Operator Monitoring during Normal Operations: Vigilance or Problem-Solving?

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Proceedings of the Human Factors and Ergonomics Society Annual Meeting 1997 41: 158
DOI: 10.1177/107118139704100137

OPERATOR MONITORING DURING NORMAL OPERATIONS: VIGILANCE OR PROBLEM-SOLVING?

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Monitoring during emergencies in dynamic environments is widely recognized to be an active, selective attention, process. In contrast monitoring during normal operations is often thought to more closely resemble a vigilance task. This paper describes a field study of power plant operator monitor during normal operations. We observed and interviewed 27 operators at two different plants for a total of over 200 hours. Despite differences in control room technology, we found that in both cases operators devised active strategies to remove or reduce meaningless changes from the interface, create information different from that intended by the designers, and make important information more salient. These findings were integrated into a model of operator monitoring, that emphasizes operators' use of strategies for knowledge-driven monitoring and proactive adaptation of the control room interface. The model is equally applicable for normal and emergency operations and underscores the commonality in cognitive demands in both environments.

INTRODUCTION

Monitoring during emergencies in complex dynamic environments (e.g., nuclear power plants; airplane cockpits) is widely recognized to be an active, selective attention, process that strongly depends on situation assessment (e.g., Orasanu, 1993; Roth, Mumaw & Lewis, 1994; Roth, 1997; Vicente et al., 1996; Woods, Wise, & Hanes, 1982; Woods, 1994). Less is known about monitoring during normal operations. A common assumption is that normal operations is a more placid environment and monitoring in those conditions more closely resembles a vigilance task. (See Moray, 1986 for a review of modeling approaches).

This paper describes a field study examining the motivations and strategies for monitoring during normal operations in a dynamic high-risk environment. The specific domain of application is Nuclear Power Plant (NPP) operations. The performance of NPP operators has long been recognized as a significant contributor to plant performance and safety. Historically, studies of operator performance have been placed in the context of emergency operations where the safety implications of operator actions are immediate (e.g., Roth et al., 1994). Little attention has been given to operator performance during normal operations where tasks are more routine. (See Mumaw, Roth, Vicente & Burns, 1995 for a literature review). However, a critical role for operators during normal operations is detecting the early signs of a problem. In order to prevent a transition to an abnormal plant state, operators need to determine that plant state indications are moving out of their normal ranges and then take appropriate actions to prevent further degradation. In order to better address how to develop improved interfaces and support systems for operator performance during normal operations it is important to have a deeper understanding of how operators monitor plant state during normal operation.

We conducted a field study to begin to fill in this gap in knowledge. The study was motivated by the desire of our project sponsor to gain a better understanding of operator monitoring strategies and practices during normal operation. There was particular interest in understanding the factors that contribute to failures to detect early symptoms of malfunctions. The assumption of the sponsor was that during normal operation plant state was quiescent, and that the monitoring required of operators resembled a vigilance task.

The study was conducted at two different Canadian plants, one with an older control room which is based almost exclusively on analog, hard-wired instrumentation, and another with a newer control room that has a slightly higher degree of computer-based technology.

Because we were interested in normal operations, and little was known about operator monitoring strategies and practices during normal operations, we chose to use an ethnographic approach to study the problem (Jordan & Henderson 1995; Sanderson & Fischer, 1994). We observed power plant operators as they went about performing their regular shift duties. The objectives were to identify established monitoring practices and to uncover undocumented techniques and strategies used to improve monitoring effectiveness during normal operations.

METHODOLOGY

The data collection was conducted in several iterative phases using a bootstrap approach.

We began with an unstructured set of on-site observations and interviews to familiarize ourselves with the operators' jobs. This first phase was conducted by two observers, each conducting independent observations in an older four-unit control room consisting primarily of analogue, hard-wired instrumentation. A total of 6 different operators were observed and informally interviewed, over the course of 10 different shifts spanning approximately 80 hours, including both day shifts and night shifts (See Mumaw, Roth, Vicente and Burns, 1995 for more details on the methods and results of this preliminary phase).

Based on these early observations we developed a preliminary model of the cognitive drivers of operator monitoring, the complexities in the domain that contributed to monitoring difficulty, and the strategies that operators had developed in response to facilitate monitoring (Mumaw et al., 1995).

In the next phase of the effort we attempted to collect additional observation and interview data to assess the validity and generality of our initial findings and preliminary model.

