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Cognitive Basis for Human Reliability Analysis

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Cognitive Basis for Human Reliability Analysis

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ABSTRACT

This report documents the results of a literature review to synthesize human cognition research into a technical basis for human reliability analysis. The U.S. Nuclear Regulatory Commission (NRC) organized a team of researchers to review literature in psychology, cognition, behavioral science, and human factors and apply it to human performance in nuclear power plant operations. The project team synthesized the results into a cognitive framework that consists of five macrocognitive functions: (1) detecting and noticing, (2) understanding and sensemaking, (3) decisionmaking, (4) action, and (5) teamwork. For each macrocognitive function, the team identified proximate causes for why the cognitive function may fail, cognitive mechanisms underlying the failures, and factors that influence the cognitive mechanisms and may lead to human performance errors. Moreover, the project team used the information in the literature to infer causal relationships and links between different types of human failures and factors that influence human performance. This report provides a cognitive basis for human performance and a structured framework to assess how human performance may contribute to errors in the context of an evolving event scenario. The information can serve as the technical foundation for the NRC's human reliability analysis methods and human factors engineering guidance.

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EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) sponsored and led the work documented in this report as part of a larger project to update the technical basis for human reliability analysis (HRA), and develop new HRA methods to address limitations of existing methods. The NRC frequently uses HRA results and insights to support risk-informed regulatory decisionmaking, and HRA is an important component of probabilistic risk assessment (PRA). As a result, the NRC has a vested interest in the quality of HRA and continues to seek to improve the robustness of HRA.

One key step toward improving HRA is to build an HRA method based on state-of-the-art knowledge about human performance and human errors. Therefore, the NRC project team conducted an extensive review and synthesis of literature in psychology, cognition, behavioral science, and human factors to consolidate current understanding of human performance in operating environments. The ultimate goal of the literature study was to develop a technical basis for understanding human errors in NPP internal, at-power events to support the development of a new HRA method called the Integrated Human Event Analysis System (IDHEAS).

The project team reviewed thousands of scientific papers and technical reports spanning from laboratory studies, simulations of task performance by operating crews, and field studies in nuclear and non-nuclear (e.g., aviation, oil production) domains. The team then developed a cognitive framework to organize the relevant results from the literature. The framework assumes that human tasks are accomplished through five macrocognitive functions: (1) *Detecting and Noticing,* (2) *Understanding and Sensemaking,* (3) *Decisionmaking,* (4) *Action,* and (5) *Teamwork*. For each function, the team synthesized the information about proximate causes for why the function may fail, cognitive mechanisms underlying the failures, and factors that influence the cognitive mechanisms and may lead to human performance errors.

Overview of the Literature Review

The first stage of the literature review focused on identifying research related to operator performance in internal, at-power NPP events, in which experienced crews are trained to use operating procedures to perform tasks. Since NPPs are operated by crews—groups who work together, are highly trained, supervised, and who work in a regulated, procedure-driven environment—the review focused on literature related to both individual and team aspects of human performance, performance when working with procedures, and research related to working with highly trained or expert personnel, rather than novices.

After reviewing various models of human cognition in complex supervised tasks, we adapted a cognitive model for NPP tasks. The model assumes that cognitive tasks are achieved through five macrocognitive functions: (1) *Detecting and Noticing,* (2) *Understanding and Sensemaking,* (3) *Decisionmaking,* (4) *Action,* and (5) *Teamwork*. We then reviewed information about how each of the functions are processed, how the function fails, and what leads to the failure. The following terms are used throughout this report to describe the various elements of the cognitive model:

> *Macrocognitive functions* – These are the high-level functions through which a cognitive task is accomplished. The macrocognitive functions work together in a loop; these functions relate to and support each other, and they share some common cognitive mechanisms, yet each function is achieved by a unique set of cognitive mechanisms and can lead to unique types of human errors.

Cognitive mechanisms – Cognitive mechanisms are the processes by which macrocognitive functions work. They are the processes by which cognition takes place in the work environment, and are thus crucial to successful performance. If part of the process fails, this failure may manifest itself as a macrocognitive function failure (e.g., a *decisionmaking* failure). To understand why humans make cognitive errors, it is necessary to understand how human cognition successfully operates. In other words, it is important to identify the processes or *mechanisms* by which a cognitive function works. Some psychological literature may discuss these processes on a behavioral or descriptive level, while other psychological research may provide a more profound understanding of the contingencies and boundary conditions with which humans can reliably perform a function.

Proximate causes – A macrocognitive function can fail in many ways due to failure of its various cognitive mechanisms. We identified the outcomes when a cognitive mechanism fails, and grouped the outcomes into types of failures. We refer to these types of failures as the *proximate causes*. While cognitive mechanisms are scientific findings described in the literature, the set of proximate causes is merely a classification scheme for grouping cognitive mechanisms. There can be different ways to classify the mechanisms. Our goal was to develop a defined set of proximate causes that have distinct non-overlapping definitions, and are observable, identifiable, or inferable in a practical manner.

