Metacognition in Nuclear Process Control

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The literature provides substantial evidence that metacognition is a central part of work for nuclear power plant operators. However, there is limited theoretical, empirical and methodological research on metacognition in nuclear process control. This article establishes the importance of metacognition by describing the construct and reviewing evidence of operator metacognition from field studies and experimental research. It also reports empirical findings on metacognition from a full-scope simulator study. The results reveal that operators are less realistic about their performance (i) in knowledge-based as compared to procedure-guided scenarios, and (ii) when the perceived workload is extreme. The implications of the results for the design of control room technology and on operations are discussed.

INTRODUCTION

Process control is increasingly knowledge-based as process plants become more complex and automated. The literature on the domain frequently characterizes process control as problem solving (e.g., Mumaw, Roth, Vicente, & Burns, 2000; Woods, 1994), suggesting that metacognition may be a critical aspect of operating process plants. Although there is ample empirical support for the role of metacogntion in cognitive tasks, particularly in problem solving and education research, the literature seldom addresses the role and importance of metacogntion in industrial work (see e.g., Huet, 1999). The paucity of human factors research on metacognition could lead to designs of work environments and processes that neglect some critical support for process operators, especially given the increasing reliance on human problem solving capabilities.

This article investigates metacognition in the context of nuclear process control. The primary goal is to promote both research attention and design consideration to support operator metacognition. The first part illustrates the importance of metacognition by describing the construct and reviewing evidence of operator metacognition from field studies and experimental research. The second part expands empirical data on metacognition in nuclear process control by presenting experimental results from a full-scope simulator study.

METACOGNITION

Metacognition refers to knowledge and regulation of cognition. Figure 1 illustrates the overall relevance of the metacognition from a human factors perspective. The responsibility of operators is to manipulate or control variables in the system or the environment (the bottom level) to maintain or achieve some desirable states. In order to manage this responsibility, operators must acquire knowledge of the system/environment and regulate system behaviours by relying on various cognitive processes (the middle level). However, cognition can also deviate from ideal behaviours and thereby misdirect the system or environment away from desirable states. In order to effectively apply cognition to control the system or environment, operators must also engage in metacognitive activities (the top level) to obtain adequate knowledge and regulation of cognition. (On the philosophical debate on infinite regress in metacognition, refer to Nelson and Narens (1994) and Nelson (1996) for a discussion.)

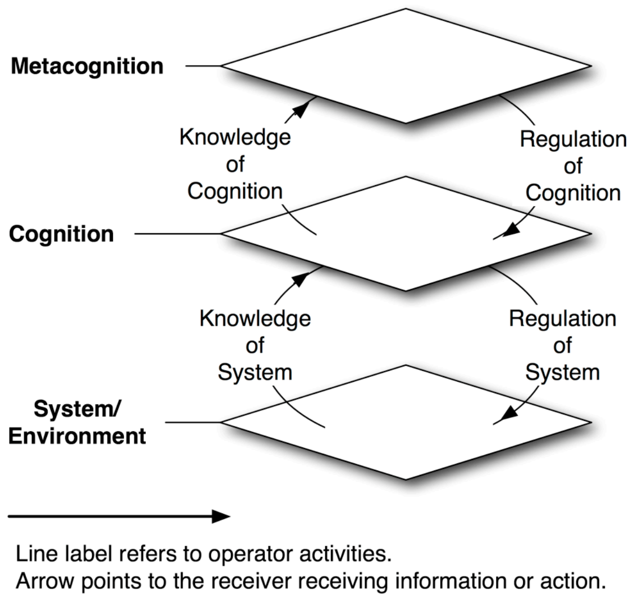

Figure 1: Relevance of Metacogntion in Industrial Work

Schraw (1998) provides a taxonomy of metacognition that divides knowledge and regulation of cognition into sub-dimensions (Table 1). Knowledge of cognition consists of three dimensions: declarative, procedural, and conditional knowledge. *Declarative knowledge* refers to knowing cognitive characteristics or properties of oneself (i.e., what) that often encapsulates factors affecting performance. For example, some people are aware of their short-term memory capacity for a string of numbers.

