N91-20711

COGNITIVE CONSEQUENCES OF 'CLUMSY' AUTOMATION ON HIGH WORKLOAD, HIGH CONSEQUENCE HUMAN PERFORMANCE

Richard I. Cook, David D. Woods, Elizabeth McColligan
Cognitive Systems Engineering Laboratory
Department of Industrial Systems and Engineering
The Ohio State University
Columbus, OH 43210

Michael B. Howie
Division of Cardiovascular Anesthesia
Department of Anesthesiology
The Ohio State University Hospitals
Columbus, OH 43210

ABSTRACT

The growth of computational power has fueled attempts to "automate" more of the human role in complex problem solving domains, especially those where system faults have high consequences and where periods of high workload may saturate the performance capacity of human operators. Examples of these domains include flightdecks, space stations, air traffic control, nuclear power operation, ground satellite control rooms, and surgical operating rooms. Automation efforts may have unanticipated effects on human performance, particularly if they increase the workload at peak workload times or change the practitioners' strategies for coping with workload. Smooth and effective changes in automation requires detailed understanding of the cognitive tasks confronting the user -- what has been called *user centered automation*[1]. We have observed the introduction of a new computerized technology in a group of hospital operating rooms used for heart surgery. The study has revealed how automation, especially *clumsy automation*[2,3], effects practitioner work patterns and suggests that clumsy automation constrains users in specific and significant ways. Users tailor both the new system and their tasks in order to accommodate the needs of process and production. The study of this tailoring may prove a powerful tool for exposing previously hidden patterns of user data processing, integration, and decision making which may, in turn, be useful in the design of more effective human-machine systems.

INTRODUCTION

Increasingly sophisticated computers and a sense that human operators need assistance in performing monitoring and control have prompted the development of "automatic" devices, especially in high consequence, semantically rich domains. The purpose of automation in these domains is to release the operator from repetitive control tasks in order to reduce operator workload or to provide the operator more precise or more extensive information about the system under control. These domains already exist and operators already accomplish tasks using skills, rules, and knowledge about the domain and current technology. New automated devices represent a *change* from one way of doing things to another.

Aiding operators, especially highly skilled operators in complex, high risk process control worlds, is itself a complex problem. Operators are facile and sophisticated information users and subtle controllers, whose performance is highly optimized to achieve specific goals or system states. Often overlooked is the fact that most automated devices make certain demands on operators (e.g. setup, device state identification, configuration control, operating sequences), including cognitive demands (e.g. tracking the automated device state, separating display elements, evaluating the automated device's performance). These demands constitute workload for the operator.

Virtually all automated devices are supposed to offset the operator workload increment with some payoff. The devices provide either better control (e.g. automated drip rate controllers instead of hand operated tubing clamps for intravenous solutions), economic value (e.g. flight management systems for commercial aircraft) or better information for control (e.g. nuclear power plant safety parameter displays) or later review (e.g. "automated" anesthesia records). Sometimes these paybacks benefit the operators by reducing their workload (the automated drip rate controller) while others benefit either the larger organization (automated anesthesia records, flight management systems) or society as a whole (safety parameter displays in nuclear plants). In domains where operator performance is critical to safe system function, automated devices are generally supposed to reduce net work, that is, the total operator work with the device is less than without it. But net work (workload integrated over time) is only a poor measure of operator performance. With some automated devices the workload increment occurs during the *peak* workload period and the payback occurs during the workload *trough*, a condition Wiener[2,3] describes as *clumsy automation*.

We have tracked the introduction of a system which has some characteristics of clumsy automation in the domain of cardiac anesthesiology. The study focused on the introduction of a new automated monitoring system, and its immediate and longer term effect on users. The opportunity to see the users adaptations as they occurred provided insight into the user task complexity and information management strategies. These, in turn, point towards specific consequences of certain approaches to automation in this and other high consequence domains.

THE SYSTEM AND THE STUDY

The new system provides monitoring and information management for cardiac surgery. It replaces a multiple discrete monitors with a single device, designed to provide a single source of information about the patient's physiologic condition. In order to accommodate the volume of information displayed, the device automates data presentation and organization. It also computes hemodynamic values from collections of data and keeps track of historical "trends". The device configuration is flexible, to permit users control over the order in which items are displayed on the screen. Virtually all major manufacturers of medical monitoring equipment have developed such devices, which represent the current state of the art in medical monitoring technology. The new device replaces older discrete technology with which the operators were quite familiar. Similar devices may be incorporated into the space station.

