USING OBSERVATIONAL STUDY AS A TOOL FOR DISCOVERY: UNCOVERING COGNITIVE AND COLLABORATIVE DEMANDS AND ADAPTIVE STRATEGIES

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INTRODUCTION

One of the primary strengths of naturalistic observations is that they support a discovery process (Woods, 1995; Mumaw, Roth, Vicente and Burns, 2000). They serve to draw attention to significant phenomena and suggest new ideas whose validity and generality can then be evaluated through additional studies.

Field observations afford the opportunity to gain a realistic view of the full complexity of the work environment and empirically grounded hypotheses for how interventions could impact the nature of work in that setting. They enable researchers to uncover and document cognitive and collaborative demands imposed by a domain, the strategies that practitioners have developed in response to those demands, and the role that existing artifacts play in meeting domain demands. The results can be used to point to and guide the development of new types of support systems.

In this paper, two studies are used to illustrate this approach. In the first case (Roth, Malsch & Multer, 2001), a series of field observations and structured interviews were conducted at train dispatching centers to inform the design of a "data link" technology intended to improve performance by reducing communications on an overloaded audio channel. In the second case (Roth & O'Hara, 1999), observations of the use of advanced human-system interfaces in a nuclear power plant simulator were conducted prior to implementation in the plant in order to uncover and document unanticipitated changes in cognitive and collaborative demands as a result of the introduction of the new technology.

The studies illustrate the methods used in conducting and analyzing the results of observational studies, as well as the kinds of insights that can be gained from observational studies.

OVERVIEW OF METHODOLOGY

Naturalistic observation studies employ a methodology similar in approach to other ethnographically derived methods (e.g., Jordan & Henderson, 1995; Nardi, 1997) and the European field study tradition (De Keyser, 1990; Heath and Luff, 2000). Observers are placed in the actual work setting to observe and interview domain practitioners as opportunities arise. Particular attention is placed on detailed capture of illustrative incidents that provide concrete

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* Presented at the 5th Naturalistic Decision Making Conference held in Sweden, May, 2000, in press.

examples of the kinds of complexities that can arise in the environment, the kinds of cognitive and collaborative strategies and facilitating activities that domain practitioners use to handle these situations, and how existing artifacts are tailored in order to meet situation demands. These illustrative incidents may be examples of practitioner performance in routine situations that arise often, or they may represent a response to a relatively rare occurrence (e.g., equipment malfunction, accident) that arises during the observational study.

Exploratory observational studies contrast to other scientific methods in that the focus of the observations and analysis is on discovery rather than hypothesis testing. Different analysts looking at the same domain might very well focus on different aspects and uncover different insights if they draw on very different conceptual frameworks in selecting what is ‘interesting’ to capture. In this type of research what matters is not 'reliability' -- would different analysts working independently have focused on the same observations? But rather how 'generative' the work is -- are the results insightful and productive with respect to pointing to sources of performance problems and opportunities for improvement?

Figure 1 provides a graphic representation of the data analysis and abstraction process used to derive generalizations from the specific observations (cf., Hollnagel et al., 1981, Patterson and Woods, 2001). Observations and analyses are guided by (1) the questions that the study is intended to address, (2) the sample of practitioners and activities observed and (3) the conceptual frameworks that the observers bring to bear.

