Theor. Issues in Ergon. Sci.
September–October 2004, vol. 5, no. 5, 359–384

# Operator monitoring in a complex dynamic work environment: a qualitative cognitive model based on field observations

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*Keywords:* Operator monitoring; nuclear power plant control room; attention cognitive modeling; process control; naturalistic decision making; human–computer interaction.

Complex and dynamic work environments provide a challenging litmus-test with which to evaluate basic and applied theories of cognition. In this work, we were interested in obtaining a better understanding of dynamic decision making by studying how human operators monitored a nuclear power plant during normal operations. Interviews and observations were conducted *in situ* at three different power plants to enhance the generalizability of results across both individuals and plants. A total of 38 operators were observed for approximately 288 hours, providing an extensive database of qualitative data. Based on these empirical observations, a cognitive model of operator monitoring was developed. This qualitative model has important theoretical implications because it integrates findings from several theoretical perspectives. There is a strong human information processing component in that operators rely extensively on active knowledge-driven monitoring rather than passively reacting to changes after they occur, but there is also a strong distributed cognition component in that operators rely extensively on the external representations to offload cognitive demands. In some cases, they even go so far as to actively shape that environment to make it easier to exploit environmental regularities, almost playing the role of designers. Finally, expert operators use workload regulation strategies, allowing them to prioritize tasks so that they avoid situations that are likely to lead to monitoring errors. These meta-cognitive processes have not received much attention in the human information processing and distributed cognition perspectives, although they have been studied by European psychologists who have studied cognition in complex work environments. Collectively, these findings shed light on dynamic decision making but they also serve an important theoretical function by integrating findings from different theoretical perspectives into one common framework.

## 1. Introduction

The history of science is replete with examples of fundamental discoveries that were derived by adopting practical problems of social significance as a vehicle for research. Perhaps one of the most salient examples is Louis Pasteur's discovery of the germ theory of disease. This work represents a landmark contribution to basic science, but much of the work was conducted in the context of practical

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*Theoretical Issues in Ergonomics Science* ISSN 1463–922X print/ISSN 1464–536X online 
http://www.tandf.co.uk/journals
DOI 10.1080/14039220412331298929

problems, such as improving the technology of fermentation and preventing the spoilage of foods and drinks (Stokes 1997).

The same approach has been adopted with great success in cognitive science, albeit infrequently. Perhaps the most notable example is Hutchins' (1995a, 1995b) work on distributed cognition. That research was conducted in a practical context, namely maritime navigation on board U.S. Navy ships. However, the primary goal was to make a fundamental contribution to cognitive science, not to solve a practical problem. The strong influence of Hutchins' work on the cognitive science community shows that practical problems can provide a productive stimulus for discovery. Such problems provide a litmus test for existing theories of cognition (Gibson 1967/1982), and can lead to new theories that are more comprehensive in scope.

Complex dynamic work environments can play this function in fundamental research in cognitive science and cognitive engineering (Patel *et al.* 1996). They provide rich settings in which many processes of interest to basic researchers can be studied (e.g., monitoring, perception, attention, diagnosis, problem solving, decision making, planning, expertise). In this article, we focus on one particular complex dynamic work environment – human operator monitoring in nuclear power plants – and use it as a litmus test of some existing theories in cognitive science. In previous phases of this research program, we conducted a number of field studies of operator monitoring under normal operating conditions (Vicente and Burns 1996, Mumaw *et al.* 2000, Vicente *et al.* 2001). In this article, we integrate those field data into a qualitative cognitive model of this phenomenon. This model brings together, under one framework, aspects of human cognition that have been emphasized by different theoretical approaches (e.g., human information processing, distributed cognition), and which thus, have not yet been integrated theoretically in the literature. Accordingly, the primary contribution of this research is to take a small step towards a more comprehensive and integrated theory of human cognition that is relevant to applied concerns.

The remainder of the article is organized as follows. In section 2, the field studies that provided the empirical foundation for the modeling effort are summarized. In section 3, a qualitative cognitive model of operator monitoring is presented. The different categories are explained and a few examples of how the model captures operator activity are presented. In section 4, the relationship between this model and related work in cognitive science and cognitive engineering is explained.

## 2. Empirical foundation for modeling: field research

The model presented later is based on qualitative data collected from several field studies of operator monitoring in nuclear power plants. The methodology, results, and applied contributions of those field studies have already been described in detail elsewhere (Vicente and Burns 1996, Mumaw *et al.* 2000, Vicente *et al.*, 2001). Therefore, in this article, we merely provide a summary account of these field studies to serve as the context for interpreting the detailed description of the model in the next section.

### 2.1. *The field setting: nuclear power plants*

Nuclear power plants are complex dynamic work environments that impose very challenging demands on human cognition. The plants themselves are composed of literally thousands of different components. There are many interactions between components, making it difficult for operators to anticipate all of the side effects of their actions. In addition, the behavior of the plant is dynamic. Even if operators feel mentally overwhelmed and want to take a break, the pace of events is externally determined, so operators must try to keep up. The dynamics also have lags, which means that operator and machine actions do not have immediate effects. Operators must learn to anticipate by timing their actions appropriately to have the desired effect. Being too late or too early can result in a failure to achieve important tasks. Furthermore, operators have to cope with both normal and abnormal operations, on-line in real-time. Failure to cope with abnormalities effectively can pose tremendous threats to the public and the environment. This great hazard potential puts a heavy burden on operators. There is also a great deal of uncertainty about the true state of the plant because of incomplete and noisy information. Sensors sometimes fail, some goal-relevant information cannot be sensed, and even under the best of circumstances, sensors have measurement error. This uncertainty complicates the cognitive process of situation assessment. Finally, the plants that we studied are also highly automated which, paradoxically, can also introduce an element of complexity. Most of the time, the operators work in a supervisory control mode (Sheridan 1987), monitoring the status of the plant while it is being controlled by automation. This task is challenging because operators are not actively in the loop controlling the plant. Nevertheless, they must try to be attentive and make sure that the plant and automation are both behaving as intended and as expected. These daunting cognitive demands are typical of those associated with other complex, dynamic work environments, such as aviation, medicine, and petrochemical processes (Woods 1988, Vicente, 1999).

### 2.2. *The human-machine interface: control room designs*

The operators we studied worked in the main control rooms of their respective plants. These control rooms provide literally thousands of displays, controls, and alarms that operators can use to do their job. In each of the three plants we visited, the main control rooms had four control units (each controlling its own nuclear reactor). Figure 1 shows the panels on a single unit from the newest of the three plants we studied. A single operator runs each unit, although there are other workers in the control room and out in the plant serving support roles.

The control room for each unit consists of stand-up control panels, displays and alarm overviews, an operator desk, several printers, and bookshelves for procedures and other operations documents. In the two older plants, the control panels are made up primarily of traditional analog meters, strip-chart recorders, and control devices, whereas in the newest plant (shown in figure 1), there is a greater reliance on computer technology to display information. Alarms (primarily those that are safety-related) are presented as a series of tiles at the top of the control panels that light up and provide an audio tone if an alarm condition occurs. Some instrumentation is located outside of the main control room.

### 2.3. *The task: monitoring under normal operations*

Operators in nuclear power plants encounter many different types of situations and are responsible for many different tasks. To provide a focus for our research, we chose to study how operators monitor the plant during normal operations.

