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Bridging Human Reliability Analysis and Psychology, Part 2: A Cognitive Framework to Support HRA

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Abstract: This is the second of two papers that discuss the literature review conducted as part of the U.S. Nuclear Regulatory Commission (NRC) effort to develop a hybrid human reliability analysis (HRA) method. This review was conducted with the goal of strengthening the technical basis within psychology, cognitive science and human factors for the hybrid HRA method being proposed. The first paper provides an overview of the literature review approach and high-level structure, whereas this paper presents the results of the review.

The psychological literature review encompassed research spanning human cognition and performance, and consequently produced an extensive list of psychological processes, mechanisms, and factors that contribute to human performance. To synthesize this large amount of information for HRA, the authors organized the results of the literature review into a *cognitive framework* that consists of proximate causes of failure of human macrocognition (i.e., types of cognitive errors), and connects those causes to psychological mechanisms that underlie human cognition, and then to performance influencing factors (PIFs) that can lead to the failure. This cognitive framework can serve as a tool to inform HRA. Beyond this, however, the cognitive framework has the potential to also support addressing human performance issues identified in human factors applications.

Keywords: human reliability analysis, IDHEAS, cognitive framework, psychological foundation for HRA

1. INTRODUCTION

This is the second of two papers that discuss the literature review conducted as part of the U.S. Nuclear Regulatory Commission (NRC) effort to develop an integrated human reliability analysis (HRA) method in response to Staff Requirements Memorandum (SRM) SRM-M061020 (NRC, 2006). A goal of this review was to strengthen the technical basis of the HRA method being proposed within psychology, cognitive science and human factors. An overview of the literature review approach and high-level structure is provided in the first paper (Whaley et al., these proceedings); this paper presents the product of the review.

One of the primary goals of the literature review was to develop a tool that could be used to inform HRA, specifically to identify the relevant causes and contributors to failure in human cognition. To accomplish this, the information identified from the literature review was organized into a framework that connects explicitly the types of cognitive errors with contributing factors, all supported by research. This paper details an excerpt from this cognitive framework and discusses how this tool may be used to inform HRA.

The HRA Good Practices document (Kolaczkowski, Lois, Forester, & Cooper, 2005) prescribes a multi-disciplinary team for conducting HRA, optimally including a member with a psychological, human factors, or human performance background. However, in practice, this is not always possible. It is also not always feasible for HRA analyses to employ experienced cognitive psychologists as analysts. The cognitive framework was developed with these two points in mind. The cognitive framework summarizes and organizes the literature into a tool that enables analysts to understand and systematically identify the reasons why humans make errors.

2. STRUCTURE OF THE COGNITIVE FRAMEWORK

2.1. Overview and Definition of terms

The purpose of the cognitive framework is to identify and provide explicit connections between plausible causes, mechanisms, and influences for failure of a macrocognitive function. The goal is to identify how failure occurs: For the possible causes of failures (proximate causes), what are the mechanisms for human error, and what context (PIFs) may activate those mechanisms?

The cognitive framework consists of five trees, one for each macrocognitive function. As discussed in Whaley et al (this proceedings), *macrocognitive functions* refer to the high-level mental activities that must be successfully accomplished to perform a task or achieve a goal in a naturalistic environment (Letsky, 2007). The five macrocognitive functions used in the framework are:

- Detecting/Noticing
- Sensemaking/Understanding
- Decision Making
- Action Implementation
- Team Coordination

See Whaley et al. (this proceedings) for definitions of each of these macrocognitive functions. For any task, operators typically have to engage in all of these macrocognitive functions in varying amounts, and often more than one at the same time. Some tasks, such as diagnosing an alarm, may involve more detecting and understanding than decision making or action, whereas other tasks, such as implementing a reactor cooling system (RCS) depressurization, rely heavily on action and team coordination. Additionally, the boundaries between the macrocognitive functions are blurry; the functions overlap and are interdependent, and the flow of human thought does not follow a linear path through the macrocognitive functions. Rather, there is much parallel thought as well as circular moving back and forth between and through all of the macrocognitive functions as the operators conduct their work.