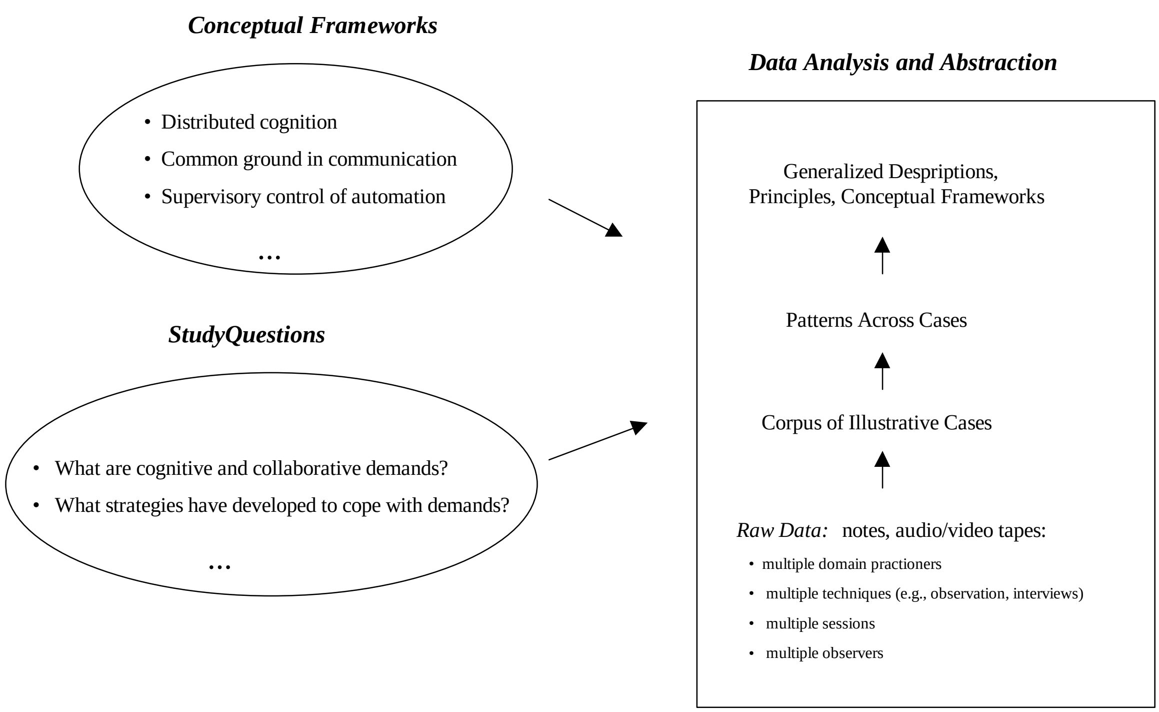

Figure 1. Conceptual frameworks and study questions that define what is ‘interesting’ and thus guide observations and the data analysis and abstraction process.

Conceptual frameworks play an important role in guiding observations and analyses (cf. Lipshitz, this volume). In the studies described below observations and analyses are informed by bodies of knowledge about the interaction of humans and supporting artifacts in complex, socio-technical systems from the field of cognitive engineering and related behavioral and social sciences (e.g., theory of distributed cognition, role of common ground in multi-agent communication, principles of human automation interaction and the consequences of clumsy automation).

These conceptual frameworks guide the identification of 'interesting' cases to capture. They enable tractability in data collection, both in terms of the amount of time spent observing (on the order of days instead months) and the level of detail of what is recorded and analyzed (sequences of events rather than second by second behavioral and verbal interactions).

Conceptual frameworks also support the analysis process used to identify common patterns across a corpus of illustrative cases, and to draw generalizations that have applicability beyond the particular cases examined. These analysis stages correspond to the levels of analysis that Lipshitz (this volume) refers to as 'paraphrasing' and 'theorizing'.

It should be pointed out that conceptual frameworks not only serve as *a starting point* for observation and analysis – a framework by which to interpret and aggregate findings, they are also an *output* of the analysis process. The general descriptions, principles and conceptual frameworks that emerge from the analysis of an observational study are expressed at a level of abstraction that allow across domain comparison and application. The results of observational studies can be used to support, expand, refine, or refute existing conceptual frameworks. They can also be used to generate new conceptual frameworks and theories.

