- *Task Demands* - Less difficult tasks are more likely to be performed concurrently than are more difficult or demanding ones. Easier tasks tend to be more "automated" in the sense that they may be performed with fewer demands on the operator's attention and working memory. Difficult tasks tend to require more cognitive resources, especially attention. As a result, there may be few cognitive resources available for performing other tasks at the same time.

- *Task Similarity* - A high degree of similarity between two tasks may result in confusion that inhibits concurrent processing. For example, an operator may wish to perform a control action and an interface management task at the same time. Similarity in perceptual signals may result in confusion in identifying the correct item to act upon. Similarity in information held in working memory may increase the degree of interference between them, causing memory failures, such as the inability to remember one or both of the items. It may also result in errors of execution (slips), such as capture errors in which the operator intends to perform one action but performs another action that is composed of similar task elements. On the other hand, similarity in the means of executing tasks can be beneficial by supporting task integration. For example, if two tasks are performed with similar actions and similar input devices, then the concurrent execution of both tasks may be enhanced by this similarity. Some concurrent tasks may actual involve rapid sequential shifts between the different ones. Similarity in the rules for executing the tasks can support these rapid shifts. That is, it is sometimes easier to alternate between different versions of the same task than it is to alternate between completely different tasks because there is a mental overhead penalty associated with switching between rule sets. Task similarity is affected by HSI consistency.

- *Task Structure* - Task structure refers to the organization of elements of the tasks and their relationships to the cognitive resources required to perform them. Certain structural differences between two tasks that are time-shared can increase the efficiency of their concurrent processing. That is, it is easier to concurrently perform two tasks that are distributed across multiple cognitive resources than to perform them within a single resource (Wickens and Carswell, 1997; Wickens, 1991; Wickens, 1980). Interference may occur to the degree that the tasks impose overlapping demands on the same resources. This overlap may account for performance differences in degraded concurrent processing and perfect parallel processing. If interface management and supervisory control tasks impose concurrent demands on the same cognitive resources, then the performance of either or both tasks may be reduced.

When considered within the context of operators performing interface management tasks under high workload conditions, operators must assess the value of information they may obtain against the cost to primary task performance. Wickens (Wickens, 1994; Wickens and Carswell, 1995; Wickens and Carswell, 1997) referred to this as information access cost which is defined as "the time and effort required to move attention from one displayed information source to another. It incorporates movement of the head, movement of the eyes (visual scanning), and movement of an internal 'attention pointer', even when no scanning is involved" (Wickens, 1994, p. 2). Information access cost results from mismatches between the requirements for accessing information and the design characteristics of the display. It places increased demands on attention and working workload. When multiple tasks impose competing demands on resources for central cognitive processing, the information access costs can result in interference and degraded performance in one or both tasks. The concept of information access cost is discussed below for two cases (1) accessing information from a single viewable area (e.g., a display page) and (2) accessing information from a display network.

Accessing Information within a Display Page

When information is accessed from a single viewable area, such as multiple items are presented on a single display page (or individual indicators on a control panel), then the information access cost is affected by such factors as the physical distance between the two locations, intervening clutter, and the degree to which the information of the two locations must be integrated. Vincow and Wickens (1993) conducted a study in which participants viewed a series of alphanumeric tables containing information regarding attributes (e.g., cost, amount) for different objects (gas and electrical utilities). The task was to find specific pieces of information that were located on either the same or different tables of a display and then performed either simple or complex integrations on the information. Simple integrations involved straight-forward comparisons of values. The complex integrations required the participants to hold one piece of information in working memory, search for the other piece of information, and then mathematically integrate the pieces using an operation such as multiplication or division. For the complex integrations, response accuracy, as indicated by the percentage of questions answered correctly, suffered under the condition of increased separation between the information pieces (i.e., the data was distributed over two tables). That is, when the task required a complex integration, there was a performance cost of separation - accuracy decreased by an average of 26 percentage points. When the task required less integration and, therefore, placed less load on working memory, the increased distance did not affect accuracy. The results suggest that the increased information access cost associated with the increased separation between the information pieces interacted with the increased working memory demands associated with the complex integration operations. Together, they decreased accuracy by overloading working memory with the stored information, the search demands, and the integration demands.

Wickens and Carswell (1995, 1997) explain this effect in terms of the proximity compatibility principle. This principle states that as task proximity increases, operator performance is enhanced by increased display proximity or impaired by decreased display proximity. O'Hara, Higgins, and Kramer (2000) discussed the proximity compatibility principle, as it relates to display design. The following are some important considerations of this principle.

Task proximity can be defined in terms of:

- *Temporal proximity* - The degree to which two tasks must be performed at the same time to achieve a goal.
- *Processing proximity* - The overlap between the information processing that is needed to process different information.
- *Statistical proximity* - The degree of covariation between information (e.g., when two parameters covary or when a change in one is reflected in a change in the other the relationship has high statistics proximity).
- *Functional proximity* - The similarity of objects as represented in the operator's mental model (e.g., all parameters describing the performance of a single component have functional proximity).

Thus, task proximity is said to increase if one or more of these four factors increases.

Display proximity addresses the perceptual similarity of displays that convey information about the same task. The following dimensions of display proximity were identified by Bennett, Nagy, and Flach (1997):

- *Spatial proximity* - The physical distance between information items.
- *Chromatic proximity* - Similarities in the use of color codes for information items.
- *Physical dimensions* - Similarities in the use of physical characteristics (e.g., length, volume) used to convey information
- *Perceptual coding* - Similarities in the format used to represent information (e.g., analog versus digital forms)

- *Geometric form* - Whether or not the information items are presented separately (i.e., lower display proximity) or as part of an integrated object (i.e., higher display proximity).

Thus, display proximity may be said to increase if one or more of these factors increases.

Display proximity supports information processing in two ways. It allows the perception of emergent features and supports object-based parallel processing (Wickens and Carswell, 1997). Emergent features are relational properties of a group of display elements that are not properties of the elements in isolation. For example, a set of moving pointer indicators that are placed side by side may produce the emergent feature of pointer alignment. If during normal operating conditions all of the pointers have the same alignment, then the perception of this alignment provides a shortcut for assessing the condition represented by each indicator (i.e., it eliminates the need to read and interpret each indicator separately).

Object-based parallel processing refers to the ability to perceive data as a single perceptual object, rather than as a collection of individual items. This type of processing reduces scanning and integration demands. It can be encouraged through the application of display design techniques to the data. One technique is to apply lines to the adjacent axes of polar graphic displays to connect the current values. This produces a perceptual object, such as a polygon. Perceptual objects may have a variety of emergent features such as global shape, symmetry, and area. Operator response may be aided if the perceptual objects and their emergent features are designed to represent task-relevant information. [HFE guidance for the review of displays that make use of emergent features and perception of visual objects is provided in O'Hara, Higgins, and Kramer, 2000.]

Therefore, when high display proximity is provided for tasks that require a high degree of integration of information, the proximity compatibility principle predicts that operator performance will be enhanced. This occurs because visual search demands are reduced by such factors as:

- Shortened distance between information items

- Reduced demands associated with identifying important variables based on the use of display objects that combine multiple variables into a single recognizable form; and

- Reduced demands for interpreting information based on emergent features that convey higher level relationships (e.g., whether values are in or out of the expected range).

Conversely, when low display proximity is provided for tasks that require a high degree of integration of information, then the cost of accessing information is *increased* by the increased distance between needed information items and the presence of clutter from information items unrelated to the task.

In low proximity tasks, the operator focuses on individual information items and uses them separately. The proximity compatibility principle predicts that attempts to provide high display proximity for low proximity tasks will *impair* operator performance. That is, reducing the distance between information items, combining unrelated data into an object, or creating emergent features from a group of unrelated data, will create visual clutter. This will increase the amount of effort required to identify the correct information item.

Vincow and Wickens (1993) provided recommendations to display designers based on their study. Also, the dimensions of display and task proximity have additional implications for the design of display pages.

Based on these considerations, the following considerations for the design of displays pages are offered. They are particularly relevant to display pages containing high quantities of information that may require extensive visual search:

- *Minimize integration demands* - Avoid complex integration operations, when possible. Displays should present information in a form that has already been synthesized and is in a directly usable form.

- *Organize related information into groups* - Anticipate interference between complex interaction operations and distant scans by grouping the information that is to be integrated.

- *Present distant data in ways that enhance identification and integration* - The identification of related information items can be supported through the use of display design techniques which enhance the similarity of related information, including chromatic proximity (e.g., similar color coding), consistent physical dimensions used to code information, and perceptual coding (e.g., consistent presentation in analog or digital form). In addition, the integration of distant information items may be supported by the consistent application of display design techniques for conveying meaning across related information items. This may include consistent use of physical dimensions to code information and consistent perceptual coding of information in analog or digital form.

When the size of the display page exceeds the size of the display device, the operator may be required to perform zoom, pan, or scroll actions to view the desired information. If complex integration of the information is required, then the operator must hold information in working memory while navigating from one location to another. In the study by Vincow and Wickens (1993), the concurrent demands of display navigation and information integration affected each other. This effect was greater when the separation between information items was greater or when the integration demands were greater (i.e., complex integration was required). In this study, navigation in the display was fairly simple; the participants moved from one location to another by merely turning their heads or by shifting their eye gaze. However, the navigation tasks in large displays that require the operator to zoom, pan, or scroll may be more cognitively demanding. The operator must comprehend the relationship between the current location and the desired location, plan a navigation move, and then execute a navigation action. These demands are likely to impose higher demands that interfere with the information integration task to a greater degree. Thus, when operators are required to integrate information across a large display, the HSI should be designed to minimize navigation burdens to make more resources available for the information integration task.

The above discussion suggests that to reduce navigation demands in large displays, the HSI should do the following:

- *Minimize the complexity of the navigation moves* - Simplifying the navigation action may reduce the demands imposed on cognitive resources, especially central cognitive processes (e.g., determining relationships between the current and desired locations) and response processes (e.g., manipulating the navigation control). The least demands are associated with displays that require no panning, scrolling, or zooming. More demands are associated with displays that require motion in one dimension (e.g., panning in either the vertical or horizontal direction, but not both). Still more demands may be associated with displays that require motion in multiple dimensions (e.g., panning in both the vertical and horizontal directions or panning plus zooming).

Therefore, displays should be designed to minimize the number of dimensions that must be manipulated to access the information.

- *Support comprehension of navigation moves* - The central processing demands associated with the move may be greater when the current and target positions cannot be seen at the same time on the display page. In such cases, cognitive demands may be imposed for developing a mental representation of the display page and for determining the relationship between the starting and target locations. If the navigation moves proceed as a series of discrete steps, then additional demands may be imposed in developing an understanding of the relationships between each of these discrete views. These processing demands may interfere with the cognitive task involved with information integration. The concept of visual momentum (Woods, 1984) addresses approaches for supporting the user's understanding of the relationships of information items in a display space. These approaches may be applied to large displays to reduce information access costs.

- *Minimize the amount of time needed to complete a display navigation move* - Moving from one location to another on the display page requires time. It may be affected by such factors as the number of steps in a navigation move, the length of the navigation moves, and the display system's response time. As the length of time increases there is an increased likelihood that the information held in working memory will be lost. Therefore, the amount of time needed to complete a navigation move should be minimized. This may be accomplished by reducing the response time of the display system or reducing the number of actions required to complete a navigation move.

- *Minimize the difficulty of target detection* - When moving from one location to another on the display page, cognitive demands are imposed on perceptual processes for detecting the target information item. These demands may increase the amount of time required to complete the navigation move and, therefore, increase the likelihood that the information held in working memory will be lost. Therefore, the HSI should be designed to facilitate target detection. For example, the targets should be visually distinct from the background. Also, the scrolling, panning, or zooming motions should be sufficiently slow when approaching the target so the operator can recognize the target.

<u>Accessing a Display From a Network</u>

When information items are distributed across pages of a display network, they are separated in "computer" space rather than physical space. A set of studies was conducted by Wickens and Seidler to examine concept of information access cost as it applies to accessing information from a display network. In the first study (Seidler and Wickens, 1992), participants used a data base to perform two kinds of tasks. In the "go find" tasks, they were required to simply access a screen to obtain a given item of information. In the "integration" tasks, they were required to traverse between two screen, holding information from the first screen in memory so it could be integrated with information on the second screen. The navigation paths varied in terms of (1) navigation distance (i.e., the number of displays between the two locations), and (2) organizational distance (i.e., whether or not the starting location and destination were within the same branch of the display network). In addition, in some trials, participants could shorten their traversal to the top of the menu structure by using a button that immediately accessed the main menu. However, in other trials participants could only ascend the display network hierarchy one level at a time by pressing a "previous" button.

This study yielded four findings that are important to interface management features for navigating display networks. First, navigation distance was found to be a prime determinant of information access cost. That is, the time required to access information increased with the navigational distance. Second, as predicted by the proximity compatibility principle, navigation distance was found to interact with the information integration requirements. As navigation distance increased, the accuracy of the integration task decreased. As in the study by Vincow and Wickens (1993), the explanation was that the concurrent tasks of holding information in working memory and navigating the display network interfered with each other. As the navigation distance increased, the interference was greater. Third, a reduction in information access time was found when the structure of the data base did not correspond to the participant's mental model. Fourth, a decrement in information access time was found when the starting and destination display pages were within the same major branch of the display network (i.e., when organizational distance was small) and the participants used the "previous" button.

The second finding is consistent with findings of usability specialists and designers for other computer-based systems. In observational studies of users navigating internet websites (Danca, 1997), it was found that the design of some websites forced the user to return to a central location before navigating to another location to begin the next step of a task. This was a serious obstacle to users who were trying to compare information from the different sections. It was concluded that the combination of requiring users to make transitions from the central location and remember information during the transitions hindered the process of mental integration. However, it was also found that requiring the user to make transitions back and fourth from a central location could be a benefit for tasks that did not require the user to remember information. For these tasks, the transitions from the central location provided a context that helped the users maintain awareness of their location in the website. It was concluded that this ability to provide context may be particularly useful when users try to perform complete complex tasks that are not very familiar.

The fourth finding reflected an increase in mental workload that resulted from difficulties in identifying the needed navigation path. Given the same number of navigational steps, participants took longer to traverse between nodes that were within the *same* branch of the display hierarchy than between *separate* branches. This decrement was attributed to difficulties that participants encountered in determining where to reverse an upward navigation path through the network (i.e., when the reversal point was below the top level of the display network hierarchy). By contrast, when the starting and destination display pages were in *different* major branches, the participants could press the "previous" button until the top-level display was accessed and then navigate down the hierarchy to the destination display. In the first case, reversing direction within the same branch was difficult because the participants had to plan the reversal, identify the reversal point, and then execute the reversal. In the second case, the participants could merely press the "previous" button until the top level display was accessed and then begin their descent down the other branch. This second strategy required less mental effort.

A later study (Seidler and Wickens 1995; Wickens and Seidler, 1997) consisted of two experiments. Experiment 1 replicated many of the conditions of Seidler and Wickens (1992) and is described here. It addressed the following factors from the earlier experiment: navigation distance, information integration requirements, and organizational distance (i.e., whether the starting and destination locations were within the same major branch of the display network). However, an additional factor was added; participants could choose whether to use one or two adjacent display devices when performing the information access tasks. The choice of using two adjacent display devices could reduce the need to hold information in working memory. Three results were found, which are consistent with the findings of earlier study.

First, navigation distance was found to influence information access cost. As the navigation distance increased, the time to complete the information access task increased. Second, when participants used only one display device, the amount of time required to traverse the display network was greater when participants performed the information integration tasks. That is, problems involving integration required more time to complete than those problems that involved the same navigation distance but no integration. This slower performance was associated with (1) greater latency of pausing at each choice point along the route, as if the working memory demands of integration disrupted the navigation choices, (2) increased frequency with which participants needed to remind themselves of the identity of the destination display, and, (3) decreased accuracy in the information access task. The effects of the integration requirement were eliminated when two display devices were used to perform the integration tasks. With two display devices, working memory demands were reduced because information from both the starting and the destination locations could be viewed at the same time and the participant was not required to hold this information in memory. Third, organizational distance, the degree to which the start and destination locations were in the same major branch of the display network, was again found to affect information retrieval time. As with the earlier study, navigation time was greater when the starting and destination locations were within the same major branch of the display than when they were in different major branches.

Experiment 2 of the study by Wickens and Seidler (Seidler and Wickens, 1995; Wickens and Seidler, 1997), was conducted to assess the extent to which users modulate their information retrieval and task management strategies in response to competing task demands. The participants (aircraft pilots) performed a monitoring task, in which they continually checked the instantaneous value of a scrolling altitude indicator. They also performed a concurrent information access task, in which they retrieved information from a hierarchically arranged display system. This information access task was essentially the same as the one used in Experiment 1 of this study.

As in Experiment 1, two display devices were provided. However, at least one device was always needed for the information access task. When the information access task required the participant to integrate information across different displays, it was desirable to allocate both display devices to the information access task. This alleviated demands on working memory that would otherwise be required for rehearsing information from one display until it could be compared with the other. However, when both devices were used for the information access task, the monitoring task could not be performed because the altitude display was not visible. In this configuration, it was possible to miss a critical altitude excursion. Thus, the experiment examined the frequency with which participants allocated one or both display devices to the information access task and the factors that influences the one- versus two-screen allocation strategies.

Based on the supervisory sampling model of Sheridan (1970), the amount of time that the display device is used for the altitude monitoring task should optimally increase with the cost of missing an important event. It should decrease as the cost of slow information retrieval on the information access task increases. This tradeoff has operational significance for the aircraft pilots. The cost of an altitude deviation is greater at low altitudes and the cost of delaying information access is greater when time-critical decisions depend upon the information being retrieved. Based on these considerations, it was hypothesized that the following factors would favor the strategy of devoting *both* display devices to the information access task:

- Lower bandwidth of the monitored signal (i.e., slowly changing altitude values)
- Lower costs for missed altitude events
- Higher reliability of operator memory of the last altitude value monitored
- The expectation that working memory would be needed to integrate information across display screens (i.e., by using two display devices the participant would not have to hold information from one display page in working memory while the next display page is accessed).

It was hypothesized that the strategy of devoting only *one* display device to the information access task would be increasingly favored as the length of the navigation path increased. That is, if both display devices were devoted to the information access task, greater time would have to be spent away from the monitoring task as the length of the navigation path increased. However, if only one display device were used for the information access task, then the monitoring task would always be visible and the participant would not have to hold the last altitude value in working memory.

The results indicated partial agreement with these hypotheses. The shifts in the allocation of the two displays generally reflected the relative costs and benefits associated with the information access task and the monitoring task. However, this allocation was generally biased in favor of the monitoring task, and was only partially sensitive to the difficulty and relative priorities of the information access and monitoring tasks. Three factors affected the participant's allocation of the display devices: the bandwidth of the monitored variable, the relative importance of the two tasks, and whether or not the participant was required to integrate data across displays. The fact that participants did change the allocation of display devices on the basis of the different bandwidth and task priority conditions suggests a sensitivity to an expected value for benefits, as Sheridan's model would predict. The responsiveness in changing the allocation of display devices for tasks requiring the integration of data across displays indicates a sensitivity to the perceived effort of working memory demands, as the Payne's contingent decision model would predict (Wickens and Seidler, 1997). However, this responsiveness was less than optimal - participants tended to allocate one display to the monitoring task even in low bandwidth conditions that largely relieved them of the need to monitor the indicator. This allocation persisted even when the information access task had higher priority than the monitoring task and even to the detriment of the data integraton tasks.

This deviation from optimal sampling behavior was considered to be consistent with other dynamic sampling studies in which operators were found to sample time-varying signals more often than normative models would predict is optimal (Wickens and Seidler, 1997). Such oversampling was attributed, in part, to failures in the memories of participants regarding the last value sampled. In addition, the participant's strategies for allocating the display devices *did not* appear to be affected by navigation distance or organizational distance of the information access task. That is, the bias toward having one display allocated to the monitoring tasks was not reduced by information access tasks that had shorter navigation paths or by the presence or absence of paths that required participants to determine reversal points.

Possible explanations were proposed for the discrepancies between actual display allocation behavior and the hypotheses stated earlier. The first is that participants may not have considered the display navigation path characteristics (i.e., navigation distance and organizational distance) that existed between the first and second target screens at the critical time when they made their display device allocation decision. That is, the participants may have relied on the menu system for guidance rather than perform an up-front determination of destination screen location. This may have been due to a lack of feedback on these display path characteristics and, consequently, the need of participants to rely on their own mental models of the display system structure.

A second proposed explanation was that the high workload conditions may have forced the participants to limit their focus of attention to only the most readily accessible information and base their display allocation decisions on this restricted set. Previous studies (Raby and Wickens, 1994; Segal and Wickens, 1990) have shown that operators are not highly sophisticated in scheduling tasks optimally on the basis of anticipated demands or current workload conditions. Raby and Wickens concluded that the additional resources needed to optimally schedule and manage tasks may become unavailable under high workload conditions.

While acknowledging that additional research is needed, Wickens and Seidler (1997) proposed the following recommendations for the design of HSIs for multiple task environments based on their studies:

- *Provide a visual representation of the menu structure* - Where space allows, some aspects of the menu structure should be presented visually so the user is not required to remember it. That is, information should provided in the user interface to augment or substitute for the user's knowledge of the display navigation structure.

- *Minimize the navigation distance between display pages that are accessed sequentially* - Minimize the navigation distance can reduce the amount of time that information must be held in working memory, thereby reducing cognitive demands on the user. One approach may be to provide broad, shallow menu structures rather than narrow, deep ones. However, Wickens and Seidler acknowledge that the former may be impractical in some settings, such as aircraft cockpits, if the total number of menu items is large and the display devices have limited space for presenting them. In such cases, additional navigational mechanisms should be considered such as direct keyword retrieval. Other features for reducing navigation distance should be used such as navigation shortcuts (e.g., buttons for jumping to the top of the menu or major branches without accessing intermediate nodes) and buttons for accessing previous displays.

- *Provide multiple viewports into a single database when it is necessary to integrate data across displays* - If separate display pages contain information that the user must compare, combine, or otherwise mentally process, then they should be presented simultaneously to reduce the information access costs associated with alternating between the display pages. This may be accomplished via duplicate display devices or via multiple display windows that can be viewed together on the same display screen.

- *Provide training on optimal strategies for using multiple viewports* - If multiple tasks compete for the same viewing space, then users should receive explicit training in the use of the most efficient and effective strategies for viewport allocation.

With regard to the fourth recommendation, Wickens and Seidler note that operators should receive interface management training because, in complex task domains, optimum strategies for performing under high workload conditions do not necessarily emerge through experience. This point is consistent with observations made during our site visits to facilities that had computer-based HSIs, which were conducted to evaluate interface management issues (see Chapter 3.4). Interviews and walk-through evaluations made at a variety of facilities indicated that formal training in the use of interface management features is not routinely provided. As a result, interface management practices that develop through operating experience tend to be inconsistent among personnel, tend to ignore the positive capabilities of the HSI, and do not optimize the performance of interface management tasks.

Based on observational studies of users navigating through internet web-sites, Danca (1997) provided design suggestions for supporting users in integrating information from different locations of a web-site. These suggestions are intended to relieve the mental burdens associated with holding information in working memory while making frequent transitions from a central location of the web-site. The first suggestion was to allow the users to make lateral transitions between the locations within a particular level of the site, rather than vertical transitions from the higher-level, central location. This may be accomplished by using Next and Previous keys to sequentially access each of the locations at a particular level. The second suggestion was to provide a brief description of each location, which the user could read before activating a link. It was suggested that providing users with even a very little amount of information about the locations can greatly aid them in selecting a link. This, presumably, would simplify the selection task and allow more cognitive resources to be available for the mental integration task. The third suggestion was to provide a capability that allows users to identify the items of information that are of interest and then create a table so they may be viewed simultaneously and compared more easily. Some web-sites have this capability. Danca cautions that if the quantity of information is high, the table may be too large to be viewed at one time and, consequently, must be scrolled. However, this may still be more effective than trying to integrate information while making frequent transitions between locations.

If the keyhole effect limits the amount of information that can be accessed at one time via a display device, then one approach for overcoming this limitation is to provide more keyholes (i.e., more display devices) so that more information can be presented at one time. Related questions that are fundamental to HSI design reviews are, "How can or should the necessary number of VDUs be determined?" Experience with design reviews indicate that the number of VDUs is usually determined long before the information content of the display system been designed. While there is guidance on the arrangement of displays, little practical guidance for determining the needed amount of display space seems to exist. For example, even simple heuristics, such as the ratio of display screens to display pages, do not appear to be used in the development of HSI design requirements. Instead, the design decision tends to be driven by factors that are not directly related to the information needs of the operator, such as the size of the control console. Given the problems associated with the keyhole effect, there does not seem to be adequate consideration of the display area that will be required in a CR to support crew operations under high workload conditions. The following discusses factors that should be considered when developing HSI design requirements and assessing the adequacy of display space.

Determining the appropriate amount of display space in a CR includes considering the information that be needed at one time by the operators, the arrangement of information within display pages, the arrangement of pages within the display network, and the means used to access the information, as well as the number and arrangement of display devices. When HSI design requirements are developed, these factors should be addressed together to reduce the overall cost associated with accessing information during peak workload conditions. Ideally, display pages should be developed first to maximize the proximity of task-related information (i.e., as defined by the proximity compatibility principle). That is, task-related information should be located within the same display page. Then, proximity requirements should be established for task-related display pages in the display network (i.e., the navigation paths should be minimized between task-related display pages). Finally, decisions on the number and proximity of display devices should be made after the needs for viewing display pages have been established.

Operators may require multiple display devices for many reasons, including:

- *Monitoring information* - Adequate display space is needed so that operators can view necessary information while incurring minimal demands on working memory for accessing information. When operators must rapidly monitor many different information items, access to the information may be supported through the use of multiple display devices (Wickens and Seidler, 1997; Seidler and Wickens, 1995). That is, operators can access the information by moving to a different display device rather than navigating within the display network. Thus, a trade-off exists between the costs and benefits of providing access via multiple display devices versus via navigation features for display networks.

- *Integrating and interpreting information* - When operators must mentally integrate information, the demands on working memory can be reduced by placing the information items in close proximity (Vincow and Wickens, 1993; Wickens and Carswell, 1997; Wickens and Carswell, 1995). If the information items do not appear in the same display page, then one approach for achieving proximity is to place them on adjacent display devices. Thus, the number of display devices needed for concurrent viewing of task-related information may increase to the extent that this information is not presented together in the same display pages.

- *Executing control actions* - When performing a control action, operators need to access the control device and plant information that supports the control action. Display devices are needed to provide access to display pages that present plant information. In addition, if soft (i.e., computer-based) controls are used, display devices are needed to provide access to these controls. If an operator must perform multiple control tasks together, then additional display devices may be needed so the necessary controls and displays are continuously in view.

- *Keeping track of in-progress and suspended tasks* - When faced with competing tasks, operators must often suspend one task so that another task can be performed. Operators in computer-based CRs often sent aside display devices, when possible, to act as holding places for suspended tasks. This strategy has two benefits. First, it provides a constantly visible reminder of the suspended task. This reduces demands on the operator's prospective memory for remembering the task and avoids distractions associated with other types of reminders, such as alarm tones or messages and displays that suddenly change. [Distractions can divert operator attention from on-going tasks and place increased demands on mental workload (Norman and Bobrow, 1975).] Second, it holds the suspended tasks in a condition that allows the operator to easily resume activity. The operator can return to the task with minimal need to adjust the display prior to resuming activity. Thus, in computer-based control rooms display space may be needed for reminding operators of suspended tasks and holding them so they can be easily resumed.

- *Anticipating future demands* - Operator performance in multi-task environments can be enhanced by using information that supports the operator in anticipating future task demands. Examples of HSI features that provide this type of information include trend plots and predictor displays that suggest the status, direction, and rate of change of plant processes and systems; alarms, warnings, and advisory systems that indicate the early stages of a problem; and plant procedures (e.g., computer- or paper-based) that allow operators to view upcoming activities. Thus, additional display space may be needed to present features for supporting this activity.

- *Coordinating and communicating with other operators* - In some cases, HSI designs can interfere with communication and coordination between crew members. For example, in computer-based CRs that feature individual operator consoles, operators may find it more difficult to share information and coordinate actions because they have different views of the plant status. Group-view displays may be introduced to provide CR personnel with a common view of plant condition (Stubler and O'Hara, 1996). Therefore, additional display devices may be needed to present these group-view displays.

These activities, described above, may not be performed one-at-a-time. Therefore, a sufficient number of displays devices should be provided to support concurrent requirements. This determination should take into account the expected costs and benefits associated with having separate display devices for each function versus having a smaller number, which requires display pages to be periodically removed so that other pages may be viewed. Thus, the design requirements for the number of display devices should reflect the maximum number of tasks that the operator will be performing at one time and the maximum number of display pages that must be viewed concurrently to support those tasks.

The number and arrangement of VDUs should also take into account coordination between personnel. For example, some displays may be shared between multiple operators at a workstation, which may reduce the total number needed in the CR. Alternatively, additional display devices may be needed to present group-view displays to support communication and coordination among personnel.

In determining the required number of display devices, it should be recognized that there may be a discrepancy between the number established through such means as analytical evaluations and observations of operator behavior. For example, there may be an overly-conservative bias among operators toward dedicating displays to ongoing monitoring tasks, as observed by Wickens and Seidler. This bias will tend to increase the required number of display devices relative to the number that would be determined through an analysis based on mathematical models of optimal monitoring behavior (Tulga and Sheridan, 1980). Therefore, the final number of VDUs should be validated through performance-based trials under operational conditions.

Thus, the required number display devices should not be determined in isolation of other HSI design considerations. Instead, it should be part of a systematic design approach intended to reduce the overall cost of accessing information. Such factors as display page design, display network design, navigation mechanisms, and the number and proximity of display devices should be addressed. Changes in one factor may affect the design requirements for the others. Therefore, all factors should be checked if one is changed.

Thus, if an operator's primary tasks and interface management tasks draw on many of the same cognitive resources, then one must consider the types of performance tradeoffs that can occur in dual-task situations where common attentional resources are demanded. Figure 3.6 illustrates the potential effects of dual-task performance at the level of performance of each individual task. If two tasks were completely independent in terms of resources, their joint performance would more likely resemble the performance of either task alone. Complete independence of resource demands is rare, therefore, there is a cost to performance of concurrently performing dual-tasks. The shaded area in the figure illustrates this performance decrement when the dual task curve is compared to the performance levels for each task performed separately.

The performance tradeoff between two tasks can be described by a function referred to as a performance operating characteristic (POC) (Norman and Bobrow, 1975), see Figure 3.6. The three dual-task performance strategies in Figure 3.6 illustrate the possible ways the two tasks could be performed (see the dashed lines labeled A, B, and C). Assume that Task 1 is the primary task and Task 2 is the interface management task. Strategy A describes a performance model where the interface management tasks draw most of the resources they require, and consequently, supervisory control performance is relatively poor.

Strategy B describes a performance model where the resources are more equally shared, but neither task is performed well. Strategy C describes a performance model where the resources for supervisory control are maintained at the expense of interface management task performance. These relationships model three different ways operators might allocate their resources in high workload situations. The actual POC function can vary from that shown in the figure. Further, while three performance models have been described, the dual-task performance strategies can fall anywhere along the POC function. In addition, during the course of real task performance, the performance tradeoff may change during different phases of the task.

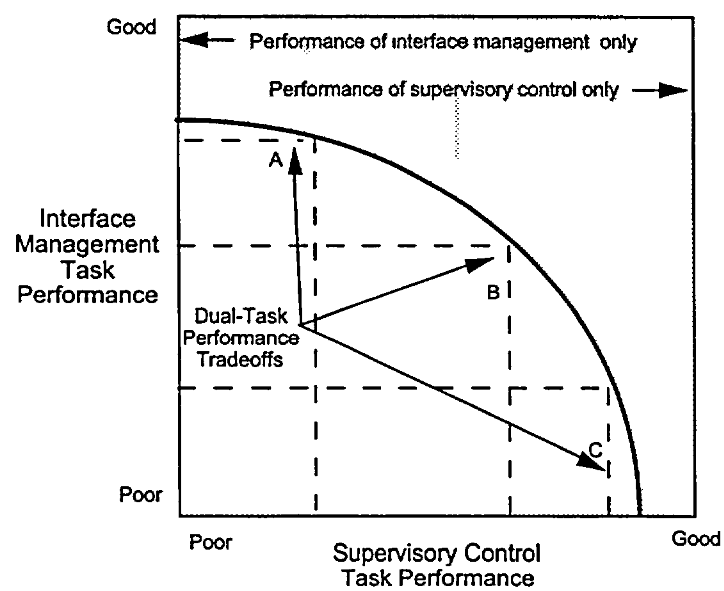

Figure 3.6 Dual-task performance operating characteristics
(adapted from Wickens, 1984)

However, when these workload regulation strategies are considered with respect to actual process control tasks in a virtual environment, the lack of task independence becomes an extremely important factor. Interface management tasks must be performed in order to obtain the information and controls necessary for primary task performance. If operators adopt the strategy represented by C, little effort is given to interface management tasks. In such a situation, operators may not navigate and retrieve information needed for situation assessment and response planning. In this case, primary task performance may actually suffer because it becomes data limited (see Figure 3.4). That is, if operators bias their performance toward supervisory control tasks at the expense of the interface management tasks, they will have to perform the supervisory control tasks with whatever information happens to be presented on their VDUs. Potentially important task information may be hidden in the virtual information space. Under these circumstances, performance can become data limited. If insufficient data is available for acceptable performance, problems can occur.

Thus, when primary tasks and interference management tasks rely on many of the same cognitive resources and use many of the same HSIs, a dual-task situation arises Based on these considerations and the dependent nature of the two classes of tasks, two hypothetical dual-task performance effects under cognitively demanding situations were defined:

- *Resource-limited effect* - Interface management tasks draw cognitive resources away from primary task performance, and primary task performance becomes resource-limited and declines.
- *Data-limited effect*- Primary tasks consume most of the cognitive resources leaving little for Interface management performance. Since the primary tasks are dependent on interface management tasks, primary task performance becomes data limited and declines when interface management tasks are not performed.

Figure 3.7 depicts a hypothetical function for the dual-dependent task relationship that may result from these effects. The actual function would depend on the unique demands of the situation relative to primary task demands, interface management demands, and HSI design.

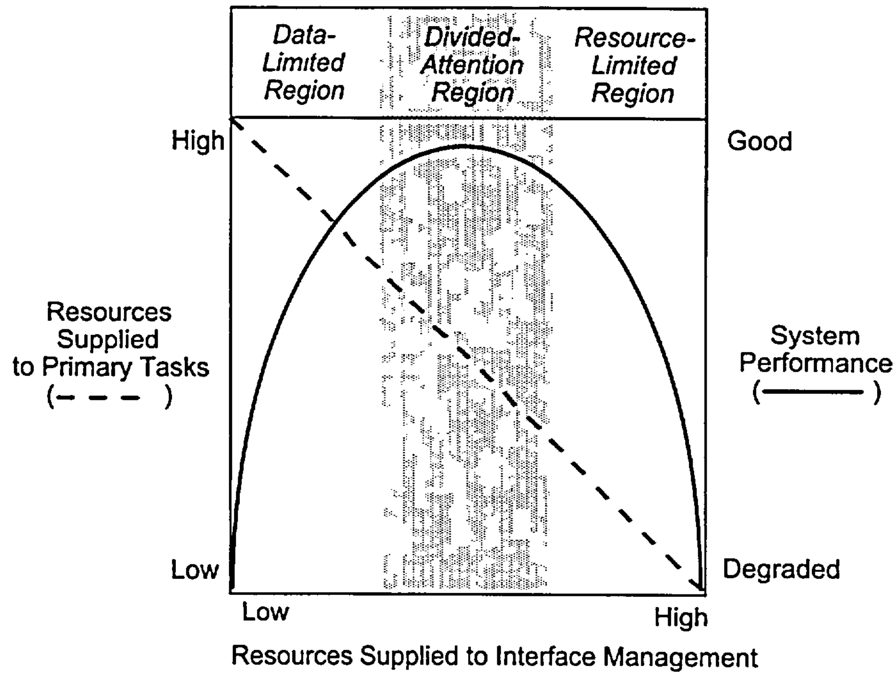

Figure 3.7 Hypothetical relationship between resource allocations and performance

3.2.1.4 Interface Management and Human Error

Several performance effects associated with interface management tasks were identified above. In this chapter, these effects are considered with respect to research on human error mechanisms. Many errors can be explained on the basis of a relatively small number of cognitive mechanisms that reflect the operator's response to high information content and complex situations that require controlled information processing and place high demands on attentional resources and WM (Norman, 1981 1988; Reason, 1988, 1990). The error mechanisms discussed by Norman, Rasmussen and Reason are considered with respect to an understanding of how interface management tasks can contribute to an increased likelihood of error.