For each of these macrocognitive functions, the authors identified the causes of failure of the function from the literature review. These causes are termed *proximate causes* in the framework, because they are readily identifiable as leading to the failure. Proximate causes are the result or manifestation of failure of a mechanism, and each cause can be associated with several mechanisms.

Mechanisms are the processes by which the macrocognitive function works. They are the processes by which cognition takes place in the work environment. If part of the process fails, either internal or external to the human, this failure may manifest itself as a proximate cause of macrocognitive function failure. An example of a mechanism is working memory, the ability to retain information in completing a task. It is important to note that the mechanisms are processes that are vulnerable to fail under certain external or internal factors. Thus, the mechanisms are the substrates of human failures.

Those circumstances that may contribute to failure of a mechanism are called *performance influencing factors* (PIFs). PIFs are contextual factors (including plant factors) that influence the likelihood that the psychological mechanisms "activate" and lead to proximate causes of macrocognitive function failure. The PIFs affect human performance and can either reduce or raise the likelihood of error. PIFs are commonly used in HRA methods to adjust the HEP depending on the context of the situation, and they are also commonly used to identify root causes of error and areas for improvement. This project adapted a list of performance influencing factors from Groth (2009). However, it is important to note that some items that appear as PIFs in Groth's taxonomy may be treated as mechanisms or proximate causes in the cognitive framework structure developed in the present work. For example, the quality and availability of information is treated as a mechanism in the Detecting/Noticing and Sensemaking/Understanding framework tree, and it is also treated as a PIF for other mechanisms used in the Sensemaking/Understanding, Decision Making, and Action trees (as human-system interface, or HSI).

The cognitive framework takes all four of these elements—macrocognitive functions, proximate causes, mechanisms, and PIFs—and organizes them into a tree structure that illustrates how macrocognition may fail and describes the reasons why; each function is represented with one tree. Such a causal tree is similar in appearance to a fault tree tipped sideways; however, there are no logic operators in the cognitive framework, nor is there an assumption of orthogonality throughout the tree branches. Specifically, the authors have endeavored to make the proximate causes as independent from each other as possible. Yet, different causes can associate to some common mechanisms, and the same mechanism may lead to more than one proximate cause.

The generic structure for each tree in the cognitive framework is shown in Figure 1. The tree is written in failure terms because the purpose of the tree is to identify how a macrocognitive function may fail. Starting from the left in Figure 1, the first purple box represents the macrocognitive function that the tree is analyzing. The blue boxes to the right of the macrocognitive function represent the proximate causes of failure for the function. Each proximate cause is then linked to a number of mechanisms, shown in turquoise boxes. Each mechanism is connected to the relevant PIFs for that mechanism, shown in the orange boxes. The causal flow moves from right to left, as indicated by the arrows: the contextual factors (PIFs) influence whether a mechanism fails, which manifests as a proximate cause of failure of the macrocognitive function.

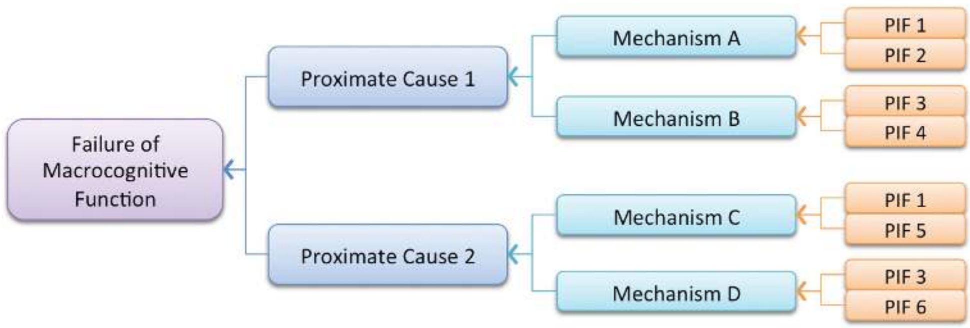

Figure 1. Generic Cognitive Framework Structure

One of the most important developments in the cognitive framework is the identification of the mechanisms. The mechanisms connect explicitly the PIFs with causes of cognitive failure. Specifically, the mechanisms:

- Provide explanation about *why* PIFs are important
- Provide information about *how* PIFs influence human cognition into errors
- Put this information in one easy-to-use tool that can inform HRA and other applications