Procedural knowledge refers to knowing the cognitive processes of oneself (i.e., how) that often manifests as strategies or heuristics. For example, some people know about chunking as a memorization strategy for a long string of numbers.

Conditional knowledge refers to knowing the conditions (i.e., when and why) to apply cognitive knowledge. For example, some people are aware of chunking as an effective cognitive strategy for themselves to memorize a string of numbers that exceed their short-term memory capacity.

Regulation of cognition also consists of three dimensions: planning, monitoring and evaluating. *Planning* refers to selecting cognitive processes and/or strategies to accomplish some goals or tasks. For example, some people employ chunking strategies to memorize a long string of numbers.

Monitoring refers to assessing the outcomes of the cognitive processes and/or strategies in real-time. For example, some people continually assess the chunking memorization process by testing their recall performance on a long string of numbers.

Evaluating refers to appraising the products and goals initially set by cognitive processes. For example, some people assess the value of recalling the long string of numbers that could have been miscalculated or changed since the time they first decide to engage in memorization.

Table 1: Taxonomy of Metacognition proposed by Schraw (1998)

Knowledge of Cognition	Declarative knowledge	Know "about" or "what"
	Procedural knowledge	Know "how"
	Conditional knowledge	Know "when" and "why"
Regulation of Cognition	Planning	Selecting strategies & allocating resource
	Monitoring	Checking performance real-time
	Evaluating	Appraising performance

For the purpose of the paper, the literature review on the metacognition construct is limited to the description of the taxonomy. The description on metacognition above should provide a sufficient foundation to illustrate the role of metacognition in operator work.

NUCLEAR PROCESS CONTROL

A comprehensive discussion to establish the practical basis of metacognition in nuclear process control is beyond the scope of this article. To illustrate the importance of metacognition, we review field evidence on how operators rely on metacognition to manage NPPs. Then, we turn to experimental research on metacognition in nuclear process control that yields more precise understanding of the construct for informing the design of control room technology and operations.

Field Evidence on Metacognition

The literature indicates that operating NPPs is increasingly knowledge-based and that the operations of NPPs depend on adaptive behaviours of human operators (e.g., Carvalho, dos Santos, & Vidal, 2006; Mumaw et al., 2000). Taking these two observations together suggests that adaptability of cognition for accomplishing various knowledge-based tasks is central to operating NPPs. Thus, metacognition – the knowledge and regulation of cognition that facilitates cognitive adaptation - must be central to operator work in NPPs. Though the perspective of metacognition is only occasionally taken, the literature contains clear examples of the metacognition in nuclear process control.

Regulating Workload. Regulation of workload is a common example of metacognition. Operators often prioritize various tasks to moderate their workload over time, especially during abnormal events (Braarud & Brendryen, 2001). In fact, some operational cultures expect operators to regulate workload by choosing appropriate times to respond to requests. Hence, managers, engineers and maintenance sometimes queue for responses from control room operators. (Vicente, Mumaw, & Roth, 2004).

Effective workload regulation relies on several of the dimensions of metacognition in Table 1. Operators must initially allocate resources to various tasks (i.e., cognitive planning). Then, the operators must continually monitor their cognitive load (i.e., monitoring cognition) as work demand changes, and must be aware of their cognitive capacity (i.e., declarative knowledge of cognition). When the composition of tasks changes significantly, the operators must re-allocate cognitive resources (i.e., cognitive re-planning). If metacognition is not available to alter the initial resource allocation strategies, operators might experience extremely high and low workload because they do not adapt their workload to the situation. Extreme workload would hinder cognitive and ultimately operator performance (Braarud, 2000; Braarud & Brendryen, 2001).

Adapting procedures. The impression of NPP operations is that all operations are highly "proceduralized" due to potential safety consequences of accidents and thus strict regulatory requirements. However, the scale and complexity of NPPs prohibit any set of procedures to cover all possible operating details and situations (Vicente, 1999). Thus, operators must adapt the procedures to the situation in order to control the nuclear process (e.g., Carvalho et al., 2006). In fact, NPPs simply could not operate with mindless application of procedures (Vicente, 1999, p. xiii).