Norman (1981, 1983) classified errors into three categories, based upon the cognitive mechanisms involved. *Description errors* result from the operator's characterization of an intended action with insufficient detail. This occurs because it takes less mental effort than constructing a detailed characterization. At such a high level of description, the operator may not have enough detail to select the appropriate actions. The second type is activation or trigger errors. These errors occur when an intention leads to the activation of knowledge in LTM, but the operator does not keep track of the resulting actions, or the automated sequence is interrupted in favor of another action. Failure to complete the set of steps required to align a set of valves is an example of this type of error. The third type is capture errors that occur when the environmental cues are present that are similar to those associated with a well-developed behavioral pattern which is inappropriately activated. Changes in equipment or procedures in the CR make an operator susceptible to this type of error if well-learned responses in the old CR are inappropriate in the new one. Also, similarity in the display of information patterns between two plant states can lead to capture errors.

Within Norman's framework, interface management tasks are likely to contribute to each of these categories of error. Task interruption is one of the central means by which secondary tasks interfere with primary tasks. When operators have to stop in the middle of a task to navigate to or reconfigure a display, the opportunity exists for failing to complete the action or missing a task step. Description errors can occur for the reasons described above with respect to flexibility. For example, operators may mistakenly take an action based on information on a display that they think pertains to one component when it actually provides information about another. Presenting controls and displays on VDUs can add sequential steps to operator tasks and eliminate spatial steps and other cues that guide operator performance. As a result, different tasks can begin to look similar. An operator may begin the series of actions required for Task A, but instead complete a similar set of actions required for Task B. This is an example of a capture error. This type of error may be less likely in conventional control rooms in which operators are constantly reminded of which tasks they are performing by their location in the CR and the different appearance and tactile characteristics of various hardwired control and display devices.

Like Norman, Rasmussen (1986) noted that errors are a function of the cognitive control of behavior and further, that they are manifestations of the efficient human adaptation to system characteristics. He defined four categories of error and their importance in system design. The first category is the result of random human variability. However, these are few and usually they have lower safety significance because they are single events, not correlated to other activities. The second category is errors related to inadequate processing resources; this is most important in knowledge-based processing since it is the most resource-dependent mode of processing. However, even rule-based activities require attentional resources. When there are insufficient resources available, errors become more likely. Therefore, this category of error is related to workload. The third category of error is associated with interference between internal control structures. Thus, this category is similar to the capture error described by Norman. The final category is related to human learning mechanisms that reflect the operator's adaptation to the system and, Rasmussen argues, cannot be completely eliminated. A major purpose for having operators in the system is to respond to unanticipated events through adaptation and innovation. Instead of eliminating this type of error, HSI design should be made error-tolerant, i.e., the system should reveal errors so their consequences can be mitigated.

Interface management tasks are likely to impact the probability of the second and third types of errors described by Rasmussen. The second type was characterized by limited resources due to high workload. Another mechanism for this type of error is when interface management tasks drain resources from the primary task making it resource limited. The third type of error is analogous to Norman's capture error described above.

Reason (1987, 1988) presented a fairly well-defined model of human error that, in its current version, embodies most of the main points of Norman's and Rasmussen's work. The central thesis is that error is predictable and based upon a tendency to overutilize cognitive processes that serve to simplify complex information tasks by applying previously established heuristics. Two heuristics used by operators to retrieve information from the knowledge base are assumed to exert a strong influence on human performance, and therefore, human errors. They are similarity matching and frequency gambling. Operators use these heuristics in situations of high workload that result from the demands on WM, and its limitations. They are also used when data are not sufficient to clearly identify appropriate knowledge structures in LTM. Similarity matching reflects the tendency for WM to attempt to match a perceived information pattern (such as a pattern of indicators) with an already existing knowledge structure. The operator tries to establish a link with some knowledge in the mental model since it contains a previously identified successful action sequence. This saves the operator the effort of knowledge-based reasoning, which is resource intensive. When the perceived information partially activates more than one knowledge structure, the discrepancy is resolved by selecting the one most frequently used in the past. This is the frequency-gambling heuristic.

According to Reason, these computational primitives cause basic error tendencies in human performance which account for most human errors (1) similarity bias - errors reflecting the undue influence of salient features of the current situation (resulting in premature identification of the situation) or the intention/expectation of the operator (resulting in a bias to see only confirmatory data), (2) frequency bias - in ill-defined situations, the most frequently performed action will be selected, (3) bounded rationality - the processing limitations of WM cause information to be lost, (4) imperfect rationality - information processing will favor heuristics over knowledge-based processing, (5) reluctant rationality - information processing acts to minimize cognitive effort and strain, and (6) incomplete/incorrect knowledge - mental models rarely contain highly accurate knowledge of the system.

The effects of interface management within the framework developed by Reason are related mainly to two effects described earlier. First, the effect of competition for attentional resources and its potentially negative effect on primary performance. Second, since operators seek to minimize cognitive effort, interface management tasks may impose an unacceptable requirement for additional resources that operators seek to reduce. This may lead to reluctance to perform interface management tasks and the consequences to primary task performance may make it data limited.

In summary, the effect of interface management tasks is to potentially increase the likelihood of cognitive errors by (1) drawing resources away from the primary task and thereby making it resource limited, (2) disrupting primary task performance by slowing the performance, causing steps to be missed or confused, or completely distracting operators from the task, (3) causing errors due to mistaking one control or display for another, and (4) imposing additional burden on operators so that they are reluctant to perform the secondary tasks under high workload situations.

3.2.1.5 Summary

Interface management tasks were evaluated with regard to theories of cognitive information processing. The significant points discussed in this chapter include

- Operators' primary supervisory control tasks are dependent on the characteristics of information processing. Interface management tasks rely on the same cognitive resources as the primary tasks, and while they are secondary tasks, they still have to be performed.

- The effects of interface management tasks on performance can be described as:

  - *Resource-limited effect* - Interface management tasks draw cognitive resources away from primary task performance, and primary task performance becomes resource-limited and declines.

  - *Data-limited effect-* Primary tasks consume most of the cognitive resources leaving little for Interface management performance. Since the primary tasks are dependent on interface management tasks, primary task performance becomes data limited and declines when interface management tasks are not performed.

- The secondary task effects can result in primary tasks being delayed, disrupted (where steps are omitted or performed below required levels), or not performed at all.
- The interface management effects are consistent with human error mechanisms.
- Due to the dual-task effects, interface management tasks should be designed to require minimal cognitive resources for their execution.
- The flexibility of computer-based HSIs can result in:
  - *Reduced automaticity* - Flexible HSI features make interface management tasks more dependent on controlled information processing.
  - *Reduced situation awareness* - Situation assessment is hampered if operators mistake one display for another.

3.2.2 Interface Management Effects on Primary Task Performance in Complex Systems

In Chapter 3.2.1, the effects of secondary tasks on independent primary tasks was discussed from theoretical perspectives derived from laboratory investigations. We now consider the effects of interface management tasks on supervisory tasks in real-world, complex systems. This is necessitated by the fact that unlike unrelated laboratory tasks, interface management tasks in a real, complex system are tasks that need to be performed to access information and controls necessary to process control tasks.

3.2.2.1 Workload Regulation in Real-World Tasks

Professional operators can perform acceptably under conditions of very high workload because their skill and expertise can often compensate for complicated situational factors and shortcomings in the plant and HSI designs. Consequently, mental workload in actual work environments does not tend to be a linear function of external task load (e.g., the number of items in the work environment for which the operator is responsible). Some laboratory experiments show a sudden and pronounced loss of performance when subjects are confronted with a quantity of information in excess of their processing capacities. This point is characterized as the overload threshold. By contrast, operators in complex human-machine systems tend to apply strategies to maintain tolerable levels of workload and system performance for as long as possible during periods of increasing task load. As a result, overall performance tends to degrade gracefully and rather than catastrophically (Sperandio, 1978; Norman and Bobrow, 1975). However, as in the laboratory studies, a task level is eventually reached at which the level of performance is no longer acceptable.

Sperandio (1978) describes the findings of a series of field studies of air traffic control, which focused on operational behavior and the regulation of workload. The controllers' responsibilities include tracking the paths of the aircraft, interpretation and planning, and instructing pilots to achieve adequate spacing and avoid mid-air collisions. In such a setting, the task load may be defined in terms of the number of aircraft in the air sector for which the air traffic controller is responsible. The greater the number of aircraft, the greater the number of targets that must be tracked and the greater the processing demands. That is, with more aircraft there is a potentially higher probability of collision. Sperandio observed that as the number of aircraft increased in a sector, the controllers changed their strategies of control. If they did not do this, the increase in traffic would require them to take into account a greater and greater number of pertinent variables to cope with the increased complexity of the situation. Instead, controllers adopted a progression of changes in operating methods and decision criteria to avoid crossing the overload threshold and, thus, delaying dysfunction as the number of aircraft increased.

The changes in operating methods progressively treated each aircraft as one link in a chain whose characteristics remain stable rather than as an independent body moving in a space of other independent bodies. This change occurred progressively as the number of aircraft increased; controllers appeared to continually deal with only the amount of information they were capable of processing competently. For example, when one to three aircraft were present and the risk of collision was slight, a controller was able to calculate optimum flight paths for aircraft, taking into account all usual variables such as course, speed, altitude and type of aircraft. With four to six aircraft, the controller encouraged pilots to adopt uniform speeds and stereotypical flight paths. The controller might still manipulate the speeds and courses of individual aircraft to maintain desired spacing. However, this could impose considerable additional workload, especially when interacting with the pilots of the individual aircraft. The goal, at this point, is not so much to optimize each flight path but rather to maintain overall control of the whole group of aircraft. In other words, flight paths are manipulated to optimize the ability of the controller to understand the situation and implement changes as necessary, rather than optimize the flying efficiency of individual aircraft. With more than six aircraft, the controller coped with the saturated airspace by creating 'stacks' of waiting aircraft, from which the controller directed individual aircraft into a traffic stream. Each individual aircraft was inserted as a link in a chain, each link having characteristics similar to its neighbors, especially for speed, descent path, and progress.

Other changes in work methods that were concurrent with the traffic handling strategies included changes in radio messages, mnemonic activity (i.e., the type of information held in working memory), distribution of tasks between controllers and assistants, and mental representation of expected traffic. This progression of changes in operating methods allowed controllers to avoid overloading their cognitive resources and, thus, delayed the point at which overall performance became unacceptable.

One strategy used by controllers to manage their workload is to delegate tasks to assistants. Shifts in the distribution of tasks between controllers and assistants occur spontaneously in response to changes in workload. However, associated with this strategy is an additional cost of communication, which imposes demands on the cognitive resources of both the controller and the assistant. The relationship between the controller and the assistant may be described as a system of two interconnecting channels. The first channel, the controller, is responsible for the cognitive work associated with the central role of air traffic control (i.e., detection and resolution of collision courses). The second channel, the assistant, is entrusted with subsidiary (i.e., supporting) tasks. However, as workload increases in this system, the subsidiary tasks become increasingly dependent upon the central tasks. This tends to increase the load on the controller even more. Consequently, the assistant becomes less and less efficient, due to a lack of input from the controller. This occurs just at the time when the assistant's contributions are needed more and more by the controller. Consequently, the level of overall personnel performance is not simply a linear function of the number of personnel working on the controller's task due to this dependency between the principal and subsidiary tasks. Thus, the overload level of personnel performance cannot be raised simply by providing more assistants and more display and control devices for them to use.

During periods of increasing traffic flow, changes also occurred in the qualitative objectives that controllers assigned to themselves for their work. These objectives are modified in a hierarchical manner such that the most essential objectives are attended to first as workload increases. The highest priority for air traffic control is safety (i.e., collision avoidance), which includes considerations of aircraft spacing. This is followed, hierarchically, by considerations of efficiency, such as the rate of progress of aircraft through the sector. These objectives conflict to the extent that reducing the spacing can increase efficiency but a minimum spacing is needed to avoid collisions. Other objectives that follow included choice of flight paths for economy of time or fuel; regard for altitudes preferred by pilots; passenger comfort (e.g., selection of smooth descent paths and rates); and minimization of pilot workload and annoyance (e.g., avoiding frequent flight changes). As workload increased in the field study, the controllers adopted solutions that were cognitively economical (less demanding) for themselves. This tended to occur by taking less account of the secondary objectives while maintaining attention on the principal objective - safety. These shifts in objectives occurred gradually in response to the controller's mental workload rather than in direct response to the objective task load (i.e.; the number of aircraft).

Operators used these changing objectives to make decisions about the acceptability of the quality of their work and the need to adjust their work methods. Skilled operators were able to perform acceptably at higher levels of task load than less-skilled operators because they have acquired the ability to adjust their work methods to accommodate changes in task load. However, Sperandio states that when task load becomes so excessive that performance is no longer consistent with at least a minimum level of acceptability, operators may refuse to perform the task. They may refuse to work under the existing conditions or may take pauses that allow them to recuperate and return to acceptable levels of performance.

Sperandio drew a number of conclusions from these field studies. First, he concluded that these findings support his hypothesis that, for a given task and for a given operator, there are some operating methods that are more economical than others (i.e., result in smaller workload), and if an individual is given sufficient latitude, then less economical operating methods will progressively give way to more economical methods. Sperandio notes that these more economical methods are not necessarily simpler, but they are organized differently to produce lower demands. In parallel with the change in operating methods, operators also modify, in a hierarchical manner, the qualitative objectives that they assign to their work.

Second, he concluded that when studying workload, it is important to thoroughly understand the changes in work methods and objects that occur as workload changes. Failure to do so may result in the adoption of insensitive human performance measures and incorrect conclusions on personnel performance.

Third, Sperandio states that HSI technologies may have characteristics that are unevenly adapted to certain work strategies of operators. In some situations, information that is pertinent at a low or moderate workload level is not usable during high workload levels due to the adjustments that operators have made in both their methods and objectives. For example, at high workload levels, information related to considerations of passenger comfort may become irrelevant to the controller because he or she has disregarded that objective to focus more closely on higher-level objectives, such as safety. Thus, displays addressing this information can be come undesired distractions that interfere with the controller's overall performance. Sperandio states that a better match between operator tasks and the presentation of information can be achieved through the use of computer-based HSI technologies. However, the effective use of the flexibility of computer-based technologies requires a good understanding of workload and operating strategies, so that HSI designs can be developed to support personnel performance over the entire range of anticipated workload conditions. That is, HSI features that provide information during low workload conditions should not become burdens when the operator must focus attention on a limited set of high-priority objectives during high workload conditions.

In general, it appears that users adopt strategies to address the potentially conflicting demands of interface management and primary tasks. These strategies help manage workload and have the general effect of decreasing system flexibility, increasing predictability, and increasing simplicity. The strategies help operators to apply the technology to their task environment in locally pragmatic ways - often in ways that were not anticipated by the designer (Woods et al., 1994; Cook and Woods, 1996). *System tailoring* refers to the manipulation of a technology, especially a new one, to be more compatible with the information processing approaches of the users and the demands of the task environment. *Task tailoring* refers to the ways that users adapt their approaches, especially cognitive processing strategies, for carrying out work such that they accommodate constraints imposed by the new technology. This description of task tailoring apparently applies to both primary tasks (e.g., operating the plant) and secondary (e.g., interface management) tasks. Woods et al. identify five classes of interrelated strategies for coping with information technology. Each strategy encompasses elements of both system tailoring and task tailoring to varying degrees.

The first class relates to workload management to prevent interface management tasks from creating bottlenecks during high-tempo periods. Users may decide to interact with devices during low-workload periods to reduce the need for interaction during anticipated high-workload or high-criticality periods. For example, users may interrupt their primary tasks during a low workload period to declutter a display screen and, thus, avoid doing this during a high workload period. (Decluttering may include removing excessive detail from a display page or closing, resizing, and moving display windows.) The second class relates to spatial organization. Rather than cope with serial interactions that are produced by the computer-based system, users may constrain the system into a spatially dedicated organization (Cook, Woods, and Howie, 1990; Woods et al., 1994).

The third class of strategies is the development of ad hoc standards for interacting with the system which simplify the interaction but do not exploit the full flexibility of the system. Users may develop and persist in using stereotypical navigation routes or interaction methods to keep from getting lost. These rigid routes prevent users from accessing information system nodes that contain many potentially useful capabilities. Thus, users "throw away" functionality to achieve simplicity of use. For example, Cook et al. (1990) observed that while physicians and technicians performed different navigation tasks with the computer-based patient monitoring system, both groups developed script-like stereotypical routines for navigating the menu-based, hierarchical display structure. When they deviated from these standard routines, they tended to get lost. This finding is consistent with the conclusions of Stevens and Coupe (1978) and Howard and Kerst (1981) that spatial knowledge is organized hierarchically. People use paths, landmarks, and boundaries to organize their understanding of the physical world into a set of "places." Darken and Sibert (1996) suggest that people represent computer-based environments similarly. Thus, when learning a new navigation environment, users initially may stay with familiar (stereotypical) paths.

The fourth class is the invention of "escape" mechanisms by users. These mechanisms allow users to abandon high-complexity modes of operation and retreat to simpler modes when workload gets too high. For example, Hagelbarger and Thompson (1983) observed that when users selected the wrong path while navigating the lower levels of hierarchical display structures, they often became confused and tended to return to the main menu rather than back up to the node where the incorrect choice had been made. Thus, the main menu button served as an escape mechanism for these users.

The fifth class is the development of workarounds (O'Hara, Stubler, and Higgins, 1996) to get the HSI to do what it was not designed to do. Operators may try to prevent an automated feature from performing actions that may interfere with operator activities, or operators may cause the feature to perform actions that can support their activities. Such an approach may be used to *work around* the automatic capabilities of interface management systems. Vicente, Mumaw and Roth (1997) identified numerous strategies operators adopted to create workarounds for limitations in designs, even when the designs are computer-based, flexible systems. For example, operators may manipulate an automated feature to prevent nuisance alarms from sounding. Cook and Woods (1996) describe a strategy employed by users of a computer-based patient monitoring system to "trick" an automatic screen arrangement feature into presenting patient data in a particular arrangement. The users employed fake input modules, monitoring channels that contained no data, which resulted in the desired arrangement of patient trend graphs. This strategy of tricking or "working around automation" was also reported in a review of operating practices at NPPs that featured mixtures of conventional and computer-based HSI technologies. In this example, operators manipulated the plant control system using approved procedures to prevent unwanted actuations of automatic systems. The workaround strategy may include elements of system tailoring (e.g., introducing bogus inputs to the automatic system), secondary task tailoring (e.g., modifying the actions one uses for accessing information), and primary task tailoring (e.g., modifying one's interaction with the plant to accommodate characteristics of the HSI).

Watts (1994) identified a similar set of strategies to those noted by Woods when studying user interactions with linked, multiple-page spreadsheet systems in normal environments. Interface management demands were high because a single spreadsheet may extend over as many as 50 display pages, and individual data cells may be linked to other spreadsheets. The first strategy Watts observed was the use of spatial dedication. Spreadsheets with spatially dedicated content allowed users to predict the location of needed information and, therefore, retrieve it faster. Spreadsheets that did not have spatially dedicated content resulted in a less efficient sequential search through display pages for needed information.

A second strategy, navigation avoidance, entails arranging the presentation of information to reduce the need to navigate later. Users identified information that would require high navigation demands and then copied this information from one area of the spreadsheet to another. This allowed them to easily compare these values without navigating the spreadsheet. Thus, users invested time and effort at the beginning of a session to reduce the navigation demands later. Watts (1994) considered the spatial dedication strategy of the anesthesiology study (Cook, Woods, and Howie, 1990; Woods et al., 1994) to be a form of navigation avoidance because it was performed to reduce navigation demands. The navigation avoidance strategy is also related to the concept of reconfigurable displays, which users employ to define display content and arrangement. By investing time to establish these displays, users can reduce future navigation demands.

A third user strategy is the use of landmarks. In the spreadsheet domain, table and column headings, page headers, bold lines, and spacing provide landmarks that can be recognized at a glance and orient the user. Watts observed that spreadsheet users added a combination of content-laden and content-free landmarks to their spreadsheets to aid navigation. Content-free landmarks, such as formatting, lines, and the position of scroll bars provided information about the user's general location in the display space (e.g., a scroll bar could indicate the middle of the spreadsheet). Content-laden landmarks, such as table headings, provided detailed information about the content of the display system or specific locations. For example, a heading can provide semantic cues about the content that follows.

An interesting finding of Watt's study was that the users preferred to use spreadsheet features that enhanced their orientation rather than use features that enhanced retrieval. That is, users used the copy and paste features to reduce navigation demands and exploited spatial dedication and landmark features which helped orient them in the display structure. They did not use the "Find," "Goto," and "Zoom" features that were intended by the system designers to help users rapidly retrieve information. Watt's explanation was that the spatial dedication and landmark capabilities were content-laden aids that provided information specific to the user's tasks, while the "Find," "Goto, and "Zoom" features were nonspecific content-free aids. Another interpretation is that the "Find," "Goto," and "Zoom" features provide navigation paths that are based on procedural knowledge. They may be considered "brittle" paths (Woods et al., 1994) because simple input errors can greatly affect their effectiveness. For example, by entering an incorrect input, a user may be sent to an unfamiliar location and quickly become lost. By contrast, the strategies adopted by the users could be considered more robust because they enhanced the users' mental representations of the information structures and supported recovery from input errors.

3.2.2.2 Research Addressing Resource-Limited Performance

Considerable concern is expressed in the literature that interface management tasks can be associated with high workload, and that during demanding situations, these tasks can interfere with the operator's primary supervisory control performance and impact plant safety. A few examples quoted from the literature are provided below.

> Computer-based HSIs can make it difficult to find information and act on the system in comparison with conventional plants... In a computer-based control room, there is a significant increase in the amount of knowledge required to operate the interface. Part of these demands arise from the fact that information is presented serially. Thus, operators need to know how to bring up the information they want to display on CRTs. The other part of the increase in knowledge demands arises from the fact that the computer-based displays are much more flexible than the hard-wired instruments. The same information can be displayed at different time scales, at different ranges, in different locations, in different forms, and in different groupings. Consequently, the operator has to have much more knowledge about the interface (not the unit) to resolve the degrees of freedom offered by the flexible design of the system .. On the one hand, one might argue that the flexibility provided by the computer-based medium should result in a performance improvement because it allows operators to view information in a form that is tailored to different types of contexts. This should reduce the need for the work-arounds that operators engage in (in) traditional control rooms to facilitate monitoring. On the other hand, one could just as well argue that this flexibility comes at the price of an increase in the time and effort that operators spend manipulating the interface rather than monitoring the unit. (Vicente, Mumaw, and Roth, 1997)

> It is during fast-paced evolutions that the multi-functional displays' partial keyhole view into the controlled system's information space requires the most highly-skilled navigation and screen-management performance from the user(s) of the interface. But this is precisely when the secondary tasks of assimilating an integrated view of the world through the keyhole, even the relatively large keyhole provided by a six-headed workstation, can become formidable. (Hoecker and Roth, 1996, p. 1135-1136)

> The lack of a simple, easily used navigation scheme may adversely impact operator performance and thus, affect plant safety. (Beltracchi, 1996, p. 413)

> There is a question as to whether operators ought to be performing these additional activities; one could argue that, not only does computer-based operation restrict the operator's window on plant activity, it also erects a barrier to task performance by requiring a whole host of trivial activities to be performed in association with the operators 'real' goals. (Barber, 1996, p. 58)

> The impact on the operator of computer interfaces, the prime component of performance support systems, is difficult to anticipate. Human performance at the computer interface is a cognitive problem. It is often the case that people expend inordinate mental effort in navigating a computer system. The actual use of a computer system within a larger task should require a minimum of attention from the user. The user should be applying his energy toward the larger task at hand. (DeTina, Poehlman, and Garland, 1995, p. 17)

However, despite the level of concern expressed in the above citations, very few studies considered dual-task performance in complex systems where the tasks are realistic tasks operators must perform, such as dual-task tradeoffs between supervisory control tasks and interface management tasks. Thus, our most significant finding was the paucity of hard data. Similar observations were noted by others (Vicente, Mumaw, and Roth, 1997). Part of the difficulty in studying the effects of interface management tasks is that the effects are unseen except during high workload periods. That is, the problems are not identified by operators or system evaluators until the cognitive demands of the interface management tasks begin to cause the process control tasks to suffer (Hoecker and Roth, 1996).

Several studies provided direct support for this effect of the dual-task performance relationship.

Two transportation studies are noteworthy because they address the relationship between complex system primary tasks (driving a truck) and realistic secondary tasks (such as operating a cell phone). The issue of secondary task effects on primary tasks is currently a significant concern in the transportation industry. The development of in-vehicle systems as part of an intelligent transportation system may have consequences for driver safety. In part, these in-vehicle systems impose secondary tasks that can affect the driver's primary task of vehicle control.

Tijerina et al. (1995) examined the effects of secondary tasks on professional operator performance while driving heavy vehicles on an actual roadway. The secondary tasks included interacting with a text messaging system, radio tuning, and cellular phone use. The results showed that lane-keeping performance was degraded. This measure was considered directly relevant to crash hazards. In addition, driver monitoring was affected. They concluded that the workload associated with these in-vehicle devices can degrade even highly overlearned driving skills. Kantowitz et al. (1996) replicated the secondary task effects in a more controlled simulator test. While the general tendency of the secondary tasks to degrade primary task performance was found, the magnitude of the effects was less. This led the authors to suggest that the actual driving creates higher workload. Thus, less spare mental capacity was available in the actual road test compared with the simulator.

The use of window-based display systems was found to impact primary task performance. Hsu and Shen (1992) conducted a comparison of the relative advantages of three presentation formats: layered windows, tiled windows, and multiple display devices (e.g., twin monitors) for supporting information integration tasks. The three formats varied with respect to spatial proximity of information and window management demands. The layered windows allowed information to be presented within the shortest viewing distance between items, but required the most effort to manage the windows. The twin monitor format presented information with the greatest viewing distance between items but required the least effort to rearrange the information presentation. The tiled window format was considered to lie between these two extremes for both spatial proximity and window management demands.

The task environment was a manufacturing shop floor. Thirty male engineers, who were familiar with shop-floor control tasks, participated in this study. Subjects monitored a simulated shop-floor control system and made decisions on allocating manufacturing resources. The decision-making tasks had two levels of cognitive demands: low and high. Both required the subject to extract relevant data, check parameters against tolerance ranges, and decide which resources should be reallocated. The tasks in the high demand category required the subject to compute data and compare it to production goals. Performance measures included time spent on each task and accuracy. Subjects received training in window management prior to the experiment because not all were familiar with the operation of the windowing system. Order scheduling and order processing data were arranged in tabular format in the displays.

With regard to task performance time, both task presentation format and level of cognitive demand were statistically significant. In addition, there was a significant interaction between presentation format and level of cognitive demand. The layered window group required the most time to complete both the low- and high-demand tasks. For the low-demand tasks, the tiled window group required more time than the twin monitor group. However, for the high-demand tasks, the twin monitor group required more time than the tiled window group. For task accuracy, both presentation format and level of cognitive demand were statistically significant. There was no significant interaction between them. The layered window group had the poorest accuracy scores for the two types of tasks, while there was no difference between the accuracies of the two monitor and tiled window groups.

Hsu and Shen (1992) concluded that window management imposes a substantial amount of workload that can distract the users from their primary tasks. When a user must integrate information and complete a complex decision-making task, the demands of window management can degrade task performance. Hsu and Shen suggest that, for information integration tasks, tiled windows and twin monitors are more appropriate than layered windows.

Hsu and Shen's findings indicate that, for the display systems and tasks studied, window management had a greater effect on users' performance than did spatial proximity. The fact that the layered windows resulted in significantly poorer performance for both accuracy and response time suggests that the window management task may have had important cognitive effects. If a performance decrement appeared for task time alone, one could argue that manipulating layered windows simply requires more time than glancing at twin monitors or using tiled windows. However, task accuracy using layered windows was about eight to 12 percent lower than the other two presentation formats (based on the plot of task accuracy). This suggests that the window management task affected cognitive components of the decision-making task.

A few studies have specifically addressed the dual-task issue in the process control environment. However, there have been efforts to assess the effects and studies that provide information on the issue, even though their main purposes were different. The rationale for the concerns and the data that are available are discussed below, together with is literature addressing interface management that is not necessarily based on empirical data. The opinions and insights of those authors can make important contributions because they are often based on years of design and operational experience related to complex systems.

In the previous chapter, three characteristics of computer-based HSI systems were identified as being especially important to interface management task performance: information volume, virtual workspaces, and HSI flexibility. It is these same characteristics that lead to the presumed negative effects of interface management effects on supervisory control performance. One of the primary causes is what Woods referred to as the "keyhole effect" (Woods et al., 1990, 1994). The operator's limited view of the vast amount of process information and displays has been compared to a view through a keyhole. The operator's access to plant information and controls may be affected by the limited size of the display area of the display device. For example, the display screen area may be quite small relative to the many display pages in its display network. Thus, only a fraction of the total set of items of a display system can be viewed at one time. The keyhole effect has broad implications for the operators' ability to process information. Because the content of the information system is divided into discrete displays, operators may be forced to make repetitive transitions between displays that contain information, an action that is sometimes referred to as display thrashing (Henderson and Card, 1987).

Another result of the keyhole effect is that operators may have difficulty in shifting attention beyond the data in currently visible display pages to data in other display pages that are currently visible. This may result in the operator losing awareness of overall plant status. Getting lost means that the user does not have a clear understanding of the relationships of items within the information structure, does not know the present location within the system, or experiences difficulty deciding where to look next in the system (Elm and Woods, 1985).

Concern about the keyhole effect or the limited view offered by computer-based CRs is a common theme in studies of human performance with computer-based display systems. Barber (1996) noted that information can be not only physically hidden, but conceptually hidden, meaning that operators do not know which display contains the best information for the current tasks. Further, information for a given task may be contained on many different displays requiring operators to navigate through many pages to find the needed information. Barber notes that this activity can lead to two error types: "finding" the wrong information and thinking it is the right information, and being unable to find the right information at all.

Difficulties in navigating computer-based systems have existed since the early development of large display networks. For example, when searching for information, users were very likely to choose menu items that did not lead to the desired information and tended to give up without locating the information on a high proportion of searches (Norman, 1991). After observing operators using a menu-based information system called ZOG, Robertson, McCracken, and Newell (1981) stated, "Users readily get lost in using ZOG. The user does not know where he is, how to get where he wants to go, or what to do; he feels lost and may take excessively long time to respond. This happens in all sorts of nets, especially complex nets or nets without regular structure" (p. 483).

Similar behavior was noted in an observational study for the initial design of a computer-based procedure system for NPPs, implemented using the ZOG human-system interface software (Elm and Woods, 1985). Three classes of users attempted to use the computer-based procedure system during a simulated accident in a high-fidelity NPP CR simulator: people experienced in operating the NPP, writers of paper-based procedures, and people knowledgeable in the ZOG system. Elm and Woods state (1985):

> All classes of test participants were unable to use the computerized version of the procedures to accomplish [plant] recovery tasks. They became "lost" in the Zog net, unable to keep procedure steps in step with plant behavior, to determine where they were in the network of frames, to decide where to go next, or even to find places where they knew they should be (i.e., they diagnosed the situation, knew the appropriate responses as trained operators, yet could not find the relevant procedural steps in the ZOG net). (p. 928)

Navigation difficulties were observed in a windows-based upgrade to an SPDS at the Millstone Nuclear Power Plant, Unit 2. During the development of the system, inconsistent navigation strategies confused the operators and made the system less usable (Brown, 1997). Operators would become lost. To recover their bearings, they would exit the display system and return to the display system from the top-level display. This led to the development of an enhanced navigation system and navigational aids (which included such features as "previous" buttons and pull-down menus showing the last six displays selected). Brown found that there were differences in operator preferences for navigation. Some preferred to use a mouse while others, the keyboard. Thus, he recommended providing options for different navigation control.

Schryver (1994) conducted a study to empirically quantify the workload imposed by navigation. Six participants were each required to retrieve and monitor one or two plant parameters from an elementary SPDS for a PWR NPP. Upon accessing each target item in the display network, participants were asked to answer a number of questions. Navigation distance was calculated by expressing the number of navigation decisions in terms of binary bits. Analyses of variance of a modified task load index (MTLX) (Nygren, 1991; Hart and Staveland, 1988) and subscales for confidence, disorientation, and effort demonstrated "...substantial support for the claim that navigation of large-scale display networks can impose additional mental workload at the advanced control workstation" (Schryver, 1994, p. 343).

While the addition of navigation aids was a successful solution in the Millstone SPDS example described above, the broader issue is why operators became lost in the first place. The conceptual structure of the display pages may be a factor. Operators use their mental models and their current situation model to develop plans and guide expectations. This same process is used in interface management. Operators appeared to need an accurate understanding of the organization of the display network (mental model), as well as an understanding of where they are (situation model) in order to formulate and execute navigation plans and recover from navigation errors when they occur.

The most common display network structure for NPPs is by plant functions and systems. Such organizations were effective for the layout of conventional displays, but a recent survey of power plants suggests it may not be effective for display network organizations (Heslinga and Herbert, 1995). Designers, managers, and operators of plants from eight European countries were surveyed on their experiences with the introduction of computer-based HSI technology either as part of new plant designs or plant modernization efforts. Operators were reported to have problems finding information in system-based display network organizations, especially for non-routine operations. The authors suggested that operators' information needs are centered not along the system hierarchy, but along task requirements. "System-based VDU displays do not provide the information required by operators during non-routine situations, where there is insufficient time to search for information and controls within a hierarchy of displays. Hence task-oriented displays, which show the operator information relevant to a particular task only, should be provided in addition to the commonly used system-based displays" (p. 257).

An alternative to the system-based and task-based network approaches is the means-ends levels of abstraction approach to display structure. This approach has been recommended because it reflects the underlying principles on which the plant functions, processes, systems, and components should be understood (Beltracchi, 1996; Biscantz and Vicente, 1994).

While there are many approaches to display network organization, there is little data on the appropriate models (or metaphors) for large, complex information systems. The common function-system model may reflect more of the design engineers' concept for information organization, which may not be well suited to plant operations, especially during process disturbances. A further complicating factor may be HSI flexibility, which may inhibit the development of an accurate model of the display structure. If operators can view the display network in many different ways, it may be more difficult to form a good understanding of its organization and, as a result, navigation plans may be less predictable.

Another factor contributing to interface management effects is the type of dialogue provided for operators to perform these tasks. DeTina, Poehlman, and Garland (1995) proposed using direct manipulation interfaces because they are presumed to require few cognitive resources and, therefore, enable users to apply cognitive resources to the task domain rather than the interface. However, even direct manipulation systems impose demands that may affect primary task performance.

Barber (1996) made a detailed comparison between CR operators' interaction with conventional HSIs and computer-based HSIs, analyzing the demands associated with computer input devices, such as mice, trackballs, and touch screens, in comparison with the controls in conventional CRs. Barber concluded that:

- The selection of computer input devices is typically made with little consideration beyond personal preference.

- The problems associated with information retrieval and control manipulation will be compounded by the fact that a small set of control actions, such as positioning a cursor, will be required for all CR activities. Vicente, Mumaw, and Roth (1997) make a similar point about monitoring. Whereas, in a conventional CR monitoring was done primarily with the eyes, in a computer-based CR it is done with the hands, meaning, that considerable manipulation of the computer-input device is needed to page through displays.

- Some characteristics of computer-input devices make them more difficult to use as control devices, such as the lack of kinesthetic feedback.

- There were many subtasks associated with these devices that require more cognitive resources than their physical analog, such as manipulating a cursor on a screen versus reaching for a control with the hand. The requirement to visually monitor cursor position makes it difficult to monitor process parameters at the same time.

While manipulating a device with a cursor seems straightforward, its movement and operation can be complex, especially when multiple buttons are included for additional activities. In addition, some individuals experience difficulty translating hand motions on an object, such as a mouse, to the physical movement of the cursor.

Barber (1996) also addressed the issue of flexibility, illustrating that it impacts control-display relationships because their flexible location can alter control-display expectations. The controls and displays of computer-based HSIs may not have unique, spatially dedicated locations to the same degree that conventional HSIs have. A particular plant variable or the user interface for controlling a particular plant variable may appear on multiple display pages, which may be accessed from multiple display devices. The operator selects display devices that contain needed information and are appropriately located near other task requirements. Multiple devices may be coordinated when performing a task. This selection and coordination task can be imposing and create new opportunities for error.

Moray (1992) described new opportunities for error that can result from the need to coordinate multiple VDU-based displays with sets of hardwired controls. For example, on an engine control console for a twin-engine ship, the controls for the port engine were located on the left side of the console and controls for the starboard engine on the right. Above these hardwired controls were three VDUs (i.e., left, middle, and right), each capable of displaying information for either engine. This flexibility makes efficient use of the available display screens but creates the opportunity for violations of display-control stereotypes. For example, if the middle VDU were occupied and the sailor opened two displays for the port engine, the second display for the port engine would appear above the controls for the starboard engine. As a result, the sailor could incorrectly associate the starboard engine controls with the port engine display because they were physically located together.