For example, it has been noted that poor safety culture may lead to errors in decision making (Reason, 1997). The cognitive framework provides an explanation and the information about how and why that can happen. As shown in Figure 3, poor safety culture likely causes decision makers to have incorrect goals (e.g., keep operating in spite of degraded conditions), experience goal conflict (e.g., conflict between not wanting to make waves and wanting to report a safety concern), or incorrectly prioritize the goals (e.g., placing safety at a lower priority in goals to be achieved). Thus, the tree elucidates the potential relationship between safety culture and goal selection. While existing HRA methods have little consideration of safety culture, this cognitive framework delineates the relationship in such a way that analysts who are not familiar with the body of research in safety culture can still identify the potential impact of safety culture on decision making. In this manner, the cognitive framework informs HRA.

It is important to note that the framework is a tool to identify which causes, mechanisms, and PIFs to consider or investigate for the situation or HFE under analysis. In addition, while the framework identifies which factors are likely to be relevant given the psychological research reviewed, the authors make no claim that the factors listed are the *only* potentially relevant factors. Other factors may fail a particular mechanism; it is also plausible that a mechanism may fail even in the absence of contextual factors. These trees simply show the factors that have been identified as relevant by psychological and human factors research.

3. EXCERPT FROM THE COGNITIVE FRAMEWORK

The cognitive framework is too large to fit it in its entirety into one paper; therefore we present one of the macrocognitive functions in detail as an example[1]. To continue the example used above, the macrocognitive function of Decision Making will be discussed in more depth.

3.1. Overview of Decision Making

Decision Making (DM) is based on the judgment of what should be done and the decision to do it. Yates (2003) defines decision as: "a commitment to a course of action that is intended to yield results that are satisfying for specified individuals" (p. 24). How decisions are made and the ability to predict the decided upon solution has been of interest to researchers for years. Modelling DM has progressed from the study of how decisions ought to be made to the study of how they are actually made. The study of DM has also evolved to include a greater emphasis on the context in which the decision is made and consideration that decisions are often made in a dynamic and changing environment. It is this dynamic context-based study of DM that will be of greatest concern when considering the decisions made within a NPP.

DM within a NPP is characterized as involving experts and being largely driven by procedures. In recognition of the complex environment inherent in NPP operation, Espinosa-Paredes et al. (2008) focus on the need to develop emergency operating procedures that aid the operator in navigating these complexities and arriving at the correct decision. Although procedures usually dictate the actions of the operators, Roth (1997) explains that the operators still maintain a mental model of the situation and will plan their course of action semi-independently of the procedures. That is, they will have an idea of what it is that needs to be accomplished and how that should be done and will look to the procedures to confirm these beliefs. Furthermore, situations may arise that procedures do not cover. In these instances, operators must rely on their expert knowledge to solve the problem and implement the appropriate decision.

There are a number of DM models, many of which are discussed in Whaley et al. (in press), but for decision making in the NPP environment, the most appropriate approach is Naturalistic Decision Making (NDM). NDM considers the decision maker in a real-world setting where decisions are typically embedded in a larger task. NDM researchers study "time pressure, uncertainty, ill-defined goals, high personal stakes, and other complexities that characterize DM in real-world settings" (Lipshitz, Klein, Orasanu, & Salas, 2001, p. 332).

One model of particular note within NDM is the recognition-primed decision (RPD) model (Klein, 1993, 1998). RPD was primarily developed in an attempt to explain DM of experts in stressful situations and under time pressures. It typically does not consider procedurally driven actions, but instead focuses on quick actions implemented by experts through their experiential knowledge. When choosing a course of action, RPD predicts that the decision maker settles on the first solution that comes to mind that provides an adequate answer – that is, the decision maker is satisficing and not optimizing the solution.