The differences in goals of exploratory observational studies, as contrasted with studies designed to test a specific hypothesis, leads to different study design considerations. For example, an important consideration in a study designed for hypothesis testing is to control the conditions of observation and minimize variability (both with respect to the range of situations observed and with respect to what observers record). In contrast, because the focus of exploratory observational studies is on discovery, the objective is to broaden the set of observations and conceptual frameworks brought to bear by observers in order to maximize the opportunity for uncovering interesting findings and drawing productive insights.

Several techniques are used to broaden the set of observations and conceptual frameworks brought to bear. These include:

- broadly sampling domain practice (e.g., multiple shifts, multiple practitioners at multiple levels of experience; multiple sites)
- use of multiple converging techniques (e.g., field observations, structured interviews, questionnaires)
- use of multiple observers who are likely to bring different conceptual frameworks

Another important concern in performing observational studies is the accuracy of the observations and their interpretation. Several strategies are used to guard against errors and biases. First, observers take advantage of opportunities to continuously 'bootstrap' their understanding of the domain complexities, iteratively refining their notion of what is 'interesting' to collect and analyze (Lipshitz, this volume). Each observation provides a potential opportunity to generate new conjectures as well as test conjectures generated in prior observations. This approach allows the discovery of critical factors not predicted in advance as well as the opportunity to discard early conjectures that are not supported by later observations. The ability to sample the domain of practice broadly (multiple practitioners, multiple levels of domain expertise, multiple session, multiple sites) provides an opportunity to look for commonalities across cases as well as divergences (contrasting cases) that reveal interesting insights.

A second technique to promote accurate interpretation is to compare the insights and perspective of multiple observers. It is common to hold meetings immediately following an observation period where the multiple observers share their observations and interpretations. This reduces the risk of forgetting critical details that are 'in the head' of the observer but not recorded in the 'raw data', and improves data reliability by allowing multiple observers to contrast their interpretations of events while their memories are still fresh and it is still possible to pursue additional data to resolve ambiguities or differences in interpretation (e.g., by conducting follow-up interviews with the domain practitioners that were the subject of the observations).

The ultimate criterion in evaluating the results of an observational study is that once the insights are made and pointed out, that other analysts (or more relevantly the domain practitioners themselves) would agree with the findings and interpretation. A common practice is to present the results of the study to domain practitioners (either in the form of a report or a presentation) and solicit feedback on the accuracy of the base observations and their interpretations.

The two studies summarized below provide concrete illustrations of this methodological approach.

STUDY 1: INFORMING THE DESIGN OF NEW TECHNOLOGY

New technologies often fail to have the desired effects on human performance when introduced into actual complex, socio-technical settings. This first study illustrates how a series of observations and interviews uncovered cognitive and collaborative demands and adaptive strategies with current communication technology that had implications for the design of a new "data link" communication technology for train dispatching (Roth, Malsch, Multer & Coplen, 1999; Roth, Malsch & Multer, 2001).

Currently, voice radio is the primary means of communication between Railroad Dispatchers and the railway workers they interact with (e.g., Locomotive Engineers; Maintenance of Way Workers). The radio channels are overloaded however, creating a data overload situation for Train Dispatchers. The railroad industry has been examining the use of data link technology to communicate in place of or in addition to voice radio communication. The guiding questions for this study were:

1. What activities could be supported more effectively with data link digital communication systems?
2. What features of the existing technology are important to effective dispatcher performance and therefore need to be considered when deploying new technology?

The study combined field observations at dispatch centers with structured interviews with experienced dispatchers. In the first phase, Railroad Dispatchers were observed as they went about their job in a railroad dispatch center that primarily handled passenger trains. Two observers participated. Each observer sat next to a different railroad dispatcher and observed the communications he or she engaged in, and the train routing and track management decisions that were made. The observer asked the dispatcher questions during low workload periods. Questions were guided by a checklist of pre-defined topics and by the observed behavior.