Just such an error occurred during tests of the system using a dynamic simulator. While troubleshooting a problem with one engine, the sailor placed a display on the opposite VDU, examined the display for a few moments, and then proceeded to use the controls located below the screen to shutdown the engine. Physical proximity and population stereotypes for the arrangement of controls and displays lead to a very strong association between displays with the wrong set of controls. After trying unsuccessfully for nearly one-half minute to shutdown the engine using the wrong controls, the sailor suggested that the simulator had developed a fault. Moray states that had this event happened at sea, one engine would have been throttled back hard while the other continued to run at full throttle. The ship would have made a full power turn at high speed, which could have had severe consequences, such as a collision.

Moray (1992) suggests that additional errors may have occurred if the console was shared by multiple personnel. For example, a sailor stationed at the controls for the starboard engine may wish to view two display pages at the same time. If the VDU in the middle is not available, the second display page would be placed on the VDU that is over the port engine controls. While this may be an acceptable display arrangement for the sailor stationed at the starboard controls, it may cause a stimulus-response incompatibility problem for the sailor stationed at the port controls. That is, information regarding the starboard engine would be displayed directly over the port engine controls and may lead to confusion. Thus, stimulus-response compatibility considerations may be especially important in shared work environments.

A similar problem can be envisioned in an NPP HSI. For example, an HSI consisting largely of hardwired controls and displays could be augmented with VDUs (e.g., as part of an upgrade). As a result, it may be possible to present a display for one train of a control system on a VDU that is located near the controls for a different train. The resulting situation would be similar to Moray's example of the engine control. Operators may unconsciously make incorrect associations between the controls and displays that are hardwired and the displays on the VDU. Consequently, the wrong control may be operated. Even greater opportunities for error may exist if the HSI provides computer-based (soft) controls in addition to displays on its VDUs. The ability to move both controls and displays between display devices may increase the number of incompatible combinations of adjacent controls and displays.

Flexibility in positioning displays on multiple VDUs also may violate population stereotypes that exist between adjacent displays. For example, operators who are used to seeing plant mimic displays arranged to reflect a left-to-right convention for process flow may be confused if they are presented in a different order. For example, displays representing later stages of the process flow could be located to the left of displays representing earlier stages. This could lead to errors in interpreting the displays. For example, when viewing complex mimic displays, the operator may become confused about the stages of the process being depicted in the displays, or may misinterpret the process flow.

Moray concluded that the current trend to provide increased flexibility may produce other types of control-display incompatibilities beyond the example provided above. Further research is needed to examine the range of stimulus-response incompatibilities that may result from the increased flexibility of computer-based display systems and to develop HFE guidance. Many of these same issues on human performance considerations of soft controls were noted in an earlier report (Stubler, O'Hara, and Kramer, 2000).

In summary, there is support for the resource-limited effect.

3.2.2.3 Research Addressing Data-Limited Performance

The above discussion concerned the demands imposed by secondary tasks and how they distract, interfere, and use resources that may be better allocated to the primary task. However, another strategy for handling the demands of interface management tasks is to follow the data-limited effect which implies that operators greatly reduce their use of resources for interface management tasks and, instead, apply those cognitive resources to the primary task. There is support for adopting this strategy as a way of managing workload under high-workload conditions. The discussion is divided into three sections: NPP operator monitoring performance, control room modernization, and related literature.

Studies of NPP Operator Monitoring Performance

Based on observation of operators monitoring a relatively advanced NPP, Vicente et al. (1997) described the kinds of decisions that operators had to make: "...where to put a given display, what the time scale on a trend graph should be, what the range on a trend graph should be, what form to present a variable in (e.g., trend, bar, bar-trend, digital), what variables should be graphed together, and so on. Not only can the operator make these decisions, but they can make them over and over again in the sense that these presentation parameters can be readily changed in a moment." However, operators tended to ignore the flexibility offered by the system. Instead, they selected a set of displays that they felt gave them a good overview of the plant, and left those on the VDUs, which was done, to some extent, at the expense of more detailed views of the plant that may have been available. This choice was attributed, in part, to the effort involved in paging through displays, a task that operators felt interfered with their ability to understand the overall status of the plant.

For monitoring, Vicente et al. (1997) commented:

> Computer-based HSIs can make it difficult to find information and act on the system in comparison with conventional plants...In a computer-based control room, there is a significant increase in the amount of knowledge required to operate the interface. Part of these demands arise from the fact that information is presented serially. Thus, operators need to know how to bring up the information they want to display on CRTs. The other part of the increase in knowledge demands arises from the fact that the computer-based displays are much more flexible than the hard-wired instruments. The same information can be displayed at different time scales, at different ranges, in different locations, in different forms, and in different groupings. Consequently, the operator has to have much more knowledge about the interface (not the unit) to resolve the degrees of freedom offered by the flexible design of the system...On the one hand, one might argue that the flexibility provided by the computer-based medium should result in a performance improvement because it allows operators to view information in a form that is tailored to different types of contexts. This should reduce the need for the work-arounds that operators engage in traditional control rooms to facilitate monitoring. On the other hand, one could just as well argue that this flexibility comes at the price of an increase in the time and effort that operators spend manipulating the interface rather than monitoring the unit.

The problems associated with information retrieval and control manipulation will be compounded by the fact that a small set of control actions, such as positioning a cursor, will be required for all CR activities. Vicente et al. (1997) make a similar point for monitoring. Whereas in a conventional CR monitoring was done primarily with the eyes, in a computer-based CR, it is done with the hands which means that considerable manipulation of the computer-input device is needed to page through displays.

Monitoring also is affected by the technological sophistication of the plant design. In fact, the classical view of monitoring is that it is a boring and tedious task that leads to vigilance difficulties associated with lack of cognitive stimulation. While this may be true in some systems, recent research in nuclear plants has shown that routine monitoring can be difficult (Mumaw et al., 1996; Vicente et al., 1997).

Some factors contributing to the difficulty were identified by Mumaw et al. (1996) following a study of monitoring performance in two NPPs. The factors included:

- *System complexity* - There are thousands of components which interact under different situations; thus, it can be difficult to understand the implications of each.

- *System reliability* - Even though the number of components is large and they are highly reliable, at any one moment there are many that are out-of-service or not working properly. Operators must factor these considerations into their situation assessment.

- *Display design* - Given the large number of parameter displays, it is often difficult to detect when an abnormal situation has occurred. There were several reasons for this. First, interpretation of displayed parameter values was memory intensive. Displays did not give clear referent values and few aids were provided to support recall of recent values. In addition, few emergent features are presented to enable operators to rapidly identify higher-level information from the displays. Complicating the use of the displays were the same reliability issues as other components, i.e., at any time, there may be displays that do not work properly. Failed displays also can be difficult to detect.

- *Automation design* - The operation of and feedback from automated systems was not well represented in the display system. For example, the actual status of components being automatically controlled was not displayed. (Murphy and Mitchel [1986] identified a number of effects on operator's cognition of automation and their implications for display design).

These factors introduce uncertainties that make monitoring difficult. In fact, the authors concluded that monitoring during normal NPP operations is "...better cast as a problem-solving activity than a vigilance task" (p. 30). It is a complex situation assessment activity dependent on imperfect, sometimes nonfunctional, displays depicting thousands of parameters.

In contrast to the well developed eye scanning patterns used by operators using conventional HSIs, when monitoring is performed using computer-based systems, it is often "unstructured" (Thurman, 1997). Operators are advised to monitor everything and given little guidance on how to accomplish this. Thus, monitoring lacks goal direction and important information can be missed. Further, display designs often fail to support monitoring because designers simply take all available status information and develop a set of displays structured around a physical representation of the system (Thurman, 1997).

Vicente, Mumaw, and Roth (1997) examined the generalizability of these factors to a more advanced CR. While they found the overall reliability and trustworthiness of the instrumentation to be improved, the same basic problems existed. In addition, they noted a new problem associated with a CRT-based information system, the keyhole effect, that adds difficulty in monitoring.

Studies of Control Room Modernization

Operator reluctance to engage in interface management tasks was found in the survey conducted by Heslinga and Herbert (1995), described above. Due to the difficulties associated with display navigation and serial information access, operators preferred to use conventional HSIs even when the computer-based HSIs were available. The study participants felt that the conventional HSI provided a better overview and more direct access to the information. Thus, an operator's use of conventional HSIs reflected, in part, a reluctance to expend the time and resources necessary to utilize the full capabilities of the computer-based system.

Two recent studies by the NRC are relevant to interface management. The primary purpose of the first study was to evaluate the impact of alarm system design characteristics on plant/system and operator performance (see footnote 1). One of the alarm system design characteristics studied was display design. Alarms were presented in three different formats: a dedicated tile format, a mixed tile and message list format, and a format in which alarm information is integrated into the process displays. Six two-person crews of professional NPP operators participated in the study. Each crew completed 16 test trials which consisted of two trials in each of eight experimental conditions (one with a low-complexity scenario, and one with a high-complexity scenario). A significant problem was identified when the list of alarms exceeded one display page (one VDU screen). The operators did not like the fact that there were alarms on pages that were not currently displayed. Due to the high level of workload during a disturbance, operators were reluctant to scroll to unseen alarm pages (older alarms). Some operators simply stopped scrolling the alarm lists when workload became high. One operator commented that when the alarm list filled up, he switched his strategy and used the tiles. In addition to their reluctance to engage in interface management tasks, the operators did not want to remove trend displays to access supplemental alarm lists. They had to choose between two potentially important displays because of limitations in the size of the viewing area. Many operators expressed the need for additional alarm VDUs. Their strategy was to set up the HSI in the configuration they felt would be most appropriate for possible events and leave it that way.

It is interesting to note that under high workload, operators generally abandoned the message lists altogether because of the time and effort needed to process the messages. Instead, they used spatially dedicated features of the alarm displays, such as tile windows. This finding is consistent with the results of Bliss and McAbee (1995). They studied alarm response and a primary task within the dual-task paradigm. They varied the criticality of the primary task across three levels and observed alarm response measures. The results indicated that, while performance on the primary task was similar across the three levels of criticality, alarm response degraded as the criticality of the primary task increased.

A second NRC study assessed the impact of introducing computer-based HSI technologies into the control room of a conventional nuclear power plant (Roth and O'Hara, 1998). This technology included an computer-based alarm system, computer-based procedures, and a computer-based display system. The study explored the effect of the new systems on the cognitive functioning of individual crew members, and on the structure and functioning of the crew as a team. The latter information was obtained by observing five crews of professional operators during full-scope training simulations of plant disturbances. In addition, operators and other knowledgeable utility and vendor personnel were interviewed.

Similar to the alarm study, it was observed that operators rarely modified or pulled up new displays once a scenario was started. Rather, they tended to select a set of trend plots to display at the start of the session and kept those up throughout the session. This supports the point that operators are reluctant to engage in interface management tasks when workload gets high, preferring instead to go with the information that is available rather than taking the time and effort to retrieve new information. A strategy used by the crews was to packed the available VDU display real estate with information. Operators were observed putting up multiple windows per VDU, occasionally overlapping and/or covering up one display with another. Covering up information by overlapping or covering one display with another was not found to create any problems.

The operators commented that in dynamic emergency conditions any requirement for display navigation or display setup is an added burden and should be minimized. While operators liked and used the trend displays, they indicated that in high-tempo situations such as an emergency, they could not afford to take the time to set up a particular trend display. There was an expressed desire to predefine displays and to have them come up with just one pushbutton mouse click. This is a more general representation of the reluctance noted above for operators to access alarm support displays.

These findings are consistent: operators are reluctant to engage in interface management tasks in high workload situations creating the potential for operator performance to become data-limited, i.e., crews may miss important information because it is not contained on the presently available displays.

Related Literature

Operator reluctance to engage in interface management tasks was observed in the medical domain as well. In a study of anesthesiology (Cook, Woods, and Howie, 1990; Woods, Johannesen, Cook, and Sarter, 1994), physicians who used a new, computer-based patient monitoring system retrieved important variables and arranged them in display windows to maximize the amount of related information that could be seen at one time on the display screen. Rather than cope with serial forms of display and interaction that are produced by the computer-based system, users constrained the system into a spatially dedicated organization. This eliminated the need to access these variables one at a time from the display system. The authors noted that they used the flexibility of the interface to "convert the device to a static, spatially-dedicated display."

3.2.2.4 Summary

An evaluation of the effects of interface management tasks on complex, primary task performance was made. The significant points discussed in this chapter are:

1. There is support for the resource-limited effect. However, the source of the effects that were responsible for primary task performance decrements, i.e., the specific characteristics of the interface management tasks (such as display network organization, dialogue format, navigation aids, and computer-input devices), is not known.

2. Perhaps the most significant finding of the review is support for the data-limited effect, i.e., operators tend to avoid secondary tasks and they turn their flexible virtual information systems into static, spatially-dedicated devices. The primary concern regarding interface management was that interface management draws resources from supervisory control tasks and negatively impacts their performance (the resource-limited effect). However, a more significant, or perhaps more unexpected finding is that as workload increases, operators reduce their performance of interface management tasks. They truly treat them as secondary tasks in the laboratory sense (i.e., as tasks that compete with the primary task and are lower in priority). Stated another way,

operators manage workload by prioritizing tasks, and interface management tasks are not as important as supervisory control tasks.

The data-limited effect presents an interesting paradox. Advanced systems are designed with vast amounts of data, which is available through hundreds and sometimes thousands of displays. This data is viewed by the operator through a keyhole, thus only a small amount of information is presented at any one time. It is the expectation of designers that operators will use the flexibility of the computer-based interfaces to configure HSI in a way that will address the specific task at hand. Interface management facilities must be used to exercise that flexibility. However, if operators opt not to do so, then a very significant question can be raised: *What is the effect of failing to perform interface management tasks on primary task performance and plant safety?* The implication of adopting such a workload management strategy may be that performance becomes data-limited, i.e., information necessary for task performance may be missed, operators could lose situation awareness, errors can be made, and plant safety may be reduced.

3. Additional research on the effects of interface management tasks on supervisory control performance in nuclear plants is needed. As discussed above, dual-task performance relationships exist. However, a better understanding of how operators manage workload, especially with respect to interface management tasks performed during complex process disturbances, is very much needed. Several of the identified strategies have the general effect of decreasing system flexibility, increasing predictability, and increasing simplicity of the HSI.

4. In general, operators utilize the HSIs in ways not anticipated by the designers. Numerous strategies are adopted by operators to create workarounds and aids to correct for limitations in designs, even when the designs are computer-based, flexible systems. HSI flexibility often still does not provide operators with HSIs that are well suited to their tasks.

5. While the above effects are the most significant issues, other issues raised in connection with performance effects are: limited viewing area, different display organizations, HSI flexibility, windows-based systems, navigational aids and features, and input devices.

6. To support operator performance, the HSI should provide:

   - sufficient viewing area
   - logical organization of the display page network that is consistent with the operator's expectations and mental model of the system
   - a consistent navigational support system providing aids to navigation, especially in the event that operators become lost
   - flexibility to enable operators to recover from situations where they encounter difficulties or where personnel preference can impact performance - but not so much that working with the system becomes a complex decision-making task

3.2.3 Effects of HSI Design on Interface Management Task Performance

The previous chapters provided support for an effect of interface management tasks on primary task performance. Thus, a significant question is the extent to which HSI design characteristics affect the performance of interface management tasks. This chapter is organized around the following HSI design characteristics (identified in NUREG-0700): command language, menus, direct manipulation interfaces, query language and natural language dialogues, navigation, hypertext, manipulation and view arrangement features, moving between multiple display devices, interrogation and user guidance, and global interface management.

Included in the discussion are studies that address interface management with respect to very simple primary tasks, such as typing, where performance of the primary task and secondary tasks are very highly correlated. The literature is richer in insights and opinions than in actual data.

3.2.3.1 Command Language

Command language is type of human-computer dialogue in which a user composes entries that are usually entered through a keyboard, possibly with minimal prompting by the computer. Command language can often be a faster way to perform interface management tasks than, for example, working through a series of menus.

Many empirical studies of command dialogues have focused on text-editing tasks. These tasks may be characterized as involving "...a series of brief, individual acts generally occurring in an unstructured order, driven by the material being edited" (Barnard and Grudin, 1988, p. 243). These studies tend to be user-paced rather than event-paced and have limited command set sizes. (Barnard and Grudin cite a series of studies that examined set sizes that ranged from 3 to 10 commands. Steinbach and Zoltan-Ford, 1990, evaluated a set of 18 commands.) The nature of the commands and the limited command set sizes seem to make these studies more applicable to using navigation commands rather than destination commands. Far fewer studies have addressed using commands for retrieving displays directly from a display system.

Two potential disadvantages of command dialogues, compared to menu-based dialogues, are increased demands on the user's recall capabilities and greater susceptibility to input errors. Each is described below.

<u>Demands on Recall Capabilities</u>

An important characteristic of command language interaction is that users must maintain the set of commands in memory, retrieve one that is appropriate for the situation, and then enter it into the computer. As a result, the memory demands on users are high. For example, with a menu-based interface, the display system can present the user with a subset of options that are appropriate for the current situation. The reduction of the full set of commands to a small set of applicable commands is performed automatically by the menu system. The user is required to recognize, rather than recall, the appropriate command.

Factors that contribute to the ability of users to recall command names include their naturalness, specificity, distinctiveness (e.g., both in meaning and in spelling), frequency of use, and concreteness. Commands that have meaningful names, such as names that accurately describe the action that will be performed, are often easier to recall than arbitrary names. An additional factor is the number of commands. For example, if a display system contains hundreds of displays accessible via destination commands, a large mental burden may be placed on user's memory (Seidler and Wickens, 1992). In addition, task conditions and user population characteristics can affect the ability of users to recall commands.

Another factor related to demands on operator recall ability is the effect of multiple operating modes in an HSI component. In this case, a given command may produce different results in each mode. Some commands may not be relevant in all modes. With a command language interface, the operator must recall which commands are relevant to the current mode. By contrast, many menu systems present only those commands that are relevant to the current condition.

Both users and designers have difficulty developing sets of command names that are clear and have common meanings to all users. Barnard and Grudin (1988) state: "What is perhaps most disturbing is the demonstrated inability of command name creators to perceive problems in the names they created, even when given a chance to examine the entire nameset as a whole, and even after they have used the names themselves in context and experienced first-hand the problems they cause" (p. 251). One conclusion drawn was that guidelines have limited generalizability due to the sensitivity of the effectiveness of command names to contextual factors, such as names, task environment, and user characteristics.

Susceptibility to Input Errors

Since commands are generally entered as text strings via keyboards, they are susceptible to input errors such as misspellings, improper syntax, and accidental substitution of synonyms. Thus, the act of providing inputs via commands may involve greater demands than providing input via an interface that contains a menu and pointing device.

For these reasons, command dialogues are often considered more appropriate for highly experienced, frequent users rather than casual users. An important consideration is whether the increased access speed that is possible through a command dialog is worth any increased demands associated with recalling and inputting the commands.

3.2.3.2 Menus

A menu is a type of dialogue in which a user selects one item out of a list of displayed alternatives. Selection may be made by actions such as pointing and clicking and by depressing an adjacent function key. This chapter discusses human performance considerations associated with menu-based interfaces. The following topics are addressed: menu panel design, menu selection techniques, menu size and search strategies, navigation tools, spatial maps and analogies, and consistency and compatibility across multiple menu systems.

Effects of Menu Panel Design

A menu panel provides the user with a set of options from which to make a selection. For example, a panel may present a set of commands that could be executed, or a set of names for other display pages that can be accessed. The way in which options are arranged on a panel can affect user performance in finding and selecting the desired option. Paap and Roske-Hofstrand (1988) identify three strategies employed by users when assessing individual options on a menu panel:

- *Identity matching* - This type of match is made at a perceptual level. The user compares each option shown on the menu to a specific target option that is held in the user's memory to see if they are identical. This search is successful if the currently viewed menu contains the target option.

- *Class-inclusion* - This search is based on a semantic evaluation of the relationship between the target and an option. With this type of search, users make judgements about whether the target option may be included in one of the current categories (e.g., is the target option "Delete" included in the category "Editing Commands"). Paap and Roske-Hofstrand state that class-inclusion matches are likely to occur at the top-level panels of a hierarchical menu organization, which frequently contain large and fairly abstract categories.

- *Equivalence* - This search is also based on a semantic evaluation of the relationship between the target and an option. Paap and Roske-Hofstrand state that it is more likely to occur at the bottom levels of a hierarchical menu organization. "Equivalence search occurs when the user knows what he wants, but doesn't know what it is called," for example, in searching for an option whose name implies the function that the user is considering (e.g., looking for a name that matches the user's intention of "getting rid of a string").

Lee and MacGregor (1985) describe two types of strategies for searching across a set of options on a menu panel. For an exhaustive search, the user reads all of the options on the panel before making the decision to choose one of them. For a self-terminating search, the user stops searching as soon as an option is encountered that seems appropriate. Therefore, the length of a self-terminating search is expected to be less than or equal to an exhaustive search, since it may not be necessary to search all options. For a menu system in which each menu panel contains the same number of options, and the options are arranged in random order, a self-terminating search would require, on average, that the user read one-half of the options before encountering the appropriate one. In this case, the self-terminating strategy would result in a search that is half as long as an exhaustive search strategy. According to the model described by Lee and MacGregor, search time is determined by the length of the search (e.g., number of options searched) as well as human response time (key-press time) and computer response time.

Paap and Roske-Hofstrand (1988) state that search time for any matching operation can be reduced by organizing options so that the scope of the search is limited (i.e., support a self-terminating search strategy). They state that the best type of menu panel organization will depend upon the type of matching strategy that is likely to occur during use of the menu system. The type of search may vary with user expertise. For example, class-inclusion searches may be facilitated by menu structures that match the user's understanding of how the overall system is structured. In an NPP, options may be grouped by plant systems or safety functions. If there is a good match between the display system organization and the plant structure, then knowledge of the plant could improve the operator's performance in navigating the display system.

The amount of time required to select an option from a menu is affected by the number of options, as well as their arrangement. Perlman (1984) compared search time as a function of list length (5, 10, 15, and 20 options) and options presented in alphabetical or random order. When the options were ordered randomly, search time increased linearly as a function of list length. For every increment of five options, search time increased by approximately one-half second. However, search times were significantly faster when the options were presented in alphabetical order. For the small- to medium-size menus, search time was reduced by about one-half when presented in alphabetical order. Card (1982) compared search time for menus containing 18 options, which were organized categorically, alphabetically, and randomly. The mean total search time after the first block of 43 trials was 0.8 seconds for the alphabetical order, 1.3 seconds for the categorical organization, and 3.2 seconds for the random order. Thus, Card's results support the conclusion that selection time is less for organized menus than for random menus, and that alphabetical orders are somewhat better than categorical listings when users are searching for specific targets. In Card's second experiment, the eye movement of subjects searching through 18-item menu lists was analyzed using an extension of the Kendall and Wodinsky search model (Paap and Roske-Hofstrand, 1988). It was found that after extensive practice (800 selections from the same menu), the benefits due to list organization disappeared. That is, if the user knows the name of the option and where it is located, then the list organization no longer matters. This implies that the effects of poor list organization may be greater for less experienced than for experienced operators.

When an operator is not sure of the precise name of the desired option, identity matching cannot be used. Instead, the user must resort to semantic-based searches, such as equivalence matching. The scope of searches based on equivalence matching will not be reduced by organizing options alphabetically because the user cannot use the alphabetical information to eliminate options from the search. However, if the options are organized into conceptually distinct categories, then a semantic search can be initiated in the appropriate category. This reduces the size of the user's search and can save time.

McDonald, Stone, and Liebelt (1983) compared searches using identity matching to equivalence matching for two conditions. In the first condition, the users received the precise name of the target option (i.e., explicit target), and in the second condition, the users received a short definition of the target option (i.e., fuzzy target). For explicit targets, both categorical and alphabetical orders yielded better performance than random order for the list. However, for fuzzy targets, the categorical organization yielded significantly better performance than either the alphabetical or random order lists. As with Card's study, McDonald et al. found that performance benefits associated with menu organization disappeared with extensive practice with the same menu implying that if the users are likely to know the names of the options, then good performance may be obtained from either categorized or alphabetized menus. If the users are uncertain of the option names, then categorized lists are likely to be more effective. However, the benefits may decrease if the users become highly familiar with the menu panels.

Paap and Roske-Hofstrand (1988) reviewed experiments that addressed class-inclusion matching. They concluded that search time is affected by four factors (1) number of categories per menu panel, (2) degree of conceptual overlap between the categories appearing on the same menu panel, (3) degree to which the category names are considered representative of the items included in the categories, and (4) use of descriptors for category names. They analyzed search time reported in experiments by Perlman (1984) and Landauer and Nachbar (1985). For both studies, search time increased with the number of options presented.

The search task addressed by the Landauer and Nachbar study featured class-inclusion matching in which each option indicated a numerical range. The subjects selected the option that bounded a target numerical value. The option categories were clearly defined (e.g., not fuzzy), mutually exclusive (i.e., no numerical ranges overlapped) and arranged sequentially. Search time was found to be a log-linear function of the number of options presented. The log-linear function follows from the Hich-Hyman Law (Hyman, 1953; Welford, 1980):

$$t = c + k \log b,$$

where b is the number of equally likely responses (options on the menu panel), c and k are constants, and t is the average response time. When the menu size was doubled (e.g., from 2 to 4 to 8 to 16) the average search time increased by a constant increment. (See the discussion below of menu size and search strategy).

The search task addressed by Perlman was based on identity matching. The average search times for the Perlman study were a linear function of the number of options and were faster than the corresponding search times obtained by Landauer and Nachbar. Paap and Roske-Hofstrand used these results to conclude that (1) search time is slower with class inclusion matching than identity matching, and (2) as the number of options increase, search time increases more slowly with class-inclusion matching than identity matching.

The user's ability to effectively limit a search to the correct category will be impaired when there is conceptual overlap between the categories appearing on the same menu panel. In addition, Paap and Roske-Hofstrand state that search time increases when the targets are less familiar examples of the option categories. They cite a series of experiments by Somberg and Picardi (1983) in which the subjects were presented first with a target and then with a menu of five options. The task was to quickly decide to which category the target belonged. The targets were either typical or atypical examples of the category. For example, "robin" was a typical example of "bird" while "penguin" was an atypical example. While the accuracy was high (over 90% correct) for both typical and atypical targets, the average response time was 200 msec slower for the atypical targets.

The meaning of options may be clarified by appending expanded descriptions. Lee et al. (Experiment 6, 1984) report a study that compared the same set of options, with and without descriptors. The descriptors listed the options from the next level of the menu hierarchy. For example, in one menu that listed seven options, the descriptor for the first option listed its 10 associated (descendent) options. The subjects made 82% fewer selection errors with the menus that contained the descriptors. In addition, subjects indicated a preference for the menus that contained the descriptors. Thus, they concluded that descriptors may improve selection accuracy when users have limited experience with a menu panel that contains fairly general and abstract categories. Two costs associated with the use of descriptors are increased demands on display space and possibly slower search times due to the increased quantity of material that must be read.

In a study by Dumais and Landauer (1983), descriptors were found to be less beneficial. The use of descriptors increased accuracy by only 6% for a selection task that had an overall error rate of 50%. Paap and Roske-Hofstrand offer two possible reasons for the discrepancy between the 6% improvement in this study and the 82% improvement in the study by Lee et al. (Experiment 6, 1984). First, in the latter, the descriptors contained menu options and were applied to the middle of the menu hierarchy. In the Dumais and Landauer study the descriptors were applied to the leaves (ends) of the menu hierarchy. Thus, in the Lee et al. study, the descriptors pertained to both the immediate and next selection made in the hierarchy rather than the final terminal selection. Second, the descriptors used by Lee et al. contained more information, with up to 11 options from the next level. In the Dumais and Landauer study, the number of examples in the descriptors systematically varied from 0 to 3.

A study by Snowberry, Parkinson, and Sisson (1985) also supports the view that errors can be significantly reduced by presenting the options of the next level of the hierarchy, especially when presented in the earlier branches of the hierarchy. Knowledge of the upcoming options was found to be useful at the higher levels of the hierarchy (errors were reduced from about 14% to about 4%). However, this knowledge was less helpful at the lower levels (errors were reduced from about 8% to about 3%).

Selection also may be affected by the clarity or vagueness of the option categories. In the Dumais and Landauer study, error rates were measured for a selection task in which subjects chose between options that had no explicit names but were represented by either one or three examples. In one experiment, subjects were given 72 items and asked to identify to which of five categories each item belonged. If the subject could do so, it could be assigned to a miscellaneous category. In a second experiment, the miscellaneous category was eliminated and subjects were forced to choose among the five categories. Accuracy in the second experiment was 45% better than the first experiment. The implication drawn by Dumais and Landauer from this comparison was that the presence of even one vague category (i.e., miscellaneous) can create confusion and entice users to make a wrong selection. In reviewing the this study, Paap and Roske-Hofstrand state that the usability of a name is very much determined by other names appearing in a menu panel. A name is too narrow if it implies fewer actions or objects than are actually included in the option, and too broad (or imprecise) if it implies more actions or options than are actually included in the option. The imprecision of names becomes costly when the apparent scopes of multiple names overlap. Then, response time and errors associated with selecting options, using class-inclusion or equivalence matching, may increase.

Based on their review of research literature, Paap and Roske-Hofstrand (1988) suggest some guidelines for the organization and naming of items on menu panels. Methods of menu panel organization include alphabetical, categorical, conventional, and frequency of use. The categorical method organizes items according to functional characteristics. The conventional method organizes items according to commonly used patterns, such as sequential relationships (e.g., the days of the week) or ordinal relationships (e.g., small, medium, and large). In general, when users have specific targets in mind (i.e., identity matching), alphabetical order should be used. However, if the list of options is short and has a conventional order, then conventional order is probably preferable to an alphabetical order. If the list is long, then the list should be alphabetized unless the opportunity for using category information is great. If the options can be arranged in distinct categories (with little conceptual overlap) that are well-known to the users, then organizing by category may be worthwhile.

When users have only fuzzy targets in mind and the list is short, then a conventional order should be used if one exists. Otherwise, the options should be placed in alphabetical order. If the list is long, grouping by category is generally recommended. However, if the list contains a subset of options that are used more often than the others, it may be preferable to list the options in decreasing order of frequency. Listing by frequency may be particularly beneficial if groupings by category would not be distinctive or if the users may not be familiar with the proper instances of each category.

Finally, Paap and Roske-Hofstrand state that option names should be precise. They should allow users to infer the included actions and objects. The names should not omit things that should be included or include things that are extraneous. Adding descriptors, such as examples or the options available at the next lower level, is helpful. However, the factors that dictate the magnitude of the benefit are not well understood. Thus, testing of menu names is important.

Effects of Menu Selection Technique

Two methods for selecting options from menus are text entry and pointing interfaces. A variety of pointing devices are used to select options from menus, including the touch screen, mouse, trackball, joystick, cursor keys, and light pen. Many studies have evaluated the relative benefits of these devices with conflicting results. For example, a comparison of a mouse, pressure-sensitive joystick, and a cursor key found the mouse to be the fastest and most accurate (Paap and Roske-Hofstrand, 1988). Karat, McDonald, and Anderson (1984) compared a mouse, touch screen, and keyboard entry of single-letter identifiers. Subjects were much faster with the touch screen and keyboard (0.8 and 1.1 seconds) than with the mouse (2.7 seconds). It is interesting to note that in the Karat et al. (1984) study, selecting options via a mouse required more than twice as much time as typing single-letter identifiers. One might expect the use of identifiers to be slower than the use of pointing interfaces because an additional cognitive task is imposed on the user - after choosing an option the user must locate the associated identifier and hold it in memory until it has been entered. Thus, the current trend toward pointing interfaces may not be to the advantage of operators. Further understanding of the factors that affect user performance for menus is needed.

Perlman (1984) studied the use of alphabetic and numeric identifiers for menu options. Eight computer terms -- assemble, buffer, compile, debug, edit, file, graph, and halt -- were always presented in alphabetical order. Four arrangements of identifiers and options were tested by pairing two types of identifiers (the letters *a* through *h* and the numbers *1* through *8*) so that the identifiers were either compatible or incompatible with the alphabetical order of the options. Examples of compatible pairings include matching *compile* with *3* or *c*. Analyses of selection times revealed a significant interaction between identifier type and compatibility. When identifiers were compatibly mapped to the options, the letter identifiers produced faster retrieval time (1.1 seconds) than the numerical identifiers (1.5 seconds). However, when the mapping was incompatible, the numerical identifiers (1.9 seconds) were faster than the letters (2.2 seconds). Perlman recommended that incompatible arrangements of letter identifiers should be
avoided.

Feedback on input actions is a means of reducing input errors and improving user performance. Paap and Roske-Hofstrand state that menu systems should provide feedback indicating:

- Which options are selectable
- Which options have been selected so far
- When a pointing device has entered the selectable area of an option
- When the selection process is ended

Two techniques for preventing users from selecting inappropriate options are to present (1) only relevant options and exclude the others, and (2) all options, using a code to designate those that are relevant or available. Three considerations regarding the appropriateness of these methods include the type of options presented (e.g., actions versus destinations), the number of options associated with each node, and the number of options that are applicable to multiple nodes. For example, there may be many options representing destinations in the information structure and only a few of them may be relevant to a particular location in the display network (e.g., the number of parent and descendant nodes that can be accessed from a given node is small compared to the total number of nodes in the network). Thus, for menus containing destination options, it would seem practical to present only the relevant options, rather than all options, and use a code to designate those that are relevant or available.

Compared to destination options, options that indicate actions may be more limited in number. Also, action options may apply to multiple nodes (e.g., the same set of actions may be applicable to a large number of display pages). In such cases, it may be possible to present all options and use a code to designate those that are appropriate. Presenting the irrelevant or unavailable action options using a low-salience code may reinforce learning of the locations of options on the menu panels and, thus, decrease option selection time. The relative advantages of these two methods are not fully understood. Also, the effects of using both methods in combination (e.g., for menu systems that contain both action and destination options) are not fully understood.

Effects of Menu Size and Search Strategy on Retrieval Time

The overall size of a display network is determined, in part, by the number of display pages. When developing a menu structure, tradeoffs can be made between breadth and depth. For example, the number of levels in the network structure (depth) can be reduced by making more display pages available at each level (e.g., increasing the breadth). The relative effects of menu structure breadth and depth on the ability of users to access information is a great topic of concern. Snowberry et al. (1985) conducted two experiments in which users found a target word by searching through menu levels. Speed and accuracy were significantly better on broad arrays even when user performed more trials on deeper menus (4 seconds per search with 3% error vs. 6 seconds per search with 12% error). Snowberry et al. suggest that for the purpose of simple menu selection, the number of items per menu frame should be increased, while the number of menu levels should be decreased. This study confirmed earlier findings that users have trouble navigating through deep menus. Also, the study found that providing the users with additional information (in particular, showing users their previous selections) actually hindered their progress. Finally, the most consistent performance was obtained when the participants received help fields during their first trial of practice, and no benefits were found when introducing help at the end of the menu. This led the researchers to conclude that it is much more effective to introduce the help fields at the very beginning of the interaction between the computer and the user (Snowberry et al., 1985).

Lee and MacGregor (1985) present a model of menu search time that is based on search strategy, scanning time, key-press time, and computer response time. They apply this model to derive the optimal menu size (e.g., number of options per menu panel). For the exhaustive search strategy, in which the user reads all of the options on the panel before choosing one, the expected number of options searched before the desired option is found is expressed as $E(A) = a$, where "a" is the number of options on the menu panel. For a self-terminating search, the expected number of options searched must be less than or equal to "a." If the options are arranged randomly, the expected number of options searched before the desired option is found is expressed as $E(A) = (a + 1)/2$ because, on average, one-half of the options will be encountered before the desired one. This equation also would be true for alphabetically arranged options

that are equally likely. If the options are instead arranged by decreasing frequency of use, the value of E(A) will decrease. For the limiting case in which the first option is always chosen, the equation becomes E(A) = 1.
The time required to access one menu panel, read the options, and make a choice is expressed as:

$$S = E(A)t + k + c$$

Where S = the search time for one menu panel, t = the time required to read one option, k = key-press time, c = computer response time (the time between the user's key press and appearance of the selected menu), and E(A) = a or (a + 1)/2 depending upon the search strategy employed.

If the information structure contains p menu pages (one per level of the hierarchy), then the total search (ST) through *p* pages is expressed as:

$$ST = p(E(A)t + k + c)$$

Lee and MacGregor state that:

$$p = (\ln n)/(\ln a)$$

where n = the number of items of information (total number of options) in the information system.