RPD is not a perfect fit for modeling DM within NPP because of its focus on non-proceduralized events. However, Greitzer, Podmore, Robinson, and Ey (2010) present an integrated NDM model that can be used to represent DM by operators. This model seems to work well in identifying the process an experienced operator goes through in making a decision, even in the presence of procedures. In the case of experienced operators when several procedures are available and numerous situations and recovery strategies are trained, the operator may take three approaches when planning a response (Cacciabue, Mancini, & Bersini, 1990):

1. In a very familiar setting in which the cues match almost perfectly the procedural guidance, the operator may follow the procedures with little diagnosis needed.
2. In a familiar setting that deviates slightly from procedural guidance or from previously encountered situations, the operator will have to adapt and plan a response based on an analogous experience.
3. In a novel setting, the operator will have to construct a new response plan using his or her knowledge of the plant and system and previous experience.

[1] For the full framework and complete discussion of all the macrocognitive functions, see NUREG-2114 (Whaley et al., in press), or contact the authors. The final document is expected to be published by late 2012.

Each of these options, but particularly the last two, may be seen through the lens of the integrated NDM model. The operator or crew will use cues presented in the situation to construct a story of what is happening and how the scenario is unfolding. This mental image will be used in developing a response plan and alternative actions; the response plan may be largely prompted by procedures or entirely conceived by the operators. The response plan or action script may be evaluated through mental simulation to evaluate its suitability and then put into action.

To facilitate the identification of relevant PIFs, the phases of the DM process where failures were likely to occur were examined. The phases examined were based on the RPD model proposed by Klein (1993, 1998) and the integrated NDM model proposed by Greitzer, Podmore, Robinson and Ey (2010). A fairly comprehensive review of literature within DM was conducted to identify the mechanisms that lead to errors within these phases and processes. This review revealed several mechanisms that could be grouped into three proximate causes. One area that is clearly important to the operations of NPP that will be seen to be missing in this list is the area of team decision making; however, distributed DM and the impact that a team may have on the decision making process is discussed in the macrocognitive function of Team Coordination. The proximate causes that were identified are shown in Figure 2 and include *incorrect goals or priorities set*, *incorrect internal pattern matching*, and *incorrect mental simulation or evaluation of options*.

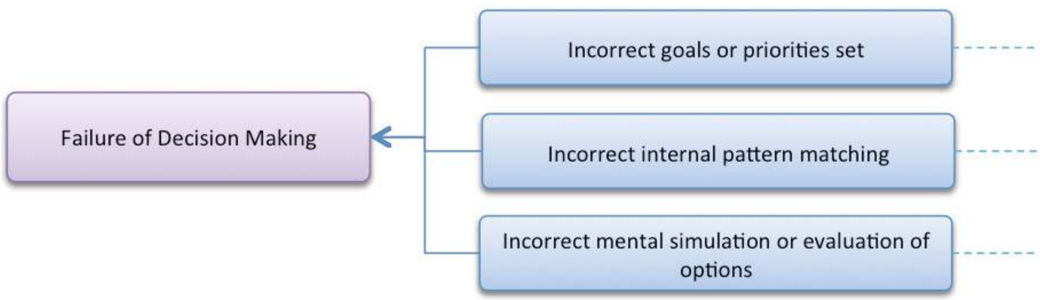

Figure 2. Top of the Decision Making Framework Tree

Each of these proximate causes has underlying mechanisms and PIFs. The cognitive framework tree for first of these, *incorrect goals or priorities set*, is shown in Figure 3. Goals are set as the objectives to be achieved by the decision and are the measure for viewing the decision as successful or not. Although goals are formed during any decision making process, they are especially relevant during novel situations when there is no previous experience to which the current situation and the outcome of the decided upon action can be compared against to measure success. If more than one goal is selected, priorities are assigned to the goals to determine the order in which they are to be addressed. This proximate cause includes errors that occur either in what goals are set or what priorities are assigned. Mechanisms for this proximate cause include:

1. Incorrect goals selected. Errors may arise if the operators select the wrong goal to work toward. A variant of this mechanism is if the operator selects an implausible goal that cannot be achieved.
2. Goal conflict. A conflict may arise in the operator's mind between the goals of safety and the continued viability of the plant.
3. Incorrect prioritization of goals. Goals may be ordered incorrectly in the operators' mind or given the wrong priority such that less important goals are addresses first.
4. Incorrect judgment of goal success. The threshold used by the operator to judge goal success may be incorrectly set too low or, the operator may incorrectly determine the goal to be met when it was not.