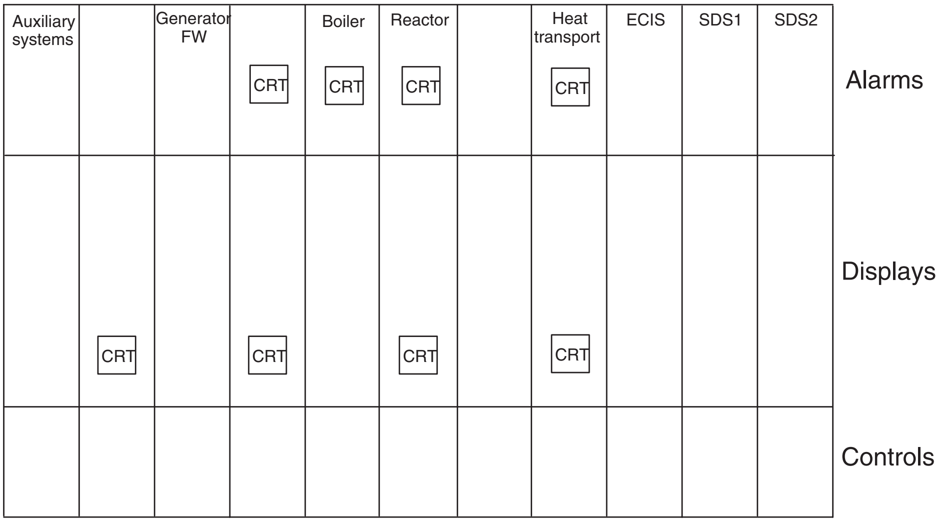


Figure 1. The main control room for one of the nuclear power plants we studied.

The primary reason for doing so was that most of the previous work in this area had studied operators during abnormal conditions (e.g., Roth *et al.* 1992, Vicente *et al.* 1996). This emphasis is understandable given the safety-critical nature of these plants, but the unintended side effect was that little was known about normal operations.

At the same time, studying monitoring under normal operations also provided us with an opportunity to study various cognitive processes that are of interest to basic researchers. One hypothesis we had was that the primary challenge to monitoring is operator vigilance. After all, large-scale accidents, such as those that occurred at Three Mile Island and Chernobyl, are rare, leading to an often-heard characterization of process control tasks as '99% boredom and 1% sheer terror'. Minor failures occur more frequently but are still relatively rare. An alternative hypothesis was that the primary demands in monitoring relate to selective attention. Given that a nuclear power plant control room consists of thousands of indicators, one might think that the difficulty is in choosing what to attend to and what to ignore – virtually impossible selective attention task. A third hypothesis was that the major difficulty in monitoring is one of visual perception. Because the control room is so large and consists of so many instruments, the key to monitoring may be to develop the visual acuity and discrimination skills that are required to detect changes and read indicators accurately. As the remainder of this article shows, none of these hypotheses does justice to the richness of the phenomena we observed. Although vigilance, attention, and visual perception are all relevant issues, we found that there is much more to monitoring than meets the eye.

### 2.4. *Methodology: observation and interviews in situ*

Interviews and observations were conducted *in situ* at three different nuclear power plants to enhance the generalizability of results across both individuals and plants. A total of 38 operators were observed for approximately 288 hours, providing an extensive database of qualitative data.

The methodology that we used was iterative and informal, in keeping with the qualitative and descriptive nature of a field study approach (Lorenz 1973). Initially, our observations were open-ended. Several different operators were observed over a period of approximately 8 hours out of a 12 hour shift. Both day and night shifts were sampled. The goal in this initial phase of data collection was to get an overall understanding of the work environment, leading to a preliminary model of operator monitoring. Additional observations were then made at the same plant using a somewhat more focused set of issues based on the understanding developed in the earlier phase. In particular, we were interested in seeing if the categories in the preliminary model were able to account for the events we observed. Modifications and additions to the model were made, as necessary. More observations were then made at two other plants to test for generalizability across operators and plants. The methodology was similar to that used in the first plant. Again, modifications and additions to the preliminary model were made, as necessary. The final research product was a qualitative cognitive model of operator monitoring that accounted for the activities of dozens of operators observed over hundreds of hours across three different plants with varying levels of computer technology.

## 3. Qualitative cognitive model of operator monitoring: overview

### 3.1. *Major elements*

The Operator Monitoring Model is shown in figures 2 and 3. Each of these two figures represents one half of the complete model; the right side of figure 2 connects to the left side of figure 3. The model is in the language of the nuclear domain because it was intended to be used as an organizing framework for the findings from our field studies.

The model has four major elements: initiating events, cognitive activities, facilitating activities, and monitoring activities. *Initiating events*, represented at the left-most side of figure 2, identify the three types of triggers that initiate monitoring. Some of these triggers are periodic (i.e., not tied to the occurrence of a specific event) and others are directly related to a particular event, such as an alarm. Once initiated, monitoring can be sustained over an indefinite period, or it can be altered and adapted via the various paths through the model. Also, multiple initiating events may be in effect at the same time, requiring the operator to time-share several monitoring activities.

The *cognitive activities* are those activities inside the large, shaded box in figure 2 – activities outside of this box are interactions with the 'world' (the control room interface, the plant, other personnel, etc.). The cognitive activities, which are in the smaller rectangular boxes, are action statements (i.e., verb–object form). Various types of knowledge that serve as inputs to the cognitive activities are shown in three ellipses. A major element that drives cognitive activities is the situation model, which is represented by the ellipse at the upper-left side of the cognitive activities box. The cognitive activities are used to identify the data that should be monitored, determine the priority and frequency of monitoring, and determine how that monitoring can be achieved.

Figure 3 shows the two remaining activities. *Facilitating activities* are actions taken by the operator to facilitate monitoring; these activities 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 easier. In some cases, facilitating

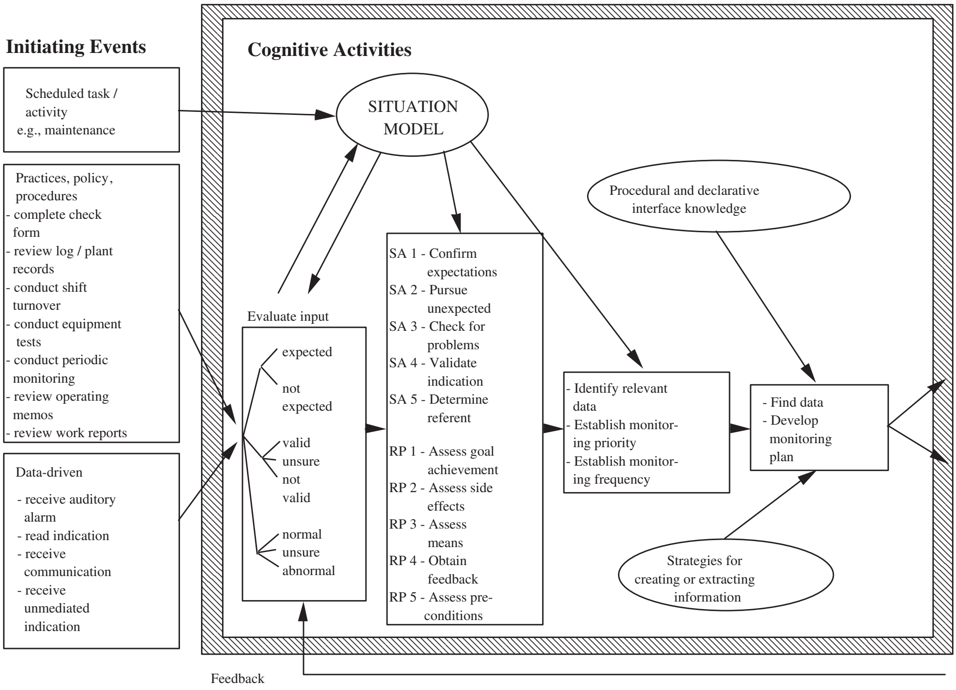


Figure 2. Left half of the operator monitoring model.