They obtain an equation for the optimum number of options per menu panel by substituting the expression (ln n)/(ln a) for p into the equation for ST, finding the first derivative with respect to a, and then setting the equation equal to zero.

For the exhaustive search strategy, the equation becomes:

$$a(\ln a - 1) = (k + c)/t$$

Given the reading speed, key-press time, and computer response time, the number of options per menu panel that minimizes search time can be computed using numerical methods of analysis. As reading speed becomes very slow relative to the other time parameters, the optimum number of alternatives per menu panel approaches *e*. In integer values, the lowest optimal value will be three options per menu panel.

For the self-terminating search strategy the equation becomes:

$$a(\ln a - 1) = 1 + 2(k + c)/t$$

In this case, the lower limit for the optimal number of options per menu panel is 3.59, or in integer values, a = 4.

Lee and MacGregor apply this model for an analytical evaluation of menu size for an information retrieval system. The following design assumptions were used. The rate at which users read the options was varied from 33 to 454 words per minute. Key-press time was varied from 0.5 to 1.0 seconds. Computer response time was varied from 0.5 to 1.35 seconds. The slower value was intended to represent the type of computer response time that may be encountered when multiple people use the system at the same time. This analysis predicted that for a wide range of conditions the optimum menu panel size varied from 4 to 8. The optimum only exceeded 10 items for the self-terminating strategy when the user's reading time was extremely fast (0.25 seconds per option) and computer response time was very slow (0.90 and 1.35 seconds). Lee and MacGregor point out that the optimum number of options per menu panel does not depend upon on the size of the display network (number of individual display pages). Larger structures increase the total search time, but they do not alter the optimum value. They also conclude that the number of errors generally does not affect the optimum value, although it does affect search time.

Lee and MacGregor's model applies to homogeneous and complete hierarchies. The hierarchies must be homogenous in the sense that the number of options per menu panel is constant. The hierarchies must be complete in the sense that each branch has the same number of descendant levels. Fisher, Yungkurth, and Moss (1990) extend this model to address information structures that are less homogenous and less complete.

Effects of Spatial Maps and Analogies

Webb and Kramer (1990) cite previous studies that addressed the effectiveness of spatial maps for supporting display navigation or the recall of hierarchically structured information (Billingsley, 1982). They state that subjects who viewed a spatial map (e.g., hierarchy diagram) prior to performing an information retrieval task performed better on the data retrieval tasks than did those who received other types of instruction, such as lists of pathways or pictures of selection points. However, Webb and Kramer propose that for large, complex information structures, the benefit of a spatial map may decrease as the size and complexity of the structure increases. They found that the ability of subjects to recall the lower-level (terminal) items of a hierarchy decreases as the size of a hierarchy increases, suggesting that the reason for the decline in recall is that words in the higher levels of the hierarchy serve as cues for the recall of lower-level words. As the size of the hierarchy increases, the number of higher-level items linked to the target item increases. As a result, the probability of forgetting a word in the path to the target item increases. This increases the probability of failure to retrieve the target item.

Webb and Kramer (1990) proposed using analogies, rather than spatial maps, to provide the system model of the information structure to aid users in the learning and performing information retrieval tasks. They believed there were two benefits in using analogies rather than maps in creating a system model: (1) analogies would be as good as spatial maps in the initial acquisition of knowledge of the information structure because both techniques provide structural information, and (2) the mental model provided through an analogy would remain relatively more intact over time than one provided through a spatial map, therefore leading to superior performance on retrieval tasks. This was their hypothesis because (1) the analogy allowed the user to navigate by inference whereas the spatial map required the user to remember paths through the information structure, and (2) the analogy contained less material to remember than did the spatial map.

Webb and Kramer compared instructional approaches for aiding novice users of a hierarchical menu retrieval system. Subjects were randomly assigned to four groups:

- *Spatial map* - subjects studied a spatial map of the display structure

- *Analogy* - subjects studied an analogy that compared the retrieval task to moving through a department store, in which items where hierarchically arranged within floors, departments, and sections

- *Combined* - subjects were presented with the spatial map and the analogy

- *Control group* - These subjects studied 100 nouns that were not related to the analogy. This group was intended to establish a baseline reference for comparing the effects of instructional aids

In Experiment 1, the 32 subjects studied their instructional aid for 15 minutes prior to performing a set of navigation trials, which entailed finding the display that contained the answer to a particular question. Eighteen trials were performed by each subject. Each trial began at a location other than the top-level display. In Session 2, which was conducted 24 hours later, a similar set of 18 trials were performed but without the benefit of reviewing the instructional aid. Performance measures included retrieval time from the initial to the target displays and search path efficiency (actual minus minimum steps).

The session factor was statistically significant and indicated that access time decreased between the first and second sessions. There was a statistically significant increase in access time as the search distance (minimum number of steps between the initial and target displays) increased. Search efficiency had a significant improvement between the first and second sessions. In addition, it decreased with search distance.

Instructional aid type also had a statistically significant effect on access time, and there was a statistically significant three-way interaction between the instruction aid type, search distance, and session. In Session 1 the analogy, map, and combined groups were equally effective, resulting in faster access time than the control group. This suggests that the analogy approach was as beneficial as the spatial map. In Session 2, the analogy group was significantly faster than the other three groups for intermediate and far navigation distances. In addition, the analogy group was the least affected of the four groups by navigation distance; its access time increased only slightly when navigation distance was increased, while the other groups showed more pronounced increases with distance. The mental model based on the analogy appeared more likely to remain intact over time. This was based on the fact that access times were not different for the three approaches in Session 1 but improved for the analogy group in Session 2. Webb and Kramer state that these results suggest that (1) analogy is a useful instructional format for helping novices retrieve information from hierarchical information structures, (2) analogy might become more useful than a spatial map as the length of search paths become longer and more difficult to remember, and (3) analogy might become more useful than a spatial map as the length of time between studying the instructional material and performing the information retrieval task increases.

Experiment 2 evaluated the generalizability of the results of Experiment 1 to more generic analogies. Webb and Kramer claim that in terms of structure mapping theory, the hierarchical database and the department store analogy used in Experiment 1 were closer to a literal similarity than to a true analogy because the objects and relational structure of both domains were quite similar. A true analogy would compare relational structures that are similar but have few or no objects in common. Experiment 2 evaluated a true analogy between a shopping center (base domain) and a hierarchical database that organizes information about classes at a hypothetical university (target domain). While the structures of a shopping center and a university are quite different, their representation in a database are similar. Thus, according to structure mapping theory, this is a more generalizable comparison than a literal similarity.

Fifty undergraduate college students who were inexperienced at computer-based data retrieval tasks were randomly assigned to five groups:

- *Analogy* - subjects studied an analogy that compared searching the database to shopping in a mall
- *Spatial map* - subjects studied a spatial map of the display structure
- *Abstraction* - subjects studied an abstraction that conveyed the structure of the hierarchy in a language that made no specific reference to any specific object or concrete relational structure. The database was described as a hierarchical branching tree in which the nodes contain increasing levels of specialization. In structure mapping theory, an abstraction is a comparison in which the base domain is an abstract relational structure rather than a concrete example of the relational structure
- *Schematic* - subjects studied a line drawing (schematic) of the database structure. The schematic represented the structure of the database but not the content. The major levels of the schematic were labeled for college, school, department, and area of concentration. However, the nodes of the hierarchy were not labeled
- *Control group* - subjects studied 100 nouns unrelated to the analogy, as in Experiment 1

In Session 1, subjects studied the instructional material for 10 minutes and then were presented with 12 retrieval tasks. Each task began at the top level of the hierarchy and required the subject to find information from three lower-level nodes. Session 2 was conducted 24 hours later. Subjects were not presented with the instructional material but were given with 12 retrieval tasks. Session 3 was conducted one week after the first session. The procedure was the same as for Session 2, except that the subjects were given a one-minute review of the instructional material to reorient them to the information retrieval task. The database structure had seven levels, 63 intermediate nodes, and 64 terminal nodes. Search distance for retrieval tasks had three levels: 16, 20, and 24 nodes of search distance. Search time was measured from the beginning to the end of an information retrieval task.

The search distance factor did not have a statistically significant effect on search time and was not involved in any interactions with other factors, such as session and type of instructional material. However, the session and instructional material factors had significant effects. There was a significant improvement in search times across the three sessions. Further analyses, using directional *t* tests indicated that in Session 1 the control group was slower than the other four groups. In Session 2, the analogy and spatial map groups were faster than the other three groups. In Session 3, the analogy group was faster than each of the other four groups. These results suggest that the effectiveness of the analogy format relative to the spatial map format might be expected to increase as the time between presentation and use increases. The results also suggest that the comparison between target and base domains does not have to be a literal similarity to be effective. This was shown by the effectiveness of the analogy between the hypothetical shopping center and the organization of the hypothetical university for aiding user performance.

Webb and Kramer (1990) identify some limitations of this study. First, the subjects of this study were mostly students from a college of liberal arts and science. Webb and Kramer point out that it is likely that a large proportion of them may have better verbal than spatial skills, introducing a performance bias that favors analogy over other instructional methods. Second, this study did not control for the systematicity of the analogies. In terms of structure mapping theory, the analogies used in the experiments had high systematicity - that is, the connected system of knowledge in the base domain applied to a high degree in the target domain. One may predict that the effectiveness of an analogy is related to its systematicity. Thus, if an analogy has low systematicity, it may be less effective, rather than more effective, than a spatial map. Further research on the effects of analogy systematicity is needed. Third, the effects of the combined use of pictorial and analogical formats was not thoroughly addressed. Their combined use was addressed in Experiment 1. However, subjects tended to use one format or the other. Thus, the effects of combined use requires further study.

A surprising result that was not discussed by Webb and Kramer was that search distance did not have a statistically significant effect on search time. Other studies, such as Seidler and Wickens (1992), found search (navigation) distance to be a major determinate of search time. The reasons for this discrepancy are unclear. For example, one may assume that a navigation task that uses small search distances may result in less noticeable effects. However, even though the Webb and Kramer information structure was less than one-half the size of the Seidler and Wickens information structure (127 versus 290 nodes, respectively), the length of the navigation searches were longer. The navigation distance ranged from 16 to 24 nodes for the Webb and Kramer study, and from 1 to 12 nodes for the Seidler and Wickens study.

Effects of Consistency and Compatibility Across Multiple Menu Systems

Where the HSI consists of more than one display system, searches based on identity matching may be facilitated by the consistent use of names for menu options across the HSI. For example, if one display system uses the name "primary coolant system" and another uses "reactor coolant system," then an identity search using the name "primary coolant system" may fail on the other display system. Thus, the operator must rely on a semantic search, such as equivalence matching, which may increase mental workload and slow the response of the operator.

Effects of System Response Time

Overall response time with respect to the ability of an operator to access information and controls needed to operate the plant is a function of system and human performance. When the response time of the information system is slow, it can determine overall response time. Norman (1991) provides the following as an example. Consider an information system that has a transmission speed of 30 cycles per second (cps), which requires approximately eight seconds to present a menu containing eight items (selection options). A 8^3 menu structure contains three levels (e.g., the first menu panel contains eight items, each of which provides access to a menu panel containing another eight options, each of which provides access to another eight items for a total of 512 terminal display pages). If the user takes three seconds to read a display page and make a selection, then the time required to access a display on the third (bottom) level would be 33 seconds [e.g., 3(8 + 3) = 33]. However, if a hierarchical menu structure did not exist and all 512 options were contained in the single, large display page, Norman estimates that 8.5 minutes would be required to present that display page at 30 cps. In this case, the use of a hierarchical menu structure meant the difference between a total response time of 33 seconds and 8.5 minutes.

Norman provides the following formulas for response time.

$$\text{Total Time} = \sum\{s(n_i) + u(n_i)\}$$

where $s(n_i)$ is the system time for transmitting a display of n items at level i, and $u(n_i)$ is the user time to select a response out of the n items at level i. The total time is summed across the number of levels. Total times calculated from this formula may be compared to requirements for operator response time (e.g., determined from operating scenarios) to evaluate the acceptability of the display system.

The total time may also be separated into system and user time, as follows:

$$\text{Total System Response Time} = \sum s(n_i)$$

$$\text{Total User Response Time} = \sum u(n_i)$$

Sisson, Parkinson, and Snowberry (1986) calculated the access times for four menu configurations that had a constant number of terminal display pages (64), varying number of levels, and transmission speeds that varied from 10 to 1,920 cps. User response time was based on values determined empirically by Snowberry, Parkinson, and Sisson (1983). They found that the broad menu of all 64 items had the best access time for transmission rates of 960 cps and faster. The 8^2 menu structure had the best time for transmission rates of 60 to 480 cps, and the 4^3 menu structure had the best times for the slowest speeds of 10 to 30 cps. The 2^6 menu structure, which was the deepest, was never optimal. Norman (1991) concluded from these results that with faster transmission rates the broader menus seem to become more efficient. Thus, he prefers broader menus, provided that the increased volume and density do not result in substantially longer search and choice times.

Norman (1991) states that research literature provides mixed recommendations on optimal values for menu breadth and depth. Within the design constraints of system response time, screen display time, size of screen, and the ability to organize items into meaningful groups, some leeway exists for designers to adjust breadth and depth. Norman provides some general recommendations. For linearly organized lists (e.g., numbers, alphabetized lists), one should increase breadth as much as possible because the linear lists can facilitate search. When the options have no inherent linear order, then the number of options per menu panel should be restricted to 12 or fewer items, depending upon user and system characteristics. However, response also can be enhanced if multiple levels of the hierarchy can be presented in an organized way on a single display page. Norman states that an overriding consideration is to provide organization to support the operator in visually locating target items. The goal should be to effectively reveal the display network structure to the operator and reduce the number of display pages and operator responses required to locate target items.

3.2.3.3 Direct Manipulation Interfaces

A direct manipulation interface is one in which the user manipulates symbols in the display by directly interacting with the symbol. The direct manipulation is generally performed by using a display structure, such as a pointer, and a cursor control device, such as a mouse. The following discussion first covers general human performance considerations associated with direct manipulation, and second, those associated with object-oriented direct manipulation interfaces.

General Considerations

Direct manipulation interfaces have the following properties (Shneiderman, 1982; quoted by Hutchins, Hollan, and Norman, 1986, p. 91):

- continuous representation of the object of interest
- physical actions associated with manipulating the object (e.g., dragging an icon)
- incremental reversible operations whose impacts on the object of interest are immediately visible

In addition, Shneiderman (1982; quoted by Hutchins et al., 1986, p. 90) suggests that direct manipulation systems have the following characteristics:

- novices can learn basic functionality quickly (usually through a demonstration by a more experienced user)
- experts can work extremely rapidly to carry out a wide range of tasks, even defining new functions and features
- knowledgeable intermittent users can retain operational concepts
- error messages are rarely needed
- users can see immediately if their actions are furthering their goals, and if not, they can change the direction of their activity
- users have reduced anxiety because the system is comprehensible and because actions are so easily reversible

Hutchins et al. (1986) defined two important aspects of direct manipulation interfaces: distance and engagement. Distance refers to the correspondence between the user's thoughts and the physical requirements of the system. A short distance means that the translation is simple and straightforward; thoughts are readily translated into the required physical actions. Engagement is the degree to which the user has a sense of acting upon the objects of the task domain themselves, rather than a sense of acting upon a representation of the object through some intermediary. Good interface metaphors increase the users engagement. Hutchins et al. state that human-computer interfaces have traditionally been based on a conversational metaphor in which the users describe (e.g., via commands) the operations they wish to have performed. The computers then perform some processing and describe, with varying degrees of clarity, what was done. Direct engagement systems are based on a "model world" metaphor - metaphors that *depict* actions and objects rather than *describe* them. Thus, direct engagement systems provide users with "...the qualitative feeling that [they] are directly engaged with control of the objects - not the programs, not with the computer, but with the semantic objects of [their] goals and intentions" (Hutchins et al., 1986, p. 95).

Hutchins et al. reviewed the claims made by Shneiderman (1982) regarding direct manipulation using the concepts of distance and engagement. In general, they agree that direct manipulation holds many potential benefits but disagree with some of the explanations of the benefits he gave. Hutchins et al. have the following comments regarding the three properties of direct manipulation interfaces that were reported by Shneiderman:

- With regard to "continuous presentation," Hutchins et al. state that this seems to be an essential aspect of direct engagement systems.

- They state that the use of "physical actions" instead of "syntax" is clearly important in establishing direct engagement.

- They state that rapid incremental operations with effects that are immediately visible are essential to direct engagement. While reversibility may be desirable, it is not a necessary aspect of direct engagement.

Hutchins et al. have the following comments about the six reported virtues of direct manipulation systems reported by Shneiderman:

- They do not fully agree with Shneiderman's statement that novices can learn functionality quickly through demonstration. They state that with a good direct manipulation interface, the user feels as though the operations are being performed directly on the task domain. If the novice is already knowledgeable of the task domain, then much of what is needed to operate the interface is already known.

- They are skeptical of Shneiderman's statement that experts can work extremely quickly. They suspect that experts would work more slowly, rather than more quickly, with a direct manipulation interface compared to a command language system because of the time required to point to, position, and otherwise manipulate objects.

- They do not agree with Shneiderman's claim that direct manipulation interfaces help intermittent users retain operational concepts. Instead they state that expertise in usage really reflects expertise in the subject matter, which is probably well established in the user's memory and not likely to fade quickly. Direct manipulation systems do not appear to provide any special benefits compared to other well-designed interfaces.

- They provide a mixed assessment of Shneiderman's claim that error messages are rarely needed with direct manipulation interfaces. They acknowledge that, in some cases, error messages may not be needed because results of actions are immediately visible or because some types of errors may be eliminated. However, they state that the design strategy of relying on the ability of operators to detect errors from the behavior of the user interface, rather than not providing error messages, has some potential problems. They state that direct manipulation interfaces have their own problems which may lead to new types of errors. Some of these errors may be difficult to detect if they are legal operations with respect to the user interface but undesirable actions with respect to the task domain (e.g., plant operation).

- They agree with Shneiderman's claim that direct manipulation interfaces can allow users to see immediately if their actions are furthering their goals. However, the second part of this claim, the ability to "change the direction of their activity," results from the natural reversibility of the actions. For those actions that are not so naturally reversible, direct manipulation systems do not provide a benefit that is different from more conventional systems.

- They provide no evaluation of Shneiderman's claim that direct manipulation systems reduce user anxiety.

Ziegler and Fahnrich (1988) state that direct manipulation interfaces may enhance the ability of novices to learn to use the interface. Note, this argument tends to agree with one of the virtues of direct manipulation interfaces suggested by Shneiderman and contradicts the counter argument by Hutchins et al. Ziegler and Fahnrich reviewed two studies that compared direct manipulation interfaces to conventional ones.

The first study compared learning and performance of document editing tasks using two different word processors (Ziegler and Fahnrich, 1988). One had a direct manipulation interface while the other had a command language interface. No performance differences were found for the first experimental session. However, user performance with the direct manipulation interface was consistently for the sessions that followed. User performance with the direct manipulation interface "...increased with the duration of the experiment and with the degree of complexity of the tasks which was higher for later sessions" (Ziegler and Fahnrich, 1988, p. 132). The second study compared user performance and preference for several standardized filing tasks using seven systems with different user interfaces. Two systems had iconic direct manipulation interfaces, while the others had menu and command language interfaces. No general advantage associated with the direct manipulation interface was found. However, since the duration was similar to the first session of the word processor study, Ziegler and Fahnrich suggest that superior performance may have been found if the study was carried out longer. Ziegler and Fahnrich observe that these findings indicate that the initial learning requirements for the novice are about equal for simple tasks. They suggest that further learning may be facilitated by the direct manipulation interface. This may be due to higher consistency within the direct manipulation interface and better retention of the required operations by the participants.

Object-Oriented Interfaces

The term "object-oriented" direct manipulation interfaces refers to a more narrowly defined class of interfaces that rely on "...concrete and visible objects, simplified sets of user actions and rapid feedback where the key activity is visibly moving screen images by pointing at them" (Verplank, 1988, p. 365). Shneiderman (1987) states that graphic representations can be helpful to a user when there are multiple relationships among objects and when the graphic representation is more compact than other forms. However, Shneiderman identifies the following potential problems with graphic representations:

- They may not produce better task performance than text format for some tasks. In a study of computer programming, subjects given graphic representations of a program did no better in a program comprehension task than subjects given textual descriptions. However, subjects who were given the data structure documentation performed consistently better than those given the flow control documentation. This study suggests that the content of graphic representations is a critical determinant of utility. Unneeded information or a cluttered presentation can lead to user confusion.

- Users must learn the meanings of components in graphic representations. For example, an icon may require as much or more learning time than the word that it represents. When graphic icons contain text labels, the available space may not be adequate to support meaningful ones. For example, names may be abbreviated to fit the icon.

- Graphic representations may be misleading. For example, a user must comprehend what is being represented and draw correct conclusions about which input actions are permissible. Some graphic representations may not be fully understood by users.

- Graphic representations may require more space on the display screen than text-based presentations. As a result, operators may be required to retrieve more display pages to access all needed information. For example, experienced users may prefer to use a single display page that contains all needed information in a text format rather than multiple display pages presented in a graphic format.

Showing which objects can be manipulated and how they can be selected are challenges in the design of graphic objects (Verplank, 1988). Verplank states that the use of familiar graphic objects can reduce the time required for users to learn their meaning and can enhance their use after they are learned. Jones (1989) states that creating an icon that conveys the same meaning to all users is difficult. Icons are most appropriate for concrete concepts and that abstract concepts should be represented using other approaches. Jones suggests that it is best to use icons that require minimal interpretation. For example, he states that icons that are miniature representations of their corresponding physical objects probably are the most effective. Developers of the Xerox Star office computing system preformed human factors tests on sets of icons for its user interface. They concluded that those sets that offered the most visual variety among individual icons were the most successful (Bewley et al., 1984). This may be due to reduced effort involved in distinguishing icons from each other.

Shneiderman (1987) states that more research is needed to better understand the contribution of each of the following characteristics to the effectiveness of direct manipulation formats: analogical representation, incremental operation, reversibility, physical action instead of syntax, immediate visibility of results, graceful evolution, and graphic form. Finally, Shneiderman states that users may have different mental models and, as a result, interpret metaphors and analogies differently than designers. This may lead to problems in learning or using an object-oriented direct manipulation interface. As indicated above, users may misinterpret the meaning of icons. In addition, users may not understand a metaphor or comprehend the limits of a metaphor (e.g., situations in which the computer system does not behave like the objects of the physical world that the metaphor represents). One particular problem that may cause users to be unsure of the meaning of objects or actions is the use of mixed metaphors. Shneiderman also stresses the need for usability testing to discover and correct problems with graphical representation in direct manipulation interfaces. Training is another approach to addressing these problems. Shneiderman states that training should include explicit descriptions of the graphical representation, including the mental model, assumptions, and limitations used in the design.

3.2.3.4 Query Language and Natural Language Dialogues

Query language is a type of dialogue in which users compose questions using a special-purpose language to retrieve information. Natural language is type of dialogue in which users compose control entries in a restricted subset of their natural language, e.g., English. Each is addressed below.

Query Language Dialogues

Query language dialogues are usually used for retrieving data from databases and, as a result, may have fewer applications in NPPs than other interaction formats that may be used for a broader range of operator activities. The use of query languages can be a difficult task (Greene, Gomez, and Devlin, 1986); users must apply a specially developed grammar to construct queries. Ogden (1988) describes three stages of the query writing process: query formation, query translation, and final query writing. The query formation stage is associated with knowledge of the user's goals, the query translation stage is associated with data knowledge, and the query writing stage is associated with language knowledge. Each stage poses different demands and is associated with different types of errors. Ogden (1988) attempted to examine in more detail the knowledge required for query writing. They concluded that there were few definite answers about the types of knowledge needed to facilitate the use of query languages. They suggest that the degree to which a given model of interaction facilitates performance depends upon the type of query to be performed. Ehrenreich (1981) provides a set of 11 guidelines for query languages based on a review of research studies.

Query languages have decreased in popularity as human-computer interfaces for non-programmers. This is most likely due to the greater degree of ease of use provided by other types of user interfaces, such as menus and object-oriented direct manipulation interfaces. Additional guidance may be needed to address mental workload imposed by query language systems if they are to be used in NPP HSIs.

Natural Language Dialogues

The development of natural language systems was prompted as a reaction to the demands that other types of computer dialogues imposed on users for learning arbitrary commands. It was hoped that computer dialogues based on a natural language, such as English, would allow novices to interact effectively with the computer without having specialized training (Jones, 1989).

Jones states that the design of natural language interfaces for computers is one of the most difficult problems in all of computer science and artificial intelligence research. While computers require precise instructions, natural languages are quite imprecise. For example, English has many ambiguities including words and phrases that have multiple meanings. To understand the full meaning of even fairly simple statements, an understanding of the broader context of a conversation is often needed. This requires the speaker and listener to have a shared body of knowledge. Speakers often rely on listeners to use this shared knowledge to "fill in" missing information in their communications (Jones, 1989). A language such as English is used differently by people of varying regional, ethnic, and educational backgrounds. In addition, natural languages are dynamic. New words are added to vocabularies while other words are deleted from use or change their meanings over time.

Finding ways to handle the ambiguity and imprecision has been a major challenge in the development of natural language interfaces. In addressing these difficulties, natural language interfaces for computers have tended to use restricted subsets of a natural language, such as a special set of words and grammar. However, this restricted subset must be learned by the users, similar to how users must learn artificial computer languages. This tends to contradict the original intent of natural language interfaces, which was to reduce learning requirements (Jones, 1989).

Aspects of English that affect its use as a natural language interface for computer interaction include the following ones (Jones, 1989):

- indefinite references such as "it" or "that"
- incompletely stated ideas that rely on previously established context for interpretation
- words and phrases that are ambiguous or have multiple meanings
- flexible syntax
- sentence structure

Based on a review of studies that compare natural and artificial language systems, Ogden (1988) found no conclusive evidence that either type of interface resulted in better performance for the user. He states that users "...do not necessarily benefit from grammars based on natural language" (Ogden, 1988, p. 298). He suggests that natural language interfaces run counter to the desire of many users to be as brief as possible when communicating with the computer. In addition, users may have difficulty with functional habitability - constraints on how the user can express what is desired. In addition, detecting and recovering from functional errors is difficult. He found that feedback from the system could greatly influence the user. For example, users began to model their entries to reflect system outputs. Thus, the design of system output should be consistent with the types of entries required by users.

In describing the potential benefits of natural language systems based on his review, Ogden states that users may benefit from a natural language system's ability to provide broader conceptual and functional coverage than what is covered with an artificial language. Broader functional coverage implies more flexibility in the ways that users can state the types of information retrieval and processing that is to be done. In addition, syntactic coverage may be improved, including the use of synonyms and the ability to leave out contextual information. Providing these benefits will depend on the ability of designers to collect and analyze information that is specific to the application domain (e.g., NPP operation). Ogden states that methods for collecting and analyzing this information "...are not well established and represent the most important area for further research concerning natural language interfaces" (1988, p. 298).

The evaluation of natural language systems poses special problems for developers because the interface management aspects (e.g., retrieving information) are so closely coupled with domain knowledge. Users often must have a good understanding of the primary task domain (e.g., NPP operations) to be able to construct natural language inquiries. In contrast, usability studies of other user interfaces, such as menus, may be conducted with users who have limited knowledge of the task domain. As a result, evaluations of natural language systems conducted early in the design process may more closely resemble validation studies than usability tests.

Ogden identifies the following specific concerns for the evaluation of natural language systems:

- *User selection and training* - Test subjects should be experienced in the target domain. The habitability of a natural language system depends on how well it matches the user's knowledge about the domain of discourse. The type and amount of training users receive should be representative of the training the users would be expected to have in actual practice.
- *Task generation* - The tasks that users perform in evaluating of natural language systems should be representative of the type of work done in the actual work environment. One approach is for the evaluator to develop a set of scenarios that will require the user to perform particular tasks.

A second approach is to allow the user to explore and use the system in user-generated tasks. A tradeoff exists between these two approaches. Evaluator-defined scenarios can ensure that relevant system features and a representative sample of operator activities are addressed. However, user-generated tasks can be very effective in exploring limitations of the conceptual and functional coverage of the system since users are free to express inquiries beyond a predefined set of scenarios; a disadvantage is that they may not address all relevant concerns because they are not systematically derived.

- *Task presentation* - The manner in which tasks are presented to the user can influence the way users express their interactions with the system. A subject should not be given a statement in a natural language format and then be asked to generate a request. While this approach is used for testing artificial language systems, it may not be appropriate for testing natural language systems because, in essence, it gives the user the answer. At the very least, it may seriously bias the subject's response (Reisner, 1988). Task presentation should not lead the user to interact with the system in a certain way because other types of interaction, which could occur in actual use, may not be evaluated.

  Ogden suggests two methods for presenting tasks. The first method entails presenting a large, generally-stated problem that requires a number of steps to solve. The users must generate their own interactions with the system to solve the problem. This method tests habitability and problem-solving ability. Similar to user-generated tasks, this method may not result in a thorough evaluation of all functions of the system because the user is free to choose the strategies and system functions that are to be used. The second method entails presenting the user with a graph, table, or other representation in which information has been omitted. The user is asked to find the missing information by using the natural language system. This method allows the experimenter to gain control over the types of information that the user will seek, and, perhaps, the types of questions that will be used. However, this approach may be limited by the ability of evaluators to develop appropriate nonlinguistic stimuli (Ogden, 1988).

- *Performance measures* - A frequently used measure of the habitability of natural language systems is the proportion of commands entered by the user that could be successfully parsed (processed) by the system. Studies that use this measure often assume that all commands are equally complex, which may not be true (Ogden, 1988). A high success rate may be due to a user strategy of generating many simple requests, rather than a smaller set of more complex ones. For example, a user was observed requesting a certain type of information for each month of the year. The user accomplished this by issuing the same request 12 times and changing the name of the month each time. This resulted in 12 correctly parsed questions. By contrast, another user made two incorrectly parsed requests before asking for each month's data in one correctly parsed question. Therefore, the second user had a lower parse success rate (i.e., one successful command out of three), even though the user's correct question resulted in making nine fewer requests. Ogden suggests that parsing success rates measures be supplemented with other performance measures, such as the number of requests per task, task solution success, and task time.

3.2.3.5 Navigation

As defined earlier, navigation refers to the access and retrieval of a specific aspect of the HSI, such as a display or control. Navigation may include accessing a single display page from a network of display pages or accessing a specific item from within a display page, when manipulations of the display system are necessary.

The concept of display navigation is associated with the spatial organization of information in the display system. Information that is not inherently spatial may nevertheless be presented spatially, often to express relationships between individual items. For example, logic may be represented as a flowchart, hierarchical relationships between items may be represented as a tree structure, and computer files may be represented using a desktop metaphor. Spatial representation of data has a number of advantages (Jones, 1989). First, relationships between items may be visualized and remembered more readily than other formats, such as text-based descriptions. Second, spatial representation can support the user in rapid scanning allowing them to use perceptual skills similar to those used when scanning a natural environment. Third, movement across displays that have spatially organized data creates paths that can be displayed, manipulated, and remembered. Fourth, maps of the information space can be provided to support the user in accessing items (Woods, 1984).

Users and designers often use spatial metaphors for describing the process used for accessing items from a display system. This process is often described in terms of *moving* to specific locations in an information space, as opposed to bringing the information to themselves. Users may state that they are unable to determine where they are in the information space, decide where to go next, or find places where they know they should be.

Navigation performance may be affected by the user's mental model of the information system, including the user's understanding of how the information space is organized, what paths exist, and how the system will respond to inputs from the user. If the user's mental model accurately reflects the behavior of the system, then the user will be more successful in learning and using the system and will likely perceive the system as being easy to use. The simplicity and consistency of the user's mental model will directly affect the ease of navigation because it affects the way users think about the system (Jones, 1989). One goal of user interface design is to support users in developing appropriate mental models of the information system that will help them access items effectively.

In the remainder of this chapter, several aspects of navigation will be discussed, including: wayfinding, visual momentum, browsing, navigating hierarchical networks, and navigating large, continuous display pages.

Wayfinding

Although the virtual space of display systems is different from the space of physical environments, the problems of getting lost in these two types of spaces have similarities. Researchers and designers of computer systems are examining how people navigate in the physical world to determine how theories and design approaches developed in this domain may be applied to support navigation in computer systems (Darken and Sibert, 1996; Jones, 1989; Woods and Watts, 1999).

The term *wayfinding* is used to describe how people navigate through physical environments (Arthur and Passini, 1992). The current concept of wayfinding addresses the perceptual, cognitive, and decision-making processes necessary to find one's way. Studies of wayfinding have led to theories, principles, and approaches for helping people understand their environment including finding their current location and paths to desired locations.

The type of knowledge that a person needs to conceptualize a space as a whole is defined as *survey knowledge* (Darken and Sibert, 1996). Survey knowledge is map-like in nature. The locations of objects and the distances between them are encoded in terms of a geocentric, fixed frame of reference. Survey knowledge is significantly different from procedural knowledge which is defined by Darken and Sibert (1996) as the sequence of actions required to follow a particular route. Thus, while survey knowledge may be involved in determining one's current position in a display network or page, procedural knowledge may be involved in the execution of a set of interactions, such as moving forward or backward in the display system.

Empirical studies indicate that spatial knowledge is hierarchical (Howard and Kerst, 1981; Stevens and Coupe, 1978). To reduce or manage the demands on human memory, the absolute positions of, and directions to, every place are not encoded. Instead, logically selected subsets of large locations are encoded, each having subnetworks of smaller, more specific places. For example, logical subsets of the U.S. may include regions, states, and cities. Stevens and Coupe state, "Generally information about spatial relationships between regions is stored only for regions encoded as part of the same superordinate unit. Relations between two regions not stored explicitly must be inferred. The inference process combines the relations between superordinates with the relations of the subregions within their respective superordinates" (Stevens and Coupe, 1978, p. 435). For example, people may store information about the relative location of cities within a state but not the relative locations of cities in different states. Instead, information about distance and differences in latitude and longitude may be inferred from the relative position of the states. Stevens and Coupe state that while this type of information storage can reduce demands on memory, the inference process can lead to errors.

The hierarchical nature of spatial (survey) knowledge is reflected in environmental design principles and design approaches. For example, Darken and Sibert (1996) suggests using urban elements such as paths, landmarks, and districts to divide the environment into smaller, clearly connected, more manageable pieces, which can be encoded into a hierarchy of spatial knowledge. Lynch also states that frequent directional cues should be provided to help wayfinders maintain their orientation. In extending these ideas to architecture, Passini (1984) states that a space should have an underlying organizational principle. For example, the streets of Manhattan are organized in a grid pattern which can be used by people to structure their spatial knowledge. A space must also have a number of "places" that are easily discernible to the wayfinder. A place may be defined as a distinct, recognizable location or region of a larger space and is often associated with a landmark. Passini states that a map should show the underlying organizational principle, the design elements described by Lynch, and the wayfinder's position using a forward-up orientation.

The theories, principles, and approaches developed to help people understand the physical environment are being applied to the virtual environment of computer-based display systems to support navigation by users (Darken and Sibert, 1996; Jones, 1989; Woods, 1984). Darken and Sibert describe skilled wayfinding behavior as purposeful, oriented movement during navigation. They state that any time an environment encompasses more "space" than can be viewed from a single vantage point, wayfinding problems will occur. They characterize wayfinding problems as follows, "Navigators may wander aimlessly when attempting to find a place for the first time. They may then have difficulty relocating places recently visited. They are often unable to grasp the overall topological structure of the space." Darken and Sibert state that, in general, wayfinding tasks in computer environments require that the navigator be able to conceptualize the information space as a whole.

Jones (1989) defines wayfinding as navigating through a physical space, or by analogy, a display space. It includes knowing one's location, and how to move to other locations in the display space without becoming lost. Jones states that while computer systems often have high information content, they are often impoverished in the way they communicate their information to users. Wayfinding is a design concept that can decrease cognitive burdens associated with navigation in computer-based environments by presenting information in ways that make use of the variety of information processing capabilities of humans.

Designers can support wayfinding in computer-based display systems by incorporating features that serve similar functions as the wayfinding features of the physical environment. For example, display networks divide the plant information into discernable places, such as individual displays. A display network is usually based on an underlying organizational principle (e.g., hierarchical, sequential, or relational). Wayfinding may be enhanced when these organizational principles can be readily understood by the user. In addition, maps of display networks may be provided in the form of overview displays to aid wayfinding. Also, large display pages, such as mimic, map, table, and trend plot displays, have underlying organizational principles that may aid wayfinding. For example, table displays have row and column organizations with "places" defined by their headings, row and column intersections, and other landmarks. Trend plot displays are based on the plot coordinates (e.g., *x*, *y*, and *z*) with "places" defined by the coordinate system and the positions of data points. Mimic displays may be organized based on functional relationships (e.g., the temporal order of flow from one plant component to the next). Places may be indicated by landmarks, such a major plant components. Map displays may be organized based on major plant components and physical structures (e.g., the arrangement of coolant loops relative to the reactor vessel).