Adapting procedures constitutes another common example of operator reliance on metacognition. When operators decide to reach a particular plant state, they would likely adopt a procedural approach/strategy initially (i.e., cognitive planning). In some cases, the procedures could fail to yied the desires plant state due to unique operating conditions. If the operators continue to follow the initial procedural approach without monitoring the performance of that cognitive strategy, they would never reach the desired plant state. In fact, mindless application of procedures could destabilize the plant. When the operators acknowledge failures in the approach and the procedures given the situation, they must deviate from procedures and engage in adaptive behaviours. Adapting procedures challenges metacognition because operators must be aware of what, how, when and why their knowledge is applicable in the given situation (i.e., knowledge of cognition) over the knowledge captured in the procedure. They must also be able to manipulate their knowledge (e.g., cognitive planning) to develop solutions to the problems that cannot be addressed by the procedures. When their solution fails, they think about how their knowledge and cognitive process fails to produce a viable solution to reach the plant states and thereby gain knowledge in developing another solution (i.e., all three dimensions of cognition regulation). In brief, metacognition provides the mechanism to operate on the contents and processes of cognition so that operator interventions are adaptive to the dynamics of the situations.

Detecting and responding to novel/unanticipated events. In addition to necessary deviation from procedures, there are other unanticipated events that rely on metacognition for detection and response. The Three Mile Island (TMI) accident is an illustrative case study on detecting and responding to unanticipated events (Toth, Malinauskas, Eidam, & Burton, 1986). Operators rely on a knowledge-driven approach to monitoring in order to mange the scale and complexity of NPPs (Mumaw et al., 2000; Vicente et al., 2004). However, the knowledge-driven approach is prone to fixation or cognitive tunneling. During the TMI accident, operators were fixated on possible "pipe bursts" due to excess coolant in the plant. Their knowledge-driven approach to monitoring and diagnosing the problem directed the operators away from relevant process parameters in the situation. Their fixation could be partly traced back to the emphasis of such problem during their training. The operators reduced coolant flow to the reactor when, in reality, the reactor was experiencing a loss of coolant - an unanticipated event prior to TMI. The problem was only diagnosed when an operator from a different shift arrived to support the crew on duty.

Both detecting and responding to novel events rely significantly on metacognition. To identify novel or unanticipated events, operators must monitor the cognitive strategies that direct their plant monitoring behaviours because it is the acknowledgement of failures in cognitive strategies to plant monitoring (i.e., an impasse in problem solving terminology) that could lead to the recognition of novel or unanticipated events. Acknowledging the failures or impasse in cognitive strategies to monitoring serves as a signal that the situation is beyond the boundary of prior knowledge or experience. If the operators do not detect the failures of their cognitive behaviours, novel and unanticipated events would go undetected due to cognitive tunneling resulting in inappropriate interventions as in the case of TMI. Responding to novel events is similar to adapting procedures. Operators must be aware of what, how, when and why their knowledge is applicable in the given situation (i.e., knowledge of cognition) and must be able to manipulate their knowledge (i.e., cognitive planning) to develop untried solutions for the unanticipated situations.

NPP operators must have good awareness and control of their own cognition or cognitive processes to manage their work activities. That is to say, metacognition is inherent to effective NPP operation. Although the role of metacognition is evident in the literature, quantitative and experimental research is necessary to provide more precise understanding of the construct and ultimately to inform designs of control room technology and operations.

Experimental Research on Metacognition

Experimental research can establish precise empirical relationships between metacognition and other human performance constructs. However, the literature contains very few experimental studies on metacognition in nuclear process control (in contrast to other constructs, such as situation awareness or workload, with substantial experimental results in their empirical foundations). Consequently, the literature does not provide the concrete knowledge on metacognition that could inform designs of control room technology and operations.

In the open literature, there are only two attempts to measure metacognition in nuclear process control. Hogg et al. (1994; 1995) created a situation awareness measure – Situation Awareness Control Room Inventory (SACRI) - using the sensitivity and bias indicators in signal detection theory. Although the measure is developed from a situation awareness perspective, the bias indicator is essentially a measure of metacognition that assesses effectiveness in regulating cognitive processes that separate signal from noise. The study results indicate that i) alarm displays tend to increase operator bias towards overestimation of parameter changes, and ii) operators tend to underestimate parameter changes in the past and present but overestimate them in the future. Unfortunately, the format of the queries appears to be in conflict with the sensitivity and bias calculation formula (see Appendix 4, Skraaning Jr. et al., 2007). Thus, the SACRI findings must be interpreted with caution.