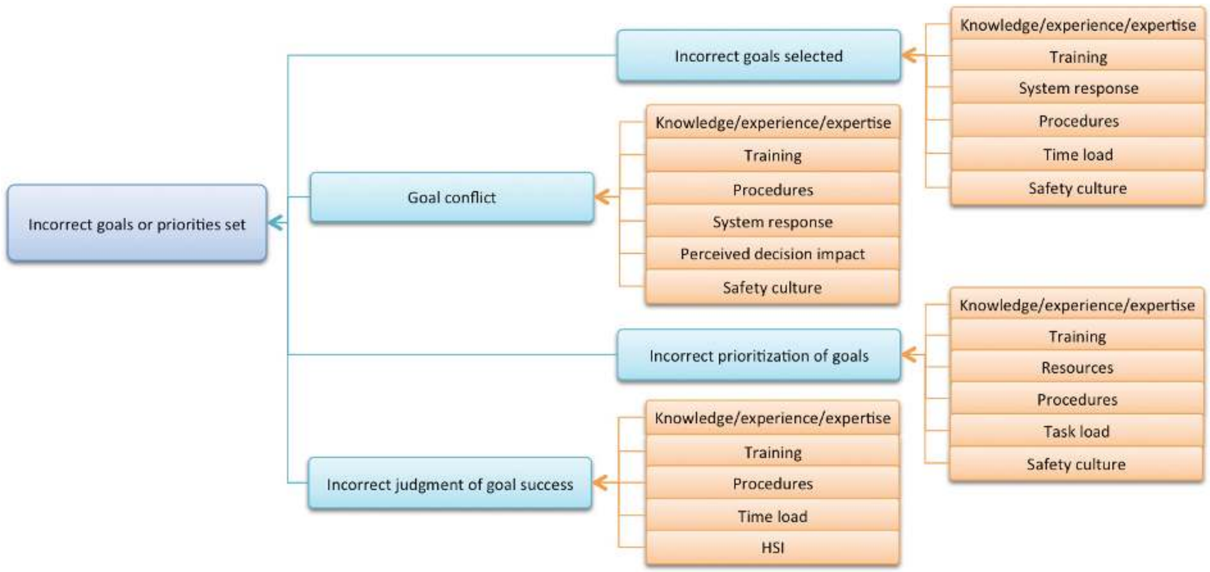

Figure 3. Tree for the Proximate Cause of *Incorrect Goals or Priorities Set*

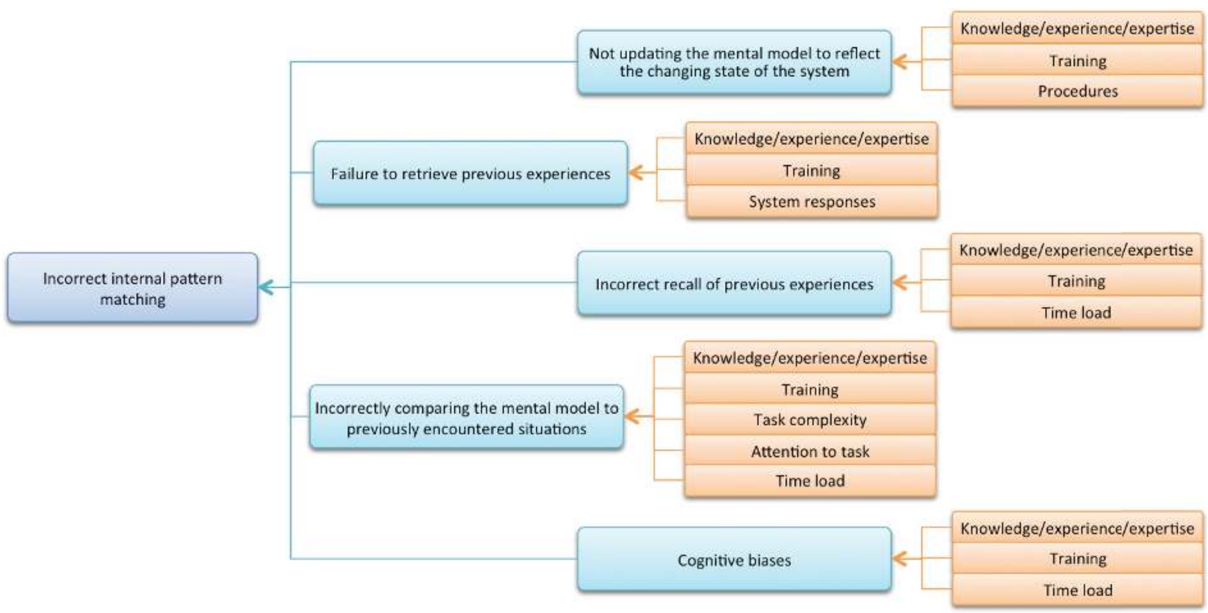

Figure 4. Tree for the Proximate Cause of *Incorrect Internal Pattern Matching*

The second proximate cause that can lead to failure of Decision Making is *incorrect pattern matching*, the tree for which is shown in Figure 4. During the understanding macrocognitive stage, a mental model is formed of the current situation. During pattern matching, this mental model is compared to previously encountered situations to judge the typicality of the situation and help in devising a plan. If the situation is judged as being typical, a previous response plan can be used again. If the situation is novel, a similar situation may be found that can be adapted to fit the current situation. This proximate cause includes errors that occur during the mental exercise of pattern matching. Mechanisms for the *incorrect pattern matching* proximate cause include:

1. Not updating the mental model to reflect the changing state of the system. Events within a NPP may evolve quickly, and the operator must update his or her mental model to reflect this dynamic nature.
2. Fail to retrieve previous experiences. During pattern matching, the operator compares the current situation to previously encountered situations in order to devise an appropriate response plan. Errors may occur in this recollection process if the operator fails to evoke appropriate previous experiences.
3. Incorrect recall of previous experiences. Similar to the previous failure mechanism dealing with the recollection of previous experiences, in this case the error may occur due to an incorrect recollection

of the previous experience. In other words, the operator may incorrectly remember how the previous experience was responded to.

4. Incorrectly comparing the mental model to previously encountered situations. The comparison with previously encountered situations may cause an error either because the comparison was incomplete or simply because a mistake occurred in the comparison.