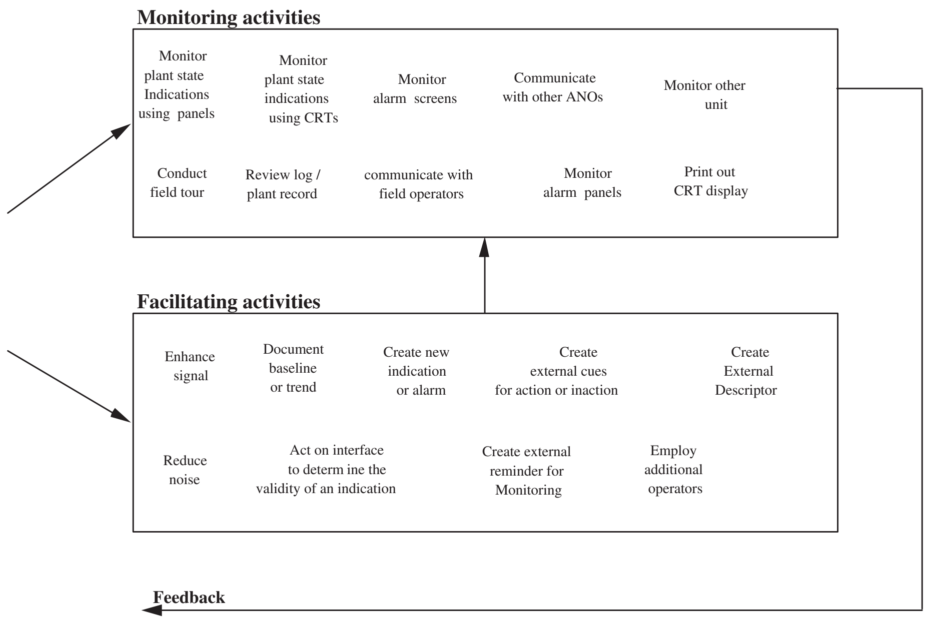


Figure 3. Right half of the operator monitoring model.

activities are not needed, and the operator can directly select an appropriate monitoring activity.

The *monitoring activities* box shows the set of resources for monitoring. The operator must select one or more of these resources to actually obtain an indication.

The set of resources listed in figure 3 represents all of the options that are available in the three control rooms we observed in our field studies. Note also that there is a feedback loop from monitoring activities to the input to cognitive activities. This feedback loop allows the operator to update the situation model after monitoring and either maintain monitoring or adapt it according to new requirements.

This brief overview of the major elements of the model is expanded in section 4 to provide a more detailed account of how the model works. Prior to that expanded account, however, it is important to describe more fully the situation model, which plays a major role in the cognitive activities box.

### 3.2. *Situation model*

The *situation model* is an incomplete mental representation that integrates the operator's current understanding of the state of both physical and functional aspects of the plant and the automated control systems. This model supports a number of general cognitive activities:

- it captures the operator's knowledge of the plant's physical systems and their characteristics and interconnections;
- it supports the operator in developing cause-and-effect relationships in explaining plant behavior and indications;
- it supports the operator in integrating separate indications and accounting for all data;
- it aids the operator in generating expected values (with more or less precision) for unmonitored parameters;
- it aids the operator in developing a description that captures plant state at a higher level than individual indications (i.e., system performance, process performance, goal achievement, etc.);
- it allows the operator to 'run' mental simulations of the plant to anticipate future states of the plant, or to evaluate plant performance under various configurations.

As shown in figure 4, an operator's training will develop a mental model of a somewhat idealized plant during basic training, which 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 up-to-the-minute mental model is what we refer to as the situation model that plays such a prominent role in monitoring.

Another important input into the situation model is episodic knowledge (Tulving 1983), which captures real and simulated operating experience with the plant. Episodic knowledge should be contrasted to knowledge of facts and static relationships, such as 'valve 29 is a motor-driven valve,' 'system x connects to system y at valve 23'. Episodic knowledge captures dynamic aspects of the plant, such as 'a large LOCA produces symptoms first in the x indications', 'it takes roughly x seconds before there is a noticeable response after taking the x action'. This type of knowledge comes from actual operating experience and from training scenarios. The training scenarios in the full-scope simulator are important because they may be the only source for this type of knowledge about certain abnormal events. Thus, both

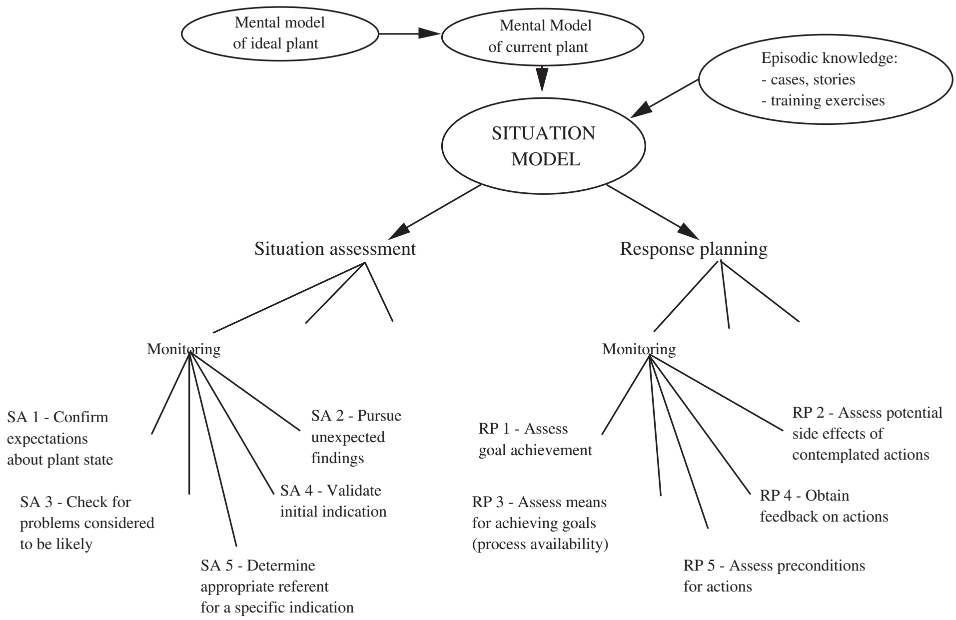


Figure 4. Role of the situation model.

episodic and declarative knowledge are critical in developing a situation model that supports the full range of cognitive activities listed above.

At a high level of description, all operator cognitive activity can be split into situation assessment and response planning. As figure 4 shows, the situation model supports both of these activities. *Situation assessment* refers to the process of constructing an explanation to account for observations. Studies show that operators actively develop a coherent understanding of the current state of the plant (e.g., Roth *et al*. 1994). Situation assessment is similar in meaning to 'diagnosis' but is broader in scope. Diagnosis typically refers to searching for the cause(s) of abnormal symptoms (e.g., a malfunctioning piece of equipment). Situation assessment encompasses explanations that are generated to account for normal as well as abnormal conditions.

