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MORE ABOUT OPERATOR MONITORING UNDER NORMAL OPERATIONS: THE ROLE OF WORKLOAD REGULATION AND THE IMPACT OF CONTROL ROOM TECHNOLOGY

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This paper is part of a research program that we have been conducting to better understand how operators monitor a nuclear power plant under normal operations. A field study was conducted in a modern plant that has more automation and more computer-based displays than the two plants that we had observed in previous studies. Eleven operators were observed for a total of approximately 88 hours. The findings suggest that operators actively adopt strategies to regulate their workload so as not to exceed their resource constraints. In addition, the results suggest that computer-based control rooms require operators to have more knowledge about the interface (not the plant itself) than do the older analog, hard-wired control rooms. Moreover, computer-based designs require operators to *reduce* the degrees of freedom in the design to have context-sensitive information, whereas hard-wired designs require operators to *expand* the degrees of freedom.

INTRODUCTION

Studies of operator cognition in nuclear power plants (NPPs) have typically focused on emergency situations (e.g., Vicente, Moray, Lee, Rasmussen, Jones, Brock, & Djemil, 1996). This focus is perfectly justifiable, given the tremendous hazards associated with faults. Nevertheless, the focus on the abnormal has led to an unintended side-effect, namely that there is little research conducted on operator cognition during routine conditions. Accordingly, we have been conducting a systematic research program with the aim of better understanding how operators monitor NPPs under normal operations. In this paper, the main empirical findings from our latest field study are presented. If we can identify operator cognitive activities under routine conditions, then we will be in a much better position to design training and interface interventions that not only make routine operations more efficient, but that also facilitate the detection and early diagnosis of emergency situations.

REVIEW OF PREVIOUS RESEARCH

Our first field study (Vicente, Burns, Mumaw, & Roth, 1996) was conducted in an older NPP whose control room consisted primarily of hard-wired, analog instrumentation with just a few CRT-based displays for alarms and process variables. Our goals were to identify:

a) the sources of information that operators can use to monitor the plant
b) the factors that make monitoring under normal operations difficult
c) the strategies that operators use to cope with these difficulties.

We found that there are many different sources of information that operators can use to get information about the status of the plant. Not only did operators obtain information from the control room panels and alarms, but they also relied on other sources of information to monitor the plant, including: other control room operators, written reports of readings taken in the field, communication with field operators, and direct perception of components in the field. We also learned that one of the primary factors that makes monitoring difficult is that the state and structure of the plant change on a daily basis, as equipment fails, as equipment is being repaired, as equipment is being maintained, and as plant tests are being performed. These changes provide the background context for monitoring because they govern the expectations about what is normal. For example, the identical set of symptoms may be absolutely normal if a test is being performed or a sign of pending catastrophe if there is no test being performed. Thus, it is essential that operators keep track of the state and structure of the plant so that they can interpret indications accordingly. This task is cognitively very demanding because there are so many items to keep track of and because the context for monitoring changes on a regular basis. Fortunately, operators have developed a number of ingenious *facilitating strategies* that allow them to cope with these difficulties. Some strategies make it easier for operators to extract information from existing sources (e.g., by making changes more noticeable), whereas other strategies actually create information that would otherwise not be available (e.g., by creating external reminders). The most interesting aspect of these strategies is that many of them involved "finishing the design" of the control room (cf. Rasmussen, 1986); that is, operators notice deficiencies in the control room design and then actively make changes to the design to make up for the deficiencies, thereby facilitating monitoring (see also Seminara, Gonzalez, & Parsons, 1977). A simple example is that the alarm system does not filter many alarms according to the context. Thus, operators will frequently delete nuisance alarm messages that are expected for the current situation from a CRT display, even though the alarm state is still enabled. This filtering minimizes the number of messages on the screen, thereby increasing the signal to noise ratio of the alarm system. Collectively, these facilitating strategies allow operators to perform what would otherwise be an extremely demanding task with great reliability and cognitive efficiency.

Our second field study (Vicente, Mumaw, Roth, & Burns, 1996) was designed to see if the findings obtained in the first study were generalizable across operators. Thus, we returned to the same NPP to observe and interview a different set of operators. The results replicated the findings of the first study.

Our third field study (Vicente, Mumaw, Roth, & Burns, 1996) was designed to see if the findings obtained in the first two studies were generalizable to another plant. Thus, we visited a second, slightly more modern NPP operated by the same utility as the first plant. This control room was also primarily based on hard-wired, analog instrumentation, although it had a few more CRT displays than the older control room. By and large, the findings obtained from this study replicated the results obtained from the first two studies.