Visual Momentum

The concept of visual momentum was originally defined by Hochberg and Brooks (cited in Woods, 1984) as the impetus to gather new visual information. It was postulated that visual momentum consisted of two components: a fast component that brings the eye to those peripherally visible regions that promise to be informative or act as landmarks, and a sustained component that obtains more detailed information about features that have already been located. Woods (1984) adapted the concept of visual momentum to develop a framework for describing the difficulties that people encounter when trying to mentally integrate data across successive pages of a computer display system. This concept may also be extended to address views of individual sections of a large display page.

Woods states that a goal of display system design should be to achieve high visual momentum - to allow the user to rapidly comprehend data across different views in the same way that viewers comprehend meaning across the cuts of a well-edited movie. This is achieved by using perceptual context to help the user to construct and maintain a mental map or understanding of the organization of the data. Thus, visual momentum may be considered a heuristic measure of the ease or difficulty of mentally integrating information across successive views. The higher the visual momentum, the less effort required to understand the relationships between views (Jones, 1989).

Woods argues that while many HFE guidelines address the design of individual displays, the concept of visual momentum addresses relationships between displays. In display systems that contain many displays, the user may become confused or lost if the relationships between individual views is not clear. When a display is shown, the users look at what they perceive to be informative areas. This viewing behavior is guided by perceptual processes which break down the display into constituent parts using visual cues on figure/ground relationships, shape, color, and location. Viewing behavior also is guided by a top-down conceptual analysis based on the user's knowledge of the context of the display. For example, NPP operators have mental models of the content and arrangement of information in the display network and understanding of the types of information that may be relevant to current conditions. A display system that provides the user with a frame of reference for understanding successive views is likely to support them in identifying informative areas of displays. If a display system does not provide a good frame of reference, users cannot rely on automatic perceptual mechanisms to guide their viewing behavior. The result is lower visual momentum; users must search displays consciously to identify needed information.

Woods also notes that the problem-solving behavior of users can be influenced by the way that problems are presented via a display system. The ease with which information is comprehended by a user can be influenced by such factors as which data is displayed, how it is formatted (e.g., graphically versus textually), and the presence of visual cues that direct the user's attention. Problem solving can be supported by data representations that group data into a smaller number of meaningful units. Display systems that have low visual momentum can result in the user inappropriately focusing attention on a small subset of information to the exclusion of other information.

The consequences of having low visual momentum in a display system, as described by Woods, may be summarized as follows: a decreased size in the user's field of attention, difficulty in locating important data, becoming lost in a complex set of displays, increased mental workload with corresponding decreased performance in tasks that require memory, and lowered problem-solving behavior.

Woods described the following display design approaches that may enhance visual momentum:

- *Long shot view* - This is a display that provides an overview of the structure of an information space, such as a display network or a large display page. A long shot view makes explicit the relationships between individual views and supports the user in developing a mental model of the whole information space.

- *Perceptual landmarks* - These are easily discernable features that appear in successive views and provide a frame of reference for establishing relationships across views.

- *Display overlap* - These are physical or functional overlaps between displays which prevent the displays from appearing as disjointed views. To achieve physical overlap, some portions of a display page may be repeated on other displays. This overlap should include only those features needed to establish across-display relationships and to call attention to other data and display frames. Functional overlap may be achieved by providing pointers to data on related displays. For example, a flowchart or mimic display may include pointers to relevant items in other displays. As another example, displays that present the same plant data at different levels of abstraction can include functionally overlapping information which connects the displays.

- *Spatial representation* - This is the assignment of spatial attributes to data to aid human information processing, even when the data has no inherent spatial attributes.

- *Spatial cognition* - This involves arranging data to provide information about the structure of the process or system to which the data relates (e.g., arranging data to reflect the flow of fluid and energy across an NPP).

In addition, Woods states that having a consistent format across display pages permits the viewer to anticipate where certain types of data can be found.

Browsing

Jones (1989, p. 112) defines browsing as "...a wondering exploration of a physical space, or by analogy, an information space." For example, while books can be read serially, from beginning to end, they also allow flexible exploration (e.g., browsing) of their content. Similarly, libraries and bookstores support exploration of topics. "...Sometimes we don't know exactly what we are looking for, or are not looking for any one thing in particular. We explore the data source in a more or less undirected fashion, seeing what turns up" (Jones, 1989, p. 27).

When using a computer-based system, a user may not have a specific topic in mind and may wish to explore the contents of the system. For example, Woods and Watts (1999) describe problems associated with knowing where to look next for items in computer-based systems. However, accessing items from a computer generally requires a degree of competency in human-computer interaction and understanding on the computer system (Jones, 1989). Many computer systems include features that support the type of exploration described in the library and bookstore example. These features are often based on spatial representation of information.

While many researchers describe the value of features that allow users to explore (browse) information systems, they often vary in their descriptions of what characteristics of browsing are important to human-computer interaction. There is no universally accepted definition of browsing. Jones (1989) states that browsing requires the following (1) a loose, more general organization of data, which may be in addition to a primary organization imposed on the data by the designer of the information system, (2) a flexible means of moving through the data, and (3) a means of expressing relationships among items, such as similarity and proximity. Relationships between items may be expressed spatially or via symbols. Jones uses the Dewey Decimal and Library of Congress classification systems as examples of symbol-based systems that support both direct access and browsing. If a user knows the exact title of a desired book, the catalog supplies an exact referent for locating the book. However, it is also possible to walk to a section of the library that addresses a particular topic, such as Space Exploration, and examine a variety of related books. Examples of spatial organization of data include flowcharts, hierarchical tree structures, and metaphors that are based on the physical world, such as the desktop metaphor.

Spence (1997) uses the following terms to describe information search and handling activities: browsing, context modeling, gradient perception, and movement. Browsing is described as the assessment of content. It supports the modeling of context - the development of a mental model of the information space. Perception of gradient is the act of determining the best path to take with respect to a goal (e.g., searching for information), based on the user's internal context model and other external models of the information space. Movement is the act of accessing locations in the information space. Spence defines navigation as the combination of gradient perception and movement toward a goal. He introduces the concept of weighted browsing to account for differences in browsing behavior, especially between novice and experienced users. Weighted browsing refers to search strategies that users apply, either consciously or unconsciously. These weights may become better defined and articulated as browsing and the associated activities of context modeling, gradient perception, and movement proceed.

Darken and Sibert (1996) studied navigation in a large, two-dimensional geographical display in which users learned about the organization of the information in the display (i.e., developed a conceptual model) as they navigated through it. While Darken and Sibert do not use the term *browsing*, they do define three categories of wayfinding tasks: exploration, naive search, and primed search. Exploration is described as a wayfinding task in which there is no target and which is performed to gain familiarity with the arrangement of the display. This task appears to be closely related to the component of browsing described by Spence that supports the development of context models. Naive search refers to a task in which the user has no a priori knowledge of the location of the target. Primed search refers to a task in which the user knows the location of the target. This study examined display features that assist users in identifying paths to target items. Using Spence's terminology, this study examined the effects of various display features on context modeling and gradient perception.

What these and other discussions of navigation behavior lack is an explicit distinction between exploring information *structure* and *content*. Many discussions of browsing, including the library and bookstore examples above, combine the notions of exploring the structure of information space with exploring the meaning of the information. Combining considerations of information format and meaning may be adequate for describing systems in which novice users must develop understandings (e.g., concept models) of the information space at the same time as they assess the meaning of the information. However, in systems that have rather stable information spaces and experienced users, such as NPPs, the distinction between browsing the information structure and browsing the information content is an important one.

Experienced NPP operators, who have adequate conceptual models of the information space of an HSI component, may not have to browse it to determine how the information is arranged throughout the display network and individual displays. Instead, operators may browse the information space to detect changes in plant condition (e.g., identify plant variables that are abnormal or unusual). Such *content browsing* may be considered "undirected" because operators may not be searching for specific variables. Content browsing may be strongly influenced by the structure of the information space. For example, in traditional hardwired CRs, operators often take advantage of the physical arrangement of controls and displays and scan a control panel from one end to the other. Similarly, the arrangement of a computer-based information space may affect content browsing. Important factors may include the arrangement of individual display pages and the accessibility of display pages (e.g., ease of retrieval from the display network). *Structure browsing*, which may be described as examining the information space to understand its arrangement, is similar to the exploration task described by Darken and Sibert (1996). In NPPs, structure browsing may be an important activity that occurs after installing an upgrade, such as an additional set of displays. For example, operators may explore the new portions of the information space to understand how they relate to the rest of it. Operators may also engage in structure browsing to refresh their understanding of how information is arranged in portions of the information space that are not used often.

Navigating Hierarchical Networks

Navigating a display network involves accessing display pages from it. The time and number of actions required to access a particular page depends to some extent upon the distance between the initial and desired displays.

Seidler and Wickens (1992) investigated three proposed measures for an operational concept of distance in hierarchical display structures. The first measure, *organizational distance*, is defined by the structure of the display network. Screens that share more recent nodes of the display network are considered to be closer together in organizational space. The second measure, *navigation distance*, is defined by the number of choice points lying between two displays as determined by the navigation tool. If the navigation tool requires that each display be accessed one-at-a-time when moving from an initial display to a target display, then the navigation distance is the same as the organization distance. Tools that allow users to jump from one display to another while skipping intermediate displays reduce the navigation distance. The third measure, *cognitive distance*, is a measure of the user's perception of the relationships between the displays. Displays are said to be separated by a shorter cognitive distance if they have greater relatedness, as defined by such factors as frequency of sequential use or shared semantic features. In this study, cognitive distance was measured using a semantic scale.

The task domain for this study was flight management. Ten subjects, who were student pilots and flight instructors, participated. The task was similar to some tasks performed by NPP operators; subjects looked for, and retrieved information from, a display system with a hierarchical structure. There were 290 nodes (display pages) in the hierarchy. This study examined the effects of the user's perception of information organization within the context of a large database. Navigational distance was varied from 1 to 12 nodes. This study compared the use of a button that accessed the upper levels of the display hierarchy one-display-at-a-time to the use of a button that accessed the top-level (e.g., main) menu in a single step. Independent variables included the distance (navigational, organizational, and cognitive) between the initial and target displays and the type of navigation method (e.g., main menu button and up button). Dependent measures included display access time, navigation path efficiency (i.e., deviation from the shortest path), and memory recall. The latter was a secondary task for assessing mental workload. Subjects were presented with a five-digit flight identification number which they held in memory during the navigation tasks. When the target display was retrieved, the subject typed in the identification number.

Navigation distance was found to be a statistically significant determinant of both retrieval time and memory recall task accuracy. Greater navigational distance resulted in greater retrieval time and decreased memory accuracy. Cognitive distance was found to affect retrieval time; it took more time to travel to a cognitively more-distant display than to a cognitively closer one, when navigation distance was held constant. When cognitive distance disagreed with organizational distance, the effects of cognitive distance dominated. That is, when the cognitive distance was long and the organizational distance was short, the resulting retrieval time was long. When the cognitive distance was short and the organizational distance was long, the resulting retrieval time was short. This effect was statistically significant. Cognitive distance had no statistically significant effect on memory accuracy - the ability to recall the five-digit flight identification.

The effect of cognitive distance seems consistent with findings from earlier studies. For example, subjects reproduce the spatial arrangement of a hierarchy when the semantic relations between items are valid, but have more trouble doing so if the semantic relations among items are contrived (Webb and Kramer, 1990). The implication is that recalling the spatial location of items in a hierarchy may depend on knowing the semantic relations between items. That is, knowledge of the semantic structure may be an important factor in navigating a hierarchical data structure.

Seidler and Wickens concluded that the effects of organizational distance were complex and required further investigation. There was a statistically significant effect of organizational distance on retrieval time and a significant interaction with the test sessions. During session 1, it took significantly more time to travel within the same major menu branch than to travel across major menu branches. Retrieval time was *faster* when the target was on the *opposite* side of the main menu (i.e., greater organizational distance) than on the same side (i.e., closer organizational distance). However, this difference disappeared in session 2, after participants gained more experience. There was no significant effect for organizational distance on memory accuracy. Seidler and Wickens state that the effect of organizational distance on retrieval time appears to depend on three factors (1) the navigational mechanism used (e.g., the main menu button versus backward button), (2) experience with the display structure, and (3) the effects of cognitive distance, which appear to dominate the effects of organizational distance.

The surprising finding that increased organizational distance could facilitate retrieval time led Seidler and Wickens to speculate that organizational distance interacts with the type of strategy that subjects used to determine a path between the initial and target displays. Seidler and Wickens discuss two strategies users invoke when navigating hierarchical displays: *top-down* and *bottom-up*. The top-down strategy involves determining the position of the target item in relation to a top-level display. This strategy was facilitated by using a main menu button which moved the user in a single step from an initial position in the lower levels of the display structure to the top of the menu structure. The user then found a path down to the target item. Navigation in the top-down direction was facilitated by the user's familiarity with the top-level items, which tended to be used more frequently than lower-level items. The bottom-up strategy involved moving from a lower-level position in the display structure to a higher level position and then descending the appropriate branch when the proper reversal point was reached. Factors which made the bottom-up strategy difficult included the possible lack of familiarity of the less frequently-traveled lower-level items, difficulty in identifying reversal points, and the possibility of overshooting reversal points.

Seidler and Wickens speculated that users are biased toward using particular strategies based on the navigation tools that are available to them. When subjects were forced to use the backward button to ascend the display hierarchy, they had to consider the relationship between the positions of the initial and target displays to determine the most efficient navigation path. This was called a bottom-up processing strategy because it included considering getting from the lower levels of the hierarchy to the upper levels. When the initial and target displays were located within the same major branch of the main menu, the bottom-up strategy was complicated by the need to identify the reversal point - the point at which the user should stop ascending and start descending the hierarchy. Reversal points located in the lower levels of the display hierarchy may not be as easy to identify as other displays, such as the main menu display. Pressing the backward button too often would result in overshooting the reversal point.

When subjects could only ascend the hierarchy using the main menu button, which immediately accessed the top-level of the display hierarchy, the relationship between the initial and target displays became less important. The subjects only needed to determine the most efficient path between the main menu and the target display. This was called a top-down processing strategy. Display retrieval using the top-down strategy is facilitated by such factors as the greater familiarity of the top-level branches of the hierarchy and the fact that the main menu display cannot be overshot. Thus, the navigation tool influenced the type of processing strategies used.

A limitation of this study was the degree of experience of the subjects; they had no long-term experience with the system, as would trained NPP operators. Extensive experience with the display system may reduce the cognitive burdens associated with identifying the location of target displays and, thus, reduce the effects of cognitive and organizational distance. If this occurs, retrieval time may be even more strongly affected by navigation distance (e.g., number of actions required, user response time, and system response time).

Seidler and Wickens offer a set of tentative "implications" for display system design. They are summarized below:

- Designers should shorten although not necessarily minimize navigation distance. The main menu button is an example of a way to shorten the distance to the top of the menu. Offering direct access to display pages via entry of keywords, which was not addressed in the study, may impose high cognitive demands when navigating large display networks. It may be more favorable as a supplemental navigation tool for experienced users for frequently accessed displays.

- Designers should allow users to employ top-down navigation strategies by providing features such as the main menu button. Determining relationships between the top-level display and the target may be less demanding than determining the relationship between a start and target screen and then identifying a path through intermediate displays.

- The display system should support users in identifying reversal points for bottom-up processing strategies. The identification of reversal points can encourage and facilitate the use of bottom-up strategies.

- Designers should strive for compatibility between cognitive and organizational distance.

Navigating Large, Continuous Display Pages

The term large, continuous display pages is used here to describe display pages that are too big to be viewed at once via a single display screen, and continuous in the sense that individual information locations reside within a connected space. The distance separating information items in these displays has some characteristics of an interval scale. When navigating between locations, users can count the number of increments separating two points or judge a position to be some proportion of the distance between two other points. By contrast, when navigating a display network, the distance between the display pages does not have this property. Large continuous information structures for process control may include overview displays of the network, mimics, maps, tables, and trend plots.

In their taxonomy of techniques for viewing large displays, Leung and Apperley (1994) distinguish between distortion-oriented and nondistortion-oriented presentation techniques. That distinction is maintained in the following discussion of human performance considerations.

Use of Nondistortion-Oriented Techniques

Nondistortion-oriented techniques do not distort the display page by presenting it in multiple levels of magnification at the same time (e.g., as in a fisheye view). Instead, they generally present only a portion of the large display page at one time. While nondistortion-oriented techniques allow a particular area to be viewed in detail, the detailed view generally lacks information about the overall structure of the display. This can result in orientation problems in which the user is not aware of how the detailed area currently in view relates to the rest of the large display. For example, the user may not have a clear understanding of which part of the large display is being viewed, what other areas of interest exist in the large display, or how to access them. To compensate for this problem, some systems provide an overview display that depicts its entire structure. Nondistortion-oriented techniques used for navigating large displays include scrolling, panning, roaming, zooming, and paging. Some human performance concerns associated with using these techniques are described below.

Beard and Walker (1990) compared three techniques (roam, roam-and-zoom, and scroll bars) for navigating a large display that depicted a hierarchical tree structure. Each technique was used with and without a miniature overview display that showed the entire tree structure and the currently accessed location. This overview display was presented in a small window called a map window. The hierarchical tree structure was a large balanced binary tree presented in a two-dimensional format and containing 280 nodes, each with one word. Six graduate students with extensive computer experience participated. Their task was to view information in the tree using the various navigation techniques and determine whether a target word was present.

The scrolling interface allowed continuous scrolling vertically and horizontally. In addition, a scrolling feature allowed paging (i.e., scrolling by discrete pages) in each direction. Roaming was accomplished by using a cursor to move a wire-frame box in the map window. The position of the wire-frame box designated a portion of the tree to be presented in the main part of the display screen, called the detail view window. Roam-and-zoom moves were accomplished by drawing a wire-frame box over the desired location in the map window. The magnification level (degree of zoom) was determined by the size of the box. The maximum level of magnification was achieved when the box was at its smallest size, because the enclosed area was expanded to fill the detailed view window.

The window map had two presentation conditions. In the first, the miniature overview display of the tree was continuously present. In the second, the tree was not shown. In this condition, users performed the roam and roam-and-zoom movements by manipulating the wire-frame box in an empty window.

Beard and Walker concluded that the presentation of the tree via the map window resulted in faster task completion time. Due to the small size of the map window, only the shape of the tree was visible; node labels were not visible. However, users were able to move to the correct location based on what they could infer from the shape of the tree. Without the map window present, the users often required more movements to move to a particular node and view its contents, so tasks took longer to complete. Beard and Walker suggest that map windows will be most useful in relatively unknown or complex information environments.

The small size of the nodes and the wire-frame box in the map window challenged users' manual dexterity. Users had difficulty grabbing the wire-frame box in the roam condition and drawing the box in the roam-and-zoom condition. Grabbing the box was especially troublesome when users wanted to move it slightly. Users commented that some type of fine control feature for positioning the wire-frame box would be beneficial.

The roam and roam-and-zoom features were both superior to the scroll bars for movement in the display space. Little difference was found between performance using the roam and roam-and-zoom techniques. Beard and Walker state that the roam-and-zoom technique may actually require fewer mental operations and hand motions than the roam technique. However, they suspect that the zoom feature requires additional attention and planning. For example, time and mental effort are required to (1) select a starting point for a zoom movement, and (2) recover from any improper zoom movements.

No users chose the scrolling feature. However, this may have been due to the slow scrolling speed of this feature. Beard and Walker suggested that if the display could be scrolled through more quickly, then this feature would be used more often. The paging mechanism of the scroll feature was determined to be useful, by observing the participants and reviewing their verbal protocol. One subject found that the paging feature could provide rapid access to the nodes on the bottom level of the tree by paging down and then paging left or right. When the overview display was not present in the map window, users made more navigation errors; they tried to navigate by interpolating the target location relative to the sides of the empty map window.

In another study (Schwarz, Bedie, and Pastoor, 1983), an experimental comparison was conducted of the paging and scrolling features of a text processor. The users, who had very little experience with the text processor, performed a reading task. No differences were found in reading speed. However, paging was clearly preferred for accuracy. The researchers attributed this to the fact that paging maintains an absolute spatial orientation of the text. In contrast, spatial relationships are relative rather than absolute when a scrolling interface is used.

Darken and Sibert (1996) studied navigation in a large, two-dimensional geographical display. The purpose was to determine how much of what is already known about wayfinding in the physical world is independent of the type of space, and therefore, can be applied to abstract computer-generated environments. The overall objective was to identify design principles that can facilitate expert-like navigation performance in novice users. Five two-dimensional geographical environments were tested. Each represented about 12,000 square kilometers of land and sea in real-world dimensions. The subjects could fly over this landscape at elevations ranging from 0 to 400 meters. Changing elevation was essentially the same as zooming a display; a low elevation showed a small area to be seen in great detail, while a high elevation showed a large area with little detail. The elevation ceiling of 400 meters prevented the subject from gaining a "bird's eye view" of the entire virtual environment. In addition, a map display, which provided overviews of the geographical display, was provided for some conditions of this study. Flying was similar to panning a large display. Subjects could fly in any direction. Their task was to search for, and identify, ships in the water.

Design principles for supporting wayfinding in physical environments (Lynch, 1960; Passini, 1984) were adapted in designing these computer-based displays. The virtual environments depicted in the geographical displays were designed according to the following organizational principles intended to support the user in mentally organizing the display environment:

- divide the large-scale world into distinct small parts, preserving a sense of "place"
- organize the small parts under a simple organizational principle
- provide frequent directional cues

The following principles were applied to the design of the map display:

- show all organizational elements (e.g., paths, landmarks, districts) and the underlying organizational principle
- always show the user's current position
- orient the map with respect to the user to accommodate the forward-up equivalence principle [This principle is unique to virtual worlds in which the user has a forward view while moving

from one location to the next. Most display systems used in process control applications provided a "bird's eye" view of the information structure with a top-up (e.g., North-up) orientation.]

Four treatments were tested: grid, map, map/grid, and control. In the grid treatment, the organizational principles were applied to the virtual environment but no map was provided. In the map condition, the organizational principles were not applied to the virtual environment. However, a map that adhered to the map principles was provided. In the map/grid treatment, the organizational principles were applied to the virtual environment, and a map, was provided which adhered to the map principles. In the control treatment, the organizational principles were not applied to the virtual environment and there was no map.

For each treatment, the users were required to perform five naive searches followed by one primed search. The user started at the home target and proceeded to search for each of five target ships. This constituted the naive searches. Once the last ship was located, the user was required to return to the home target (i.e., the primed search). Users were instructed to think aloud while navigating. At the conclusion of each trial (i.e., the six searches), the users were required to draw the environment in as much detail as possible. Ten subjects participated, who had technical backgrounds and were between the ages of 20 and 45.

Darken and Sibert (1996) found that orientation was critical to wayfinding. When subjects began the trials, they first oriented themselves in the virtual environment by acquiring their position and direction. If at any time they lost their orientation, they reacquired it before proceeding. Task performance was profoundly affected by the type of stimuli presented. The control treatment, which lacked cues for direction and spatial organization, led to ineffective search strategies and frequent disorientation. The radial grid treatment provided sufficient information to support successful searches. However, the users had to perform actions periodically to maintain their orientation. The map treatment fostered the use of landmarks for navigation and allowed users to optimize their search methods. For example, they could review the overall information structure using the map and then optimize their searches by apply heuristics to identify locations that had a higher probability of containing the target items.

The general conclusions from this study are restated below. They have been reworded slightly to be applicable to a broad range of information structures, rather than to apply to virtual worlds alone:

- If adequate directional cues are not provided, disorientation will result which will inhibit both wayfinding performance and the acquisition of representational knowledge.
- An information space that has no explicit structure is difficult, if not impossible, to search exhaustively.
- If an organized exhaustive search of the information space is to be attempted, an organizing structure must be imposed on it. If an explicit structure does not exist, then a conceptual coordinate system, which acts as a divider, may be imposed by the user.
- Path following is a natural behavior, even in computer-based environments. Subjects frequently used display features, such as gridlines and region outlines, as if they were paths.

- Maps can be considered external supplements to internal survey knowledge, allowing users to optimize their search strategies.

- Dead reckoning, choosing a direction toward a target and then estimating the travel time until arrival, is an intuitive and natural part of navigation in information structures. While inferring position from a past location and constant velocity over time may be complex in the real world, it appears to be more easily understood and implemented in the virtual space of computer-based environment.

Use of Distortion-Oriented Techniques

As discussed, distortion-oriented techniques allow a user to view details of an area of a large display page while keeping the rest of the display page in sight. This is accomplished by presenting the focus area at a higher level of magnification than the rest of the display page. One type of distortion-oriented view is the hyperbolic browser (Lamping and Rao, 1996). With this approach, an information structure such as a hierarchy or network is mapped onto a hyperbolic plane in which exponentially more space is available with increased distance from the center. A view is created by projecting a portion of this space onto a flat circular surface. The current position is presented in the center of this space so its associated parent and descendant nodes are presented around it. Views may be changed by selecting a node and dragging it into the center of the viewing area.

With such visualization, successive views of an overview display may look quite different. One potential problem is that the set of nodes and the relative distances between adjacent nodes will be different in the initial and final views. Some nodes will come into view and others with be removed. The separations between nodes will expand toward the center and contract toward the periphery. A second potential problem is that successive transitions in the hyperbolic plane will, in general, cause rotations, which are disorienting. These factors could result in poor visual momentum (Woods, 1984). Users may not be able to comprehend the relationships between successive views and become disoriented (Lamping and Rao, 1996).

Lamping and Rao (1996) describe a variety of techniques to enhance visual momentum. First, animation is used to convey the transition between the initial and final views. A node may be selected by pointing to it with a cursor and entering a command, or by dragging it into the focus area. The animation allows the selected node to move slowly toward the focal area while its associated parent and descendant nodes come into view (e.g., nodes change in size and node labels are appear). Second, to address the rotation effect, a rotation component is automatically added to the transitions so the node in the focal area of the display will have the same canonical orientation each time. This is similar to maintaining a map so that North is always at the top. Lamping and Rao (1996) did not describe any performance-based evaluations of the use of these features.

Currently, a broad variety of distortion-oriented techniques are being developed. Such techniques hold promise for supporting navigation of displays that contain complex information spaces. For example, such displays may be used to view a complex display network by indicating the user's current location in the display network and identifying other displays that can be accessed from it. Another application may be to view large mimic displays by showing the focus area in greater detail and surrounding areas in less detail. To date, there have been few performance-based evaluations of the use of these techniques. Thus, their potential effectiveness in operational settings is not fully understood.

3.2.3.6 Hypertext

Hypertext is a method for organizing, presenting, and accessing information based on relational links. Information is parsed into modules called nodes each containing a potentially useful chunk of information. Nodes are connected by links to form a relational network. The individual user may determine which path to follow through the network of nodes at the time of use. However, because the nodes and links are usually established by a hypertext-system designer, difficulties may occur when the design does not match the task requirements or capabilities of the users. Human performance considerations associated with hypertext are described below.

Identifying Selection Points

The designation of anchor nodes is a concern. The presence of many visually coded, selectable items may add visual clutter and decrease the overall effectiveness of the coding scheme. Also, codes such as bold, italics, and underline may conflict with other uses of these conventions in the text, such as to emphasize certain words, and thus, may confuse the user (Nielsen, 1990). Coding the cursor to indicate anchors also has disadvantages. First, the changes in the cursor are momentary; they only occur when the cursor is positioned near an anchor. This reduces the ability of users to anticipate the anchor node. Second, the visual codes, such as changing the shape from a pointer to a set of cross hairs, may be less salient than coding applied directly to the anchor. These factors may increase attentional demands for locating anchor nodes. Nielsen recommends combing cursor coding with other means, such as node coding, so the users are not reduced to "playing mine sweeper" (Nielsen, 1990, p. 108).

Evaluating Links to Determine Which Will Yield Desired Information Prior to Retrieval

The information content of hypertext-based structures is often modular (i.e., distributed over a number of individual nodes). Users may find it necessary to access multiple nodes to obtain the full set of information related to a desired topic. If the user is not sure where a desired topic resides in the information structure, many nodes may be accessed before the user can determine that a portion of the information structure does not contain the desired information (Nielsen, 1990). The act of deciding whether to access a particular node imposes a cognitive burden that may interfere with other important tasks (Cronklin, 1988). In addition, unproductive searches may interfere with operator responses or result in the operator becoming lost in the information structure during time-critical situations. Cronklin (1988) describes three techniques that can aid users in determining whether a hypertext node may yield desired information (1) provide a brief description of the new node (e.g., via a pop-up window) prior to retrieving it, (2) show the descendent nodes of the new node prior to retrieving the new node, and, (3) have the new node appear rapidly when selected so the user can evaluate and accept or reject it with minimal interruptions to ongoing activities.

Retaining a Sense of Location in a Hypertext Structure

Hypertext-based information structures are often characterized by links that are based on conceptual relationships between the information content (relational links) rather than on structural relationships (e.g., relationships that result from a regular hierarchical structure). Relational links may be different between similar sets of nodes. For example, two major branches of an information structure may contain similar types of information but have different link structures due to conceptual relationships that are unique to each branch. These differences may make the overall link structure difficult to visualize. Information structures that are easier to comprehend may result in better navigation. For example, Mohageg (1992) found that ability of the user to find information in a hierarchical information structure was significantly better than in one that had a relational network (hypertext) structure. Mohageg suggests that hierarchical structure produced better performance because its link structure was predictable, which allowed users to formulate structure-based strategies for their searches. Users could predict where particular types of information resided in one branch of the hierarchical structure based on their experiences with other branches of the structure. When using the hypertext structure, users could not make such predictions but instead relied on more semantically based search strategies which were more time consuming.

When hypertext documents are highly modular, as in the Mohageg study, information is distributed over many nodes. The users must understand the link structure to understand their current location in the document. One approach is to provide an overview display which depicts the overall link structure and the location of the currently accessed node (Nielsen, 1990). Cronklin (1988) states that the designers of graphical browsers for hypertext can create viable virtual space environments by placing nodes and links in a two- or three-dimensional space, employing properties that are useful for visual differentiation (e.g., color, size, shape, texture), and maintaining similarities to the physical world (e.g., objects are stationary, two objects cannot occupy the same space). Users can use these visual cues to orient themselves in a way similar to how people orient themselves when driving or walking in a familiar city. However, since there is no natural topography to a hypertext space, users must become familiar with the overview display before it becomes a useful aid to navigation. New users, who are not familiar, are likely to become disoriented even with the overview display.

Some hypertext documents superimpose a set of relational links on a traditional serial document structure. For example, an encyclopedia may have the traditional organization of volumes and sections that can be read from front to back. Hypertext links may be added to this structure to allow the reader to jump between related topics. In such documents, the user can rely on the familiar structure of the document for orientation, instead of having an understanding of the link structure. For example, a reader can relate the current location to the overall structure of the document by noting which volume, section, and subsection is currently accessed. The human performance tradeoffs between using the document structure versus overviews of the link structure to orient the user are not fully understood.

Understanding Successive Views

Disorientation can occur when users do not understand the relationships between successive views of a display system. Such conditions may be said to exhibit poor visual momentum (Woods, 1984). In hypertext-based information systems, disorientation can occur when making transitions between nodes of the information structure if the relationship between the information of the current and previous nodes is not clear. Nielsen (1990) states that, in general, a hypertext design should convey how a destination node is relevant to the user by relating it to the point of departure in the anchor node. That is, the basis of the relational link should be apparent to the user through explanatory text or graphical display techniques. Disorientation may also occur when looking at an overview display after making a transition between nodes. Successive views of the overview display may look quite different due to the complexity of the links between the nodes. For example, when a new node is selected, a new set of relational links may be presented in the overview display.

Navigating Individual Nodes

Nielsen (1990) cites tradeoffs associated with node size. When the nodes are larger than the display screen, the user may have to scroll, pan, or zoom to view its information. However, when smaller nodes are used, information may be spread over multiple nodes requiring the use of multiple links to access required information. Limited guidance exists on the tradeoff between the demands of manipulating large nodes and accessing multiple nodes. Kreitzberg and Shneiderman (1988) found that a text document was divided into large nodes (46 articles of between 4 and 83 lines) and smaller nodes (five articles of between 104 to 150 lines). It was found that users could answer questions significantly faster using the system that contained the many smaller nodes (125 seconds versus 178 seconds per answer). Nielsen states that one reason for this difference may be that the hypertext system used for this study had links to the beginning of the destination node and not to the place within the node where the information of interest is located. Had the hypertext system identified the desired information within the large node, the results may have been different.

Window Navigation and Management

Some hypertext systems can retrieve a set of destination nodes that are linked to an anchor node. If the destination nodes are presented as separate windows, a window management task may result. The user may be required to move, resize, and open and close windows in order to view them. The demands of navigating and managing windows also may be associated with hypertext systems that contain nodes that are not uniform in size. When a hypertext system uses a fixed window size for presenting nodes, each node always takes that same amount of space regardless of the amount of information it contains. The use of variable window sizes may increase interface management demands by preventing users from anticipating the amount of display space required for each node and increasing the amount of effort required for window management.

Supporting Retrieval and Recovery

Backtrack capabilities, which almost all hypertext systems feature, are vital for allowing users to become reoriented. Some hypertext systems use this capability inconsistently, especially where multiple means are provided for accessing information. This inconsistency can cause problems. For example, in one hypertext study (Nielsen and Lyngbaek, 1990), 44% of the subjects indicated that they were often confused about how to access previously visited nodes. One probable reason cited for this confusion was that the hypertext system used different backtrack mechanisms depending on the type of link mechanism originally used. Nielsen (1990) states that since backtrack capabilities are essential to building user confidence in a hypertext system they should always be available, always operate in the same way, and allow the user to backtrack to the introduction node.

Integration of Hypertext Navigation Capabilities

Some hypertext systems contain multiple capabilities for supporting movement and orientation, such as maps of hypertext links, bookmarks, and footprints. When multiple capabilities are not well integrated with the rest of the information system, their operation may be clumsy (Toms, 1996) and impose undesirable secondary tasks. Users may have to learn different or conflicting strategies for each capability. For example, in one study, users became frustrated when using backtrack capabilities because different procedures were required depending upon the mechanism that had originally been used to select the node (Nielsen, 1990). Such poor integration may detract from, rather than, enhance user performance.

3.2.3.7 Manipulation and View Arrangement Features

Two tasks associated with manipulating and arranging views are addressed in this chapter: decluttering displays and decluttering display windows.

Decluttering Displays

The amount of information that needs to be on a display to support operator activities depends on their specific tasks. When a display does not contain all of the information that an operator needs to perform a task, the operator may be forced to make rapid transitions between two or more displays to access and mentally integrate the needed information. Display designers can reduce the need for these transitions by developing displays that contain broader sets of integrated data. Woods and Watts (1999) state that users, at least in event-driven worlds such as NPPs, seem to prefer data-rich displays to simpler displays, if the displays reduce navigation burdens. However, an operator may not use a display the same way each time it is accessed. Depending upon the operator's task, the operators may look at different subsets of data from the display or analyze them differently. What is essential data for one task may be unnecessary clutter during another task.

The presence of unneeded data (clutter) in a display may interfere with the operator's task. For example, it may increase the difficulty of a visual search for information by providing more targets to review and assess. Many studies have shown that search time increases significantly with the number of items in a display [See Tullis (1988) for a review of several studies, including his own]. Also, unneeded data may interfere with ongoing monitoring tasks by drawing operator attention away from information that is the focus of their task. Comments to this effect were received from operators in an alarm experiment where suppressed alarm lists were presented (see footnote 1).

Display systems from other domains address this problem by providing decluttering capabilities, which allow a high volume of data to be presented when needed and removed when not needed. Decluttering capabilities are especially useful when personnel must handle a large volume of data and the available display space is limited. Two domains that use display decluttering are air traffic control and military aircraft. Air traffic controllers can monitor many aircraft via a single radar display. Each aircraft is represented by an icon that indicates its position. In addition, descriptive information such as flight number, heading, and speed also can be presented. When many aircraft are present, the density of displayed information can be quite high. Information that is not being used at a given moment can be distracting. Air traffic controllers can control the amount of information presented on the display. For example, they can declutter a display by suppressing the detailed flight information for all but a subset of aircraft. In military aircraft, crew members may also handle a great amount of information via a limited display space. Similar techniques are used to control the amount of information shown.

Similar decluttering features may be used in NPP HSIs. Two possible examples include mimic displays of plant processes and overviews of display networks. Mimic displays depict the relationships between components in a plant process. They can contain a wide array of information in graphical and alphanumeric format. Decluttering capabilities may be used to remove information that is not of immediate interest to the operator, such as control and alarm setpoint values for components that are not the focus of the current task.