We believe that some monitoring activities serve this situation assessment activity. Note that, in figure 4, there are placeholders under situation assessment for other unspecified activities that comprise situation assessment. We have chosen to restrict our scope by leaving those unspecified. However, all of the categories listed in figure 4 were observed during our field studies. We have identified five types of monitoring that support situation assessment (SA).

1. *Confirm expectations about plant state (SA1)* – 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 disprove the expectation.
2. *Pursue unexpected findings (SA2)* – an operator will occasionally encounter an indication that he believes to be valid but is unexpected. In these cases, the operator will actively direct monitoring to seek other indications that might help him understand the unexpected indication.

3. *Check for problems considered to be likely (SA3)* – the operator is a central element of plant operations and is continuously aware of the set of maintenance, test, and repair activities being carried out on his unit. The operator understands that certain activities create the potential for particular problems (e.g., a particular malfunction in a system, or a vulnerability to a particular type of error), and he needs to be vigilant to such problems. Therefore, monitoring is actively directed to indications that can reveal the occurrence of a likely problem.
4. *Validate initial indication (SA4)* – in general, control room and interface technology are not perfectly reliable, and operators are often unwilling to trust any single indication. Therefore, an operator will sometimes locate and monitor indications that can validate or invalidate the veracity of an initial indication.
5. *Determine an appropriate referent for a specific indication (SA5)* – there are some cases for which the operator obtains an indication but does not have a clear reference value for the indication. The reference value serves 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* refers to deciding on a course of action, given a particular situation assessment. In general, response planning involves identifying goals, generating one or more alternative response plans, evaluating the response plans, and selecting the response plan that best meets the goals identified. In general, operators have formal written procedures that guide their response, but studies show that operators do not execute procedures purely on faith (Roth *et al.* 1994). Operators continue to identify appropriate goals based on their own situation assessment, evaluate whether the actions they are taking based on the procedure are sufficient to achieve these goals, and adapt the procedure to the situation if they decide it is necessary to do so. As shown in figure 4, we have identified four types of monitoring that support response planning (RP).

1. *Assess goal achievement (RP1)* – operator actions are taken in order to achieve some operational goal. As an 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 (RP2)* – an important activity for operators is ensuring that their actions, and the actions of others working on the unit, do not have side effects (unintended consequences). 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) (RP3)* – an activity related to the previous activity (RP2) is assessing the availability of plant systems that can be used for achieving operational goals. In response planning, 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 (RP4)* – 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). Active monitoring is required to obtain this feedback.

5. *Assess pre-conditions for action (RP5)* – In some cases, particular actions can only be taken after certain pre-conditions are satisfied. Thus, operators will monitor the plant with the specific intent of assessing the status of those pre-conditions.

These nine types of monitoring are all various forms of knowledge-driven monitoring that are generated from the situation model. Top-down, knowledge-driven monitoring can be contrasted to bottom-up, data-driven monitoring. *Data-driven monitoring* is affected by the form of the information, its physical salience (size, brightness, loudness, etc.) and its behavior (e.g., bandwidth and the rate of change of the information signal) (Moray 1986). For example, a signal that is changing rapidly may be sampled more frequently by the observer. In the extreme, this type of monitoring can be viewed as 'passive' in that the operator's monitoring behavior is driven solely by the characteristics of the information. *Knowledge-driven monitoring*, on the other hand, can be viewed as 'active' monitoring in that the operator is not merely responding to characteristics of the environment that 'shout out', but is deliberately directing attention to areas of the control room environment that are expected to provide specific information that can be used to achieve specific goals. These specific goals are captured by the nine types of monitoring enumerated above and illustrated in figure 4. We will return to this distinction again later, as we describe the operator monitoring model in more detail.

## 4. Qualitative cognitive model of operator monitoring: overview: detailed description

Our description of the model will follow the layout from left to right in figures 2 and 3, beginning with initiating events, followed by cognitive activities, facilitating activities, and finally the monitoring activities themselves. At the end of this section, we will also show how the concepts in this qualitative cognitive model capture the activities in two specific instances of monitoring practice that we observed in the field. Because our model is in domain specific terms (in contrast to frameworks, like cognitive work analysis (Vicente 1999), which are stated in domain-independent terms), we would expect the detailed behaviors it represents to differ across domains. However, the general types of activities and the cognitive functions they support have the potential to be generalized across other domains of expertise (see section 6).

### 4.1. *Initiating events*

We have identified three types of triggers that initiate monitoring. The first category, *data-driven* events, are not actively sought by the operator, but are rather prompted by changes in the environment. Four cases of this category were noted:

- *Receive auditory alarm* – when an alarm is triggered, an auditory signal is emitted in addition to a visual indication of the alarm. Thus, the control room interface 'alerts' the operator that a significant event has occurred. The operator obtains the alarm message, and must now evaluate the meaning and importance of the alarm.
- *Read indication* – as an operator scans the control room interface (e.g., a panel of meters) to locate a particular indication, he/she may unintentionally read other indications in the same area. There are cases in which one of these

indications 'jumps out' at the operator. Often, the operator notices an abnormal or unusual reading.

- *Receive communication* – there are many other people involved with running and maintaining a unit, as well as equipment common to all units. These personnel (e.g., field operators, maintenance workers) may identify a situation that they want to let the operator know about. The operator can receive a communication from these other workers by phone, in person, or by radio transmission.
- *Receive 'unmediated' indication* – the designers of the plant have placed sensors throughout the plant to measure various aspects of the process performance (e.g., pressure, temperature). These sensors are ultimately connected to indicators on the control room interface. Thus, the sensed information is mediated by technology and brought to the interface. However, there are cases in which the operator receives information through his own senses (vision, hearing, feeling, smelling) instead of through the interface (Vicente and Burns 1996). This information is not 'mediated' by technology.

The second category of initiating events shown on the left of figure 2 are those that are defined by *standard operator practices, plant policy,* or *plant procedures*. In general, these events are designed to ensure that operators stay in touch with the state of the plant. Typically, these are events that are required periodically. Note that these are considered knowledge-driven. The full set of initiating events in this category are:

