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Applying the Skill-Rule-Knowledge Framework to Understanding Operators' Behaviors and Workload in Advanced Main Control Rooms

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HIGHLIGHTS

- Operator behaviors were analyzed according to Rasmussen's SRK classification.
- Different job positions connote different abilities to perform the job successfully.
- Rule-based behavior comprised the main behavior patterns of the operating crew.

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ABSTRACT

For the past years, a number of researches have focused on operators' behaviors and workloads in advanced main control rooms (MCRs) in either the procedure-domain or knowledge-domain and in either workload-increased or workload-decreased conditions. Different job positions connote different responsibilities and abilities that are required to perform the job successfully. However, it may be inappropriate to apply a dichotomy in these issues. In this study, we clarified these controversial points through the analysis of the time, frequency, and workload of the behaviors based on Rasmussen's skill–rule–knowledge classification (SRK framework) according to the supervisor operator (SRO), reactor operator (RO), and assistant reactor operator (ARO). The results showed that, for the SRO, rule- and knowledge-based behaviors occurred more often than skill-based behavior in terms of time and frequency, and knowledge-based behavior was the main source of workload. For the RO, no significant differences were found among the three behavior types in terms of frequency and workload, but more time was spent on rule-based behaviors than on skill- and knowledge-based behaviors. The ARO spent more time performing skill-based behaviors than rule- and knowledge-based behaviors, but in terms of frequency and workload, rule-based behavior was the predominant type. Operators' behaviors contribute to a plant's defense-in-depth approach to safety and serve a vital function in ensuring its safe operation. Research on behavioral taxonomies of advanced MCRs has many significant benefits in both scientific-theoretical and applied practical fields.

1. Introduction

Nowadays, digital technology, software, and multiplexing network techniques are generally adopted to help operators to perform tasks that are repetitive, error-prone, and burdensome in the advanced main control rooms (MCRs) of complex industries. The cognitive processes, behaviors, job requirements, and reliability in advanced MCRs are very different from those in conventional MCRs (Wang and Ma, 2006; Liu, 2008). Some researchers posit that, with automation increasingly taking over tasks, the operator's behavior is shifting from mainly operation to mainly supervision and diagnosis, and as a result, cognitive operation will become the major behavior in the operating processes. Manual acts are no longer considered an integral part of the control task, relegated to being merely a general interface manipulation skill (Rasmussen, 1983). Cognitive flexibility and knowledge developed by the operators can be an effective way to increase reliability (O'Hara and Hall, 1992; Huang and Hwang, 2009; Jou et al., 2009). It is expected that operator workloads will be reduced by the transfer to computers of functions that are routine, tedious, physically demanding, and

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burdensome to operators (Chuang and Chou, 2005; Dhar and Dhar, 2010).

At the same time, scholars also believe that the natural variability of complex human agents must be controlled by establishing strict procedures, reducing the complexity of operations, and allowing activities to be accomplished according to if-then rules, especially in high-stress conditions (Schmidt, 1999). Reducing the variations of human response and individual autonomy, which are considered potential sources of human error, is essential to safe operations (Carvalho et al., 2006). Not adhering to procedures and a lack of procedures has both been implicated in a number of high-profile catastrophic accidents and incidents, including the Chernobyl, Bhopal, and Clapham junction disasters. In addition, it is possible that in an advanced MCR, when the operators attempt to cope with computerized systems, the cognitive effort required for managing interfaces, navigating through VDUs, and having to retrieve information, rather than having it consistently presented, may all contribute to higher workloads for operators. Automatic operation may relieve some of the burden, yet it also places new loads on the operator's perception and cognitive systems, especially in high-stress and emergency situations (O'Hara and Hall, 1992).

Different job positions connote different responsibilities, authorities, and abilities that are required to perform the job successfully (Cook and Salvendy, 1999; Wei and Salvendy, 2004; Persensky et al., 2005). The application of a dichotomy in related questions (knowledge/procedure-domain or increase/decrease workload) may be inappropriate. In this research, large quantities of behavioral data were gathered systematically from operators during training courses and human factors validation activities in a full-scale Advanced Boiling Water Reactor (ABWR) plant simulator in Taiwan. All the behavioral data were gathered for the positions of shift supervisor operator (SRO), reactor operator (RO), and assistant reactor operator (ARO). The time, frequency, and workload of the behaviors were recorded and analyzed based on Rasmussen's skill-rule-knowledge framework. The following research issues will be addressed both in time and frequency measurements:

1. What is the major behavior type of SRO, RO and ARO in advanced MCRs?
2. What is the distribution of workload of SRO, RO and ARO in advanced MCRs?