We were able to observe the introduction of the device beginning on the first day of use. The devices were purchased specifically for cardiac surgery purposes and are installed in rooms dedicated to thoracic surgery. Coronary artery bypass grafting, the most common cardiac surgery, was observed by a physician observer and the activities of the anesthesiologists recorded. These raw records were coded for protocol analysis and incidents evaluated, paying particular attention to the way the monitoring system was used, who used it, and what the context of the use was. At least two cases per week were recorded, and the observations continued for several months.

RESULTS

The new system replaces discrete monitors using fixed controls and displays with a menu oriented device using a color display showing multiple windows. Menus are displayed one line at a time at the bottom of the screen, and the device automates the recognition of various modules and the management of display formats.

Setup

Device setup is more complicated than with predecessor equipment; operators traverse at least seven major menu branches and enter between twenty and sixty keypresses. Setup occurs as the patient enters the operating room, a time of peak activity for anesthesiologists. For this reason, circulation technologists setup the monitoring equipment and perform configuration. We observed system crashes in mid-case, requiring complete setup during critical periods. Anesthesiologists rely on easily setup backup monitors (ECG, oxygen saturation, end-tidal CO_2) during the initial instrumentation period and also during the case. As time progressed, anesthesiologist users began to connect some new device sensors early (e.g. pulse oximeter) but the reliance on the old ECG was maintained throughout our period of observation.

Data Presentation

Data presented in the default system configuration is highly processed. Default waveform displays, the traditional form of data representation for anesthesiologists, are segregated and unscaled. The presentation segregates each data channel and minimizes the display area occupied by each waveform, maximizing the number of waveforms displayed and eliminating waveform overlap. This *data packing* changes the characteristics of displayed data and reduces information available from the waveform. Users universally and immediately call up a blood pressure graph window for display of blood pressure data and work to maintain it throughout each case.

Another processed data form is the digital representation of waveform characteristics (systolic, diastolic, and mean pressures). Although these representations are highly precise (three significant digits) users relied heavily on waveform presentations. The digital values are averaged; rapid changes in blood pressure appear immediately in the waveform but lag twenty to thirty seconds behind in the digital representations. These rapid pressure fluctuations occur relatively frequently during cardiac procedures and anesthesiologist users rely on waveforms for detecting them.

Determining cardiac output requires calling up a special window. The system automatically removes the blood pressure graph window and replaces it with the segregated traces when the cardiac output window is on the screen. Cognitive task analysis shows that determination of blood pressure and cardiac output occur in parallel during critical periods. Because of the system design, anesthesiologists must manage the display to interleave cardiac output windows with the desired scaled pressure representations. This information management task is new; the discrete monitor predecessors by necessity supported parallel display since cardiac output and blood pressure monitors were separate devices. Early in the study the cardiac output window was left in place on the screen for long periods after cardiac output related activities were complete. Once they were aware of the tradeoffs between windows, anesthesiologist users adapted to this new task of managing serial displays.

In addition, the determination of cardiac output in the new system takes considerably longer than it did in the old one. Multiple cardiac output readings could be obtained in a short period with the old system while the new one has a very slow measurement cycle time.

Screen Organization

The order and color of traces on the screen is flexible. Users may configure trace order in an elaborate menu which specifies relative priority. Fortuitously, when three blood pressures and cardiac output are connected to the system, arranged together, and the pressures placed on the graph window, the blood pressure graph window overlaps exactly these four areas on screen. This means that the blood pressure traces and other traces (end-tidal CO_2, oxygen saturation) are visible when the blood pressure graph window is on the screen. However, when only a single pressure is monitored (for some lung surgery cases), the priority management system places the other traces immediately below the single blood pressure trace. The blood pressure graph window then hides these traces from view. Anesthesiologist and technician users tried various methods of arranging traces so that none would be hidden by the blood pressure graph window. These included complete screen reorganization and sham modules.

In screen reorganization, the other traces were assigned higher priority than the blood pressure traces so they appeared above the pressure traces. When the scaled pressure window is on screen it's top edge begins at the level of the highest priority pressure trace shown on the scale; since the other traces are literally "above" the pressure traces, the scale fills the lower portion of the screen and the other traces are visible. Unfortunately, this scheme destroys the spatial dedication of traces that anesthesiologist and surgeon users expect and interposes unrelated trace groups between two related traces (blood pressure and electrocardiogram). For these reasons, the screen reorganization approach was abandoned.

A clever approach was the use of sham modules. Inserting pressure transducers reserves space for them on the screen, even if they are not connected to the patient. By placing modules in the system, technician users were able to "fool" the system into the desired configuration.

These strategies represent user efforts to tailor the device into a static, spatially dedicated device with fixed data display. Users expend substantial effort to preserve the fixed relationship between data items on the display screen.

DISCUSSION

Operators in high-risk process control settings can and do adapt to technologic change. We observed two broad classes of adaptation, *system tailoring* and *task tailoring*.