Based on the results we obtained from the 27 operators we observed for 200 hours in these three field studies, we proposed a preliminary model of NPP operator monitoring under normal operations (Vicente, Mumaw, Roth, & Burns, 1996; Roth, Mumaw, Vicente, & Burns, 1997). The model is far too complex to describe here, but we can note that it emphasizes operators' use of facilitating strategies for knowledge-driven monitoring and proactive adaptation of the control room interface.

The results of the fourth field study conducted in this research program are reported here for the first time. This study was designed with two goals in mind: a) to identify any cognitive processes that may have been missing from our preliminary model of operator monitoring; and, b) to determine if our model was applicable to a more modern NPP with more automation and more CRT-based displays. Accordingly, we visited the newest NPP operated by the same utility to document how operators monitored the plant under normal operating conditions. This plant was of the same type as the previous two, but it had a distinctively different control room design. Although there were some hard-wired, analog instruments, most of the information in the control room was presented on computer-based displays.

FIELD STUDY METHODOLOGY

Observations were first made using an open-ended methodology. Three different operators were observed over three day-shifts for a total of approximately 24 hours. The goal in this phase of data collection was to get an overall understanding of the control room design, and a preliminary assessment of the similarities and differences with the two plants that had been observed in previous phases of this work. Additional observations were then made using a more structured, directed methodology that we had used before (see Roth et al., 1997 for details). Four different operators were observed on four different day shifts for about 8 hours at a time. The goal of this phase of data collection was to get a more detailed understanding of operator monitoring activities at this more modern plant. In summary, we were able to observe 11 of the 28 operators at this NPP for a total of approximately 88 hours, thereby providing a comparatively representative sample of observations.

RESULTS

In this paper, we will focus on two of the primary themes to emerge from our study: a) the role of workload regulation; and b) the impact of control room technology (see Vicente, Mumaw, & Roth, 1997 for a full account of the results).

The Role of Workload Regulation

Most of the features of our preliminary model of operator monitoring were confirmed by the results from this study. However, we did observe one very important cognitive phenomenon that had not been documented in our previous studies, namely the way in which operators regulated their workload to make monitoring more manageable (cf. Sperandio, 1978). This task is accomplished by approving and scheduling work requests in such a way that monitoring is not ignored or degraded. To achieve this goal, operators must have a well-calibrated sense of their capabilities that they can use to set priorities so as not to overextend themselves. Several examples can be offered to illustrate this strategy.

In one case, an operator was in the middle of refueling when a worker came to get approval to perform a job in the field. If approved, this job would bring in nuisance alarms, which would be added to the nuisance alarms normally triggered during refueling. These alarms would greatly increase the demands associated with monitoring because the operator would be frequently interrupted by alarms. Furthermore, the operator would have to determine if any alarm that came up was merely due to the job being performed in the field, by the refueling, or by some other (perhaps critical) event. Under these conditions, it would be very easy to miss an important alarm amongst the constant stream of nuisance alarms. For this reason, the operator decided to defer the job until later in the day, after refueling was completed. Thus, this operator made a conscious decision to regulate his workload by spreading out task demands more uniformly during his shift rather than creating a demand peak that would increase the likelihood of monitoring errors.

It was also not at all uncommon to see maintenance/ engineering staff wait patiently until the operator was ready to attend to them. This resulted in a highly unusual style of interpersonal interaction, where the operator would not even acknowledge the presence of the individual(s) queued up, until he was ready to attend to them. The unusual interaction style simply reflected an adaptation to the operator's high attentional demands and was understood that way by the engineering and maintenance staff, who respected the need of the operator to regulate when he could attend to them.

There are a number of generic methods that operators use to regulate their workload when prioritizing jobs. Among the factors they consider are the following:

- what else is going on at the same time?
- which meters will be unreliable or unavailable?
- what is the worst case scenario with respect to the potential impact on operation?
- how much attention and dedicated effort will the job require of the operator?
- how much operator field support is it going to need?
- does the job have to be done now (i.e., is it urgent)?
- is there a time later in the day when the demands will be lower?

In summary, one of the ways in which operators can deal with the challenging demands associated with monitoring (see previous section) is by explicitly regulating their workload to make sure that it does not reach their resource limits.