A total of 8 dispatchers were observed across two shifts. Observations included high workload early morning rush-hour periods, lower workload mid-day periods, and shift turnovers. Phase 2 consisted of structured interviews with experienced railroad dispatchers and related personnel from the same railroad dispatch. Phase 3 involved field observations at a second dispatch center that primarily handled freight trains. This was to assess the generality of the results obtained at the first dispatch center. The fourth phase involved a second set of field observations at the same dispatch center observed during Phase 1. This was to verify and expand on the results obtained in the previous three phases**.** In general, the results from each phase confirmed and extended the results from the previous phase.

Uncovering the Role of Radio 'Party-Line' in Facilitating Railroad Dispatching

Railroad dispatching involves extensive communication and coordination among individuals distributed in time and space. In a typical railroad dispatch center, there are multiple dispatchers working in parallel, each responsible for different territories, who must coordinate with others in order to manage track usage efficiently and minimize train delays. Observations were therefore guided by concepts from the distributed cognition, common ground, and distributed planning literatures. The observations revealed the cognitive and collaborative demands and the cooperative planning and error detection strategies that dispatchers have developed with the current technology.

What makes railroad dispatching cognitively difficult is the need to deal with *unplanned demands* on track usage (e.g., the need to accommodate unscheduled trains and requests for time on the track for maintenance work), and the need for dynamic *re-planning* in response to unanticipated events (e.g., train delays, track outages). The observational study revealed that successful performance depends on the ability of dispatchers to monitor train movement beyond their territory, anticipate delays, balance multiple demands placed on track usage, and make rapid decisions. This requires keeping track of where trains are, whether they will reach destination points (meets, stations) on time or will be delayed, and how long the delays will be.

To meet these demands, dispatchers have developed information-gathering strategies that allow them to anticipate requirements for changes to schedules and planned meets early so as to have time to take compensatory action. Many of these strategies depend on communication and coordination among individuals distributed across time and space. This includes coordination among dispatchers managing abutting territories within a dispatch center as well as coordination among the various crafts within a railroad (e.g., locomotive engineers, train masters, dispatchers, and roadway personnel).

One of the most salient findings was that railroad dispatchers took advantage of the broadcast/'party-line' feature of radio to anticipate and plan ahead. The ability to "listen in" on communications directed at others that have a bearing on achievement of your own goals and to recognize when information in your possession is of relevance to others and broadcast it, were found to be important contributors to efficient management of track use (cf., the use of voice loops technology in space shuttle mission control, Patterson et al., 2001).

Dispatchers routinely "listen for" information on the radio channel that is not directly addressed to them but provides important clues to potential delays, problems or need for assistance. As one dispatcher put it, "after a while you kind of fine tune your ear to pick up certain key things." Examples include:

- *Identifying when a train has left a station*: A train conductor will generally tell the locomotive engineer "OK out of New London." By comparing the actual departure time to the scheduled departure, a dispatcher can calculate train delays.
- *Identifying equipment problems:* By overhearing conversation between a locomotive engineer and the mechanical department, the dispatcher gets early notice of malfunctioning train engines that will need to be replaced.
- *Listening for/heading off potential interactions and conflicts:* Dispatchers listen for commitments made by others that may impact activity in their territory. The ability to listen ahead allows dispatchers to nip potential conflicts before they arise.
- *Listening for mistakes.* An experienced train dispatcher will pick up key information that may signal a misunderstanding, confusion, or error.

Implications for the Design of Data Link Technology

There are several implications for the design of data link technology from this study. First, there was clear evidence from several observed incidents that the radio channel is now overloaded and that there is a need to off-load some of the communication onto other media. Data link technology provides a vehicle for taking information that is now communicated orally and instead presenting it visually on a computer display. This has clear benefits for certain types of information. For example having dispatchers read aloud and train crews repeat back complicated movement authorization forms is time consuming and error prone. Transmitting the information as a visual text or graphical display should reduce radio congestion and may reduce the number of 'read back' errors and other errors of confusion and misunderstanding that sometimes occur during verbal radio transmissions.