Skraaning Jr. and Skjerve (2006) formulated a metacognition measure based on the difference of standardized scores between plant and self-rated performance. The measure reflects the operators awareness of their own performance in controlling the nuclear process. In a full scope simulator study, they reveal that trust in automation correlates with self-rating bias in knowledge-based scenarios. Specifically, high levels of trust in automation coincide with overestimation of their performance while low levels of trust in automation coincide with underestimation. Interestingly, the correlation between trust in automation and self-rating bias disappears in rule-based scenarios. Skraaning Jr. and Skjerve (2006) conclude that mis-calibrated trust in automation may lead to over- or under- estimation of performance when well-defined criteria of performance are absent (i.e., in knowledge-based scenarios).

The metacognition measure formulated by Skraaning Jr. and Skjerve (2006) demonstrates promise, revealing the relationship between trust, self-assessment, and type of situations (i.e., scenario types). Thus, we have adapted the measure to study metacognition further in another full-scope simulator study. In particular, we expect to observe effects of scenario type on metacognition, which is sensitive to psychologically different situations (e.g., routine vs novel events).

METHOD

A full-scope simulator experiment was conducted to evaluate the performance of different display types under different conditions using many measures. The results related to the display designs are reported elsewhere (Burns et al., 2008; Lau, Jamieson, Skraaning Jr., & Burns, 2008). In this article, we report our findings on metacognition from this empirical study.

Participants

Six licensed operator crews (n=6) were recruited from a Boiling Water Reactor power plant identical to the simulated process. Each crew consisted of one reactor operator (RO) and one turbine operator (TO), responsible for the primary and secondary side of the simulated process, respectively. However, the results and discussion in this article only pertain to the performance of the TOs because the experimental manipulations were specifically designed to challenge the TOs.

Experimental Environment

The HAlden Man-machine laboratory BOiling water reactor (HAMBO) (Karlsson et al., 2001; Øwre, Kvalem, Karlsson, & Nihlwing, 2002) was employed as the experimental platform for this study. HAMBO, a high-fidelity simulator of a 1200MW BWR plant (in operation), offers a realistic environment of industrial nuclear processes.

Experimental Design

A 3x2x2 within-subjects design was originally employed with treatments of display type (Traditional, Advanced and Ecological), scenario type (Procedure-guided and Knowledge-based), and scenario phase (Detection and Mitigation). The treatments were completely crossed and counterbalanced using a Latin-square technique.

The analysis in this article simplifies the original experimental design to a one-way repeated-measure design by aggregating data across display types and scenario phases. The final experimental design only contains one treatment because scenario type is the only manipulation hypothesized to influence metacognition (also see RESULTS section).

Experimental Manipulations

The study consisted of three experimental manipulations:

Display Type. Three display types – Traditional, Advanced, and Ecological – were selected for comparison. The Traditional displays are the computerized version of the hard-wired wall panels originally installed in the operating nuclear plant. The Advanced displays are an improved version of the Traditional displays, containing some configural graphics (Øwre et al., 2002). The Ecological displays were designed according to the Ecological Interface Design framework and are described elsewhere (Lau, Veland et al., 2008).

Scenario Type. This study contained three Procedure-guided and three Knowledge-based scenarios. For the purpose of this study, Procedure-guided scenarios were defined by a set of disturbances that could be resolved by referencing plant procedures. Scenarios in which disturbances could not be resolved by procedures were classified as Knowledge-based. In other words, equipment failures anticipated by the utilities and job responsibilities familiar to operators characterized the Procedure-guided scenarios, while unanticipated and unfamiliar ones characterized the Knowledge-based scenarios.

Scenario Phases. Each scenario started with a "Detection" phase, a time period just before the first alarm sounded, and then ended with a "Mitigation" phase that consisted of all subsequent events.

Hypothesis

Metacognition should be superior in Procedure-guided scenarios, in which procedures could provide some basis of task performance, than in Knowledge-based scenarios, in which explicit criteria are absent (see, Skraaning Jr. & Skjerve, 2006).