- *Complete check form* – check forms are used periodically by field operators to document the status of certain variables. To fill out these forms, field operators must go out into the field to see the information and the component. These forms are subsequently reviewed by the operator in the main control room, enabling him/her to monitor parameters in the field indirectly.
- *Review log/plant records* – the log is a hand-written, chronological record of notable activities (not necessarily abnormal) that have occurred during a shift, and can include tests completed, significant alarms, deficiency reports, work permits, jumpers, changes in reactor power, which channels were refueled, pieces of equipment taken out of service, etc. This is a short-term record of the unit's history, as opposed to the longer-term events logged in the long-term status binder. The log is reviewed during the shift turnover, but it can also be consulted during a shift to remind the operator of what had been done on the previous or even earlier shifts. The log provides a means by which operators can be aware of the recent status of a unit (e.g., what components are not working, which meters are not working, what is currently being repaired, etc.). This provides a valuable context for monitoring and interpreting information on a shift.
- *Conduct shift turnover* – an operator arrives in the control room approximately 15 to 30 minutes before his/her shift is scheduled to begin. At this time, he/she conducts a shift turnover with the operator he is relieving. The turnover consists of several activities. Perhaps most importantly, there is a discussion between operators regarding the state of key variables, any unusual alarms, jobs completed and jobs outstanding, plans that are active, variables that need to be monitored more closely than normal, which field operators or technicians

are working on which components, what the field operators are aware of, any significant operating memos, and a review of the log. After these discussions, the operator coming on shift will also look at the call-up sheets to see what tests are scheduled for that shift, and the daily work plan that documents upcoming maintenance and call-ups. He/she will also review the computer summaries and alarms. At this point, the operator will try to explain every alarm until he/she has a satisfactory understanding of why these alarms are in. Operators are also required to execute a formal panel check procedure that involves following a check sheet that requires making checks of specific values on the control panels to determine whether they are in an acceptable state. Some operators were also observed to conduct an informal panel walk-through before beginning the required turnover activities. They would walk by the panels and quickly scan them to get a general feel for the status of the unit and review any tags. Finally, operators who were not intimately familiar with a particular unit would review the long-term status binder that documents the 'quirks' of that unit.

- *Conduct equipment tests* – a number of equipment tests are scheduled on every shift. The purpose of these tests is to ensure that back-up systems and safety systems are in an acceptable state, should they be required. These tests provide operators with a means by which they can monitor the status of these systems (e.g., which safety systems are working properly, how quickly they are responding, which meters are working, etc.).
- *Conduct periodic monitoring* – a standard operating practice is to conduct a review of plant indications on a regular basis. Operators can scan the control panel and CRT indications from their desks, or they may walk down the panels on a periodic basis.
- *Review operating memos* – a tag is placed on a control to indicate that a temporary procedure has been developed to govern that control device. This temporary procedure is either not yet in the procedure manual, or it temporarily supersedes the procedure in the manual. Operators review the new operating memos early in a shift.
- *Review work reports* – work reports describe major maintenance and testing activities on a unit. The operator needs to be aware of these activities because they can remove equipment from operation or set up other situations that may make some safety systems temporarily unavailable. Also, the operator must be concerned with violations of the technical specifications, which can result from interactions between multiple work activities.

The third category of initiating events in the top left of figure 2 are *scheduled tasks and activities* that are to be carried out on the unit or on another unit. The operator is made aware of maintenance and testing activities, which are a daily occurrence, as well as control room activities, such as refueling, equipment upgrades, etc. These activities become incorporated into the operator's situation model and establish expectations of what is 'normal' for the shift.

### 4.2. *Cognitive activities*

The model illustrated in figure 2 shows that the initiating events can prompt monitoring in two ways. First, when an initiating event occurs due to practices, policy, procedures or due to a data-driven signal, the operator obtains some information from the control room interface. At this point, a cycle of cognitive activities begins. As shown by the evaluate input box, the information is evaluated in several ways, seemingly in parallel: was it expected or not expected? Is it valid, clearly not valid, or is there uncertainty about its validity? Is the indication in the normal range, abnormal, or is it unclear whether it's normal? There may be other evaluations also being applied, but these three are the ones we identified through our interviews.

This input evaluation is guided by information from the situation model, as shown by the arrow from the situation model ellipse to the evaluate input box. For example, an alarm may appear regarding fuel channel outlet temperatures. Because the operator's situation model shows that refueling is on-going, this alarm is expected; it is an indication that refueling is progressing as planned. The arrow from the evaluate input box to the situation model ellipse represents an update to the situation model with the just-acquired, just-evaluated information.

The second way in which initiating events initiate monitoring is via the scheduled task/activity box, which is connected directly to the situation model. When monitoring is initiated by a scheduled task/activity event, the first step involves updating the situation model rather than evaluate input. For example, the operator is told that a certain component will be removed for service for the next four hours. This information is incorporated into the situation model to refine the knowledge of what is normal and what is expected. Also, the operator will continue to test the internal coherence of his situation model. If this new information conflicts with existing knowledge, the operator will work to resolve the conflict.

Thus, these two paths from initiating events always lead to updates to the situation model, and the first path leads to an initial evaluation of information that was obtained by the operator. These paths then converge to identify an appropriate type of knowledge-driven monitoring (SA1–A5 and RP1–P5). The nine types of monitoring that were defined earlier represent, we believe, the complete set of motivations for monitoring at this stage of the model. Note that some of these are tied to the evaluate input box. For example, SA4 (validate initial indication) is needed when the evaluate input box determines that the initial indication may not be valid (unsure). Monitoring takes on the role of locating and obtaining additional indications that can establish the validity of the initial indication. As a more specific example, an alarm may come on that is unexpected and abnormal, but the operator is unsure about its validity. The situation model is used to make these judgments and is updated to reflect the new alarm. Next, the operator initiates monitoring (knowledge-driven) to better assess the validity of the alarm.

Other types of monitoring are tied more closely to the situation model. For example, SA3 (check for problems considered to be likely) may be a response to a scheduled activity that the situation model reveals can often lead to the failure of a particular piece of equipment. Thus, the operator initiates monitoring (again, knowledge-driven) to keep a vigil on the status of that piece of equipment so that if it fails, the failure will be detected early.

No matter which type of monitoring is selected, the operator needs to make a series of other decisions before actual monitoring activities can commence. As the next rectangular box in figure 2 shows, the next set of decisions has to do with establishing which data and monitoring priority and frequency. The situation model is used to identify the data or indications that are most relevant to monitor, given the monitoring goal. For example, if the objective is to validate an initial indication, the operator needs to identify back-up indications that measure the same process.

Decisions regarding priority reflect the importance of the task being supported by monitoring. For example, if a safety system-related alarm has come in and was unexpected, monitoring to better understand the nature of the alarm violation is likely to be assigned a high priority, pushing aside all other tasks. On the other hand, monitoring that supports tracking the progress of a simple, low-risk system test may be assigned a low priority, conducted only as time permits.

The decision about monitoring frequency determines how often some monitoring should be done – e.g., every 5 seconds, every 2 hours, once per shift. The operator will use knowledge of how quickly relevant indications change. If significant changes can occur rapidly, a higher frequency is required. If, on the other hand, the possible rate of change is severely limited, monitoring frequency can be low. There is an extensive literature on this topic (Moray 1986).

The next rectangular box in figure 2 identifies two other decisions that need to be made before monitoring begins. These decisions are guided by different types of knowledge, which are also shown in the figure. First, the operator needs to determine where to find the data or indication: is it on the control panel, on a CRT display, at some local control station so that a call to a field operator is required? The operator has detailed knowledge of the control room interface. The ellipse titled procedural and declarative interface knowledge includes the following types of information:

- the set of indications available (declarative);
- the location of indications (declarative);
- how to read indicators, how they work, and how they fail (procedural);
- how to access and configure CRT displays (procedural).

In addition to knowing the location of an indication and how to acquire that indication, the operator also needs to develop a plan for how to execute the monitoring effectively. The operator has knowledge (represented by the strategies for creating and/or extracting information ellipse) about effective methods for monitoring. That is, the operator has a set of skills that can be used to monitor the relevant data with the appropriate priority and at the appropriate frequency. The operator develops a plan that may require manipulating the interface to facilitate monitoring, or it may simply identify what to monitor and how frequently.