At the same time, the results of the observational study revealed the importance of the "broadcast/party line" aspect of radio communication that provides a shared frame of reference and allows dispatchers and others working on the railroad to anticipate situations and act proactively. The study identified the need to preserve the 'broadcast/party-line' aspect of radio communication when shifting to data link technology.

While data link technology is often implemented as a private communication channel where only the specified receiver has access to the information transmitted, this is not an inherent characteristic of the technology. It is possible to envision 'broadcast' versions of data link technology where multiple individuals can access a transmitted message or view common graphical displays regarding real time status of track and train information.

In order to explore this hypothesis under more controlled conditions, a follow-on laboratory study was conducted. Malsch (1999) implemented two data link systems: a directed system with no broadcasting capacity and a broadcast system. The systems were compared for their effectiveness in a simulated railroad dispatching task with scenario elements abstracted from the observed incidents. While both versions of data link resulted in more efficient communication as compared to radio transmission, the broadcast version of data link produced better dispatcher performance than the directed data link system on several measures such as train safety.

In summary, one of the most significant contributions of the study was that it revealed the important role that the broadcast/'party-line' feature of the radio communication media played in facilitating safe and efficient dispatch operation in the current environment. Observed *illustrative incidents* suggested that changing the design of the new data link technology in order to preserve this ‘broadcast’ aspect of dispatcher communication would improve performance, which was then confirmed in a follow-on controlled laboratory study.

STUDY 2: MAKING THE INTRODUCTION OF NEW TECHNOLOGY SAFER

The first study illustrated the use of an observational study to improve the design of a new technology prior to implementation. Observational studies can also be used to reduce unintended effects on performance from the introduction of new technology into a field of practice by identifying training and operational changes that should accompany the implementation. The next study illustrates how observation of operators in a high-fidelity simulator was used to identify new training and operational needs prior to the implementation of advanced human-system interfaces (HSI) in a nuclear power plant (Roth & O’Hara, 1999).

Introduction of new technology inevitably changes the nature of cognitive and collaborative work. Some of these changes are explicitly engineered with the goal of improving performance. However, there can also be unanticipated effects. It is easy to find examples where the introduction of new systems have had unanticipated negative effects, creating new burdens for practitioners, often at the busiest or most critical times (Roth, Malin, and Schreckenghost, 1997; Woods, Johannesen, Cook and Sarter, 1994).

Woods and his colleagues (1998; Potter, Roth, Woods and Elm, 2000) have argued that new support technologies should be regarded as *hypotheses* about what constitutes effective support, and how technological change is expected to shape cognition and collaboration in the “envisioned world” that contains the new technology (Dekker and Woods, 1999). Observational studies provide a powerful tool for exploring the envisioned world both to evaluate the validity of designer assumptions, and to drive further discovery and innovation. In this study, advanced human-system interfaces (HSIs), including a computer-based procedure system, an advanced alarm system, and a graphic-based plant information display system, were in the final phases prior to implementation in a conventional nuclear power plant control room. Operators were undergoing training on the use of the new interfaces on a high-fidelity full-scope simulator, which provided an opportunity to observe the use of the technology by experienced operators while handling plant disturbances and interview the operators immediately following the simulation.

The guiding questions for this study were:

1) What aspects of the new HSIs were clear improvements over traditional control boards?
2) Were there any new unanticipated challenges or issues that emerged with the introduction of the new HSIs?

The cognitive engineering literature on teamwork, the importance of shared representations for supporting communication and coordination among team members, and the potential for new technologies to create private ‘keyholes’ that can disrupt individual and team situation awareness are examples of conceptual frameworks that were relevant and served to guide observations and inquiries.

Approach

Five professional operating crews were observed and interviewed during a week of training in a full scope, dynamic plant simulator. Each crew was unobtrusively observed during four simulated emergency scenarios by two observers placed in an observation deck (instructor's area.)