We returned to the first plant to determine whether our initial conclusions, which were based on a limited set of crews, would continue to hold when we expanded the sample of crews we observed. We also went into a second plant, with somewhat more advanced, computer-based, control-room interfaces, to assess whether the core findings regarding the cognitive drivers of operator monitoring, and the activities operators engage in to facilitate monitoring generalize across plants and interface technology.

First, we wanted to determine if the initial set of findings obtained in Phase 1 were specific to the few operators that we had observed or whether in fact those findings were representative of the operators as a group. To accomplish this goal, we circulated a report of our findings from the first phase (Vicente, Burns, Mumaw, & Roth, 1996) to operators. A total of 17 operators read the report. This provided operator feedback on their assessment of the validity and generality of the findings and interpretations.

We also collected additional observational data, on a new sample of operators at the plant using the results of phase 1 as a framework to guide and focus our subsequent observations and interviews.

The following set of issues provided the framework that guided observations and opportunistic interviews at the two plants:

1. Overview of the control room interface and information resources for the operator (with particular focus on alarms, computer-based displays and automation).
2. Plant or crew policy and procedures for guiding monitoring
3. The motivations for monitoring
4. Problems with control room technology or operation that complicate monitoring
5. Monitoring strategies
6. Operator interactions with the interface to support monitoring

Particular attention was placed on documenting and analyzing: (1) *critical* incidents (e.g., cases where actual equipment malfunctions occurred that led to plant shutdowns or threatened shutdowns) that illustrated the kinds of complexities that can arise in the environment and the kinds of monitoring strategies and facilitating activities that operators use to handle these situations; and (2) behaviors that represented *deviations exceptions from the canonical* descriptions of standard practice (e.g., cases where operator behavior differed from formally documented practices and procedures).

In the older control room, seven different operators were observed over eight different shifts on various units. This data collection phase consisted of a total of approximately 65 hours of observation conducted by two observers. In the newer control room, two observers each spent approximately 32 hours observing and interviewing 14 different operators over 10 different shifts. This allowed us to develop a deeper understanding of cognitive monitoring, while also providing some initial insight into the impact that computer-based technology might have on monitoring performance and strategies.

These additional observations and interviews largely supported our initial findings and model. We found a number of additional interesting specific cases that supported our earlier analysis, and identified additional types of problems and critical incidents that related to monitoring.

TASK DEMANDS: WHAT MAKES MONITORING DIFFICULT?

Contrary to the prevailing view of our sponsors, and our own initial expectations, we found that monitoring during normal operations was a complex, cognitively demanding task that was better viewed as a problem-solving task than a vigilance task. The challenge operators faced was not how to pick up subtle abnormal indications against a quiescent background. The challenge was how to identify and pursue relevant findings against a cognitively noisy background. As in the case of fault management during emergency operations, the cognitive demands involved data filtering and directed attention rather than vigilance (Woods, 1994). Before we discuss the strategies exhibited by operators it is important to discuss the task demands associated with cognitive monitoring that we observed. What makes monitoring difficult?

System Complexity and Reliability

Each unit consists of thousands of components and instruments. Even though the reliability of each individual component or sensor may be high, when there are so many of them, equipment failures are bound to occur on a regular basis. Furthermore, some of these failures can only be effectively repaired when a unit is shut down. Failures of this type that are not essential to the safe and efficient operation of the unit may therefore persist for a long time until there is an opportunity for repair. For all of these reasons there are always components, instruments, or subsystems that are missing, broken, working imperfectly, or being worked on. Despite this, the unit can still function safely.

Nevertheless, small failures or imperfections have very important implication for cognitive monitoring. More specifically, they change the way in which information should be interpreted. That is, whether a reading or set of readings is normal or abnormal depends very strongly on which components are broken, being repaired, or working imperfectly. The same set of readings can be perfectly acceptable in one context and safety threatening in another. Thus, the operational status of the unit's components provide a background, or context, for monitoring. Consequently, effective monitoring depends very heavily on an accurate and comprehensive understanding of the current status of plant components and instrumentation. This understanding can then be used to derive expectations about what is normal/abnormal, given the current state of the unit. These expectations then serve as referents for cognitive monitoring.

Design of Alarm System

Operators rely extensively on the alarm system, but deficiencies in the alarm system resulted in a 'noisy' environment, both literally, and from an information theoretic perspective. Nuisance alarms of various types abound. For example, some alarms are always on because the plant is not currently operated the way it was originally intended to be. Others appear because a certain component is being repaired, maintained, or not working perfectly.