5. Cognitive biases. Confirmation bias and availability bias may be particularly pertinent to causing errors in this phase of DM (Einhorn & Hogarth, 1978; Tversky & Kahneman, 1974). Confirmation bias states that people tend to seek out evidence that confirms their current position. Availability bias states that the ease with which an item can be brought out of memory will influence the value assigned to the memory. These biases may affect the recollection of previously encountered situations, the comparison of the mental model to the previously encountered situations, or the updated of the mental model.

The last proximate cause for failure of Decision Making is *incorrect mental simulation or evaluation of options* (Figure 5). To evaluate the appropriateness of the different proposed actions, a mental simulation is done in which the operator runs through the application of the actions. The operators may not do an exhaustive mental simulation of all proposed solutions thus they may end up with the non-optimal option that leads to errors. This proximate cause includes errors that occur during the mental simulation or evaluation of options. Mechanisms for this proximate cause include:

1. Inaccurate portrayal of action. This failure mechanism includes incorrectly characterizing the action (i.e., forgetting a step of the action during the mental simulation) or incorrectly predicting how the action will be implemented.
2. Incorrect inclusion of alternatives. The operator may not include some alternatives that should be considered.
3. Inaccurate portrayal of the system response to the proposed action. This failure mechanism manifests in the operator incorrectly predicting how the system will respond to the proposed action.
4. Misinterpretation of procedures. Response planning within the NPP is done by consulting procedures. An error may occur because either the wrong procedures are used to address the situation or the procedures have complicated logic for operators to understand and follow.
5. Cognitive Biases. The cognitive biases and the anchoring effect may be especially prevalent for this failure mechanism. If the operator has had previous success with an action, he or she may be biased when coping with the present case. The anchoring effect states that people are biased toward the first option they see or the first judgment they make. Therefore, an operator may choose the first action that occurs to him or her, and apply an unsuitable action.