At the end of the two days of observation, the operators were interviewed in crews. The primary purpose of the interviews was to obtain the operators' perspective on how they used the new HSI systems and how the new systems affected their performance as individuals and as a team. Questions probed the perceived impact of the new systems on operator workload, situation awareness, distribution of tasks and responsibilities among team members, and communication and coordination among the team members.

Controlling a nuclear power plant involves dynamic, real-time communication and coordination among individuals with dedicated roles and responsibilities. A control room crew is typically made up of 3 individuals: a shift supervisor and two board operators, although others augment the crew during emergencies. When there is an emergency that causes the plant to shut down (i.e., a plant trip) in the current environment, the shift supervisor reads aloud paper-based procedures, called Emergency Operating Procedures (EOP), that guide the crew step-by-step through the emergency response. The board operators' job is to read plant parameter values from the board for the shift supervisor and take control actions as directed by the procedures that the shift supervisor reads aloud. With the new HSI design, the parameters are automatically provided to the shift supervisor as part of the computer-based procedure system.

Findings about Individual and Team Situation Awareness

We identified several aspects of the new HSIs that gave clear improvements, as well as had unanticipated impacts on individual and team situation awareness. One of the most interesting findings of the study was the impact of the HSI systems on the structure and dynamics of the crew. The introduction of the new HSI affected the scope of responsibility of the different crew members, the communication pattern among crew members, and the situation awareness of the different crew members.

The new HSIs removed the need for detailed communication between the shift supervisor and the board operator because the computer based procedure automatically provided the shift supervisor with the plant parameter data required for him or her to work through the procedures. The shift supervisor and board operators were able to work more in parallel. The shift supervisor concentrated on working through the procedures and the board operators concentrated on monitoring the advanced alarm system, graphics display, and control board HSIs. As a result, the shift supervisor and the board operators individually reported improved situation awareness and greater confidence in the accuracy and speed of their performance within their own locus of responsibility.

There was an unanticipated effect, however. Operators reported that more conscious effort was required to maintain awareness of each other's situation assessment and activities than with the older hard-wired control board technology. While the computerized procedure reduced the shift supervisor's overall workload, it also introduced a new demand -- the need to keep the crew informed of his or her assessment of the situation and the status and direction of the procedural path as he worked through the procedure. Shift supervisors reported a need to consciously remember to inform the crew of their status through the procedure and to consciously formulate what to communicate. The new communication requirement is a substantial cognitive task that appeared to improve with training and experience.

Findings on the Ability To Monitor Effectiveness Of Procedures

Another question of interest was the impact of the new HSIs on the ability of crews to monitor the effectiveness of the procedures in handling emergency scenarios. This included the ability of the crews to detect and respond to cases where the actions specified in the procedures were not fully appropriate to the specific situation. Several studies examining both actual and simulated incidents have shown that conditions sometimes arise where response guidance in the procedures are not fully appropriate to the situation (Kauffman, Lanik, Trager & Spence, 1992; Roth, Mumaw & Lewis, 1994). In those cases, the ability of the crews to recognize that the actions specified in the procedures are not fully appropriate to the specific plant conditions and to take corrective action are important cognitive activities. As a consequence, one of the points of focus in the present study was on how the computer-based procedures affected the operators' ability to monitor the effectiveness of the procedures, and detect and respond to situations where the actions specified by a procedural step were not fully appropriate to the situation.

In the study, three instances arose where the computer-based procedure provided misleading information or directed the operators down the wrong procedural path. These instances constitute an '*existence proof*' of the fact that situations can arise where the procedural path taken is not appropriate to the situation.

Given that situations can arise where the decision aid is off-track, important questions are: (1) Can operators detect when the decision aid is off track? (2) Are they able to redirect the decision aid and get back on track? In all three cases observed in the study, the operators were able to correctly detect that the computer-based procedure direction was inappropriate to the situation and overrode it. The examples illustrated important positive features of the computer-based procedure, and raised questions about the conditions that are necessary to foster the ability of crews to detect that a computer-based procedure is off-track and redirect it.