2. Background

2.1. Working in advanced main control rooms

In place of the traditional switches, knobs, and handles, advanced MCRs use video display units (VDUs), large-screen and overview displays. VDUs, which present integrated information, are the main interface for operators to manipulate and monitor the status of the equipment. A typical advanced MCR of a nuclear power plant (NPP) is shown in Fig. 1 (Chuang and Chou, 2005). Operating crews are mainly responsible for monitoring the plant and stabilizing the plant in emergent situations. These crews are often referred to as the "brains" of the complex systems they manage, because they are responsible for interpreting information from multiple systems and making decisions during abnormal, time-pressured, high-workload situations (Waller et al., 2004). When everything works smoothly, human monitors are merely spare parts, and the operators need only to monitor the information on the VDUs and wide display panel (WDP) to make sure every function of plant operation is going right. However, when incidents or emergency conditions occur, as indicated by signals that deviate from the expected and desired values, multiple warning messages may present at the same time, all of which require urgent attention from the operators (Lin et al., 2010).

In such cases, operators must immediately diagnose system problems and causes in the shortest time possible and make a decision on which procedures to apply. Various approved operating procedures provide descriptions of the prescribed actions for emergency or abnormal situations. The operators are not to willfully deviate from following the instructions and steps of the operating procedures. In such a situation, human performance becomes both highly cognitive and structured. Subsequent diagnosing and decision tasks impose a heavy mental workload and stress on human operators during abnormal operating procedures (Meister, 1995). The characteristics of operators' behavior in such a complex, dynamic, and highly-stress situation are summarized by Woods and Roth (1986) as follows: (1) a continuous situation assessment is needed, rather than a single diagnosis; (2) according to changing assessments of the situation, operators must revise their responses to dynamic circumstances; (3) there is a need to anticipate and monitor what could occur next and as a consequence to revise hypothesis; (4) repeated inspection of the process is needed to adjust the solutions to problems; (5) operators retrieve prospective memories frequently; (6) adequate feedback in time is essential to operators; and (7) time is critical to deal with uncertainty in systems. Parasuraman and his colleagues (2000) pointed out that for investigating the interactions between human and machine, the Skill-Rule-Knowledge classification (known as the SRK framework) is very useful in analyzing behaviors that involve both overt and covert processes. This SRK framework, which provided us a structure for data analyses, is the theoretical backbone of this research.

2.2. Skill-, rule-, and knowledge-based classification

Humans are not simple passive input-out devices but goal-oriented creatures that actively select goals and seek relevant information for decision making (Rasmussen, 1983). Based on this consideration, Rasmussen provided a useful framework to describe human behaviors, from the observation of information to the actions covered a wide range of situations ranging from daily routine work to novel events. In terms of the hierarchical structure, observed behaviors are categorized as skill-, rule-, and knowledge-based behaviors (Rasmussen, 1983, 1985). This model is particularly useful for analyzing behaviors in modern systems because it involves both overt and covert processes with a combination of familiar and unfamiliar situations, and it is widely used in diverse domains (Besnard and Greathead, 2003; Wentink et al., 2003; Marcus, 2006). Skill-, rule-, and knowledge-based behaviors are distinguished by the degree of attentional resources/consciousness exercised by the individual in his/her activities. These three levels and a simplified illustration of their interrelation are shown in Fig. 2 (Rasmussen, 1983).

(1) Skill-based behavior: Skill-based behavior represents a very close coupling between sensory input and response action. It refers to smooth, automated, and highly integrated patterns of action, that take place without attentional monitoring. Sometimes individuals are unable to describe how they perform the actions. In this category, human behavior is governed by stored patterns of pre-programmed instructions characteristic of well-practiced and routine situations (Drivalou and Marmaras, 2009). In MCRs, operators develop an ability to initiate "stimulus-action" response patterns through extensive practice. Manual control of fuel rod insertion and withdrawal is one common skill-based behavior in MCR.

(2) Rule-based behaviors: Rule-based behaviors involve the execution of actions learned through formal (e.g. official guidelines, instructions given) or informal (e.g. actions learned through