We did not explicitly identify this strategy in previous phases of this research. However, looking back at the comments we had obtained, we have strong reasons to believe that this phenomenon is not at all unique to this more modern plant. On the contrary, we believe it is an integral, albeit high-level, part of monitoring strategies in any type of control room design.

The Impact of Control Room Technology

By comparing the findings from this advanced control room from those that we had obtained in previous studies, we are able to develop some insights regarding the impact of control room technology on operator monitoring. Our results suggest that the primary differences between hard-wired instruments and computer-based displays lie in two factors, namely interface knowledge and strategies for creating/extracting information.

Interface knowledge. The impact of control room technology on operators' procedural and declarative interface knowledge is relatively straightforward. In a hard-wired control room, information is presented in a static, parallel form so the main requirement on operators is to know where all of the different indicators are located. In a computer-based control room, however, 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 i nformation 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 plant) to resolve the degrees of freedom offered by the flexible design of the interface. In summary, changes in control room technology have significant but relatively straightforward implications for procedural and declarative interface knowledge.

These differences in knowledge are intimately linked with differences in monitoring behavior. In a hard-wired control room, much of the work is done with the eyes (i.e., visual scanning). In contrast, with a computer-based control room, more of the work needs to be done with the hands as well (i.e., interacting with the computer to search for, and customize, displays). An important question is whether these differences result in a net benefit or decrement in performance. 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 in which 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. Deeper insight can be gained into this issue by comparing the strategies that operators use to create and extract information in hard-wired vs. computer-based control rooms. As we will see, differences in strategies turn out to be more subtle and more interesting than the differences in knowledge.

Strategies for creating/extracting information. The implications of control room technology for monitoring strategies can be captured by comparing the degrees of freedom in hard-wired instruments vs. computer-based displays. With hard-wired technology, the designer is required to make numerous decisions that are then frozen into the design (e.g., what variables to display, which variables to trend, where each variable should be located, how variables should be grouped together, what form the variables should be presented in, and so on). As a result, the intended design leaves no degrees of freedom for information presentation - everything is specified ahead of time. One way to think of this property is that the control room is intended to have only one "look", which does not change as a function of context.

The word "intended" is used because, as we have seen in previous phases of our research, in practice things are quite different. Because the control room is not tailored to operators' activities, monitoring can be a very difficult and demanding task. To reduce these demands to a manageable level, operators will adopt facilitating activities that try to contextualize the control room to make it fit their needs at the time. These facilitating activities have two important characteristics. First, they are accomplished by using means that are outside of those that are intentionally provided by the designer. At the older control room we observed in our first study, for instance, we frequently saw operators using post-its, creating external reminders, opening up strip chart recorder doors, and manipulating alarm setpoints on analog meters. *None of these means were anticipated or intentionally provided by the control room designers*. We will therefore refer to these as *extrinsic* facilitating activities. Second, these facilitating activities have the effect of opening up the degrees of freedom in the control room. Different facilitating activities are adopted at different times, so the control room no longer has one "look". Rather, it is made to have different looks depending on what the operator is currently doing. The significance of these two points can be made more clear by examining the degrees of freedom associated with computer-based displays.

Because of their flexibility, computer-based displays intentionally leave a considerable number of degrees of freedom to the operator. For example, at the modern control room we observed in this study, operators can: decide 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 operators 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.

There are several interesting implications that follow from these observations. First, when operators are required to perform a particular monitoring task, they now have flexibility that they can exploit to present information in a way that makes monitoring easier. When this occurs, the operator is using means that were intentionally provided by control room designers. For example, the fact that the computer-based display allows operators to change the range on a trend graph is a result of a deliberate decision on the part of a designer. Facilitating activities that are performed using such means can therefore be said to be *intrinsic*. Second, in a computer-based control room, intrinsic facilitating activities have the result of reducing, not expanding, the degrees of freedom. Operators do not use all of the flexibility offered by the interface. In the control room observed in this study, for instance, there are at least tens of thousands of different "looks" that the control room can have depending on what displays are brought up on what CRTs, and how those displays are configured. Intrinsic facilitating activities pick out one useful display configuration from the myriad of available possibilities, a configuration that makes the task at hand easier to perform.