Implications for Training with the Introduction of the HSIs

The study suggested ways to make the introduction of the new HSIs safer through training and operational changes. First, the new demand of supporting team situation awareness given the elimination of "low level" communication about parameter values between the board operator and shift supervisor can be addressed by explicit training and changes to communication protocols to include periodic updates from the shift supervisor to the team about his or her assessment of the situation and the location in a procedure.

Second, the three observed instances where the computer-based procedure was not appropriate constituted *an existence proof* that instances where the computer-based procedure is off-track can occur, and consequently that the task of detecting and redirecting the computer-based procedure needs to be supported. The findings suggest the importance of having (1) multiple diverse sources of information available to operators in the control room, and (2) effective communication among the operators in order to detect and correct cases where the computer-based procedure is off-track.

The ability of the operators to recognize that the actions specified were inappropriate seemed to depend on three factors that have implications for training and operational changes:

1. accurate understanding of current plant state,
2. solid knowledge of the goals and assumptions of the procedures and the consequences of the actions indicated by the procedure, and
3. strong communication between the shift supervisor and the board operators that allowed the board operators to keep track of the procedural path that the shift

supervisor was following.

While the study provided some suggestive evidence of the kinds of factors that contribute to the ability of crews to detect if a computer-based procedure was off-track, clearly more research is required to fully address this issue. First, only three instances were observed and analyzed, and these three instances might not be a representative sampling of the ways in which the computer-based procedure could be misleading. Second, the observation that the control room crew easily detected that the computer-based procedure was inappropriate for the situation may not generalize to other individuals, teams, or situations, particularly since only one instance of each situation was observed so there was no way to measure response variability. Further research is needed to generate detailed recommendations for change and to verify that the recommendations would have the desired effects on performance.

In summary, this study illustrates three important roles of observational studies

1. uncovering new cognitive and collaborative demands that were previously unanticipated and could be addressed with training before the implementation of a system in an actual, high-consequence work setting;
2. documenting illustrative cases that provide an 'existence proof' that certain situations can arise that need to be explicitly considered by system designers, trainers, evaluators, and managers; and
3. providing suggestive evidence that inform hypotheses for improving performance by changes to training and operational procedures that can then be explored under more controlled conditions.

DISCUSSION

In this chapter, two recent studies were used to illustrate the ways in which observational studies can contribute to the growth of knowledge on human decision-making in complex domains. In the first study, an important function of the current communication technology in railroad dispatching was uncovered that had significant implications for the design of a new data link digital communication technology. This function was "hidden" in the sense that it was an adaptation that was not officially supported by the current technology and unlikely to have been reported by the operators to be important. In the second study, a new demand for shift supervisors to explicitly communicate situation assessments to a team using new advanced displays in a nuclear power plant control room was uncovered. Because the observations were conducted in a high-fidelity simulator prior to implementation, this new demand could be included in training and operational changes that could be implemented at the same time as the new system, therefore making the transition period safer. In addition, three instances where the computer-based procedure was inappropriate to the situation were uncovered and documented. They provided an existence proof that the situations could arise, and therefore that provisions to support these situations and other similar situations needed to be made.

There are two phases that are important to the advancement of science. One is the controlled experiment phase that is used to confirm a hypothesis by controlling for, and thus eliminating, all other possible explanations for a given phenomenon. This controlled experiment phase is generally associated with the concept of "Science". But there is also another element of the scientific process that is less widely discussed and that is the discovery phase. This is the phase during which fruitful conjectures are generated that can then be tested under more controlled conditions

Naturalistic observation studies are one of the tools that support this discovery phase of the scientific process by increasing the empirical grounding of hypotheses about how tools will affect work in complex settings. They serve to draw attention to significant phenomena and relationships that might otherwise have been missed, and which can then be further explored in more controlled investigations.

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