Measures

Workload. We collected workload data using a subjective task-complexity scale developed by the OECD Halden Reactor Project (Braarud & Brendryen, 2001). The scale is a self-rating instrument focusing on task-related difficulties that control room operators experience while they work. Participants rate eight items in a seven-point Likert scale anchored by 'very difficult' (1) and 'very easy' (7).

Actual task performance. Operator task performance was captured and quantified using the Operator Performance Assessment System (OPAS) (Skraaning Jr., 2003; Skraaning Jr. et al., 2007). OPAS provides a structure for the assessment of whether operators carry out their task work in accordance with scenario solutions prescribed a priori by experts in control room operation.

Self-rated task performance. We collected data on the operators' assessment of their own performance using a subjective self-rated task performance scale developed by the OECD Halden Reactor Project (Skraaning Jr. et al., 2007). The scale is a self-rating instrument focusing on general aspects of task performance (e.g., performing correct interventions) in operating a NPP. Participants rate eight items in a five-point Likert scale anchored by 'strongly agree' (1) and 'strongly disagree' (5) at the end of the scenario. Participants also rate four out of the eight items during a simulator freeze within the scenario.

Metacognitive bias. We use Actual task performance and Self-rated task performance scores to calculate Metacgonitive bias, which expresses the under- and over-estimation of operator self-assessment in their own task performance. Metacognitive bias is the difference between the standardized actual task performance scores and the standardized self-rated task performance scores (c.f., Skraaning Jr. & Skjerve, 2006). Hence, a Metacognitive bias score of zero represents the ideal, zero bias. Positive and negative scores represent over- and under- estimation of one's own performance, respectively.

Metacognitive accuracy. Common statistical methods do not yield easily interpretable results on bias scores. To employ Analysis of Variance (ANOVA), we formulated Metacognitive accuracy by i) calculating the root-mean-square (rms) of the Metacognitive bias scores, and ii) subtracting each (rms) score from the maximum score. Thus, higher Metacogntive accuracy scores reflect more realistic self-assessment.

Procedure

The participation of each crew was divided over three consecutive days. The first day was dedicated to the training program after obtaining informed consent and demographic information. Six hours of training occurred on the first day. The second day started with a one-hour training session to refresh the materials presented on the first day, followed by three scenarios with fifteen-minute breaks in between. The third day started with three scenarios also with fifteen-minute breaks in between, followed by a debriefing/closing session.

For all scenarios, crews were asked to maintain the original power level and safe operation. A process expert registered OPAS scores to corresponding performance items at various points of the scenarios by observing the participants while they monitored system states and resolved disturbances. The participants also responded to the subjective task-complexity and self-rated task performance questionnaires during a short simulator freeze and at the end of each scenario. The simulation freeze occurred at the end of the Detection phase, which took up the first five to ten minutes of the scenario. The scenario then continued with the Mitigation phase, which was marked by the onset of the first alarm within the first minute. The Mitigation phase usually lasted 30 to 40 minutes, followed by another administration of the subjective task-complexity and self-rated task performance questionnaires at the end of the scenario.

RESULTS

Experimental Manipulations

Exploratory analysis indicated that Metacognitive accuracy could not reveal any main and interaction effects besides scenario type. This is consistent with our knowledge and hypothesis that scenario type is the only manipulation affecting Metacognitive accuracy. Therefore, we reduce our experimental design for analysis to illustrate the finding relevant to metacognition by aggregating the data across display types and scenario phases.

Metacognitive *accuracy* was analyzed in an ANOVA with a fixed factor of scenario type (Procedure-guided and Knowledge-based) and with a random factor of crew. A significant main effect of scenario type ($F(1,5)=18.49$, $p=.01$, $\eta^2=.79$) was observed (Table 2).

Table 2: ANOVA results on Metacognitive Accuracy

Effects	SS	df	MS	SS_{er}	df_{er}	MS_{er}	F	p
Scenario	3.05	1	3.05	0.83	5	0.17	18.49	0.01

The main effect plot (Figure 2) illustrates that Metacognitive accuracy is better in Procedure-guided (M=2.40, SE=.08) than Knowledge-based scenarios (M=1.99, SE=0.11).