So far, the discussion of the degrees of freedom in a computer-based control room has proceeded under the assumption that the flexibility offered by the designer is sufficient to tailor information presentation to facilitate monitoring. Our findings show that this assumption is not always valid. Operators using a computer-based display sometimes also have to resort to extrinsic facilitating activities because they cannot make monitoring easier within the capabilities afforded by the designer. In these situations, we see operators resorting to post-its, tags, and paper messages, just like the operators at older control rooms with hard-wired technology. Even in computer-based control rooms, extrinsic facilitating activities have the role of opening up the degrees of freedom intentionally provided in the design to reduce the demands associated with monitoring.

DISCUSSION

One of the more important findings from this study is that our model of operator monitoring needs to include workload regulation as a key ingredient in making monitoring more manageable. A revised model can be conceived as consisting of three nested loops. The lowest level loop comprises the *monitoring activities* themselves, of which there are various types (see Roth et al., 1997). The middle level loop comprises the *facilitating activities* that operators have cleverly adopted to make monitoring a more manageable task. These activities represent an outer, nested loop because they directly influence the performance of monitoring activities. Similarly, *workload regulation activities* represent an outer third loop that constrains both facilitating and monitoring activities. This higher level of control deals with issues such as setting priorities, scheduling jobs, and allocating personnel. The success of monitoring depends, to a great extent, on the decisions made at this outer level. If operators can effectively regulate their workload, then they will rarely put themselves in a position where errors will occur. If operators do not effectively regulate their workload, then errors are almost sure to occur, even if clever facilitating activities are adopted.

Newer operators find it very difficult to regulate their workload effectively because they receive no formal training and very little practice at more "mundane" non-emergency activities, particularly those dealing with work order requests. As a result, they have not yet calibrated themselves to the level of activity that they can reliably handle without significantly increasing the potential for error. Yet the effective regulation of activity (i.e., ensuring that current demands do not exceed existing resources) is critical to effective monitoring.

While the topic of workload regulation has not been very well addressed in the human factors literature in North America, it is a well-known phenomenon in the Francophone ergonomics literature in Europe (e.g., Sperandio, 1978). Given its importance to operator monitoring, the topic seems worthy of additional study.

Another important finding from this research is the impact that the control room technology can have on operator monitoring. Because they offer more possibilities, computer-based control displays require more interface knowledge than hard-wired displays. More interestingly, however, the strategies for creating/extracting information also differ as a function of control room technology. In hard-wired control rooms, designers decided ahead of time what variables to display, which variables to trend, where each variable should be located, how variables should be grouped together, what form the variables should be presented in, and so on. Thus, operators have to expand the degrees of freedom in the design to make the control room context-sensitive. In contrast, with the largely computer-based control room we observed in this study, the purpose of operators' strategies for creating and extracting information differs noticeably. Because of the flexibility of computer-based technology, information can be presented according to different groupings, in different locations, and in different formats. Thus, rather than expand the degrees of freedom associated with a fixed design, operators instead have to reduce the many degrees of freedom with which designers have provided them. These results show that the medium in which information is presented can have subtle influences on human performance, another factor that has not received the attention it deserves (cf. Gaver, 1996).

Given the formulation presented here, we can pose the following set of questions to further investigate the impact of control room technology on operator monitoring:

1. How much effort does it take for operators to resolve the degrees of freedom in a computer-based control room (i.e., to manage the interface), and how can this effort be reduced?
2. How much effort does it take for operators to expand the degrees of freedom in a hard-wired control room (i.e., to "finish the design"), and how can this effort be reduced?
3. Does reliance on extrinsic facilitating activities in a hard-wired control room lead to better or worse monitoring performance (i.e., reliability, workload, accuracy) than reliance on intrinsic facilitating activities in a computer-based control room?
4. What steps can be taken to ensure that the flexibility provided by designers in computer-based control rooms is of the type that operators require to facilitate monitoring?
5. Is there a significant difference between extrinsic facilitating activities in a computer-based control room compared to those in a hard-wired control room?

We are not able to answer these questions with the limited descriptive evidence we collected in this research. However, we offer the following speculative comment with regard to the final point. We suspect that extrinsic facilitating activities are more difficult to implement in a computer-based control room than in a traditional control room. Because the former is dealing with software rather than hardware, certain actions are more difficult or impossible to take. For example, in one of the cases we observed, an operator pulled a flashing light out of the panel because it was distracting him. If an analogous situation occurred with a computer-based display (e.g., one value among the several on the screen flashing), the same action could not be taken. The operator could of course remove the display from the CRT but then he might lose valuable information provided by the other non-flashing variables. Thus, it seems that computer technology can bring some benefits to operator monitoring, but some hidden costs as well.

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