For example, we found that operators can define a range of approaches and select a specific approach based on priority, frequency, and resources available. At one extreme, the operator can monitor a parameter himself (or assign another person to it) at a very high frequency (almost continuously). If the operator places the parameter on a CRT-based trend display, changes become easier to see, and the monitoring effort is reduced so that other tasks can be time-shared. Finally, the operator might set up some type of alert, such as an auditory cue that indicates the parameter passed a setpoint. This last case is like setting an alarm on a parameter for a operator-defined event, and this case requires the least operator resources for monitoring – in effect, the interface will alert the operator that something important has happened. Whatever approach is adopted, the plan leads to actual operator actions on the control room environment and takes us out of the cognitive activities box and into figure 3.

4.3. *Facilitating activities*

We identified a set of activities that operators use, not to monitor *per se*, but to make monitoring more effective. We believe that this is one of the more significant findings from this research: operators actively configure the interface to facilitate their monitoring of important indications. A description of each facilitating activity and brief examples of its use are described next (Mumaw *et al*. 1995, 2000 contain a larger set of examples).

1. *Enhance signal* – this action serves to increase the salience or visibility of an indication or piece of information. It increases the signal-to-noise ratio by improving the signal.
   *Example*: at one plant, we found that operators would expand the fuel channel outlet temperature trend graph on the CRT to better monitor small changes in temperature. Normally, an indication is assigned to a single trend line on the CRT, which has a range of half the height of the display. Some operators would expand the trend so that it covered the full height of the display, and therefore, create a more salient trend graph. In this way, small changes in temperature, which are associated with refueling actions, are more easily discerned on the trend graph because they result in a larger change on the display.
2. *Reduce noise* – this action reduces or removes noise (i.e., meaningless change) from the complete set of indications. It too has the effect of enhancing the salience of meaningful indications by increasing signal-to-noise ratio.
   *Example*: the most common example of noise reduction were the frequent operator battles with nuisance alarms. In one case, we found the same alarm appeared six times in approximately 15 minutes, and the operator indicated that the message was not meaningful. One action operators can take to reduce a nuisance alarm is to change the alarm settings temporarily. This action typically requires permission from control room management.
3. *Document baseline or trend* – this action documents a baseline condition (e.g., beginning of the shift) or establishes a trend over a period of time for comparison to a later time. It provides a concrete description of plant state at a point in time so that later changes can be more easily identified since it is difficult to monitor all indications and their changes. Thus, it creates a referent for evaluating changes over time.
   *Example*: the most common example of this facilitating activity was that operators typically obtain a hard copy of several CRT displays at the beginning of the shift. At one plant, we found that operators typically printed the following types of displays when they would come on shift: the plant schematic diagram, zone deviations, and boiler level control status. Then, if they thought these values changed later in the shift, they could compare current values to the values printed at the start of the shift.
4. *Act on interface to determine the validity of an indication* – in some situations, 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.
   *Example*: in one situation we observed, an operator had just finished refueling and a channel outlet, narrow-range, temperature alarm failed to clear. This alarm might mean that there is an out-of-range temperature or that the indication is

not valid. The operator had just been trending the outlet temperature, which moved over a wide range, and therefore inferred that the sensor was 'alive'. He then called up the actual value and found that it was in the normal range. Then, he used his knowledge of how the alarm is triggered to decide that the indicated value was valid and the alarm logic was responsible for the delay in clearing. Thus, he used his interaction with the changing indication to determine its validity.

5. *Create new indication or alarm* – the control room interface has a set of indications and alarms that are already defined. Sometimes, an operator modifies that interface to create indications or alarms that did not exist before.
   *Example*: We saw several cases where operators created new alarms to aid monitoring. In one case, operators changed the setpoint on the heat transport storage tank level alarm to monitor draining that tank. Normally, the alarm setpoint is high, and the tank level is maintained around 75%. When the unit is being shut down, however, the tank is drained down to around 50%. The draining is a fairly slow process, occurring over several hours. Instead of having to remember to monitor the process over this period, operators will instead adjust the alarm setpoint down to around 55%. By doing so, an auditory alarm will be generated just before the tank reaches the desired value of 50%. This alarm then serves as a reminder to begin monitoring and controlling draining more closely. In this way, operators have defined a new event that is alarmed so that monitoring can be conducted less frequently and more reliably.
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 facilitating action creates an external (i.e., something in the world, not in the head) reminder to monitor an indication, thereby reducing the load on short-term memory.
   *Example*: At one plant, we found that operators would open a door on a particular strip chart recorder to make it stand out from the other recorders when it is important to monitor that parameter more closely than usual (e.g., open doors on feedtrain tank levels while blowing down boilers). The open door serves as an easily recognized and very salient external reminder to monitor that strip chart.
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.
   *Example*: At one plant, there is a set of analog automatic control devices in a row on one of the control panels. These controllers are normally set on auto mode, instead of manual mode. If an operator temporarily changes one to manual, he will slide the controller out of the panel an inch as an external signal to himself and to others that it was intentionally placed in the manual mode.
8. *Employ additional operators* – in some cases, what is needed to support monitoring is more 'eyes.' The operator may be required to monitor an indication closely and may be unable to dedicate himself to that task because of other competing activities. Thus, another operator is brought into the unit and dedicated to monitoring.

*Example*: Several operators mentioned that when workload gets high, and there are too many monitoring demands, a junior operator can be dedicated to monitor a small set of indications (perhaps even one).

9. *Create external descriptor* – in some cases, operators create an external descriptor, whether it be of a variable label, variable limits, or variable state. This descriptor is subsequently used as an external referent for monitoring, thereby relieving the load on operators' memory.
   *Example*: An operator asked a field operator to make up a list of all of the nuisance alarms that could be brought in by the repair work that the field operator was going to be doing. The operator was then going to use this list as a referent for monitoring alarms. If an alarm came in that was on this list, then he would know that it was probably a nuisance alarm. On the other hand, if an alarm that was not on the list came in, he would know that it was probably caused by some other factor that might require further investigation.

4.4. *Monitoring activities*
The final element of our model describes the actual monitoring activities themselves – the acquisition of an indication or some other piece of information. The following list is a comprehensive set of resources that operators can use to obtain information at the plants we observed.

1. *Monitor plant state indications using panels* – operators can obtain indications from the control panels in the control room (includes 'back' panels behind control panels in room just off of control room).
2. *Conduct field tour* – operators can leave the control room to make observations or obtain indications from equipment in the plant.
3. *Monitor plant state indications using CRTs* – operators can obtain indications from the CRTs in the control room.
4. *Review log/plant record* – operators can acquire information recorded in the unit log or related plant documents.
5. *Monitor alarm screens* – operators can acquire information from an alarm message or from the central alarm screens in the control room.
6. *Communicate with field operators* – operators can communicate by phone or radio with operators at some locations in the field to obtain an indication or receive information about plant state.
7. *Communicate with operators from other units* – operators can communicate by phone or in person with operators at another unit to obtain an indication or receive information about plant state.
8. *Monitor alarm panels* – operators can acquire information from an alarm message or from the individual windows (annunciator tiles) found on the alarm panels above the control panels in the control room (see figure 1).
9. *Monitor other unit* – operators can also acquire relevant information by monitoring the information describing the status of other reactor units. Such information may be relevant to their own unit (e.g., if the operator on another unit is conducting a test that affects the alarm messages on the operator's own unit, as is sometimes the case).
10. *Print out CRT display* – operators can acquire historical information by using the laser printer to record the current status of a CRT display. This paper record can then be used as a source of information for monitoring.