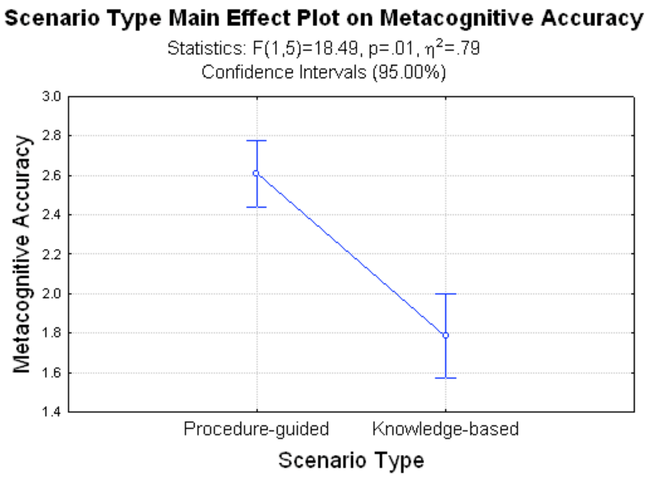

Figure 2: Main effect plot of scenario types. The confidence intervals are graphed according the method proposed by Cosineau (2007) to remove within-subject variance.

Measurement Correlation

Metacognitive *bias* inversely correlated with Workload ($r(72)=-.67$, $p=.00$, $r^2=.45$). The regression line in the Metacognitive Bias and Workload scatter plot (Figure 3) illustrates that low mental workload coincides with overestimation and high mental workload coincides with underestimation of task performance.

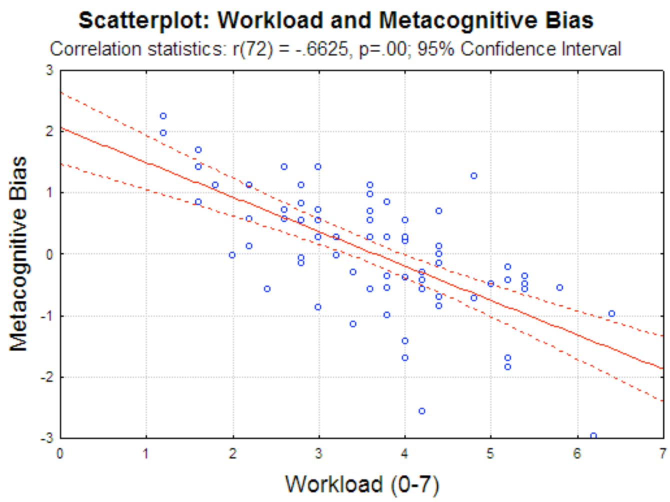

Figure 3: Scatter plot of workload and metacognitive bias.

DISCUSSION

Experimental Effects

Knowledge-based scenarios challenge operators in their self-assessment of task performance more than Procedure-guided scenarios, supporting the hypothesis and corroborating findings in a pervious study (Skraaning Jr. & Skjerve, 2006). In Procedure-guided scenarios, the operators can rely on procedures as the basis for criteria to assess their task performance. However, in Knowledge-based scenarios, the operators not only lack procedural support but also engage in adaptive behaviours - untried solutions developed in real time - to address novel events. Thus, operators tend to be less realistic about their self-assessment. Unfortunately, accident investigations (e.g., TMI) suggest that metacognition is more critical for managing novel events (i.e., knowledge-based scenarios) than routine events (i.e., procedure-guided scenarios). Therefore, this finding directly prompts further research and greater design considerations to support metacognition in nuclear process control, particularly during unanticipated events.

Amongst all the measures employed in this study, Metacognitive accuracy is the only measure revealing a main effect of scenario type (see, Skraaning Jr. et al., 2007). The metacognition construct advocates that Metacognitive accuracy could be the most sensitive measure to scenario types because metacognition is responsible for adapting cognition to psychologically different situations (e.g., applying procedures versus creating novel solutions). From a methodological perspective, Metacognitive accuracy is thus a valuable measure for investigating the novelty of scenario designs or situations to operators. Novel or unanticipated events are often the precursor of major NPP accidents, and are thus an important topic for control room design and future research. As a measure, Metacognitive accuracy is also meaningful for evaluating technology and training effectiveness in supporting metacognition in managing novel or unanticipated events.