Overview displays of display networks may be used to show the overall structure of the display network, the operator's current location in the network, and the locations of other display pages that are of interest. Some viewing techniques automatically declutter the displays by emphasizing some information and eliminating other information. For example, the Information Visualizer (Hearst, 1997) and the Hyperbolic Browser (Lamping and Rao, 1996) discussed earlier bring some network nodes into view while they move other nodes out of view, based on user input. Manual methods for controlling the amount of information presented also are possible.

One potential human performance concern associated with display decluttering is its effect on the ability of the operator to maintain awareness of changes in plant status. The act of decluttering the display removes information from the operator's immediate view, so that the operator may not observe indications important to assessing changes in plant status or evaluate the implications of possible control actions. A second potential concern is the ability of the operator to recover from the decluttered mode. The operator may not be able to rapidly access the suppressed information.

Decluttering Display Windows

Window management is an example of a view arrangement task. Windowing systems allow users to rapidly switch between display windows that may contain different types of information or address different primary tasks. Thus, windowing systems may avoid some interruptions to operator tasks associated with closing one display to open another. However, the task of manipulating display windows is, in itself, an interface management task that may detract from the primary tasks of operators. The following discusses human performance considerations associated with manual and automated window management systems.

Manual Window Management

Manual window management systems require the user to open, close, move, and resize display windows. These are secondary tasks that may detract from the operator's primary task of controlling the plant. Woods and Watts (1999) describe potential problems associated with display window management. To maintain their awareness of plant status, operators must remove unused windows from the display screen to allow them to view other displays of plant data. If they do not manage the windows, significant events in the monitored process may be missed. Also, when new events occur, operators may suddenly realize the need to arrange the windows to monitor the change. At this point, the window management task may detract from the operator's primary task of assessing the change in the plant.

Davies, Bury, and Darnell (1985) found that a windowing system did not yield better user performance in terms of task time than a non-windowing system. When subjects used the windowing system, they spent more time managing windows and less time on the primary task. Bly and Rosenberg (1986) examined the appropriate circumstances for using tiled versus layered windows. They found that tiled windows were superior to layered windows when the window content was in a regular arrangement that did not require too much management.

The proximity of information can affect its use. Andre and Wickens (1988) studied the effect of spatial proximity of information for both focused-attention and information integration tasks using a cluttered display environment. They found that the closer the distance between relevant and irrelevant information, the more adverse were the effects on the information integration tasks. They concluded that the spatial proximity of relevant to irrelevant information affected the process of *searching* for relevant data, rather than the process for cognitive information *processing*.

Automated Window Management

An alternative approach to manual window management is to have the display system handle it automatically. While automation may relieve the operator of the largely mechanical task of opening, closing, moving, and resizing windows, it may create new cognitive demands associated with monitoring the automated system. Woods and Watts (1999) identified the following cognitive demands:

- *Monitoring* - determining whether the display has changed
- *Situation assessment* - determining why the system operated as it did (e.g., why did it select or not select a particular display window now?)
- *Mental simulation* - anticipating what it will do next
- *Coordination* - tracking the system's assessments and actions and coordinating it with one's goals

These concerns can be illustrated by two examples in which the operator must interpret the unanticipated behavior of the automated window management system. In the first, an operator is monitoring a plant display when that window is closed and replaced with one presenting a different display. In such a case, the operator must determine why the display was changed. For example, was it caused by the system's interpretation of operator intentions, plant status, or display system status? The operator must also determine which pieces of data in the new display should be attended to. In addition, the change in the display window may have interrupted the operator's activities with the other display. The operator must determine which activity is more important, the one that was in progress or the one represented by the new display window. If the operator gives higher priority to the activity represented by the new display window, some actions may still be required with the display in the old window before performing activities with the new display window. As a second example, an operator may perform an action, such as attempting to access a particular display page or window, and an unexpected display window appears. The operator may be uncertain whether the window selection resulted from the operator's action (e.g., an input error) or from the automated window management system. These two examples indicate new types of uncertainties and cognitive demands that did not exist before introducing the automated window management system.

Woods and Watts (1999) state that problems with automated window management systems do not stem from the level of automation per se, but instead from the type of feedback provided to the user and the coordination of the automated system with operator tasks. The system needs to make selections that are relevant to the operator's tasks and effectively convey information that resolves questions associated with the operator's cognitive demands. This will require that the system contain, or be based on, a good model of the operator's functions for the task domain.

Woods and Watts refer to the adaptive windowing feature of a simulated satellite control center as an example of a successful automatic window management system. The system contained a model of operator functions for the task domain. It identified topics that were of interest to operators based on the controls and displays they selected. The system then identified other controls and information that might be of interest. It presented them in a display window in parallel with the window containing the items selected by the operator. The success of this system stemmed, in part, from the effectiveness of the model of operator functions which allowed context-sensitive presentation of information and controls.

3.2.3.8 Moving Between Multiple Display Devices

In some cases, an operator may use the same set of input devices to interact with more than one display device. For example, displays from multiple CRTs may be accessed from the same mouse and keyboard. Difficulties can arise if the design of the user interface does not support the operator in transferring between the display devices. For example, the operator response to an event may be delayed while the operator tries to determine which display is currently active. Also, the operator may try to provide an input to one display device while a different display device is active. If the purpose of the input action is to select a display, then the result may be the failure to select the display or selecting a display on the wrong display device. There may be a delay in the operator's response to an event. If the purpose of the input action is to provide control input to plant equipment via a computer-based (soft) control, then the result may be that the wrong plant component is operated. The HSI should provide sufficient feedback to allow the operator to rapidly determine which display device is currently active. It should have a mechanism for rapidly transferring between the display devices. There should be features that prevent accidental actuation of soft controls.

Following is a discussion of some design approaches for facilitating the use of multiple display devices, which are also described in Stubler and O'Hara (1996). They are given as examples of interface management tasks and human performance considerations that may result from moving between multiple display devices.

One technique used for moving between multiple display devices is the use of continuous cursor motion. If the displays are the same size and are located adjacent to each other, then the cursor can move in a smooth, continuous motion from one display device to the next. However, if the display devices are physically separated, have different orientations, or different sizes, the cursor motion between them may not be perceptually smooth. That is, the user must translate motion on one display into a different motion in the other or follow the cursor as it "jumps" across the space separating the displays. These factors may cause the user to lose track of the cursor's location. Three methods that support the user in following the cursor motion between display screens are specified entry point, computational correction, and designated overlap. Each is described below.

- *Specified Entry Point* - The cursor always enters the other display at a uniquely specified entry point. This method allows the user to anticipate the cursor's location on the other display, which may reduce the time associated with finding it. However, the user must first locate the specified entry point.
- *Computational Technique* - If the display screens have different proportions of height and width, then the operator may have difficulty understanding how the cursor position on the edge of one display screen corresponds to a position on the other screen. This may interfere with the perception of smooth, continuous movement between the display screens. Tani et al. (1994) describe a computational technique that compensates for the differences in screen sizes to make cursor motion appear more continuous. In this application, the horizontal dimension of the large, group-view display device had twice as many pixels (display elements) as a smaller display device, while the vertical dimensions of both displays had the same number of pixels. When a cursor entered a narrow area at the top of an individual-view display, its position was translated

into the coordinate system of the larger display and appeared at the bottom of that display device. The coordinate system of the large display device was established such that a horizontal movement of the mouse that would have caused the cursor to move one pixel on the smaller device resulted in a movement of two pixels on the larger one. There was no difference in cursor movements vertically. This computational technique allowed the small display device to overlap the entire length of the large display device. The authors noted that this arrangement was acceptable to users, although the evaluation method was not described. The authors also noted that it was unclear whether a similar approach would be acceptable if the differences in screen sizes were larger.

- *Overlap* - An alternative approach for compensating for differences in screen sizes is to have the small-screen display overlap a smaller portion of the large-screen display, such that a one-to-one relationship in cursor motion is maintained. For example, if one display screen is twice as large as the other, then the smaller display screen would be mapped onto one-half of the larger screen. Thus, when moving the cursor horizontally to the right, it would stop when reaching the right edge of the small-screen display. However, once the cursor is moved vertically into the large-screen display, the horizontal motion of the cursor may continue until the right edge of the large-screen display is reached. If the overlapping areas of the large- and small-screen displays are properly designated, then this approach would be consistent with the visual momentum principle (Woods, 1984) of perceptual landmarks.

Many other approaches may exist for coordinating the use of multiple display devices, and are likely to impose different interface management tasks. Research is needed to identify these approaches and develop appropriate HFE review guidance.

3.2.3.9 Interrogation and User Guidance

Guidance features can support experienced users in their ongoing use of the system and help novice users learn the user interface system. The former role is of primary concern in NPPs because the user population usually is highly trained. Guidance features help users recall information about the operation of the user interface. Elkerton (1988) states that, in general, little is known about how computer-based dialogues should be designed to improve user performance. Deficiencies in these systems result from fundamental problems with the theories and methods used in their design. Described below are human performance considerations associated with online help systems. A brief description is given of general design process considerations that may affect user performance.

Online help systems are intended to provide assistance to users while they are performing computer-based tasks. Shneiderman (1987) identified the following potential benefits of online help systems. First, there is no need to have hardcopy manuals which take up room in the workspace and which can distract the user from the video display and computer task. Second, the user can retrieve information more quickly than from hardcopy manuals when online guidance is designed with indexes and cross-references. Third, new graphics technologies, such as diagrams and animation, may support user understanding of the interface and help them learn and remember interaction procedures. However, not all of these benefits have been verified by research.

Elkerton (1988) states that while there are many types of online help systems, there have been few behavioral studies evaluating their effectiveness or their integration with user tasks. Of the studies mentioned by Elkerton, several demonstrated that online aids may actually *increase* the amount of time that a user requires to solve a problem. Elkerton states that online help is often little more than an electronic version of a hardcopy manual. Using online help manuals as an example, he describes several problems with these systems: information content, presentation format, guidance needs for experts and novices, intelligent online help, and design process considerations. Each is discussed below.

Information Content

The knowledge represented in online help manuals often was inadequate for users tasks. Most users do not want detailed, fact-oriented information, such as hierarchical lists showing the syntax of commands. Instead, users need procedural information. They need to know the methods for completing specific tasks. Without adequate procedural knowledge, users may resort to browsing through the manual with little understanding of which topics may be helpful. In two of the studies that found performance decrements when online help was provided (Elkerton, 1988), the decrements may have been related to the poor procedural content of the help dialogues. The resulting searches for help information may have disrupted the primary tasks.

Elkerton (1988) states that it is necessary to understand what interface methods the user needs to extract from online help, and how this information could be provided by the guidance system without disrupting the actual computer task. Guidance is needed about the type of help information that should be given and the form in which it should be presented.

Presentation Format

Cohill and Williges (1985) evaluated the use of help by novice users performing a text-editing task. They evaluated eight types of help which varied in format (e.g., online or hardcopy), initiation (e.g., user or computer), and selection of help topic (e.g., user or computer). These help conditions were compared to a control condition without help. All help conditions yielded better performance than the control condition. However, the best performance in terms of time and errors was obtained when the users initiated and selected help material from a hardcopy manual. Cohill and Williges concluded that the hardcopy manual allowed users to browse through the help information without removing the text-editing task from the display screen. Citing this finding, Elkerton suggests that the content of manuals should be condensed to reduce search time and, for online versions, minimize the amount of screen space that they require.

Online help systems that are window-based can be beneficial because they show the help information and the user's task display on the same screen. Users can glance between the help and the task rather than accessing separate displays, so reducing demands on the user's short term memory. However, if multiple windows are already open, the presence of an additional help window may obscure important information. As a result, the user may be required to perform additional window management tasks, such as moving or resizing windows. Thus, the introduction of the window may increase the cognitive load on the operator (Shneiderman, 1987).

Guidance Needs For Experts and Novices

Operators may vary in their degree of proficiency in using some interface management techniques. For example, Elkerton (1988) found that an expert used search string procedures in a computer-based system, while a novice scrolled and paged through information. This was because the novice may not have been aware of the appropriate selection rules. Online help should be consistent with the range of expertise of the users.

Intelligent Online Help

Aaronson and Carroll (1987) observed and analyzed dialogues between a user and a human consultant to discover what questions and responses would be required with intelligent online help. The study used verbal protocols of one-time consultations conducted via electronic mail to identify strategies which could be used in designing future help systems. The following strategies were included: make the assumptions about user goals explicit, provide alternative solutions, assume an interface configuration, avoid the problem, and direct users to reference sources.

Design Process Considerations

Elkerton (1988) states that some problems associated with computer-based user guidance systems result from inadequate processes for system development. One problem is that online guidance systems often are not addressed as integral parts of interface design, but rather as a remedy for poor interface design. As a result, the user is faced with the double burden of coping with the help system as well as with the original deficiency. Also, the online help may not address all situations for which users may need guidance.

Elkerton (1988) notes that more systematic approaches are needed to support the development of user requirements for guidance systems. For example, while the protocol analysis conducted by Aaronson and Carroll was a useful and creative technique for identifying requirements for intelligent online help, it was also time consuming and required skilled analysts. He suggests that other techniques are also needed to develop user requirements, and proposes using cognitive task analyses to identify procedural knowledge that users need to operate computer-based systems. Such analyses would identify detailed procedures for operating the user interface, provide the content for user guidance dialogues, and provide a capability for predicting user performance with these guidance dialogues.

To undertake cognitive task analyses, Elkerton recommends the use of the Goals, Operators, Methods, and Selection Rules (GOMS) model developed by Card, Moran, and Newell (1983). This model describes user knowledge of a computer-based interface in terms of the following:

- *Goals* - what the user must accomplish
- *Operators* - individual actions, such as moving a cursor or pressing a button
- *Methods* - step-by-step procedures for achieving goals
- *Selection Rules* - heuristics for specifying which method to use in specific circumstances

GOMS can provide user requirements for both the user interface of a computer-based system and the online user guidance so that they can be designed together in an integrated fashion (Elkerton and Palmiter, 1991; Elkerton,1988). Elkerton (1988) gives specific recommendations for applying GOMS to develop online aiding. In addition, such approaches may provide a basis for independent evaluation of the effectiveness of online help systems.

3.2.3.10 Global Interface Management

The previous chapters addressed human performance considerations associated with individual devices. However, an HSI usually consists of a collection of devices with different user interfaces and different interface management requirements. This chapter addresses the HSI as a whole. In particular, two topics are addressed (1) compatibility of interface management tasks across the HSI and (2) the coordination of interface management tasks among crew members.

Interface Management Consistency and Compatibility

An NPP HSI usually consists of an assortment of display and input devices. Inconsistencies may exist between these HSI components in the ways the information is presented and user interactions are performed. These inconsistencies may affect operator performance. For example, if the interaction methods of two devices are similar, the operator may apply the wrong method to a device. Tanaka, Eberts, and Salvendy (1990, 1991) state that when users must interact with multiple types of computer systems, the consistency of the user interfaces should be an important factor in enhancing the user's transfer of skill from one system to another and in reducing workload. However, they consider that consistency in user interface design is not a well-defined concept that has been tested experimentally. Tanaka et al. (1990, 1991) suggest that the theoretical and empirical basis for consistency measures for human-computer interactions exist in the areas of human information processing and skill training. Empirical studies in these areas show that consistent tasks are performed very quickly with few errors and little effort, while inconsistent tasks are slow, effortful, and prone to errors.

One way of examining consistency within an HSI is to assess transfer of training between one HSI component and another. Gentner (1983) offered a structure-mapping theory of analogy as a framework for analyzing and predicting the transfer of training. The two major factors of this framework are (1) surface similarity i.e., similarity between individual device components, and (2) shared systematicity (i.e., whether the learner possesses a coherent mental model of the original (base) device that can be applied to the second (target) device). Gentner and Schumacker (1986) applied this framework to analyze transfer of training effects associated with the use of different sets of controls and displays for a complex system. Subjects learned an operating task for a simulated device and then transferred that task to a new device. The systematicity factor had two levels; subjects were either given a causal model of the base system or simply a set of operating procedures. The surface similarity factor had three levels: high, medium, and low. The results showed that having a systematic (causal) mental model greatly facilitated learning the base system. There was some evidence that having the systematic mental model may have facilitated learning the target system, but this effect was not highly reliable (statistically significant at the .06 level). Surface similarity had strong effects on transfer. Subjects learned the new system device fastest when controls and displays of the base system were highly similar to those of the target system. Learning was slowest when controls and displays of the base system had spurious similarities to non-corresponding controls and displays of the target system.

Tanaka et al. (1990, 1991) developed a quantitative measure of user interface consistency by building on research from the areas of human information processing and skill training. They defined cognitive consistency as consistency in what the user knows. A quantitative value is determined by analyzing the number of changes which would have to be made to change one method of interaction into another. They defined display layout consistency as the consistency in the layout of the screen displays. It was defined in terms of overall display density, local density, grouping, and layout complexity. These measures were incorporated into a model called the Text-Editing Method (TEM).

An empirical study was made to test the predictions of this model using a text editing task. Cognitively inconsistent tasks and inconsistent display layouts had a slight detrimental effect on the speed of performance during an initial test session. However, in a repeat session conducted several days later, performance on the cognitive inconsistent tasks was slower than on the inconsistent display layout tasks. The results indicated that users will not necessarily have difficulty learning inconsistent interactive methods but problems may occur once the methods are learned and the user must switch between systems that use inconsistent methods of interaction. For example, Tanaka et al. (1991) state:

> For human-computer interaction tasks in the past, consistency has been equated with similarity of features or elements. Consistency of tasks, in this sense, has been predictive of performance when transferring from a learned task to a target task. Once a user returns to the learned task after performing the target task, this consistency analysis becomes inappropriate. Analyzing consistency when alternating tasks indicates that high overlap of rules will result in low consistencies. The same two tasks can be both high and low consistent depending on the pattern of use. Two highly similar tasks will be highly consistent in the transfer situation but will have lower consistency when alternating between the two. (p. 673)

This study suggests that gaps may exist in the conventional human factors wisdom on how consistency should be assessed, especially with regard to skill transfer.

The study by Tanaka et al. is significant because it shows that consistency can be defined quantitatively. Because the measures are analytical, they can be applied to evaluate computer systems before working prototypes are built. The TEM and similar measures of consistency should be examined in more detail to assess their appropriateness for measuring consistency between the various user interfaces in an HSI, and to assess the effects of inconsistency on operator performance.

Two special sources of HSI inconsistency are discussed below: upgrades and flexible features.

Inconsistency Resulting from Upgrades

When new HSI hardware or software is installed as part of an upgrade, inconsistencies may be created between the upgrade and the hardware or software that it replaces. That is, an operator may have to adapt to the operating characteristics of the new version. Some insights into HFE concerns related to upgrading HSI components can be gained from the experiences of the computer industry in introducing upgrades. Tognazzini (1990) describes the need for consistency between subsequent versions of a software product. In examining different aspects of consistency, he concludes that the look and feel of a product can be changed in an upgrade as long as the user's previously learned interpretations and subconscious behaviors are honored. Tognazzini states that users can adapt better to changes in the way that the system communicates information to the user than to changes in the way the system interprets inputs sent by the user. He thinks that the product's interpretation of a user input should not change as a result of an upgrade. For example, the entry "Command-R" should not produce a benign action in one version of a product and a destructive action, such as erasing data, in a subsequent version.

Tognazzini believes that it is better for an upgrade to require the user to learn additional skills rather than expect the user to change existing ones. Thus, changes in the information presented by the system (e.g., messages, graphic symbols) are less difficult to adapt to if they do not require users to modify their skills or strategies. For example, Tognazzini states, "If a system object has changed appearance, people do not go into a blind panic - they learn the meaning of the new appearance" (1990, p. 76). However, sometimes the appearance of a system is strongly linked to user skills. As an example, he states that the layout of tools on the palette of a drawing program should not be changed in subsequent versions. Users who rely on spatial memory for retrieving tools from the palette will find that this skill leads them to select the wrong tool.

Tognazzini suggests two strategies when modifying a product. First, conduct testing to identify user expectations. This can help identify skills that may be violated by the new version of the product. Second, when changes must be made, make sure they are salient. Drawing the user's attention to characteristics that have changed can help them to adapt their skills. For example, injecting a single new word into a message is not recommended. Adding the word "not" to a question, such as "Do you want to save this document before closing?" will change the meaning of the message. However, it may not be detected by the user until an error occurs. Many actions become automatic as users become skilled in using a product. If product changes are obvious, users may be able to block their automatic response and develop a new one.

Inconsistency Due to Flexible Features

Some displays allow operators to modify the display of information. For example, operator-configurable displays are pages that can be modified by operators to address particular task needs or personal preferences. For example, a user may be able to select plant variables to be included in or excluded from the display page, define coding for displayed items, and define axes and scales for plots. However, the use of operator-selected symbols and coding schemes may be inconsistent with other parts of the HSI. Moray (1992) offers the following general principle to guide the use of flexibility in computer-based HSIs: "As far as possible, make the software responsible for preventing the human from [producing] a configuration that violates good human factors principles, and if the latter must be violated, minimize the violation and give very strong feedback as long as the violation remains" (p. 63). This principle may be applied to any flexible (i.e., reconfigurable) feature of the HSI. Thus, it may be advisable for operator-configurable displays to include automated features that identify inconsistent use of symbols and codes and then either eliminate options that are not compatible or provide feedback to alert operators to potential errors.

Coordinating HSI Usage Between Crew Members

The HSI provides the media for sharing information and coordinating actions between crew members. Compared to conventional HSIs with hardwired controls and displays, computer-based HSIs may impose increased demands for coordination between operators. For example, in his discussion of the effects of flexible display system capabilities on operator error, Moray (1992) identified potential errors associated with multiple users of computer-based display systems. He states that if multiple crew members share a control console and each can reconfigure portions of it according to personal preferences, there is enormous opportunity for introducing mutual incompatibility across it. One crew member's preference may cause serious problems for the other member.

When a control or display can be used by more than one operator, mechanisms are needed to regulate modifications to the shared device (e.g., support operators in "taking turns"), inform operators of changes introduced by another operator, and to protect modifications that operators wish to retain. These considerations are described below for three HSI features:

- *Shared display devices* - when a display device is viewed by more than one operator, mechanisms may be needed to regulate its use so that one operator does not remove a display that is still needed by another operator, or present a display that may interfere with another operator's activities (e.g., see discussion of layout and distribution of information and controls, above).

- *Operator-configured displays* - these are display pages that can be modified by operators to address particular task needs or personal preferences. For example, a user may be able to select plant variables to be included in or excluded from the display page, define coding for displayed items, and define axes and scales for plots. When multiple operators can manipulate the same displays, coordination may be needed to ensure that they are aware of the current content. Also, mechanisms are needed to ensure that displays created by one operator are not changed or eliminated by other operators. Possible solutions include password protection, special directories for storing these displays, and administrative procedures.

- *Computer-based "soft" controls with multiple access* - some input interfaces for controlling plant variables can be accessed from multiple locations in the HSI. Mechanisms may be needed to ensure that operators are aware of control inputs made by each other, and to ensure that the control actions of one operator are not unknowingly reversing another operator's actions. Some process plants with computer-based HSIs address this problem by assigning control capabilities for a plant variable to a particular control console. Operators at other consoles can observe the control setting but cannot initiate changes.

Thus, computer-based HSIs can pose new demands on personnel for coordinating their use among crew members.

3.2.3.11 Conclusion

The design of the interface management HSIs impacts the performance of interface management tasks. However, except in a few cases such as menu design, there has not been a great deal of research comparing the characteristics across types of HSIs.

3.2.4 Analysis of Interface Management Tasks Based on Site Visits

The detailed findings for the site visits at NPP1, NPP2, and the chemical processing facilities are presented in Appendices A, B, and C, respectively. In this chapter, the results are summarized into several interface management topics:

- Relationship Between Interface Management and Primary Task Performance

- Cognitive Resources of Primary and Secondary Task Performance

- The Relationship Between the Keyhole and Display Area

- Flexibility versus Performance Tradeoff
- Mental Models and Display Organization
- Role of Conventional and Computer-Based HSIs
- The Effects of HSI Design Features on Interface Management Task Performance

Within each topic, a description of the topic is given, the findings are summarized, and the conclusions are presented.

3.2.4.1 Relationship Between Interface Management and Primary Task Performance

Description

Several effects addressing dual-task performance were identified and support was found for them. However, two basic question remain unsatisfactorily answered:

- How much time and cognitive resources can be taken from the primary task by the secondary task before primary task performance becomes affected?
- If interface management tasks are not performed, how well can the primary tasks be performed?

The resource-limited effect predicts that when demands increase, performance on the primary task will suffer. Evidence for this was found. The data-limited effect also has merit; operators tend to stop performing interface management tasks when diagnosis and planning become highly demanding. As operators are deprived of information (e.g., through the failure to undertake interface management tasks) their ability to perform the primary task may deteriorate. An important consideration is that, unlike many laboratory studies of dual task performance, the primary and secondary tasks in NPP operations are not independent. Operators must perform the secondary task, interface management, to obtain information used in the primary task (controlling the plant).

In addition to the two basic questions posed above, a further question is: "When do operators shift between resource-limited and data-limited strategies when dealing with changing plant conditions?" For example, under what conditions do operators decide to abandon interface management tasks and when do they decide that some interface management tasks are again needed? In general, a better understanding of how operators manage or regulate their workload and make tradeoffs, especially during complex process disturbances, is required for a technical basis to address performance limitations of computer-based HSI systems. As a corollary, it is important to identify the strategies operators adopt to minimize interface management task demands, such as decreasing the inherent flexibility of the HSI, increasing the predictability of HSI appearance and behavior, and increasing the simplicity of HSI configurations. A related consideration is how to measure the use of these strategies and their effects on plant performance.

Findings

Information on this issue was found at each site. Therefore, they are described separately.

Nuclear Power Plant 1

This HSI is a hybrid design. Much of the plant information is provided via VDUs while most of the control actions are performed via hardwired controls. Interface management is an important activity for obtaining information, especially for maintaining awareness of changes in plant status. Two areas of particular concern are the use of the alarm system, and retrieving displays that are not frequently used.

A high volume of alarms can occur during abnormal (e.g., plant startup) and transient conditions. While the most important alarms have spatially dedicated annunciator tiles, the full set of alarms is presented via VDUs. High levels of workload may be associated with using these VDUs to view alarms during abnormal and transient conditions. For example, each alarm display can display as many as 20 alarm messages. After this limit has been reached, the next new message is written over the oldest one. To view the overwritten messages, the operator must transfer the alarm display to a different display device and then page through the old messages. As an alternative, the operator may print the list of alarm messages. These tasks are time consuming and may detract from other activities, such as reviewing other alarms, monitoring plant indications, and taking control actions to respond to the event. For this reason, operators may be reluctant to review the older alarms until after the plant has been stabilized. As a result, some alarms may not be seen by the operators because they cannot keep pace or because too much effort is required to access the alarm information. This can affect the operators' awareness of plant conditions and affect their ability to respond promptly.

Another problem is that operators sometimes have difficulty retrieving information because they are not aware or may not remember that certain types of information can be accessed from the display system. Although the display system is addressed by training, there is usually too much information for an operator to remember every available display and variable. Operators rely on cues, such as menu options and dedicated buttons, to remind them of the types of available information and available retrieval paths. Operators have difficulty when an item is not frequently accessed and the relationship between the cues and the desired item are not apparent. For example, an operator may not associate a high-level menu option with a desired item that resides at a lower level. In such cases, operators at this plant must access supporting documentation to more clearly define the type of information desired and to identify a path to the information. For example, when troubleshooting equipment failures, operators sometimes need to retrieve displays that depict the electrical wiring or control logic. The path to such information may not be obvious from the display menu system. Sometimes operators retrieve paper P&ID displays to view plant systems and identify component identification numbers; then, they use the numbers to locate the appropriate display page in the network. Thus, the use of the P&IDs is an additional information retrieval process that is performed to support another retrieval process - selecting the right display from the display system. This process is time consuming and can delay operator response when diagnosing or correcting a problem with a plant system.

Nuclear Power Plant 2

In this HSI, plant information is provided through thousands of display pages which are viewed through a small number of CRTs. Thus, a considerable amount of interface management is required and the HSI has many ways to perform interface management tasks (See Appendix B). Based upon discussions with one of the principal HSI designers, it appears that the paths for selecting displays from computer-based HSIs may not always be clear - operators may be misled when trying to select displays. Once a display has been retrieved, the system may lack adequate cues for helping operators determine whether it is the appropriate one. During one reported simulation, an operator became disoriented in the display network for approximately 20 minutes. After he navigated to a particular display, a supervisor came to his assistance. Together they tried to figure out why the parameter values were as they were displayed. Neither realized that they were looking at the wrong display. This incident demonstrates how an interface management task, like trying to find a display, can interfere with the operator's primary task of controlling the plant. Presumably, while the operator was examining the wrong display and trying to find the right one, the operator's primary task of monitoring, diagnosing, and controlling the plant was neglected.

The HSI used soft controls for performing control actions. The interface management tasks required for control actions may impose additional demands compared to conventional control rooms. Rather than simply reaching for a control and operating it, an operator must retrieve a display that contains the desired variable, select the variable, access a separate display that contains the input field, provide the input, confirm it, and then monitor the plant response on possibly another display. This series of steps imposes sequential constraints on plant control. Only one variable can be accessed and operated at one time. The ability to rapidly switch from one control action to another or to view one controller while operating another is restricted by the types of interface management tasks that are required. Thus, these tasks places sequential limitations on the primary task.

Chemical Manufacturing Facilities

The three chemical plants visited in the facility had computer-based HSIs that ranged from about 2 to 10 years old. The HSI in each plant consisted of three consoles, which were each normally staffed by a single operator. Each console contained multiple CRTs.

Operators at each plant stated that during upset conditions, the level of workload associated with interface management is so high that at least one additional operator is needed at their console. The comment that "...a separate set of hands and eyes is needed" reflects the high level of interface management demands that are imposed on the operators. The absence of additional personnel at the console may result in the operator becoming data limited - the operator may not be able to access information that is needed and available.

Interviews with plant personnel also indicated a reluctance by some operators to initiate navigation of displays, even when workload levels are not high. At the beginning of the workshift, operators tend to retrieve a limited set of displays and arrange them on the display screens so they can be viewed with a minimal amount of interaction with the display system. Operators tend to rely on this set of displays rather than actively searching through the display system to identify anomalies in plant status.

Another example of reluctance to perform interface management tasks is the reported tendency of some operators to "operate by exception." Some operators wait until alarms occur before they interact with the plant. This strategy is not encouraged by plant management but indicates that some operators feel that they can perform more efficiently by correcting alarm conditions rather than carrying out interface management tasks to anticipate and prevent them.

Supervisors observed that in control rooms that have fewer VDUs, operators tend to become more dependent upon the alarm system for detecting problems in the plant.

Operators sometimes disregard or ignore alarms rather than investigate their causes, especially when they think they already know the reason for the alarm. In one reported incident that occurred in Plant B, an operator experienced a series of alarms but did not perform the display navigation tasks required to investigate their causes, apparently feeling that they were nuisance alarms. As a result, the operator failed to detect the early stages of a serious cascading failure. The condition was detected by an operator in the next workshift.

3.2.4.2 Cognitive Resources of Primary and Secondary Task Performance

Description

One of the secondary task effects summarized above is that the interface management and supervisory control tasks demand the same cognitive resources. For example, they both rely heavily on visual perception of stimuli, processing of symbolic data, and manipulation by hand of a limited set of input devices and formats. The relationship between the cognitive resources required of primary and secondary tasks can affect performance, specifically impacting the operator's ability to engage in dual task performance where attention is divided between primary and secondary tasks. For example, if the same cognitive resources are required for controlling the plant, then during periods of high demand, one task may suffer as resources are directed to the other. However, if different cognitive resources are required for these two tasks, then it is less likely that one task will interfere with the other and overall operator performance may be enhanced. Thus, a better assessment is needed of these resources and the role of decoupling the resources required for primary and secondary task performance. For example, shifting interface management tasks to take advantage of resources that are less in demand, such as using speech input to accomplish navigation, may facilitate dual task performance.

Findings

The site visits indicated that operators often must use many of the same cognitive resources when diagnosing plant condition (a primary task) and trying to determine why a selected displays does not seem to be the right one (a secondary task). Both tasks rely on the ability of the operator to sense and process visual data including text and graphics. Thus, the primary and secondary tasks may compete with each other. In each of the sites, the alarm system was cited as posing particularly high interface management demands during abnormal and upset conditions. Demands for accessing and viewing alarm information completed with the task of analyzing and using that information. At NPP 1 and the chemical manufacturing plants, operators assigned specific displays to particular VDUs at the beginning of their workshift to prevent interface management tasks from detracting from their ability to monitor the plant. They chose to restrict the number of displays that they would routinely monitor in order to prevent the navigation tasks from detracting from their monitoring task.

Unfortunately, we were not able to observe situations where the cognitive resources required for the primary and interface management tasks were less tightly coupled. Such a condition would have allowed comparisons to be made with the observed conditions and may have allowed performance effects to be assessed.

3.2.4.3 The Relationship Between the Keyhole and Display Area

Description

The keyhole effect has been identified as a root cause of many of the performance challenges associated with interface management. The keyhole effect exists because of the large number of displays that may occur in a display network and the limited display area provided by a VDU (and perhaps group-view displays, as well). In addition to the interface management burden of navigating and retrieving many displays, operators have commented that they have difficulty obtaining an overview of the plant situation. Loss of situation awareness may be a consequence of the keyhole effect, in addition to increased demands for navigating the display system. Thus, a better identification of the difficulties associated with the keyhole effect is needed.

A question that is fundamental to HSI design reviews is "How can or should the necessary number of VDUs be determined?" In the authors' experience with both NRC design reviews and design efforts, the number of VDUs is usually determined long before the information content of the display system been designed. No practical guidance appears to exist for determining the needed amount of display space. For example, even simple heuristics, such as the ratio of display screens to display pages do not appear to be used. Instead, the design decision tends to be driven by factors that are not directly related to the information needs of the operator, such as the size of the control console. Given the problems associated with the keyhole effect, there does not seem to be adequate consideration of the display area that will be required in a CR to support crew operations under high workload conditions. Thus, a frequent complaint of operators is that they need additional VDUs in their CR.

The effect of the keyhole and its relationship to the number of VDUs needs to be investigated further. The rationale for determining the display area needs further examination. Consideration of the two issues should lead to guidance for reviewing this performance concern.

Findings

The number of VDUs was clearly a concern at the chemical manufacturing plants. In Plant B, each operator console was equipped with four CRTs - typically, two for presenting process displays and two for showing trend displays. Due to the limited number of display screens, the operators at each console monitor plant process alarms via summary displays, which give the status of groups of variables rather than each variable individually. This was considered a contributing factor in an incident in which an operator failed to detect a cascading plant failure. Had there been additional VDUs, the alarm variables could have been viewed directly, rather than as summary displays, and the operator might have detected the failure sooner.

In Plant A, each operator console had twice as many VDUs as those in Plant B. However, a senior operator said that more were needed to handle upset conditions. While there are plans to increase the number of VDUs at that console from eight to ten, the operator would like an increase to 14 VDUs. This would allow some VDUs to be used to continuously present key displays, while other VDUs are used for retrieving displays that are used intermittently.

The current number of VDUs in Plant A also was considered a limiting factor in the ability of the operator to resume tasks after an interruption. When a task is interrupted by another, the operator must access additional display pages. This may cause the displays associated with the first task to be removed from a VDU. After the interrupting task has been dealt with, the operator sometimes has difficulty recalling which task was suspended. In a conventional, hardwired control room an operator may be able to use a variety of spatial cues to recall the suspended task, such as remembering where he was standing at a control panel when he performed that task. Such cues may not be present in a computer-based HSI. However, operator recall may be supported by providing additional VDUs for suspended tasks or providing a historical record of displays retrieved from each VDU.

Evidence of insufficient VDUs was not found in NPP 1. However, this HSI had spatially dedicated, hardwired controls, which were used for most control actions. A much smaller number of control actions were accomplished using soft controls. Thus, most control actions did not require display navigation. In addition, the spatially dedicated, hardwired controls gave constantly visible indications of the status of plant systems. Thus, the keyhole effect for this HSI was apparently less of a constraint than it was in the chemical plants.

The issue of the number of VDUs was not specifically addressed at NPP 2. However, this HSI required the use of multiple VDUs for controlling the plant, whereas the chemical plants allowed monitoring and control from the same VDU. Thus, the need for multiple VDUs in NPP 2 could exacerbate the keyhole effect. The HSI at this plant included a wall panel display that provided an overview of plant status and the values of key parameters. Thus, it tended to compensate for the keyhole effect associated with the CRT displays (see Appendix B). Perhaps most interesting about this plant was the large number of display pages relative to the number of available VDUs. However, we do not know how the operators use the variety of display devices during operating conditions and whether the number of VDUs is sufficient.