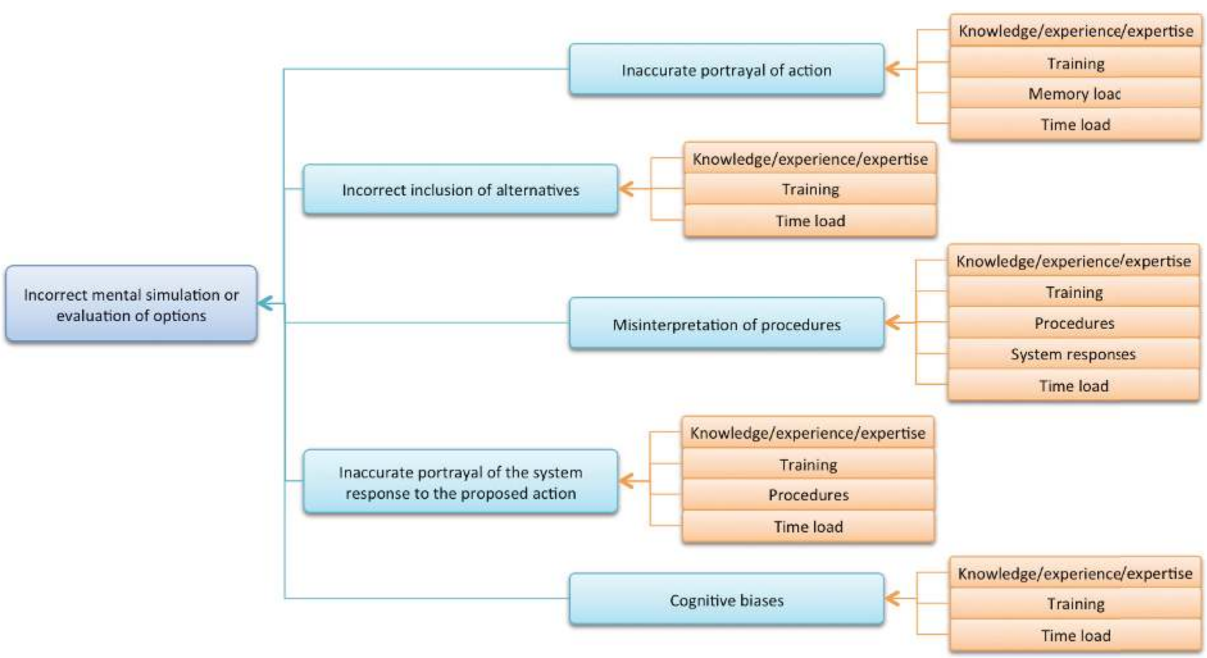

Figure 5. Tree for the Proximate Cause of *Incorrect Mental Simulation or Evaluation of Options*

Table 2. Excerpt from the Table for the Proximate Cause *Incorrect Goals or Priorities Set*