Correlations

Observed correlations cannot confirm or prove any causal relationships. Therefore, the correlation between Metcognitive bias and Workload may be interpreted as either a workload imbalance (i.e., too low or too high) inducing bias in self-assessment, or a bias in self-assessment inducing workload imbalance. The two interpretations have different implications in supporting NPP operators.

In the case of a Workload imbalance affecting Metacognitive bias, one likely explanation is that low workload yields a false perception of good performance because additional work capacity would be available to manage further deterioration of plant states. On the other hand, high workload may yield a false perception of poor performance because the work capacity to manage current and additional problems may be close to the limit forcing the operators to consider drastic actions such as cold shut down. Should workload affect metacognition, the work processes (e.g., crew composition) or support tools (e.g., adaptive automation) must moderate workload accordingly to minimize either under- or over- reacting to the situation that may reduce the stability of the nuclear process.

In the case of Metacogntive bias affecting Workload, one likely explanation is that operators commit errors of omission due to false perceptions of good performance in their self-assessment. In other words, operators may experience low workload because they did not perceive any work activities as necessary to achieve safety and productivity goals given the situation. On the other hand, when perceived performance is erroneously low, they may have actively tried to improve performance by engaging in additional work activities (e.g., verifications) that are potentially unnecessary, and thereby experienced high workload. As in the case of workload affecting metacognition, the operators could destabilize the nuclear process due to either under- or over- reacting that is driven by poor metacognition. However, the work processes/procedures or control room designs should support metacognitive processes as opposed to workload moderation in this case. While some work processes/procedures (e.g., reflection time at the beginning of an emergency) and training may contain implicit consideration, there are very few design approaches or technology that explicitly aims to support metacognition.

FUTURE WORK

Future work needs to address many aspects of research on metacognition. Qualitative research such as field studies is necessary to expand the practical understanding of metacognition at work. These studies may focus on specific aspects of metacognition such as how operators suddenly detect a novel event or how they decide to switch cognitive strategies as a result of an unanticipated problem. These empirical data are useful to formulate theory and define metacognitive challenges faced by operators.

Qualitative field studies should also seek out methods employed by the operators to assist their metacognitive activities. The methods used by operators to facilitate metacognition may serve as direct inputs for developing support tools, training and procedures. These design inputs may have direct impact on safety and productivity of NPPs.

Quantitative research provides a data-driven approach to study metacognition. Future studies should investigate relationships between metacognition and other human factors constructs. Besides trust in automation and workload, metacognition probably relates to expertise, situation awareness, teamwork, and task performance. Furthermore, future work should begin investigating causal relationships as opposed to correlations that are presented in previous studies.

Quantitative studies could also assess the impact of technology, training, procedures and operational conditions on different dimensions of metacognition. These assessment studies could inform human factors practitioners on methods to improve support for metacognition.

When sufficient quantitative data is available, modeling human performance in consideration of metacognition could provide great insights to the theory of metacognition. Human performance models are also useful tools for industry to improve human factors engineering in general.

Future work must address methodological challenges in studying metacognition qualitatively and quantitatively. Specialized knowledge elicitation and inference techniques for qualitative research on metacognition, in addition to cognition, would be valuable. Existing quantitative measures on metacognition only concentrate on self-assessment. Additional measures are necessary to assess other dimensions of metacognition. Measurements are not only useful for research to acquire knowledge on the construct but also for the industry to evaluate designs of control room technology and operations.

CONCLUSION

The literature provides substantial evidence that metacognition is a central part of NPP operator work. However, there is limited theoretical, empirical and methodological research on metacognition in nuclear process control. As a result, the knowledge on metacognition in nuclear process control is sparse, failing to inform practitioners on how to support a key aspect of operator work. The paucity of knowledge is reflected in the lack of design approaches and support tools that explicitly aim to facilitate effective metacognition. This article reviews the field evidence and presents experimental results on operator metacognition that have direct implications on designs of control room technology and operational processes. The intention is to promote research attention and design consideration to support operator metacognition.

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