Other Sources of Complexity

Other sources of complexity included characteristics of displays, controls, automation and procedures. Examples include meters whose needles stick or fail in positions, light bulb indications that burn out, deficient CRT displays, and automated systems that provide limited feedback. (See Mumaw et al., 1995 for a complete description.)

WHAT GUIDES OPERATOR MONITORING?

The results summarized above, highlight the complexities inherent in the monitoring task. Because of the large number of available data sources and complexity of interpretation, operators have to be selective in where they focus their attention. Some operator monitoring is guided by standard practices, plant policy, or plant procedures (e.g., check forms that need to be filled out, equipment tests that need to be conducted, activity logs that are maintained, shift-turnover briefings). Most monitoring activities are determined by the operators themselves and are strongly guided by their own knowledge of the plant and understanding of current plant state and ongoing activities.

We observed that operators developed active strategies to remove or reduce meaningless changes from the interface, create information different from that intended by the designers, and make important information more salient. These findings were integrated into a model of operator monitoring, that emphasizes operators' use of strategies for knowledge-driven monitoring and proactive adaptation of the control room interface.

Central to our model is the view that operator monitoring is strongly guided by a *situation model*. The situation model is a mental representation that integrates the operator's understanding of both physical and functional aspects of the plant state and systems. Operators engage in a number of cognitive activities which are governed by, and serve to update, a situation model. Operators begin by evaluating the input obtained from the initiating event. This then leads to a particular purpose for further monitoring.

Before monitoring activities can actually be performed, two additional cognitive steps must be undertaken. Operators must determine which data to monitor, how frequently they should be monitored, and how critical the monitoring task is. Then, they must find the data and develop a monitoring plan. This is accomplished by their knowledge of the interface, and frequently, by adopting strategies for creating/extracting information. The latter leads to ***Facilitating Activities*** which provide a set of options for configuring the interface or acting on the control room environment in other ways to make a specific monitoring task more easy.

Below we summarize some of the key elements of the model. A complete description of the model and extensive supporting examples can be found in Mumaw et al. (1996).

Situation Model

The Situation Model is a mental representation that integrates the operator's understanding of both physical and functional aspects of the plant state and systems. During an operator's training, he will develop a mental model of a somewhat idealized plant since basic training focuses on original plant design and theoretical foundations. Over time, as an operator becomes familiar with the plant through actual operation, his mental model will continue to evolve to better reflect the current plant (e.g., original systems may have been removed or replaced). Finally, the operator must adjust his mental model at the beginning of a shift by updating system status, operating mode, on-going maintenance activities, etc. This contextualized instantiation of the mental model, which we refer to as the Situation Model.

The Situation Model supports monitoring for *Situation Assessment* and monitoring for *Response Planning*. Situation assessment refers to the process of constructing an explanation to account for observations. Studies of operator performance show that operators actively develop a coherent understanding of the current state of the plant (e.g., Roth et al., 1994). Response planning refers to deciding on a course of action, given a particular situation assessment.

Situation Assessment

We identified five types of monitoring that support Situation Assessment:

1. Confirm expectations about plant state - The operator can have expectations regarding plant response (to a change in the system, etc.) or regarding unmonitored indications. In both cases, the operator has developed an expectation about some indications, and monitoring serves to obtain those indications to either confirm or disconfirm the expectation.
2. Pursue unexpected findings - A operator will occasionally encounter an indication that he believes to be valid but is unexpected. This will lead operators to actively direct monitoring to seek other indications that might help them understand the unexpected indication.
3. Check for problems considered to be likely - The operator is a central element of operations and is continuously aware of the set of activities being carried out on his unit. The operator understands that certain activities create the potential for problems (e.g., failures, human error), and he needs to be vigilant for those problems. Therefore, monitoring is actively directed to indications that can reveal the occurrence of a problem.
4. Validate initial indication - In general, the control room interface technology is not perfectly reliable, and operators are often unwilling to trust any single indication. Therefore, an operator will locate and monitor indications that can validate an initial indication.
5. Determine an appropriate referent for a specific indication - There are some cases in which the operator does not have a clear referent value for evaluating an observed indication. This referent is required to give meaning to the indication (e.g., normal or abnormal). When an appropriate referent is not provided with the indication, the operator must actively seek other indications to establish that referent.