3.2.4.4 Flexibility versus Performance Tradeoff

Description

In addition to the keyhole effect, flexibility of the HSI was identified as another root cause of many of the performance challenges identified in this report. The management and manipulation of flexible user interface features requires cognitive resources that operators may not want to divert from the primary task. Additional research is needed on the tradeoff between HSI flexibility and interface task demands. Design approaches that preserve HSI flexibility at a low cognitive cost may enable the advantages of flexibility to emerge. For example, the use of automatic display configuration may provide operators with sets of displays that are better tailored to plant conditions than if they retrieved the displays and configured their workstation themselves. In general, additional research is needed to provide guidance on strategies to enable operators to minimize interface management workload while taking advantage of computer-based HSIs.

Findings

During the development of NPP 2, the designers of this HSI originally intended to provide a large set of interaction methods and then reduce that set based on the results of testing with operators. However, the tests indicated that the preference of operators toward interaction methods varied greatly. Further, the same operator may prefer different dialog methods under different circumstances. It was recognized that operators do not tend to use all the flexibility of the interface management techniques that are available through the HSI, but instead adopt specific strategies. These results are consistent with the observation that operators may be reluctant to explore the full range of flexibility provided by the user interface, but instead select a narrower set of stereotypical methods for interacting with the display system.

NPP 1 did not provide the type of flexibility that was addressed by this issue.

Interviews with operators at Plant A indicated that flexible features can introduce new opportunities for error. Operators rely heavily on the use of trend displays when monitoring plant status. Some trend displays can be configured by the operator. For example, operators can select plant variables, ranges, scales, and time intervals and then save these characteristics so the display can be viewed again in the future. Difficulties have occurred when operators modified or deleted plots that had been created by other operators. This introduced the possibility that an operator may use a operator-configured display without realizing that it had been modified by another operator. This may result in operators making improper conclusions about plant condition and, as a result, performing improper control actions or failing to take needed ones.

3.2.4.5 Mental Models and Display Organization

Description

It is known that well-developed mental models are needed for accurate situation assessment and good performance. These mental models help improve performance by enabling the HSI to be predictable and enabling operator performance to become less effortful and more guided by expectations. A key in the ability of operators to perform interface management tasks effectively is their mental model of the organization and behavior of the HSI. While the design approach of organizing controls and displays around plant systems may have been adequate for conventional CRs, it may pose difficulties in computer-based CRs. For example, a system-based organization may be rather easy to understand, but may lead to excessive display retrieval actions during actual use when the system-based organization of displays does not match operator task requirements (e.g., tasks require interactions with displays and controls from multiple systems). Alternative models have been proposed but their acceptability is not known. Research is needed to address the issue of organizing a display that leads to an acceptable interface management workload so that operators can easily retrieve the information they need for acceptable primary task performance.

Findings

In NPP 1, the organization of the display network reflects the functional organization of the plant. Operators used this organization during the walk-through exercises. However, in some cases, the organization of the information may not be consistent with the operator's mental model. In the absence of a good model to guide interaction with the HSI, operators have difficulty locating detailed information that is not used frequently. In more significant instances, operators cannot determine from the HSI whether specific information is included in the display system.

Similar findings were obtained in NPP 2, which used the organization plant systems as a model for organizing the process displays. The situation described earlier regarding the operator who became disoriented in the display network for approximately 20 minutes may be an example of this issue.

The display systems at chemical manufacturing Plants A, B, and C are arranged to reflect the physical structure of the plant. The display network is organized into sections which reflect specific stages of the chemical production process. Each operator console is responsible for an area that includes several sections. In Plants A and C, the top-level display for each section is a mimic display. Operators can point to plant components depicted in these mimics and retrieve more-detailed displays or retrieve display windows for control inputs. This arrangement of the display system appeared to be consistent with the operators' understandings of the plant. Operators were very familiar with the high-level mimic displays for each section. One reason is that field operators use these same mimics when learning about plant and operating equipment locally in the plant. They are required to draw these mimic diagrams from memory before they can be promoted to control room operators. Thus, the top-level displays for each major branch of the display system is consistent with the operators' understanding of how the plant is structured.

The ability to select detailed displays by pointing to icons on these mimic displays appears to be superior to other methods provided. Operators stated that the alternative method of recalling the identification number of a display and then pressing a dedicated button or typing the code via a keyboard imposed higher cognitive demands on them. Plants A and C allow display retrieval both through the mimic displays and the display identification numbers. However, in these plants the operators directly select from the mimic display almost exclusively for retrieving displays.

A senior operator at Plant A stated that selecting controls via a mimic display also had advantages compared to conventional analog control rooms. If an analog control panel did not have a mimic diagram superimposed on it, then the operator would have to remember the relationship between individual controllers and the rest of the control system. That is, he would have to remember which system and train the control belonged to. He also would have to remember how the plant component, which is operated by the controller, relates to the other components in the system. By contrast, less mental workload is associated with using the mimic displays because these relationships are depicted in them and do not have to be recalled from memory.

3.2.4.6 Role of Conventional and Computer-Based HSIs

Description

We noted earlier that operators may prefer conventional HSIs under high workloads. It has also been the authors' observation that there is usually a migration toward the inclusion of more and more conventional equipment into CRs that start out being based completely on advanced technologies. This observation also was made by others (e.g., Heslinga and Herbert, 1995).

It is possible that the desire for conventional HSI technologies reflects a preference for the types of display and control designs (such as gauges and J-handles) that are available. Perhaps more likely, it may be that the characteristics of spatially-dedicated, parallel presentations of controls and displays are more appropriate to plant control tasks than those of non-spatially dedicated, flexible, virtual controls and displays. Research is needed on the relative role of conventional and computer-based HSIs and the design characteristics that are important to these preferences.

Findings

NPP 1 is about ten years old and has a hybrid design. It features many characteristics of conventional HSIs, such as a rather large spatially-dedicated main control panel, hardwired control devices, and spatially dedicated annunciator tiles. It also features more advanced features such as a computer-based display system. This mixture of conventional and more computer-based HSI technologies is the result of the state of the art of HSI design when the plant was designed.

In NPP 2, the design of this plant has changed over its development to include an increasing number of conventional HSI technologies. For example, more hardwired, spatially dedicated control devices were provided. These more conventional technologies were added to either augment the use of VDU-based controls and displays, or to serve a backup role in the event of VDU failures.

While the HSIs in the chemical manufacturing plants did not include conventional HSI technologies, walk-through exercises and interviews with operators indicated that operators employed spatial dedication strategies when assigning displays to specific display screens. This strategy reflects the spatial dedication characteristic of conventional HSIs. Operator comments indicated a desire for additional VDUs, which would allow further spatial dedication of displays.

3.2.4.7 The Effects of HSI Design Features on Interface Management Task Performance

Description

We noted earlier that the detailed design of HSIs affects interface management task performance. A set of issues that address specific aspects of HSI design were identified that focus on the interface management, as well as, the relationships between multiple HSI components in a CR. Further, the overall focus of these issues would be to reduce interface management workload while maintaining high HSI situation awareness.

Findings

The following is a brief discussion of human performance considerations associated with specific HSI features used for interface management. Comparisons are made between HSI features used at the various facilities that were visited.

Command Language Interfaces

The use of command language interfaces at the chemical manufacturing plants to retrieve displays resulted in difficulties accessing the correct display. In Plant B, operators are required to remember the three-digit code identification number. Problems appeared to be related to the number of displays that had to be remembered (approximately 25 to 35), the fact that the codes were not highly descriptive because they were in numerical rather than text form, and the fact that they had to be typed on a keyboard. Operators indicated that they preferred to press the dedicated buttons for retrieving displays rather than using the keyboard to type the three digit code. The dedicated buttons required a single press while entering the display code required four presses (three number keys plus an Enter key). Chemical Plants A and C also provided a similar capability, but it was seldom used by operators because other, less demanding display retrieval methods were available. It is interesting that NPP 2, which contains nearly 10 times as many display pages as any of the chemical manufacturing plants, also has a command language interface for display retrieval. The display system for NPP 2 requires operators to enter a nine-digit, rather than a three-digit code to retrieve a display. The limited command language interface was found to be somewhat undesirable at the chemical plants. However, tests conducted during the design of NPP 2 found this to be an acceptable display retrieval method. The parameters that define the acceptability of command language interfaces for display retrieval need to be identified.

Menus

As mentioned earlier, operators at NPP 1 sometimes have difficulty retrieving detailed displays that are not used frequently. The menus may not provide adequate guidance for these items. As a result, operators are sometimes not aware (1) that some types of information are available from the display system, or (2) how to access some types of information from the display system. For example, when troubleshooting equipment failures, operators sometimes need to retrieve displays that depict the electrical wiring or control logic. The path to such information may not be obvious from the display menu system. Sometimes, operators must retrieve paper P&ID drawings to view plant systems and obtain component identification numbers to help them identify the relevant VDU displays. This shift between VDU and paper drawings is time consuming and can delay operator response when diagnosing or correcting a problem with a plant system.

Dedicated Buttons

Dedicated buttons are used as a primary method for retrieving key displays in NPP 1. Each of the VDUs has a keyboard with dedicated buttons for assessing particular displays. Approximately 25 to 35 buttons are provided at each VDU for accessing key displays; the set of displays is specific to each VDU. They are used by operators without any apparent problems. However, in chemical manufacturing Plant B, operators also used approximately 25 to 35 dedicated buttons to access displays. Problems with remembering and selecting the correct button were noted (see discussion of command language interface, above).

Use of Windows and View Arrangement Features

Three different methods were identified for providing control input fields. In chemical manufacturing Plant C, control actions were performed by pointing to a component on a mimic display. The point action caused a special input window, called a faceplate, to be displayed. The faceplate overlapped and partially obscured the mimic display. To avoid this window management problem, NPP 2 uses a separate VDU to display the input field. Thus, one VDU is used to select the plant variable and a second is used to enter input values. However, this arrangement requires the operator to coordinate the use of two separate VDUs. In chemical manufacturing Plant A, control actions were made in a dedicated window, called a change zone, located at the bottom on the plant process display. Because this portion of the display is dedicated to the change zone, no window management tasks are required. However, the total available display space is reduced. Thus, more display pages may be needed to compensate for the reduced amount of space per display page. Thus, each method for providing input fields has some limitations and imposes demands on operators.

Global HSI Considerations

A wide variety of input methods are used in NPP 2. Different methods are used by people for different tasks. Thus, there are variations in the use of interaction methods both between users and across tasks for individual users. Designers have expressed concern that excessive interaction methods may have negative effects on operator performance. However, it is not clear when diversity becomes excessive.

3.2.4.8 Conclusion

Based on the information obtained in the site visits, the following conclusions are made:

- The dual-task effects of interface management are supported. Situations were reported in which interface management tasks and primary tasks imposed competing demands upon the cognitive resources of operators. Operator performance was negatively affected by the failure to perform interface management. In addition, reluctance to engage in interface management tasks was reported, even during low workload.

- Evidence was obtained of primary and secondary tasks competing for the same cognitive resources. However, the potential benefits of decoupling the primary and interface management tasks (i.e., using HSI components that required different cognitive resources that the primary tasks) could not be assessed.

- Evidence for this issue was found in the chemical plants which relied heavily of a limited set of CRTs for accessing plant displays and executing control actions. There was no specific evidence of this problem at NPP 1, which featured many spatially dedicated, hardwired controls. This issue was not addressed at NPP 2.

- Some evidence of the negative aspects of HSI flexibility was observed in the site visits. In addition, positive aspects of flexibility were observed. Thus, questions remain about how much flexibility is enough, how much is too much, and how designers can get users to use those HSI capabilities that can help primary task performance.

- Mimic displays are less cognitively demanding method for selecting displays than other methods, which required operators to remember the identification codes for individual displays. However, results were conflicting regarding the effects of arranging the displays based on plant systems and the physical structure of the plant. While operators at the NPPs encountered some difficulties, operators at the chemical manufacturing plants did not appear to have problems. This may be related to the increased complexity of the NPP display system, relative to the chemical plants. However, alternative display organizations, such as a task-based organization, were not observed during the site visits. Thus, no comparisons to system-based organizations could be made.

- Spatial dedication, rather than the type of interface technology (e.g., gauges and J-handles), is important to operators. Operators at the chemical manufacturing plants, including those who had experience in conventional plants with hardwired controls, did not express any desire to return to older HSI technologies. However, the design of NPP 2 has been modified to provide a greater degree of spatial dedication for control devices. In the chemical manufacturing plants, operators tended to introduce spatial dedication through the arrangement of displays on the VDUs.

- Specific interface management problems that were identified for specific HSI technologies in the earlier chapters of this report were confirmed. These findings suggest that additional guidance may be needed to address the application of these HSI technologies to NPP operation, especially for interface management concerns.

3.2.5 Analysis of Interface Management Tasks Based on Information from Subject Matter Experts

Interviews were conducted with SMEs involved with the systems employing computer-based HSIs. The interviews were an effort to identify interface management effects and concerns based on the design and operations of actual systems. The results of the interviews are summarized in the following topics: display navigation, general-purpose versus functionally dedicated display devices, operator-configurable displays, window management, input interfaces and devices, and general guidelines and standards.

3.2.5.1 Display Navigation

Display navigation is a recognized concern in many domains such as process control, medical devices, and information systems, such as those used by financial institutions. All interviewees acknowledged that display navigation was an important HSI design consideration. Five symptoms of navigational difficulty, which had consequences ranging from minor to very severe, were discussed:

- getting lost
- not finding needed items
- navigation errors (e.g., going to the wrong display)
- delays and inefficiencies in accessing information
- poor usability and operator frustration

Getting lost was defined as not being able to determine one's location in the display system. It was described by one HF engineer from an NPP vendor as the worst-case scenario. None of the individuals interviewed indicated that this problem was typical, which may be consistent with the observation that the negative effects of interface management occur when workload is high, such as during a process disturbance. Users are usually able to determine their location or move to a familiar display. The manager of a user interface design organization for a financial institution stated that, in some systems, knowing one's location in the display network may not be necessary for accessing the next desired location, but it may be important for interpreting the displayed information. Some characteristics of the displayed data are determined by its location in the display network.

Another significant concern was that users may be unable to find needed displays or they may access the wrong one because of inadequate or misleading navigation cues. One problem was that menu titles are not sufficiently descriptive or are misinterpreted by users. Another problem was that organization of the display network or the content of individual display pages does not match user expectations. As a result, the user looks for items under the wrong headings. These problems may occur when the designer's understanding of the system is different from that of the user. Detailed below are three examples of display navigation problems.

- *Difficulty in Developing Awareness of Overall Plant Status* - A training instructor from a foreign NPP that used an extensive set of CRT-based plant displays stated that operators sometimes have difficulty in developing an awareness of overall plant status. Factors that contribute to this problem include (1) the quantity of information that is provided by the display system, (2) the number of display devices, and (3) the number of individual displays. The problem was worse in upset conditions in which plant status changes quickly. Operators must develop skills for quickly extracting status information from the HSI. The instructor stated that he knows that an operator is having trouble following a plant trip in a training scenario when he sees the operator paging through the display hierarchy, rather than looking at the dedicated displays. In this case, the operator is usually lost in the detailed information of a plant subsystem rather than developing an understanding of overall status.

- *Difficulty in Finding Detailed Displays* - One SME indicated that operators sometimes have difficulty retrieving detailed displays that are not used frequently. For example, when troubleshooting equipment failures, operators sometimes need to retrieve displays that depict the electrical wiring or control logic. The path to such information may not be obvious from the display menu system. Rather than expend the effort to search for the displays, the operators will retrieve paper P&ID displays to view plant systems and obtain component identification numbers. These identification numbers then are used to locate the appropriate display page in the network. This process is time consuming and can delay operator response when diagnosing or correcting a problem with a system. In chemical plants with computer-based HSIs, operators can encounter problems retrieving displays that provide detailed information on alarms. For example, a human factors consultant stated that when an alarm occurs, the operator must identify the nature of the alarm, determine where detailed information resides in the display system, and then access it. In some display systems, operators must access these displays by entering a display identification number via a keyboard. Difficulties in retrieving detailed information can occur when the operator is unable to determine where to find this information in the display network (i.e., which of the displays relate to a particular alarm), or is unable to recall the code for accessing the desired display.

- *Difficulty in Achieving Rapid Access to Critical Information* - An anesthesiologist stated that there has been an increasing use of windowing and display capabilities in medical devices such as those used to monitor patients in operating rooms. One recent development is a dedicated button which returns the device to a standard display that depicts the most important monitored variables. Another trend is toward providing additional display devices (e.g., two displays for monitors which have traditionally contained only one). This allows the primary display screen to be dedicated to the most critical variables, while other screens are used for less critical information. It is suspected that many of the features of computer-based medical devices are underutilized due to problems with navigation.

One human factors consultant stated that limited screen space was a serious problem in chemical facilities with computer-based HSIs. As a result, the display system may hide important information from operators and may cause two problems. First, operators may not access information because they are not aware that it exists. Second, operators may be aware that new information exists but they do not retrieve it because they assume that they are already aware of the information content. For example, operators may be aware that an alarm has sounded but they do not retrieve supporting information from the display system because they attribute the alarm to the wrong cause. Important information may be missed if the operator is required to access it from the display system before viewing it. For example, some display systems feature alarm summary displays that provide a single indication for a group of displays. These displays typically provide indications when one or more of the variables enters an alarm state, but may not identify the particular variables involved. Instead, additional display navigation may be required to make this determination. The failure of operators to detect alarms or obtain additional information from the display system has resulted in serious damage to some chemical plants.

A good example of this issue was provided by an HFE consultant. Operators of a foreign NPP were unaware of new alarm information because it was not visible in the limited viewing space of a computer-based display system. In 1984, operators at an advanced gas-cooled reactor station failed to respond when computer-based data and alarm displays registered higher than average temperatures in fuel channels. Operators missed alarms in two channels. Computer scans one-half hour later highlighted the abnormality and the reactor was shutdown manually. The original alarms appeared on two VDU screens on the unit operator's desk. The alarms were presented as text lists, about 24 per page, on a monochrome VDU. There were no annunciators. Because of the number of standing alarms, it seems that the key high temperature messages scrolled off the screen without being noticed. As a result of this event and the subsequent investigation, the plant underwent a large scale refurbishment and enlargement of the HSI. This example illustrates problems that can result from a scrolling display. However, information may be hidden by other features, such as displays that have not been retrieved or overlapping display windows that obscure important information.

Another factor affecting navigation is poorly organized display networks. Personnel from NPP vendor organizations indicated that the number of display pages in their display networks numbered in the several hundreds and even thousands for new plant designs. Display pages were generally organized according to plant systems (e.g., primary coolant) and functions (e.g., safety injection). A human factors consultant to the chemical industry stated that many display systems are not well organized. The organization of both the display pages and the display network reflects the arrangement of plant equipment, rather than the requirements of operator tasks. Often, display pages are arranged linearly rather than hierarchically. When performing a task, such as starting a set of pumps, it may be necessary for operators to access one display for each piece of plant equipment rather than a single display that addresses the whole task. As a result, operators may have to make rapid transitions between displays to access needed information. In addition, the linear arrangement of display pages may require operators to access more displays than necessary because they tend to search sequentially through the set of displays rather than accessing a desired display directly. This increases cognitive workload. During periods when workload is already high, such as upset conditions, the demands on operators to access displays and integrate information across displays can detract from the mental resources needed to diagnose plant condition and develop responses. In addition, the time required to perform interface management tasks can delay operator response.

Designers stated that they generally tried to provide multiple paths to information locations. The availability of multiple paths was considered an asset. One human factors engineer from an NPP vendor stated that by making navigation paths more flexible and less strict, designers were able to reduce the need for operators to know where they are in the display network. For example, the display network has six to eight major branches with about 50 displays within each branch. The display system essentially has four levels: a menu display which depicts the branches, mimic displays for each of the major branches, display pages which support the mimic displays, and detailed information which supports the display pages. Operators can use the menu to move from any display page to any one of the major display network branches. This reduces the length of the navigation path to the destinations. The engineer stated that hypertext is being considered for computer-based procedure systems that will incorporate real-time plant data for the plant variables addressed by the procedure steps.

Techniques to help users determine their location in the display network or select new locations include providing a display menu and an overview display depicting the structure of the display network. In some display systems, portions of the display menu appear in a window in the display pages. A manager of a user interface design organization for a financial institution stated that the introductory display is usually designed to indicate the overall arrangement of the display network. For example, a tab folder metaphor may be used in which large and small tabs indicate the first two levels of the display network.

The tradeoff between display density and display network navigation was an important concern. By distributing information over many displays, designers may achieve less dense displays (usually considered a good design characteristic); however, users may be required to navigate between these individual displays. By increasing the amount of information in the display pages, designers can reduce the need to navigate between individual display pages, but this may result in displays that appear more cluttered. One approach to handling display density was the use of zoom capabilities. The zoom capability described by an NPP HSI design engineer could change both the level of magnification and the content of the display. In some cases, zooming-in increases the size of the material in the viewing area. In other cases, zooming-in replaces the display with one that contains information at a different level of abstraction. The zoom capability described by the manager of a user interface design organization for a financial institution changed the information content of the display.

3.2.5.2 General-Purpose versus Functionally Dedicated Display Devices

The tradeoff between general-purpose and functionally dedicated display devices was discussed. The former are used to access a broad variety of displays. Functionally dedicated display devices are reserved for accessing specific displays or controls. They can support rapid monitoring and control actions because fewer navigation operations may be required to access the displays. The tradeoff is that such functionally dedicated devices require additional workstation space.

An HFE engineer from one NPP vendor organization stated that no firm rules exist for determining when functionally dedicated display devices should be provided, rather than general-purpose ones. Some factors considered in this determination include whether the control or display is important to safety or a critical plant function, and whether placing a control in a general-purpose display device will affect the operator's ability to promptly locate and operate the control.

3.2.5.3 Operator-Configurable Displays

Operator-configurable displays are display pages that can be modified by operators to address particular tasks or personal preferences. Personnel from two NPP vendors stated that their HSI designs include trend displays that operators can configure. For example, an operator may be able to select plant variables to be included in the trend plot and define axes and scales. Modifying the operator-defined displays should not be difficult. When asked about the possibility of an operator misinterpreting a trend plot because another operator had modified it, the personnel interviewed stated that these displays would be assigned to the work areas of individual operators. They felt that it is the assignment of displays to individuals that would prevent operators from modifying each other's displays.

A human factors engineer from another NPP vendor stated that the steps involved in establishing operator-configurable displays, such as entering identification codes for plant variables, were somewhat awkward. As a result, he thought that it was unlikely that operators would modify them frequently. Even though these displays may be shared by multiple operators, it was unlikely that an operator could modify one of these displays without the other operator being aware of the change because of the time and effort involved. It should be noted that this may reflect limits of the design and not that operator-configurable displays are inherently awkward.

3.2.5.4 Window Management

While most of the display systems for NPP applications used full-size VDU displays, windows-based systems are increasingly being used. However, the display systems used for financial information systems have different characteristics. Some have window management systems that automatically close windows when others are opened. A pushpin metaphor allows the user to designate the windows that should remain open, and they will not close until the user removes the pushpin. The user can change the size of the windows and reposition them. This task can be demanding when the user must manage a large number of windows on a single screen.

3.2.5.5 Input Interfaces and Devices

Displays were generally retrieved using menus or by direct manipulation of display icons via cursor motion or touch screen, and less frequently, by command language dialogues. Control inputs may be entered by several means. One human factors engineer from a foreign NPP vendor stated that control inputs, such as setpoint values, may be entered via the keyboard, a soft slider, or arrow keys. Two sets of arrow keys are provided: one set for large changes, and one set for small final adjustments. He stated that some operators use the slider for gross adjustments and the arrow keys for fine adjustments. Sharing two interface management techniques for one action is common. Another designer indicated that to select a display, operators will often use the keyboard to type part of the display title (which corresponds to a system identifier) that results in a display selection list on the CRT for that system. The final selection is made by pointing the cursor at the appropriate display.

Conflicts can occur between interfaces used for display selection and control input actions. In one non-nuclear plant that has a computer-based HSI, some plant equipment can be operated accidentally because of similarities in the methods used to access information and perform control actions. The HSI has a direct manipulation interface which operators manipulate via a trackball or touch screen. Displays are navigated by manipulating buttons or icons. Plant equipment, such as electrical breakers, can be operated by manipulating their display icons. For example, a breaker can be opened or closed by pointing to its icon. As a result, some plant equipment has been unintentionally operated by moving the cursor or touching the screen over the wrong icon. Even though operators know which icons can cause equipment operation, unintended operation still occurs occasionally.

3.2.5.6 Crew Training in HSI Use

Several of the SMEs noted that one problem crews face in using computer-based systems, especially in facilities that have modernized from conventional systems, is that training in the use of the HSIs is lacking and sometimes nonexistent. The complexity of the HSI design and operation is frequently not well understood by trainers. Many training departments focus on emergency response and the operational aspects of response planning and execution, and not on how the HSI works and what interface management strategies should or could be used in different situations.

3.2.5.7 General Guidelines and Standards

None of those individuals interviewed identified specific HFE handbooks or standards for designing navigation features. This is indicative of the lack of HFE guidelines addressing this topic. One NPP vendor is developing a document that describes their design approach for supporting interface management for their specific HSIs. Other NPP vendors have general design concepts for supporting display navigation, which they intend to validate when the design is complete. However, they do not have explicitly documented design guidelines on interface management.

3.2.5.8 Conclusions

Interface management effects were assessed based on the information obtained in these interviews with SMEs. The following significant points were discussed in this chapter:

1. Many of the same issues identified in the previous chapters were identified. In general, these were:

   - current computer-based systems have many displays and vast amounts of information that are viewed by the operators through a relatively limited display area

   - the limited display area requires considerable use of secondary tasks, especially display navigation

   - given limited display area, the flexibility of computer-based systems can both support operators, as well as, create opportunities for errors

2. The SMEs consider interface management to be an important consideration. One SME felt it was a serious concern because it affects the ability of operators to access information and controls needed for primary tasks. Accidental operation of plant equipment may occur if the actions required to control this equipment are not sufficiently different from those for performing interface management tasks, such as selecting display pages.

3. Primary task performance can be affected not only by the performance of interface management tasks, but also by the failure to perform them. Display system navigation methods can create barriers between operators and plant information even when the effort to retrieve information is not high. Operators may not access information if they do not feel that the information will be worth the effort to retrieve it. During periods of high workload, such as major transients, operators may decide to not access additional information because the retrieval effort may detract from their primary task of analyzing plant condition. Also, the selection of new displays may disrupt displays that are in use. In some cases, the operators may not access information because they do not know that it exists. Information may not be monitored if the operator forgets to retrieve it or has an incorrect understanding of plant condition.

4. Interface management problems can occur when the designer's understanding of the operators' information needs does not meet the operators' task requirements. Designers provide cues such as menus and display page layouts, to help users access information. If these cues are not consistent with the operators' understanding of the plant or the flow of their information needs,

then the operators may not know where to look for information or they may make errors when selecting displays. This can delay the operators in diagnosing failure or planning actions.

5. Operator training in the use and management of the HSI often is lacking.

6. SMEs recognized a lack of formal design guidance for interface management topics. This was also identified in site visits which revealed many different approaches to interface management (reflecting a lack of guidance, standards, or industry consensus).

4 THE EFFECT OF INTERFACE MANAGEMENT ON PLANT SAFETY

This chapter addresses the effects of interface management on plant safety. Although interface management tasks may affect primary task performance, it does not follow that this effect has an impact on plant safety. Therefore, a safety significance analysis was performed to examine this relationship.

The potential mechanism by which interface management tasks can impact plant safety is through their impact on human actions that are important to safety. If the types of effects discussed in the previous chapter lead to human errors in the performance of risk-important actions, then safety can be affected.

As was discussed in the previous chapter, human errors can be explained on the basis of a relatively small number of cognitive mechanisms. The error mechanisms typically relate to the human information processor's response to factors such as unfamiliar situations, high workload, and disruptions of ongoing actions. Under such circumstances, people use heuristics (information processing short cuts) to cope with the demands.

The interface management effects as discussed in the previous chapter provide the potential of increasing the likelihood of human errors, through a number of means:

- Risk-important actions can be directly affected by the tasks that operators are required to perform when engaging in interface management, such as by (1) delaying the completion of risk-important actions, (2) distracting the operator from important information needed to perform the risk-important actions, and (3) interrupting the task sequence for the performance of risk-important actions.

- Risk-important actions can be affected by a failure to perform interface management tasks. Possible reasons for this failure include (1) not being aware that important information is hidden from view, (2) knowing information is available, but, because it is hidden from view not knowing its importance or misinterpreting it, and (3) knowing information is available, but choosing not to retrieve it because of high workload or general reluctance to engage in interface management tasks. With respect to the latter, during periods of high workload, such as major disturbances, operators may decide to not access additional information because the retrieval effort may detract from the operators' primary task of analyzing the situation. Also, selecting new displays may disrupt ongoing risk-important actions or may interfere with current information being used.

- Interface management tasks can be performed incorrectly and lead to misinterpretations or errors such as operating the wrong control due to confusion resulting from a lack of spatial dedication.

- Similarity of HSI features that are used for risk-important actions and interface management tasks can lead to errors. For example, accidental operation of plant equipment may occur if the operator actions required to control equipment are not sufficiently different from those for performing interface management tasks.

Therefore, an evaluation was performed to determine whether there was a link between the performance effects identified for interface management and plant safety. The methodology and results are described below.

4.1 Methodology

The authors developed a safety significance analysis methodology in earlier NRC research addressing the potential safety significance of computer-based HSI technology in hybrid control rooms (O'Hara, Stubler, and Higgins, 1998). The methodology was based on an adaptation of the approach to digital upgrade safety evaluations that was developed by EPRI (EPRI, 1993) using the 10 CFR 50.59 process. The EPRI methodology was endorsed by the NRC in Generic Letter 95-02 (NRC, 1995). Since we completed this research, the NRC and industry have modified the technical approach to 50.59 evaluations. However, the generic approach of our evaluation in not affected by these changes .

The safety analysis methodology was successfully used in our earlier study and was considered by independent peer reviewers to be an appropriate method of analysis. Thus, it is an appropriate method for analyzing interface management. In brief, a subject matter review team performs an evaluation of a hypothetical plant modification that embodies the HSI technology and issues involved in interface management. The review team is guided in their evaluation by questions and evaluations that were adapted from the EPRI methodology.

The analysis methodology is described below. The discussion is divided in Interface Management Characterization, Review Team Composition, Evaluation Procedures. Additional detail regarding the method can be found in the cited document.

Interface Management Characterization

A hypothetical plant modification was developed based on the HSI characterizations for the sites visited (described in Appendices A, B, and C). The modification was based on features extracted from all three sites visited; it was not based on a characterization for one specific plant. The baseline configuration was a typical, conventional control room design and the plant HSI modification was a computerized display and procedure system with soft control capability. The characterization is provided in Appendix D.

Review Team Composition

The topic evaluation forms were completed by four subject matter experts (SMEs) in the areas:

- human factors HSI design
- NPP operations
- probabilistic risk assessment
- SAR analysis

Evaluation Procedures

The review team was briefed on the hypothetical plant modification reflecting the interface management characterization. They were then asked to evaluate the proposed modification using a set of questions adapted from the EPRI methodology. The questions are contained in Table 4.1. There are seven primary questions and several supplemental considerations that addressed specific characteristics of digital systems. The questions generally addressed (1) failure modes that are caused or aggravated by personnel actions, and (2) failure modes and equipment characteristics that have negative effects on personnel performance. The SME's were asked to indicate whether the response to each of the primary question is "likely" or "not likely" taking into account the supplemental considerations. The SME's were also asked to provide an explanation of their evaluations.

Following the evaluation of the seven primary questions, an overall assessment of whether the modification was "potentially safety significant" was made. An indication of "likely" to any of the primary questions, results in the identification of the modification as "Likely to be potentially safety significant."

The evaluation form was first completed by each evaluator independently, then the evaluators met as a group to discuss their assessments and arrive at a consensus. A final evaluation form was compiled.

Table 4.1 Evaluation Form

Analysis of the Modification:

1. May the proposed modification increase the probability of occurrence of an accident evaluated previously in the SAR? Supplemental considerations - Does the system exhibit performance characteristics that increase the need for operator intervention or increase operator burden to support operation of the system in normal or off-normal conditions? Could this increase the probability of an accident that was previously analyzed?

   Not likely __ Likely __

   Explanation:

2. May the proposed modification increase the consequences of an accident evaluated previously in the SAR? Supplemental considerations - Does the human-machine interface design introduce increased burdens or constraints on the operators' ability to adequately respond to an accident, for operator actions credited in the licensing basis, such that there are more severe consequential effects (e g , inability to access and operate more than one control at a time)?

   Not likely __ Likely __

   Explanation:

3. May the proposed modification increase the probability of occurrence of a malfunction of equipment important to safety evaluated previously in the SAR?

   Not likely __ Likely __

   Explanation:

4 May the proposed modification increase the consequences of a malfunction of equipment important to safety that was evaluated previously in the SAR?

   Not likely __ Likely __

   Explanation:

5. May the proposed modification create the possibility of an accident of a different type than any evaluated previously in the SAR?

   Not likely __ Likely __

   Explanation:

6. May the proposed modification create the possibility of a malfunction of equipment important to safety when the malfunction is of a different type than any evaluated previously in the SAR?

   Not likely __ Likely __

   Explanation:

7. Does the proposed modification reduce the margin of safety as defined in the basis for any technical specification?

   Not likely __ Likely __

   Explanation:

Overall Assessment of the Modification:

Likely to be potentially safety significant __
(Note: This line is checked if the answer to any of questions 1 to 7 is "Likely".)

NOT likely to be potentially safety significant __

4.2 Results

Overall Assessment of the Modification

The overall evaluation of the review team was that the modification was "Likely to be potentially safety significant." The reasons for this evaluation are provided in the discussions of the individual questions provided below.

Assessment of Question 1

The review team concluded that it was "likely" that the proposed modification could increase the probability of occurrence of an accident evaluated previously in the SAR.

The reasons provided for this evaluation were as follows. The characteristics of computer-based displays may impair the ability of operators to detect or maintain awareness of plant conditions that are important to plant safety. For example, the ability of operators to obtain an overall assessment of plant condition or to review alarms and other changing information may be impaired by the demands of interface management tasks. In addition, prompt access to, and use of, needed controls and plant process, alarm, and procedure displays may be impaired by the demands of interface management tasks. These factors may affect the ability of operators to properly plan and execute actions in response to plant transients and may result in the increased probability of accidents typically evaluated in a SAR. Also, the lack of situation awareness resulting from interface management demands may cause operators to take actions that are inappropriate for the true condition of the plant. Thus, an increase in operator burdens associated with interface management tasks during normal or off-normal conditions may increase the probability of accidents typically evaluated in a SAR.

Assessment of Question 2

The review team concluded that it was "likely" that the proposed modification could increase the consequences of an accident evaluated previously in the SAR.

The reasons provided for this evaluation were as follows. The three primary characteristics of computer-based HSIs (i.e., high information volume, virtual workspaces, and HSI flexibility) may impair the ability of operators to properly determine plant conditions during an accident. For example, operators may improperly assess the plant condition because they cannot keep pace with the interface management tasks of reading and analyzing rapidly changing information from the alarm system and plant displays. Improper situation awareness may lead to inappropriate responses, such as operators taking actions that are not appropriate for plant conditions or failing to take needed ones. Thus, this may increase the consequences of those accidents evaluated in the SAR that require operator diagnosis and timely response. (Note that failure modes, such as software common cause failures, were not considered in this response because a direct link to the interface management tasks of operators has not been established.)

Assessment of Question 3

The review team concluded that it was "likely" that the proposed modification could increase the probability of occurrence of a malfunction of equipment important to safety evaluated previously in the SAR.

The reasons provided for this evaluation were as follows. The three primary characteristics of computer-based HSIs (i.e., high information volume, virtual workspaces, and HSI flexibility) may impair the ability of operators to detect and properly respond to abnormal conditions (e.g., plant variables that are behaving unusually or trending toward an undesirable state). In addition, inappropriate organization and presentation of plant data may cause operators to misunderstand the importance of information or the relationships between such information. This may lead to an improper assessment of plant conditions. The failure to properly detect, interpret, and respond to abnormal conditions may result in damage to plant equipment that is important to safety. Thus, this issue may increase the likelihood of a malfunction of plant equipment that is important to safety that was evaluated previously in the SAR.

Assessment of Question 4

The review team concluded that it was "likely" that the proposed modification could increase the consequences of a malfunction of equipment important to safety that was evaluated previously in the SAR.