System tailoring is the configuration or modification of the new device and related devices to support user cognitive tasks. Most initial tailoring involves trying to make the new system look as much like the old as possible, since this is the easiest way to transfer knowledge about "how things work" from the old system to the new and because the users possess highly refined information processing strategies which depend on features of the old system. The use of redundant monitors is not simply a "backup" technique, but also represents a modification of the new system to maintain characteristics of the old by literally preserving components of the old system in the new. As time goes on users appear to develop confidence in the new components and to gradually get weaned away from the old. System tailoring may also involves exploiting system features in orthodox and unorthodox ways. The orthodox system tailoring is that supported by the device designers, e.g. the trace priority assignment. Unorthodox system tailoring involves approaches not anticipated by designers, e.g. sham modules insertion to preserve trace order. System tailoring actions may go on at any time but are usually heavily weighted to periods of setup.

Task tailoring is the modification or alteration of user activities to accommodate new devices. The goal of task tailoring is to maintain critical functions necessary to achieve the goals of operation. When system tailoring is limited or unsuccessful, users are forced to tailor their tasks. In the most simple form, they add new tasks to their collection. Users learn how to manipulate the serial data display of cardiac output and blood pressure graph windows in order to preserve the flow of high reliability data and they add this device tending task to their activities. These data management tasks occur during critical periods (e.g. coming off bypass) where user cognitive workload is high, a hallmark of clumsy automation. There may also be a more complex task tailoring involving the way users gather and manipulate data; with slower cardiac output determinations and the elimination of scaled pressure waveforms during cardiac output determination, users have an incentive to measure cardiac output less frequently and to develop operating strategies which make less use of output.

System tailoring can usually be developed and refined over a short learning period to achieve a locally optimal arrangement. With devices which can save configuration information, the costs of system tailoring are borne once and, so long as the technical cadre with configuration know how is maintained, can be accomplished with little effort. As time passes, the tailoring gives way to a new routine system. Encoding this collection of details is usually described as 'standard operating procedures' or 'the way we've always done things' and comprises a *ritual*, a collection of actions compiled and performed together but separate from the motivations and purposes which gave rise to them. System tailoring is not limited to automated devices. Anesthesiologists do a great deal of system tailoring to reduce workload, for example drawing up drugs in syringes well before the anesthetic begins. The point is that automated devices constrain system tailoring in specific and complex ways.

Task tailoring, on the other hand, is a continuing operator demand. Added tasks do not, at least in our system, go away, although users become progressively more efficient at accomplishing them. Tailored tasks become permanent fixtures of the work environment. Significantly, the task tailoring we observed was prominent during critical hi-tempo periods. Periods of activity and criticality coincide in this domain, as they do in others, and this tends to concentrate user tasks and task tailoring at these junctions. This may be an intrinsic feature of high consequence, high complexity domains: new technology impacts most directly on crucial periods with high workload which in turn provides the motivation for system and task tailoring by users.

Introducing automation into high reliability environments impacts the work of operators in specific ways, ways related to the tasks of the operators rather than to the technology *per se*. Operators demonstrate sophisticated approaches to tailoring their systems and their tasks for routine operations. They work to accommodate technology smoothly. Paradoxically, the operators' work to tailor the technology may make it appear smooth, hiding the clumsy automation from designers.

Introducing new technology gives rise to system and task tailoring by users. But tailoring, once complete, may be invisible. System tailoring becomes part of 'standard operating procedures'. The tailored and untailored tasks may become indistinguishable as operation of the devices becomes skillful and interwoven with other tasks. Observing task tailoring *as it occurs* can bring into sharp focus user information processing and cognitive strategies. It is this information which is essential to the designers wishing to avoid clumsy automation.

ACKNOWLEDGEMENTS

This research was sponsored in part by the Aerospace Human Factors Division of the NASA Ames Research Center under grant NCC2-592 and by The Ohio State University Department of Anesthesiology. We are grateful to the residents, faculty, and technicians of the Department for their generous assistance and guidance.

REFERENCES

1. Norman, D.A., and Draper, S.W., USER CENTERED SYSTEM DESIGN: NEW PERSPECTIVES ON HUMAN-COMPUTER INTERACTION, Lawrence Erlbaum, Hillsdale, NJ, 1986.
2. Wiener, E.L., "Human Factors of Advanced Technology ("Glass Cockpit") Transport Aircraft", TECHNICAL REPORT 117528, NASA, Washington, D.C., 1989.
3. Wiener, E.L., "Field Studies in Automation", In Norman, S. and Orlady, H.W. Ed.s, FLIGHTDECK AUTOMATION: PROMISES AND REALITIES, NASA Ames Research Center, Moffett Field, CA, 1989.