Note that figures 2 and 3 show that after an indication or some piece of information is obtained from a monitoring activity, there is a feedback loop into the evaluate input box that is part of the cognitive activities. This allows monitoring to be an on-going, cyclical activity. The indication that comes back may be expected, valid, and normal and can even only serve to update the situation model without changing significantly the monitoring plan and activity. On the other hand, the indication can also introduce the need for a change in monitoring. Examples of these different cases are provided next.

### 4.5. *Workload regulation*

The facilitating activities and the monitoring activities just described are nested in that the former provide a context for the latter. This relationship is shown in figure 5. Note, however, that there is also a third, outer loop that provides a context for the facilitating activities. The purpose of this outer loop is to regulate the operator's workload so that monitoring is cognitively more manageable. 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 so that it is well calibrated to their cognitive capabilities, then they will rarely put themselves in a position where errors will occur. On the other hand, if operators do not effectively regulate their workload and over-extend themselves, then errors are almost sure to occur, even if facilitating activities are adopted. In Rochlin's (1997) terms, operators will 'lose the bubble'.

A few examples of workload regulation can illustrate its importance to operator monitoring. In the first 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. This would greatly increase the demands associated with monitoring because the operator would be frequently interrupted by alarms and he would have to calculate expected symptoms for several different

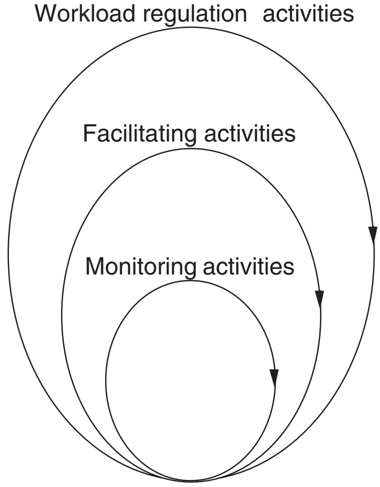


Figure 5. The nested relationship between monitoring activities, facilitating activities, and workload regulation activities.

classes of events (i.e., refueling, maintenance, other). Furthermore, the operator would have the added cognitive burden of using his situation model to calculate expected symptoms for several classes of events so that he could 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 or misinterpret 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. In terms of our model, the end effect was to reduce the complexity of the situation model that was needed to deal with the event.

As a second example, we frequently saw 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/she was ready to attend to them. To the uninitiated, this felt socially uncomfortable (as if it signaled an extreme difference in status.) However, the operators were on excellent terms with the maintenance and engineering staff. The unusual interaction style simply reflected an adaptation to the operator's high attention 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.

It is interesting to note that 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 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.

### 4.6. *Exercising the model: illustrations of monitoring practice*

Qualitative evidence showing the explanatory adequacy of our model can be illustrated by showing how the model categories can account for episodes of monitoring behavior that we observed in the field. Each episode can be viewed as a trajectory through the model, specifying a particular sequence of physical and cognitive activities. Two such trajectories are described here. We chose relatively simple trajectories because the more complex trajectories (described in Appendix A of Mumaw *et al.* 1995) can only be interpreted with considerably more knowledge of nuclear power plant operations.

1. *Pursuing reheater alarm after maintenance.*
   *Case*: An operator was aware that there had been a problem with the stage 2 element of the unit's moisture separator reheater. It had been taken out of service, repaired, and then placed back on-line. Early in the shift, the operator began working with someone in the field to place the element back into service. However, when stage 2 was placed into service, an alarm came on: stage 1 reheater flow unbalanced. At this point, the operator accessed the 'moisture separator/stage 1 reheat' display on a nearby CRT. Specifically, he/she looked at temperature, flow,

and pressure in the four parallel channels. The corresponding values were found to be very close across the four channels. The operator called someone from maintenance to look at the component, and he mentioned that there may be problems with the relay or limit switch in the alarm.

*Analysis*: The initiating event for this situation was the auditory alarm (data-driven). The evaluation of this alarm seemed to be 'not expected, unsure about validity, abnormal'. The situation model was updated and further monitoring began. The knowledge-driven monitoring was either SA2 (pursue unexpected finding) or SA4 (validate initial indication). The operator used his/her situation model to identify relevant data and (moving directly to a straightforward monitoring activity) monitor plant state indications using a CRT display. The indications obtained from the CRT display were taken as valid and as evidence that the problem suggested by the alarm did not exist. Thus, the input from the feedback loop is evaluated as 'not expected, valid, normal'. Updating the situation model suggests that perhaps the alarm is malfunctioning in some way (not a valid indication). The operator, probably using SA1 (confirm expectations about plant state), identifies relevant data (relay and limit switch on alarm), and communicates with personnel in the field to carry out the monitoring.

2. *Tracking lake water temperatures to check for potential problems.*

   *Case*: When an operator sees that lake temperature has changed significantly, he knows that there is a danger that there will be temperature differences between the pumps that bring lake water into the plant. If the temperature difference is too large, damage can be caused in the pumps. Because of this, when the temperature change is detected, the operator sets up a trend on a CRT to track temperatures.

   *Analysis*: The operator's situation model, which incorporates episodic knowledge, is used to identify the fact that significant changes in lake temperature can create the possibility for damage to pumps. This initiates a periodic monitoring activity (practices, policy, procedures) that aids the operator in detecting the change in lake water temperature. This input is evaluated as 'not expected, valid, and normal'. The update to the situation model leads to knowledge-driven monitoring through SA 3 (check for problems considered to be likely). The situation model is used to identify the relevant data, establish priority, and monitoring frequency. In this case, a facilitating activity is used: enhance signal. To make the temperature differences between pumps more easily monitored, the operator sets up a trend that is prominently displayed on one of the panel CRTs. Then the operator can monitor the critical indications using the CRT.

These two cases are not very complex, but they allow us to illustrate several of the general properties of our model, specifically:

- the interactions between data-driven and knowledge-driven monitoring;
- the various roles of the situation model;
- the variety of knowledge-driven monitoring types.

Mumaw *et al.* (1995) describe other longer cases that we observed during our site visits that allowed us to see the full complexity of monitoring.

## 5. Discussion

In section 1 of this article, we claimed that complex and dynamic work environments provide a challenging 'litmus-test' with which to evaluate theories of cognition. How can our model of operator monitoring in nuclear power plants during normal operations help us improve existing theories in cognitive science and cognitive engineering?

Clearly, there are certain aspects of our model that underscore and generalize very familiar findings that are at the core of cognitive science. The most salient example is the strong role played by knowledge-driven monitoring, which exemplifies the top-down active processing that is largely responsible for the development of cognitive psychology (Neisser 1967). Even just a cursory examination of figures 2 to 5 reveals that passive, data-driven monitoring plays a weak role in operator monitoring in nuclear power plants.

But while knowledge-driven processing is crucial, the role that problem solving plays appears to be somewhat different in our model than in many existing theories of cognition. It is common to view problem solving as a final resort that people turn to when their more efficient cognitive resources do not achieve task goals. Kintsch (1998: 3) provides a representative example of this view: 'when an impasse develops in perception or understanding they [i.e., people] resort to problem solving as a repair process'. A very similar claim is embedded in Reason's (1990) influential model of human error. In that framework, people turn to problem solving when they realize that the heuristics they normally use are inadequate for the task at hand. This may be the case in some situations, perhaps those where the people are not highly experienced or where the consequences of error are not severe (e.g., Newell and Simon 1972).