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Incorrect goals selected	During goal setting, the operator chooses the wrong goal(s) to work toward. The wrong goal(s) may be selected due to an improper understanding of the situation.	Although the operator may initially have classified the situation correctly (i.e., had a correct mental model), the situation may evolve to something different and the operator does not update the goals to reflect this new situation.	• Procedures • Knowledge/ Experience/ Expertise • Training • System Reponses • Safety culture	• Procedures may mislead the operator to believe the situation is changing slower than it really is. • Experience with this situation may be lacking and the operator does not expect the situation to change so quickly or to evolve to the new state at all. • Training with this type of situation may be non-existent or have been given too long ago to be relevant. • The cues and responses being presented by the system may be ambiguous making it difficult for the operator and crew to diagnose the situation and develop the correct response plan.	(Cacciabue, et al., 1990) (Klein, 1993) (Lipshitz, 1993) (Orasanu, 1993) (Reason, 1997)
Goal conflict	A conflict may exist in the operator's mind between the goals of safety and continued viability of the plant.	An improper balance of priorities may lead them to choose a response option that is less optimal (with regards to plant integrity or safety). The consequences of the actions may be less than desirable in one sense (e.g., reduces system life expectancy; will result in significant plant outage duration), so the crew would be reluctant to execute a specific response path.	• Procedures • Knowledge/ Experience/ Expertise • Training • System responses • Perceived decision impact [plant] (awareness of the economic consequences) • Safety culture	• Procedures may be poorly written or have complicated logic such that the crew does not fully understand the seriousness of the situation. • Experience and knowledge may be lacking such that the operator does not recognize the seriousness of the situation or understand the ramifications of the decision. • Training may be infrequent and the operator does not know how to balance the priorities appropriately. • System responses may be difficult to understand or misleading causing the operator to misunderstand the seriousness of the situation. • The crew or operator may have an incorrect assessment of the impact of the decision and value the continued viability of the plant more. • Poor safety culture increases the likelihood that operators will experience goal conflict.	(Orasanu, 1993) (Reason, 1997)
Incorrect prioritization of goals	Goals may be ordered incorrectly and assigned the wrong priority either because the operator didn't understand the importance of the goal or didn't understand the impact of the action.	The operator or team become distracted by problems with the secondary system and devote time and resources solving that issue and do not prioritize the issue with the primary system.	• Training • Knowledge/ Experience/ Expertise • Safety culture	• Training may be incomplete in how to prioritize goals and what systems should be recovered first and what actions should be performed first. • Experience with the plant may be lacking, and therefore, the operator doesn't know how to prioritize the goals and actions and doesn't fully understand the impact the actions will have on future goals. • Poor safety culture increases the likelihood that operators will incorrectly prioritize goals.	(Amendola, Bersini, Cacciabue, & Mancini, 1987) (Kasbi & de Montmollin, 1991) (Rouse, 1983) (Reason, 1997)
Incorrect judgment of goal success	During goal setting, errors may occur if the threshold for determining goal satisfaction is set at the wrong level, and the goal is judged as being achieved before it actually is.	Actions may be implemented and then abandoned or terminated too early if the goal is considered attained when it is not.	• Procedures • Training • Knowledge/ Experience/ Expertise	• Procedures may be written poorly such that it is hard for the operator to determine when success has been achieved. • Training on determining a value for a parameter may be lacking such that the operator is unsure if success has been achieved. • Experience with the system may be lacking such that the operator believes the system is in a safe state (or moving toward a safe state) when it is not.	(Cacciabue, et al., 1990) (Vicente, Mumaw, & Roth, 2004)

4. USING THE COGNITIVE FRAMEWORK AND ASSOCIATED TABLES

As shown in Figures 3-5, each of the mechanisms are connected to a number of PIFs that the literature review has identified as relevant for this aspect of decision making. Common PIFs such as procedures, knowledge/experience, and training, are unsurprising. Other identified PIFs may not be as commonly considered in various HRA methods, such as system responses, time load, safety culture, task complexity, attention, perceived decision impact, resources, and information available from the human system interface (HSI). Knowing that these PIFs are relevant is important, but not sufficient to understand how the PIFs influence the mechanisms. For that, the analyst must consult the tables that are associated with each tree.

Each framework tree has a supporting table that provides discussion of each mechanism, provides an example, identifies the relevant PIFs, and explains *why* the PIF is important, how the PIF impacts the mechanism, or where possible, what characteristics of the PIF are most likely to lead to failure of the mechanism. References for this information are also included.

The cognitive framework trees and their associated tables are presented as two appendixes in Whaley et al (Whaley, et al., in press). Together, the trees and tables are a tool that analysts can use to understand what can lead to cognitive failure in a situation, and to identify PIFs that are likely to be relevant. There is far too much information in the tables to include more than a small excerpt in the present paper. See Table 1 for an excerpt of the information available in the table for the proximate cause of *incorrect goals or priorities set*.

5. CONCLUSION

In an effort to support the development of an integrated HRA model, the authors conducted a literature review to synthesize the understanding of the cognitive aspects of NPP crew behavior in response to plant upsets, based on research results and findings in cognitive psychology, human factors, and organizational behavior. We developed a cognitive framework to organize the psychological concepts related to human performance in NPP and identify relevant PIFs leading to crew failure modes. The framework presents the links between the PIFs, psychological mechanisms, proximate causes of failure, and ultimately to macrocognitive functions. The framework serves as the foundation for the hybrid HRA method being developed. It informs HRA qualitative analysis and quantification approach, the crew failure modes, and the associated decision trees in the new method.

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