The reasons provided for this evaluation were as follows. As stated in the response to Question 3, three primary characteristics of computer-based HSIs may impair the ability of operators to detect and properly respond to abnormal conditions (e.g., plant variables that are behaving unusually or trending toward an undesirable state). In addition, inappropriate organization and presentation of plant data may cause operators to misunderstand the importance of information or the relationships between the information displayed. This may lead to improper assessment of plant conditions. The failure to properly detect, interpret, and respond to abnormal conditions may increase the consequences of a malfunction of equipment important to safety that was evaluated previously in the SAR.

Assessment of Question 5

The review team concluded that it was "not likely" that the proposed modification could create the possibility of an accident of a different type than any evaluated previously in the SAR.

The reasons provided for this evaluation were as follows. Human performance problems associated with interface management tasks in computer-based HSIs may impair the ability to personnel to detect important indications of plant condition and to plan and promptly execute appropriate responses. Also, the lack of situation awareness that may result from interface management demands may result in operators performing actions that are inappropriate for the true condition of the plant. However, it is unclear where these factors could create the possibility of an accident of a *different type* than any evaluated previously in the SAR.

Assessment of Question 6

The review team concluded that it was "not likely" that the proposed modification could create the possibility of a malfunction of equipment important to safety when the malfunction is of a different type than any evaluated previously in the SAR.

The reasons provided for this evaluation were as follows. Human performance problems associated with interface management tasks in computer-based HSIs may impair the ability to personnel to detect important indications of plant condition and to plan and promptly execute appropriate responses. Also, the lack of situation awareness that may result from interface management demands may result in operators performing actions that are inappropriate for the true condition of the plant. However, it is unclear where these factors could create the possibility of an equipment malfunction that is of a *different type* than any previously evaluated in the SAR.

Assessment of Question 7

The review team concluded that it was "likely" that the proposed modification could reduce the margin of safety as defined in the basis for any technical specification.

The reasons provided for this evaluation were as follows. Acceptance limits are reviewed and approved by the NRC as part of the licensing basis of a NPP. The margin of safety is considered to be the range above the acceptance limit and below the design failure point or system limitation value. The margin of safety is reduced when the acceptance limit is exceeded or the design failure point or system limitation value is reduced. Changes in the display system were not considered to have a direct bearing on acceptance limits of plant parameters. (Those cases in which interface management demands may result in improper operator responses, which may negatively affect plant status, already were discussed in Question 2, 3, 4 and 5.) Likewise, changes in the display system do not directly affect the design failure point or system limitation values. Thus, it was considered unlikely that changes in HSI technology and the resulting interface management demands would reduce the margin of safety as defined in the EPRI (1993) document. (Note that the HSI and the I&C system failures and their effects upon plant systems were not considered in this response. These failures are only considered when they result from personnel actions or impose specific interface management demands.)

4.3 Conclusion

The results of the safety evaluation indicated that the plant modification reflecting interface management issues was "likely to be potentially safety significant." That is, if HSI systems are not adequately designed and implemented, interface management effects may increase the probability or consequences of an accident or a malfunction of equipment important to safety.

Such an evaluation does not mean that the types of plant modifications represented by the characterization are *necessarily* unsafe. It means that its human performance concerns associated with interface management have the potential to compromise plant safety and, therefore, should a review of such a modification be necessary, HSI review guidance addressing interface management will be needed by NRC staff to help ensure that the modifications do not compromise safety.

5 HUMAN PERFORMANCE ISSUES

Based on the information reviewed in the previous chapters, several human performance issues related to interface management were identified. From a research standpoint, issues reflect topics that will require additional investigation to resolve. From a review standpoint, issues reflect aspects of design that will have to be addressed on a case-by-case basis, e.g., using design-specific tests and evaluations. These issues were used to help develop the Technology-Specific, Design-Process Review Guidelines described above.

The Relationship Between Interface Management and Primary Task

Additional research is needed on the effects of interface management on supervisory control performance in NPPs. Several human performance effects addressing dual-task performance were identified, and support was found for them. However, two basic questions remain unsatisfactorily answered:

- How much time and cognitive resources can be taken from the primary task by the secondary task before primary task performance becomes affected?
- How well can the primary task be performed if interface management tasks are not performed?

A further question is: *When do operators shift between resource-limited and data-limited strategies when dealing with changing plant conditions?* Under what conditions do operators decide to abandon interface management tasks, and when do they decide that some interface management tasks again are needed? In general, a better understanding of how operators manage or regulate their workload and make performance tradeoffs, especially during complex process disturbances, is required as a technical basis to address the performance limitations of computer-based HSI systems. As a corollary, it is important to identify the strategies operators adopt to minimize the demands of interface management tasks, such as decreasing the inherent flexibility of the HSI, enhancing its appearance and behavior, and increasing the simplicity of its configurations. A related consideration is how to measure the use of these strategies and their effects on plant performance.

Cognitive Resources of Primary and Secondary Task Performance

One of the root causes for the secondary task effects summarized above is that the interface management and supervisory control tasks demand the same cognitive resources. For example, they both rely heavily on visual perception of stimuli, processing of symbolic data, and manual manipulation of a limited set of input devices and formats. The relationship between the cognitive resources required of primary and secondary tasks can affect performance, specifically impacting the operator's ability to engage in dual-task performance where attention is divided between the two types of task. For example, if the same cognitive resources are required for controlling the plant, then during periods of high demand, one task may suffer as resources are directed to the other. However, if different cognitive resources are required for them, then it is less likely that one task will interfere with the other, and overall operator performance may be enhanced. Thus, a better assessment is needed of these resources and the role of decoupling the resources required for primary and secondary task performance. For example, shifting interface management tasks to take advantage of resources that are less in demand (for example, speech as a navigational input) may facilitate dual-task performance.

The Relationship Between the Keyhole Effect and Display Area

The keyhole effect was a root cause of many of the performance challenges identified in this report. The keyhole effect exists because of the limited display area provided by the VDU (and perhaps group-view displays as well). In addition to the sheer burden of navigating and retrieving many displays, operators commented that they have difficulty obtaining an overview of the plant situation. Loss of situation awareness and the big picture may be consequences of the keyhole effect, in addition to increased demands for navigating the display system. Thus, a better definition is needed of the difficulties associated with the keyhole effect.

A question that is fundamental to HSI design reviews is "How can or should the necessary number of VDUs be determined?" In the authors' experience with both NRC design reviews and with other design efforts, the number of VDUs is usually determined long before the information content of the display system has been designed. No practical guidance appears to exist for determining the needed amount of display space. For example, even simple heuristics such as the ratio of display screens to display pages, do not appear to be used. Instead, the design decision tends to be driven by factors that are not directly related to the information needs of the operator, such as the size of the control console. Given the problems associated with the keyhole effect, there does not seem be adequate consideration of the display area that will be required in a CR to support crew operations under high workload conditions. Thus, a frequent complaint of operators is that they need additional VDUs in their CR.

The keyhole effect and its relationship to the number of VDUs needs to be investigated further. The rationale for determining display area needs further examination. Consideration of the two issues should lead to guidance for the review of this performance concern.

Criteria are also needed for calculating acceptable limits for the information access costs associated with displays and display networks. When developing a control room, designers are faced with a tradeoff between concentrating information in a limited number of display devices, or providing it via multiple display devices. Each approach has potential benefits and costs. Using a small number of display devices may be beneficial for reducing the size of control console and panels and reducing the physical distance between display devices. One potential cost is more complex display networks due to an increased number of display pages that must be accessible from each device. The more complex display networks may impose greater navigation demands on users for accessing desired displays. The alternative approach is to provide more display devices with fewer pages assigned to each device. For example, each display device may contain a subset of pages (e.g., from a major branch of the display network) that relate to a specific set of operator tasks, rather than the entire network. This approach has the potential benefit of reducing the complexity of the display navigation task since fewer steps may be required to access a particular page and displays for tasks that are in-progress may be left in place rather than removed. Previous studies and interviews with operators have shown a clear preference for multiple, dedicated display devices. However, the increased number of display devices has some potential costs associated with the increased physical navigation between them. Thus, the tradeoff between the number of display devices and the complexity of the network may be envisioned as an inverted U-shaped function, in which user performance is optimized for some intermediate level of display devices and network complexity. Outside this optimum value, performance decreases, as either the number of display devices is increased or the complexity of the display network increases. Rapid and easy access to displays is important for managing multiple concurrent tasks (e.g., operators must be able to check the status of one system while controlling another). Therefore, guidance is needed on this tradeoff - particularly, the points at which performance may become unacceptable and the factors that may mitigate these effects.

Display Density Versus Display Clutter

Better metrics are needed for defining display clutter and better criteria for determining levels of acceptability. Visual clutter in computer-based displays has long been considered an obstacle to user performance. Visual clutter, the presence of distracting information in a display, increases the difficulty of a visual search by requiring the user to focus on many individual items to identify those relevant to a particular task. It increases information access cost by increasing the effort required to search for, and identify, desired items of information. Visual clutter also can increase the distance between such information items, causing task related information to be located on different display pages or in separate areas of the same page. This increased distance heightens the demands associated with finding and mentally integrating information.

While it is desirable to minimize or eliminate visual clutter, HFE review guidelines traditionally have focused on display density - the quantity of information per unit area on a display screen. However, display density is an indirect measure of clutter. Other factors may be more important than density in determining whether content will have negative effects on user performance. The first consideration is whether or not the information items in a display are task-related (i.e, used together by the user for tasks). The proximity compatibility principle (Wickens and Carswell, 1995; 1997) states that the cost of accessing information, in terms of time and effort required to focus attention, is decreased when task-related information is in close spatial proximity, but the presence of items that are not related to the task causes clutter which increases information access costs. Placing task-related information items together on the same screen, rather than on separate screens, can reduce the need for display navigation. Placing task-related information items closer together within a display can enhance the speed and accuracy of integrating information. Other important considerations include visibility and legibility of information items, ease of locating items, and the ease of accessing and manipulating items (e.g., selecting items with a pointing device).

Techniques that support mental integration of displayed items, such as placing task-related items close together, grouping task-related items, and integrating alphanumerics and graphics into visual objects, may enhance performance while actually increasing display density. Newer display forms such as integral formats and configural display formats, may greatly increase display density while reducing information access costs and improving user performance (O'Hara, Higgins, and Kramer, 2000). Current HFE design guidelines are not adequate for reviewing this topic because (1) they do not adequately define and describe display design considerations, such as the degree to which items are task related, (2) the technical basis for display density criteria is weak (e.g., it is not clear that task relatedness was addressed), and (3) they have not been applied to computer-based display formats, such as integral formats and configural display formats. As a result, HSI designs that contain these computer-based formats may be inadequately or improperly reviewed and assessed by existing guidelines. Additional guidance is needed to more accurately define the dimensions of visual clutter and their levels of acceptability.

Flexibility vs. Performance Tradeoff

Flexibility of the HSI was found to be another root cause of many of the challenges to performance identified in this report. The management and manipulation of flexible user interface features requires cognitive resources that operators may not want to take from the primary task. Additional research is needed on the tradeoff between HSI flexibility and interface task demands.

Conventional CRs tend to have inflexible display systems; that is, the indicators themselves cannot be manipulated or configured for their location, content, or presentation format. They reflect the designer's best understanding as to what information is needed, in what format, and sequence of use. The display system may be adequate for most tasks, but not exactly right for any one task. Operators may need to transition between multiple displays to get all the information they need for the task at hand.

A desirable aspect of the flexibility of many computer-based systems is that operators can better tailor the displays and workstation resources to meet the requirements of a specific task. It is difficult for designers to anticipate all of the information needs of the operators and provide displays that meet those needs. Flexibility in the HSI gives operators the capability to perform task-specific tailoring so the displays more closely approximate what is needed.

Flexible user interface features have been introduced in response to earlier design approaches that assumed a stereotypical user population - a group of individuals having characteristics, needs, preferences, and capabilities that were highly similar or nearly identical. These approaches failed to adequately consider the range of performance that may result from such factors as differences in expertise, personality traits, demographic characteristics, and physiological attributes. Computer-based technologies provide opportunities for making systems adjustable and adaptable to users and situations. However, designing more personalized systems that many people can use yet remain responsive to individual needs is an elusive goal (DoD, 1996).

Users always have tailored the interfaces of their systems to some degree. Two categories of flexibility may be considered in design reviews. *Inherent* flexibility of the HSI technology includes ways of modifying the HSI that were not specifically intended by its designers. For example, a computer-based display system may use the scroll bar to create a landmark for locating information in large tables (Watts, 1994). *Designed* flexibility includes features specifically created by the designer to give the user flexibility in using the HSI. For example, a computer-based display system may allow operators to select plant variables and scales to plot operator-defined trends. However, the types of flexible features and their degree are likely to change as computer-based HSI technologies advance.

A further distinction may be made between flexibility features that (1) can be directly modified manually by users, and (2) those that incorporate automation (DoD, 1996). For the former, the user determines the need for a change in the HSI and then undertakes actions to carry out the change. Some direct user modification features for displays include features for moving display pages or soft controls to particular display devices and features for creating operator-defined trend displays. A direct user modification feature for controls may allow an operator to provide inputs as a single, compound command, rather than as individual commands in response to a series of prompts. The disadvantages of direct user modification of the HSI include the following:

- additional learning requirements for new users
- increased difficulty for casual users in making modifications (e.g., supervisory personnel may experience difficulty setting up or viewing user-defined trend graphs)
- trade-offs in time and effort associated with setting up a flexible feature and completing a task
- difficulty in over-the shoulder viewing of flexible features (e.g., by supervisory personnel)
- difficulties in coordinating the use of a flexible feature among multiple personnel

Flexible HSI features that incorporate automation may adjust the HSI based on plant conditions, user behavior, or both. Adaptive modeling (DoD, 1996) refers to a system's ability to alter the user interface (1) for specific individuals, based on their preferences or past behavior and performance, or (2) to meet changing needs of the user based on current task demands. A computer-based model of the user is employed to predict the user's interface management needs and support adjustments of the HSI. This model may contain a profile of the user's characteristics and a program for determining interface management needs. This model may be manually updated by a system administrator or accomplished automatically based on the system's monitoring of the user's behavior. Such systems may recognize differences in expertise of users and act accordingly (e.g., providing assistance to novices each time they make mistakes, but assisting experts only upon request).

An example of a flexibility feature that incorporates automation may be a display configuration system that automatically provides the operator with a set of displays tailored to plant conditions. In such systems, automation may serve two functions: identifying the need for a change, and executing the change (Sheridan, 1997). Various combinations of these two functions are possible. For example, the automation may identify the need but let the operator execute it, or the operator may identify the need but let the automation execute it, or the automation may do both. In these cases, additional cognitive burdens are imposed on the operator for anticipating the actions of the automation and understanding the changes after they have occurred. For example, after the automation has acted, the operator must determine why it acted and whether the result is correct. When these actions are not anticipated by the operator, additional cognitive demands may be involved in shifting attention to the flexible feature and recognizing its actions. Based on the observations of Segal and Wickens (1990) and Norman and Bobrow (1975), HSI features that support planning and expectation should be encouraged, but features that draw attention unnecessarily (i.e., cause distractions) may be undesirable. Examples of attentional distractions may include flexible user interface features that draw excessive attention from the operator when they automatically change displays and features that give little feedback when they produce a change but then require the operator to divert attention to determine whether the change has occurred.

There are many factors that affect the use of flexible features by operators. However, users are more likely to employ a particular feature when it provides a potential benefit to task performance, when its benefit is perceived to be worth the effort to execute, and when its use is not prohibited by organizational policies. Sperandio (1978) describes some of the potential benefits of flexibility.

In field investigations of air traffic control, Sperandio observed that controllers shifted their work objectives as workload increased. That is, as the traffic in their air sectors increased, the controllers focused on their higher priority objectives, such as safety, and neglected lower priority objectives. Coincident with these shifts, the controllers made changes in the types of information they sought and their methods for performing actions. Sperandio observed that information that is pertinent at low and moderate workload levels may not be usable during high workload levels due to the operators' adjustments in their work methods and objectives. He stated that personnel performance may be negatively affected if the HSI characteristics are unevenly adapted to the controller's strategies. He also stated that the flexibility of computer-based technologies may also enhance operator performance by allowing the HSI to provide the right information for the operator's current work methods and work objectives while removing unneeded information that may become a nuisance. Designing HSI features to accomplish this requires a knowledge of task requirements and strategies used by personnel for modifying work methods in response to changes in external task load.

These findings also are applicable to NPP operations. For example, operators have many objectives when operating a NPP. During plant transients, the primary goal of maintaining safety may override other considerations, such as protection of investment in equipment and productivity (cost-efficient power generation). Changes in work methods that occur during transients affect the types of information that operators must gather and means they use for gathering it. Therefore, computer-based HSI technologies should support the gathering and processing of information for a broad range of workloads. The inherent flexibility of computer-based technologies may be beneficial for ensuring that information and control capabilities are provided in ways consistent with the work methods used by operators during the various workloads.

The high-level design review principle of *Flexibility* in NUREG-0700 states that flexibility should be limited to situations in which it offers advantages in task performance, but should not be provided for its own sake. This is because there are tradeoffs between the benefits of flexibility and the costs it imposes on operators. These human performance costs to individual operators include (1) interface management demands, such as the degree to which the workload associated with using the flexible feature diverts cognitive resources from the primary tasks, and (2) the effects that the flexibility have on the primary task (i.e., the degree to which changes to the HSI brought about by flexibility impair the operator's ability to perform the primary tasks). There also may be human performance costs when other crew members must view or use HSI components that have been modified by others. Examples include (1) difficulty in using shared HSI components, and (2) difficulty in over-the-shoulder supervision (e.g., a shift supervisor may have difficulty viewing a display that has been modified by the operator) (DoD, 1996).

Another aspect of the dual-task effects discussed above is that flexible HSI features make interface management tasks more dependent on controlled information processing. The cognitive tradeoffs associated with the flexibility of computer-based interfaces were noted previously (Woods, 1993). Operators must decide what information they want, how to retrieve it, what HSI to utilize to retrieve it, where and how it should be displayed, and they must coordinate the existing displays with the new information. To the extent that the CR and workstations provide dedicated HSIs with no flexibility, the HSI is highly predictable. If the environment is constant, the mental model of the HSI becomes highly detailed; the location, form, and function of the HSI becomes very predictable. Under these conditions, the operator's interface management tasks become highly automated. Flexibility and reconfigurability work against predictability and automaticity.

As an example, consider monitoring functions. In conventional CRs, operators can get a good overview of the plant functions and systems through a quick glance at the annunciator tiles. This is possible because human pattern recognition capabilities are very powerful. Once the location and arrangement of the tiles is learned, operators no longer have to read the individual tiles to comprehend the overall status. Contrast this with a computer-based CR having a message list system that is not organized by functions and systems. There are no identifiable patterns to recognize at a glance because of the lack of spatial dedication (except, perhaps, the severity of the condition based on the number of incoming alarms). With such an alarm system, determining that there is a problem requires reading individual alarm messages. This is a much more effortful task than glancing at tile displays. Interface management tasks can be automated to the extent that the interface is predictable.

Another human performance consideration associated with the lack of predictability of the HSI stems from its flexible characteristics. That is, in a spatially dedicated CR, operators know what information is located on the various panels. In a virtual workspace, when operators view a VDU, they do not necessarily know what is displayed because the display context can change. If the displays located on a specific VDU are frequently changed or tailored, then operators must examine each display screen to see what is now included. This requires controlled information processing capability. If operators fail to perform this recognition task, they may misidentify the display. Thus, situation assessment can be hampered by such errors.

In general, highly predictable HSIs do not have to be thought about a great deal, and can be largely addressed by the operator's automatic information processing resources. This discussion is not intended to suggest that flexibility is a negative feature and should be avoided. The positive aspects of flexibility were noted above. What is important to note is that there are tradeoffs between the workload associated with flexibility and its beneficial characteristics. A balance between the two is needed; however, guidance is lacking on how to achieve this balance.

Therefore, the flexible user interface features provided should be the result of careful analyses of user requirements. A flexible user interface feature should address the need to optimize operator performance under specific conditions. They should not be provided by designers as a way of avoiding analyses of user requirements. That is, designers should not avoid the work of analyzing operator requirements by setting up a design that can be used in many different ways. Flexibility without proper analysis can expose the operator to configurations that may impair performance, such as by increasing the likelihood of errors or delays.

Mental Models and Display Organization

It is known that well-developed mental models are needed for accurate situation assessment and good performance. These mental models improve performance by enabling the HSI to be predictable and enabling operator performance to become less effortful and guided more by expectations. A key in the ability of operators to perform interface management tasks effectively is their mental model of the organization and behavior of the HSI. While organizing controls and displays around plant systems may have been adequate for conventional CRs, it may pose difficulties in computer-based CRs. For example, a system-based organization may be rather easy to understand, but may require excessive work for display retrieval when the system-based organization of displays does not match operator task requirements (e.g., tasks require interactions with displays and controls from multiple systems). Alternative models have been proposed but their acceptability is not known. Research is needed to address the issue of providing a display organization that leads to an acceptable interface management load so that operators can easily retrieve the information they need for acceptable primary task performance.

Effects of Information Access Costs on Routine Monitoring

Additional research is needed to determine the degree to which information access costs may negatively affect the frequency and accuracy with which operators routinely monitor the status of plant systems. One of the root causes for the negative effects of secondary tasks upon primary tasks is that they demand the same cognitive resources at the same time. For example, if the same cognitive resources are required for both manipulating the HSI and controlling the plant, then during periods of high demand, one task may suffer as resources are directed to the other. However, if different cognitive resources are required for these two tasks, then it is less likely that one task will interfere with the other, and, consequently, a higher overall level of performance may be maintained. In this document, there was an initial discussion of the potential benefits and difficulties of using speech input for interface management tasks. However, the literature did not have sufficient information on control room environments to support the development of guidelines. Additional research is needed explore approaches for performing interface management tasks and to assess their acceptability and potential benefits for using them in a control room.

The literature also indicates that operators are less likely to perform an interface management activity if they do not expect the benefits to outweigh the associated costs (e.g., time and effort). Just as the design of displays (e.g., the keyhole effect) can increase information access cost and reduce the likelihood of monitoring, the design of interface management controls may also increase such costs. As a result, operators may be less likely to perform routine monitoring if the controls are difficult or awkward to operate (e.g., poorly placed relative to the operator or associated displays, awkward means of operation, or not reliable in operation). For example, a display device that has a touch interface located outside of the operator's immediate reach may be monitored less often than one within easy reach. Also, a display device having a touchscreen or lightpen interface the actuation of which is not highly reliable (i.e., an operator may have to press a button multiple times to select a desired display) may not be monitored as frequently as displays that are easier to operate. Additional research is needed to assess the extent to which monitoring frequency may decrease as a result of control device characteristics and the acceptable limits for these characteristics.

Role of Conventional and Computer-Based HSIs

One finding in this study was that operators may prefer conventional HSIs under high workloads. The authors observed that there is usually a migration toward the inclusion of more and more conventional equipment into CRs that start out being based completely on advanced technologies. This has been true of several advanced NPP CRs (such as ABWR and EDF N4). Heslinga and Herbert (1995) likewise noted:

> It was a general finding that introducing a new HMI (human-machine interface) in an existing situation where both old and new systems are available leads to a situation where the old systems continues to be used. This occurs particularly in incident situations where, partly because of time pressure, operators tend to return to well-known information sources. This happened in three HMI projects. The control room of in one project was first completely based on Visual Displays Units; however, a conventional desk was introduced because the users required this. (p. 256)

It is possible that the desire for the conventional HSIs reflects a preference for the types of display and control designs (such as gauges and J-handles) available in analog HSIs. Perhaps more likely, it may be that the characteristics of spatially dedicated, parallel presentations of controls and displays are more appropriate to control tasks than those of non-spatially dedicated, flexible, virtual controls and displays.

The relative role of conventional and computer-based HSIs and the design characteristics that are important to these preferences need to be better understood.

The Effects of HSI Design Features on Interface Management Task Performance

We concluded above that the detailed design of HSIs affects the performance of interface management tasks. Below are issues that address different aspects of HSI design. NUREG-0700 gives guidance on many aspects of these HSIs. However, the issues below are focused more on interface management aspects, as well as the relationships between multiple HSI components in a CR. Further, the overall focus of these issues would be to reduce interface management workload, while maintaining high HSI situation awareness.

Relative Comparisons of HSIs

What are the relative advantages of different HSI design features for supporting interface management tasks?

Command Language Interfaces

Command dialogues have some advantages compared to other dialogues, such as menus. For example, it may be possible to retrieve a display in a single step by entering an identification code rather than through a set of steps in a series of hierarchically arranged menu screens. Commands also have drawbacks, such as increased demands on the user's memory for recall and susceptibility to input error; e.g., incorrect or transposed letters or digits. There are design trends away from command language dialogues and toward direct manipulation and menu-based systems. However, many studies found information retrieval is better using command language dialogues. Thus, guidance is needed on their appropriate use. This guidance should take into consideration the skill level of trained operators and the fact that multiple interaction methods may be available at the same time. Much of the current literature addresses only novice users. Research has shown that command names should be evaluated as a set, rather than be considered individually. Many factors, such as nameset effects (relationships between individual commands; size of set), task conditions, and user population characteristics can affect the ability of users to recall commands. Additional guidance is needed for determining the acceptability of command namesets. The use of command dialogues also may be affected by such features as on-line help and *undo* commands. In addition, some command dialog systems allow users to abbreviate or customize commands. Guidance is needed for determining the acceptability of these features. Owing to the effects of contextual factors such as nameset, task conditions, and user population characteristics, it was recommended that system developers rely heavily on tests and evaluations to ensure that command dialogues can be used effectively. Many protocols established for evaluating command dialogues were developed for text processing tasks which may not be relevant to NPP operations. In addition, simplistic approaches to measuring task times and errors may overlook the range of consequences of different types of errors or delays associated with command usage. Thus, guidance is needed too for tests and evaluations of command dialogues for NPP HSIs.

Menus

A menu is a type of dialogue in which a user selects one item out of a list of displayed alternatives by actions such as pointing and clicking, entering an associated option code, or activating an adjacent function key. Menu interfaces have gained widespread use in many computer-based systems. By presenting the user with a set of options, menus can reduce cognitive demands on users (e.g., the need to recognize rather than recall options). Many menu systems reduce the set of options to those relevant to the current situation. However, menus can pose potential problems for users. For example, studies have shown that as menus increase in size, the time required to access items may increase greatly. Users may become unable to determine the location of, or successfully retrieve, desired items. Research studies and operating experience identified a number of factors that affect user performance with menus, including techniques for depicting the display network and the user's current location, techniques for highlighting relevant options, and "look ahead" features that indicate options that can be accessed from a current one. Guidance is needed on the appropriate use of these features.

Direct Manipulation Interfaces

Direct manipulation interfaces, especially those that are object-oriented, are being adopted into a broad range of human-computer interfaces in many domains. They offer many potential benefits in terms of reduced mental demands associated with interpreting display information and executing actions. Potential applications in NPP HSIs may include display icons (e.g., icons in mimic displays), displays for organizing information that are based on metaphors (e.g., the desktop metaphor), and interfaces for managing display windows. Direct manipulation interfaces rely heavily on the use of metaphors and analogies. Because users may have different mental models than designers, they may interpret the interface in ways that are different from the designer's intentions. In addition, metaphors may have limited applicability. Usually, there are situations in which the metaphor is not consistent with the task domain (e.g., the metaphor suggests actions that are not supported by the HSI or are inconsistent with the operation of the plant). This may lead to problems in learning or using the interface. In addition, these interfaces may be prone to errors that differ from those of more conventional display interfaces (e.g., an input action may be legal with respect to the user interface but undesirable for the task domain). Guidance is needed on the appropriate use of direct manipulation interfaces and to provide a better understanding how the characteristics of direct manipulation formats contribute to their effectiveness.

Function Keys, Programmable Keys, and Macros

The use of these HSI design features may support increased automation of interface management tasks. Their potential advantages and disadvantages need to be defined, and their potential to increase the probability of errors needs to be assessed.

Query Language, Natural Language, and Question and Answer Dialogues

Query language, and question and answer dialogues have a long history as user interfaces in computer systems, especially for interrogating databases. Natural language interfaces have a more recent history. All three methods use conversation metaphors for interacting with the computer and inputs are usually entered as text strings via a keyboard. Question and answer dialogues are slow; users must wait for the system to ask questions before they can express their needs. Query language interfaces have developed special terms and grammars that must be used when generating requests. High mental demands are associated with determining the type of processing (information sorting) that is desired and then translating the request into query language. In addition, execution errors are associated with keyboard entry of queries. Natural language interfaces were developed to reduce the cognitive demands of formulating inputs. Compared to query language systems, inputs to natural language systems more closely resemble the types of phrases used in normal communication. However, owing to the complexity and ambiguity of natural languages, these interfaces still require the use of special, restricted terms and grammar. Users still encounter difficulty in determining the type of processing (information sorting) that is desired, and then translating the request into an expression that will be understood by the computer system. In addition, requests expressed in natural language may be lengthy, which may increase operator response time and impose high demands on keyboard entry skills. Guidance is needed to ensure that burdens associated with query language, natural language, and question and answer dialogues do not detract the operator from tasks that are more directly involved in assessing and controlling the condition of the plant.

Speech

As identified above, one of the problems associated with computer-based HSI interface management is that it shares the same cognitive resources as supervisory control tasks. Speech offers an alternative cognitive resource that may result in less competition with primary tasks that are performed using the HSI. However, the possible conflicts need to be assessed between using speech as an HSI input mode, and speech during operator communication tasks.

Navigation of Display Networks

The issue of "Mental Models and Display Organization" above, addresses appropriate organizational approaches for NPP displays. Related to that issue is what navigation features support the use of the displays. Navigation methods that are based on spatial principles can require operators to access multiple displays before reaching the desired one. Multiple navigation methods (e.g., menus, commands, direct manipulation methods) may be provided within a single display system, requiring users to conceptualize paths to the target display. It also introduces opportunities for navigation errors that can affect the operators' ability to monitor plant condition or to respond promptly to changes. A goal of display system design is to support the user in developing an accurate understanding of how data is organized, which navigation paths are available, and how the system will respond to user inputs. This is called the user's conceptual model. Conceptual models for display navigation support users in understanding the relationships between display pages, planning paths to needed data, and developing appropriate courses of action in novel situations. A variety of design approaches can be used to support the user in developing conceptual models for display navigation, such as metaphors (e.g., desktop metaphors), overview displays that depict the organization of the display network, display landmarks, and display page designation schemes that indicate relationships between them. The user's conceptual model of the display system may differ from that of the designer, leading to the development of features that do not support an appropriate conceptual model of the display system. Guidance is needed about the appropriate use of these design approaches for supporting operator understanding and use of the display system, especially with regard to understanding the structure of the display network and planning and executing navigation paths.

Navigation of Large Display Pages

Large display pages allow large amounts of related data to be presented together, which reduces the need for operators to access many individual pages. In NPPs, large displays with graphical data may include overviews of the display network, mimic displays (e.g., plant system representations), flowcharts (e.g., representations of procedure steps), and maps (e.g., a representation of the physical arrangement of equipment in the containment building). Large displays with nongraphical data may include text displays, such as tables of plant data with long columns and many rows. In some cases, display pages are too large to be viewed at once from a single display screen with a level of resolution that is sufficient for user tasks. For example, if the page were reduced in size to fit the available space of the display device, the text and other details would be too small for the user to read. Navigation techniques for finding and retrieving items from large display pages include nondistortion-oriented techniques (e.g., scrolling, paging, zooming and panning, hierarchical paging), and distortion-oriented techniques (e.g., fisheye views that show both detail and context). While these techniques contain features for enhancing user orientation and retrieval, they also impose new demands. Human factors guidance is needed to address these techniques, including their appropriate use, potential benefits, and characteristics for reducing orientation and retrieval errors.

Hypertext and Hypermedia

Hypertext-based systems consist of information nodes connected by organizational and relational links. Nodes may vary in size, content, and format. While hypertext systems can provide rapid access to information items, studies have shown that they are associated with disorientation (difficulty determining current location) and difficulty in identifying paths to desired information. In addition to difficulties with navigating between nodes, problems have been associated with managing windows that contain retrieved nodes and finding information within large nodes. Guidance is needed on the appropriate use of hypertext and specific characteristics, such as network structure, orientation aids (e.g., overview displays, landmarks), retrieval features (e.g., bookmarks, histories, "previous node" buttons, and features that support users in determining whether a node should be accessed), window management, and retrieval of information. In addition, guidance is needed about the appropriate use of hypermedia capabilities that can show information in a variety of media, including text, graphics (still and animated), video, audio, and executable programs.

Use of Windows and View Arrangement Features

Operators adjust the way that items are presented in the display system to make them easier to view. Two of these tasks include decluttering displays and decluttering display windows. Display decluttering capabilities allow a high volume of data to be presented when needed and removed when it is not needed. This is especially useful when personnel must handle a large volume of data and the available display space is limited. Potential applications in NPP HSIs are mimic displays of plant processes and overviews of display networks. Decluttering capabilities may affect operator awareness of changes in plant status. Because information is removed from immediate view, the operator may not observe indications that are important to assessing changes in plant status or evaluating possible control actions. A second potential concern is the ability of the operator to recover from the decluttered mode. Display windows are decluttered through window management features. While window-based display systems can provide flexibility for information access and use, window management (e.g., opening, closing, moving, and resizing windows) is a secondary task that can detract from the primary task. Studies suggest that the need to manually adjust display windows can interfere with operator performance in monitoring and decision-making. Automated display management systems, which perform window management operations automatically based on their interpretations of operator intentions or changes in plant or display system status, may impose new cognitive demands on operators. These may include determining whether a display has been changed, determining why the window management system operated as it did, anticipating what the system will do next, and tracking the system's assessments and actions and coordinating them with one's goals. If such automated systems are not based on adequate models of operator functions and the task environment, they may increase, rather than decrease, the mental workload for operators and detract from overall performance. Guidance is needed on the appropriate use of display decluttering features and manual and automated window management systems.

Features For Moving Between Multiple Display Devices

In some systems, an operator may use the same input device (e.g., mouse) to interact with different display devices. For example, the operator may switch control of one display device to another via a selection command. As another example, two adjacent displays may be coordinated to act as a single display device (e.g., each presenting portions of a larger display). The HSI should provide features that support the operators in maintaining awareness of the currently active display device and preventing input errors (e.g., providing the right input to the wrong display). The consequences of errors may range from accidentally operating the wrong plant component, to selecting the wrong display, to delays in their response to an event. Research is needed to more thoroughly review interface management tasks and develop review guidance addressing the coordinated use of multiple displays.

Input Devices

Issues associated with providing many different interface management input devices were identified as were issues associated with having all computer input (interface management and process control inputs) entered through one input device. These problems need to be explored further.

User Guidance Features

User guidance features, such as online help, support users in learning and using the interfaces of HSI components. A broad range of systems exist, ranging from manually operated systems with static information to automatic systems with intelligent guidance generation. Often, the use of these features represents yet another interface management task. Little is understood about how these systems can be systematically designed to support human-computer interaction in complex systems. For example, some studies showed that online help systems may increase, rather than decrease, the amount of time a user takes to solve a problem. Some systems do not provide the appropriate type of information to support user tasks. Also, information that is not presented in an appropriate format can generate additional interface management tasks, such as window management and searches for information. Guidance is needed regarding such topics as information content, presentation style, interaction methods, and integration with the HSI design process.

Global HSI Considerations

An NPP HSI will likely contain many display devices, often featuring multiple methods of interaction. Global HSI considerations encompass the effect that the HSI, as a whole, has on crew performance. There are three major topics. The first topic, layout and distribution of information and controls, addresses the fact that controls and displays can be accessed from multiple locations through multiple paths in the HSI. New opportunities for operator error may be created by HSI features that provide flexibility in presenting controls and displays. For example, they may be shown in ways that violate stimulus-response or population stereotypes. Controls and displays that are functionally unrelated may be presented in ways that suggest they are functionally dependent, leading to errors in interpreting the information or in executing control actions. The second topic, interface management consistency and compatibility, covers the variety of presentation and interaction methods that may be obtained from the many components of the HSI. Studies have shown that users can encounter difficulties when switching between different interaction methods (e.g., operators providing inputs in a manner that is consistent with another HSI component but inconsistent with the components being used). Conflicts can arise when similar interaction methods are not compatible. These inconsistencies can arise from upgrades that use different technologies that are not well integrated with the rest of the HSI. Also, features that provide flexibility in the ways that information is given (e.g., operator-configured displays) can result in the use of symbols and coding schemes that are inconsistent with the rest of the HSI and may lead to operator errors. The third topic, coordinating HSI usage between crew members, refers to the fact that the HSI acts as a communication medium through which members monitor each other's activities and coordinate their actions. HSI features, such as shared display devices, operator-configured displays, and computer-based "soft" controls create new requirements for such coordination. Crew performance can be disrupted when these devices are not used in a coordinated fashion (e.g., operators lose awareness of the state of the HSI or the plant). Guidance is needed to ensure that the individual components of the HSI are properly integrated to support crew performance.

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