However, our qualitative observations and model clearly show that people do not resort to knowledge-driven problem solving only when they exhaust more economic cognitive resources. We frequently found that people engaged in deliberate reasoning and active processing to avoid problems, to confirm that their actions were having the desired effect, and to anticipate problems before they became severe. They did not wait until their normal routines failed before engaging in problem solving activities. This proactive aspect of problem solving has been noted before in the cognitive engineering literature (Decortis 1993), but it does not appear to be represented in many models in the cognitive science and cognitive engineering literatures (e.g., Newell and Simon 1972, Kintsch 1998, Klein 1989, Reason 1990, Cacciabue *et al*. 1992).

Another important feature of our work is that the situation model is a mental construction based on input from the environment, probably somewhat like the process described by Kintsch (1998). This construction process differs from the recognition process that takes a central place in other models of expert cognitive activity, such as Klein's (1989) recognition-primed decision making model. Rather than matching patterns, the operators we observed appear to be engaged in an active construction process that integrates the input they receive from the environment with the knowledge they have gathered through experience to create a situation model that represents their understanding of what is currently going on in the plant.

Another basic finding in cognitive science that is captured in our model is the highly distributed nature of cognition in complex dynamic work environments (Hutchins 1995a, 1995b). The strong role of facilitating activities in our model shows that people frequently tried to offload their cognitive demands by using their external environment. They created external reminders, created cues for action where none existed, enhanced the saliency of existing cues, and reduced the noise associated with existing cues – all to reduce the psychological requirements of a very demanding set of tasks to a manageable level. Without these facilitating activities, monitoring a nuclear power plant would probably be an impossibly complex task, given people's memory and computational limitations. This is not a new finding (e.g., Seminara *et al* 1977), but it is not well represented in traditional cognitive science theories. Thus, our work generalizes Hutchins' (1995a, 1995b) research on distributed cognition to a new domain (i.e., nuclear power plants vs. maritime navigation or aviation). Perhaps more importantly, our work also generalizes those ideas to a more complex task. The number of variables that need to be monitored (thousands) and the amount of time that it takes to become a licensed operator in a nuclear power plant (7 years) exceeds the requirements associated with the more specific, and thus delimited, tasks studied by Hutchins.

Again, however, our model emphasizes a pattern that has not received a great deal of attention in cognitive science theories. Much of the work on distributed cognition emphasizes the fact that cognitive activities are distributed spatially between resources 'in the head' and those 'in the world' (e.g., Zhang and Norman 1994). The fact that cognition can, and sometimes must, be distributed temporally has received much less attention. The workload regulation feature of our model emphasizes this temporal aspect. If operators are to monitor the plant reliably, they must be very clever in the way in which they distribute their tasks over time. This skill takes some time to acquire. Operators must become calibrated so that they do not put themselves in situations where they are bound to fail, even if they rely on facilitating activities. Experienced operators use knowledge of their own limited capabilities and the demands of various – frequently mundane – tasks to distribute their responsibilities over time in such a way as not to exceed their resource limits. Such workload regulation strategies have been observed in the cognitive engineering literature (e.g., Xiao *et al.* 1997) and in the Francophone ergonomics literature in Europe (e.g., Sperandio 1978), but they have not played a prominent role in the cognitive science literature.

Finally, our research also has important implications for the feasibility of studying human cognition in terms of reductionistic stages of information processing (e.g., Wickens 1992). It is not uncommon to see a diagram parsing human cognitive activity into a number of stages (e.g., sensation, perception, decision making, problem solving, planning, action). And while these diagrams are usually accompanied by caveats stating that the delineation of psychological activity into a number of discrete stages is a gross simplification, these disclaimers are frequently ignored in empirical research. Psychological phenomena are frequently studied in relative isolation from one another.

The weaknesses of such a reductionistic approach were noted over 100 years ago in a seminal article by Dewey (1896) that was subsequently judged to be the most important paper published in *Psychological Review* at the time of that prestigious journal's 50 year anniversary. Our model serves as a modest reminder of Dewey's forgotten message. Because we set out to study monitoring, one might think that we would be limiting ourselves to studying the stages of human information processing commonly referred to as sensation, perception, and attention. However, because we used a complex dynamic work environment as a litmus test, we opened ourselves to study much more than that – indeed, this is what our results have revealed.

If we define monitoring as the activities that are directly intended to pick up information from the environment, then even a cursory glance at figures 2 to 5 shows – paradoxically – that monitoring activities play a very small role in our model of monitoring. When we study psychological phenomena in rich, naturalistic environments, we see that the stages that have traditionally been studied in isolation are all tangled up in practice. Monitoring is as much about problem solving and workload regulation as it is about sensation and perception, perhaps even more so. Furthermore, it is not possible to disentangle monitoring from response planning or action (see figure 4), despite the long tradition in studying perception and action separately. Therefore, our results suggest that a holistic, nonlinear approach to the study of cognition may provide a more accurate portrayal of human cognition in unfettered situations outside of the laboratory. The types of models being developed in the dynamical systems perspective seem to be a promising approach to follow in this respect (e.g., Thelen *et al.* 2001).

## 6. Conclusions

Using complex dynamic work environments as a test bed for basic research has led to novel insights. The qualitative model of cognitive monitoring developed here appears to be unique in that it integrates the following features into a common framework:

- bottom-up, data-driven processes;
- top-down, knowledge-driven processes;
- inferential problem solving processes being activated without a failure of more automatic heuristic and perceptual processes;
- facilitating activities representing cognition distributed over space;
- workload regulation activities representing cognition distributed over time;
- a holistic, nonlinear model without clearly defined, separable stages.

As far as we know, there is no other cognitive model that contains all of these features.

At the same time, there are several limitations to this work that can motivate future research. First, to some extent, the model is embedded in the language of the application domain for which it was developed (i.e., nuclear power plants), although it has been recently applied with success to a second, different domain – monitoring aircraft engine indicators (Mumaw *et al.* 2002). It would be useful to generalize these concepts further in a way that would allow us to see the features that remain invariant over the idiosyncratic details of particular domains. Second, the model is qualitative in nature, and thus, does not have the rigor or precision of the cognitive models that are typically developed by cognitive scientists. It would be useful to determine if the ideas we have presented here can be integrated with the mechanisms specified by existing computational models. The comprehension-integration model of Kintsch (1998), the pertinence generation model of Raufaste *et al.* (1998), and the dynamical systems model of Thelen *et al.* (2001) appear to be promising paths worth exploring. By addressing these limitations, we may be able to integrate existing findings in cognitive science and cognitive engineering into a single framework, and thereby develop more unified theories with broader explanatory power and scope.

**Acknowledgements**

This research was sponsored by several research contracts with the Atomic Energy Control Board of Canada. We would like to thank Les Innes and Felicity Harrison (contract monitors), Francis Sarmiento and Mel Grandame, and Rick Manners and Brian Duncan for their help in coordinating our field study. Also, we are deeply indebted to all but one of the nuclear power plant operators who patiently answered our questions and generously shared their insights regarding the demands and skills associated with their jobs. This research would not have been possible without their cooperation.

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