Response Planning

We identified four types of monitoring that support response planning:

1. Assess goal achievement - operator actions are taken in order to achieve some operational goal. As a operator moves through a procedure, he needs to determine whether the intended goal is being achieved, and he must actively identify and monitor indications that can aid the assessment of goal achievement.
2. Assess the potential side effects of contemplated actions - An important activity for operators is ensuring that their actions and the actions of others working on the unit do not have unintended side effects. While the Situation Model is the primary tool for assessing the potential for unintended consequences, monitoring is required to support the mental simulation.
3. Assess means for achieving goals (i.e., evaluate process availability) - A related activity is assessing the availability of plant systems that can be used for achieving operational goals. In RP, the operator needs to consider the possibility that a process could fail and an alternative process would be required. Thus, active monitoring is needed to support the evaluation of process availability.
4. Obtain feedback on actions - As actions are taken, the operator needs to obtain feedback that the intended action was indeed carried out (e.g., the valve did close, the pump did start) and that relevant parameters are responding in appropriate ways (e.g., pressure is decreasing, level is increasing).

Facilitating Activities

There are a variety of effective strategies that operators have developed to compensate for limitations in the existing human-system interfaces, and reduce the cognitive demands associated with monitoring. These activities fall into several classes: (1) activities that are designed to enhance information extraction by increasing the salience of important indications and reducing the background 'noise'; (2) activities designed to create new information; and (3) activities designed to off-load some of the cognitive load onto the interface (e.g., creating external aids and reminders for monitoring). These results reinforce and expand on findings in other domains that stress the importance of the tailoring strategies developed by domain practitioners to compensate for limitations in system interfaces (e.g., Cook, 1996; Obradovich, & Woods, 1996; Watts, Woods, Corban, Patterson, Kerr & Hicks, 1996).

Below we present the classes of facilitating activities that we identified. Specific examples are documented in Vicente, Burns, Mumaw & Roth (1996).

1. Enhance signal - This is an action that serves to increase the salience or visibility of an indication or piece of information. It increases signal-to-noise ratio by improving the signal.
2. Reduce noise - This is an action that reduces or removes "noise" (i.e., meaningless change) from the indications. This also has the effect of enhancing the salience of meaningful indications by increasing signal-to-noise ratio.
3. Document baseline or trend - This is an action to document a baseline condition (e.g., beginning of the shift) or to establish a trend over a period of time for comparison to a later time. It creates a referent monitoring, so that state changes can be easily identified without having to rely on memory for the previous state.
4. Act on interface to determine the validity of an indication - In some cases, there may be questions about whether an important indication is valid (e.g., because it may conflict with some other information). One method to determine its validity is to use the

interface to look for evidence that the sensor and indicator are working properly.

5. Create new indication or alarm - The control room interface has a set of indications and alarms that are already defined. However, operators can modify the interface to create indications or alarms that did not exist before.
6. Create external reminder for monitoring - When it becomes important to monitor an indication frequently, the operator must somehow keep track of the monitoring task--that is, remember to monitor. This is an action to create an external reminder to monitor an indication.
7. Create external cues for action or inaction - External cues are also created to remind an operator about interface actions and configuration. In some cases, monitoring is supported by configuring the interface in a particular way, and that configuration needs to be preserved over a period of time. Operators create an external reminder that indicates that the special configuration is to be maintained.

CONCLUSIONS

The results of our study suggest that monitoring during normal operations is better cast as a problem-solving activity than as a vigilance task. Early models of monitoring (see Moray, 1986 for a review) typically cast monitoring as a task in which the operator is trying to track a large number of indications waiting for some event to occur. Instead, our work emphasizes the active, knowledge-driven role of the operator to seek information because he is trying to support situation assessment or response planning. Certainly, there is some element of vigilance and responding to indications in monitoring, but the data-driven aspects of monitoring are often just the initiator of knowledge-driven monitoring.

The empirical findings have been synthesized into a model of operator monitoring that emphasizes operators' use of strategies for knowledge-driven monitoring and proactive adaptation of the control room interface. The model applies to normal and emergency operations and underscores the commonality in cognitive demands in both environments (cf. Roth et al., 1994, Roth, 1997).

ACKNOWLEDGEMENTS

This work was funded by research contracts with the Atomic Energy Control Board of Canada. We wish to thank Les Innes and Felicity Harrison, who were the contract monitors, and the operators who participated in the study.

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