Performance influencing factors (PIFs) – These are circumstances or contextual factors that contribute to human performance in a work environment. They are commonly used in HRA methods to quantify human error probabilities. They are also used to identify root causes of errors and areas for improvement. Typical PIFs in HRA include task complexity, available time for performance, human-system interfaces, procedures, stress, etc. To understand how PIFs influence task performance and contribute to human errors, we identified the PIFs relevant to every macrocognitive function and compiled some example studies that demonstrated the effects of certain PIFs on the success or failure of the macrocognitive functions.

We organized information about each of the macrocognitive functions into separate chapters of this report. Together the information in these chapters forms a structured understanding of human errors. Since the information is largely taken from cognitive and psychological literature, it is generic to human performance. However, the scope of the review was limited to research relevant to NPP control room tasks in internal, at-power events. Research that did not fit one or more assumptions of the tasks (e.g., distributed decisionmaking, action execution without procedures) was not fully covered or integrated into this framework.

Stage two of the review was to infer links between the cognitive mechanisms identified and the relevant performance influencing factors. However, the information needed to make these connections was not always readily available in the literature. We established these links through analysis and inference from the information available in the literature. For every cognitive mechanism under each proximate cause, we link it to known cognitive theories or models explaining how the mechanism works. We then went through known performance influencing factors to analyze whether the factor affects the mechanism. Furthermore, we listed some examples of how the factor affects the mechanism. The information about the linkages is documented in the tables in Appendix A. HRA analysts should use these tables as a tool to determine types of potential failures in a human event and relevant factors that contribute to the failure. Note that due to the incompleteness in the literature and limitations in our review, we had to infer many of the relationships in the tables based on our understanding of the existing information. The inferences are considered expert judgment and thus have inherent subjectivity. In the future, information in the tables should be validated and updated with new findings in cognitive research.

Overview of Macrocognition

Literature on human information processing and human performance spans many research domains such as cognitive psychology, cognitive neuroscience, psychophysics, behavioral science, and human factors. The level of detail at which each research effort addresses human information processing also varies from neural responses, cognitive system activities, to behavioral measures. Macrocognition is a term to describe cognition in real-world settings. It focuses on the nature of human performance "in the field," where decisions are often very complex, have to be made quickly, by domain experts, in risky or high-stakes situations. That is, macrocognition focuses on what humans do with their brains, rather than on the fundamentals of how the brain works. Consequently, macrocognition is a useful way to model human cognition in HRA because it is at a sufficiently high level so that it is practical to use in predictive analyses. At the same time, it is also detailed enough to yield a coherent understanding of how humans perform tasks and what makes humans fail to perform the tasks. By synthesizing existing macrocognitive models, we adapted a macrocognitive model for human performance in NPP operations. In the model, a cognitive task is accomplished through the following five macrocognitive functions:

Detecting and Noticing is the function to detect and become aware of important information in the work environment. This macrocognitive function allows humans to perceive large amounts of information and focus selectively on those pieces of information that are pertinent to present activities. The cognitive processes associated with *Detecting and Noticing* include sensing, attending, perceiving, and recognizing the key information. Sensation has a large capacity for input, but sensory information can only be retained for a short interval before being replaced by new sensory information. Moreover, a person can only attend to a limited amount of information at a time. Attention determines which pieces of sensed information are processed and enter into the human's awareness. Raw information must be filtered or selected, and meaningful information is processed and extracted for further cognitive processing. When there is too much meaningful sensory information, the individual may not be able to detect and notice all of that information, resulting in sensory overload. Conversely, a lack of salient sensory information may cause important plant information to go undetected or unnoticed. Finally, individuals' past experiences and training may affect the meaning associated with a particular percept. That is, the raw sensory stream is imbued with meaning, thus meaning is perceived and is subject to the cognition of the individual beholding it. Therefore, the outcome of *Detecting and Noticing* is determined by the physical sensory inputs, the process of filtering and perceiving information, and the memory that recognizes the meanings of the information.

Understanding and Sensemaking is the function to bind the meaning of individual pieces of information that has been detected and form a coherent understanding of the information. This function allows people to question what is known, evaluate what is conjectured, hypothesize and diagnose, and integrate facts with theories. The outcome of understanding can be situation awareness, evaluation, diagnosis, and resolution of conflicts. The process of achieving this function involves interpreting pieces of information with existing mental models of the information, integrating the information, and generating the output of understanding. The central theme of the process is its dynamic aspect (i.e., the process iterates until a satisfactory outcome is achieved). This can be best explained by Klein's data-frame theory. The theory posits that information coming into the sensemaking process is data. This data is integrated with an existing frame, which is a mental representation that links data with other elements to explain and describe the relationship of the data with other entities. A frame encompasses the concepts of a mental representation, a mental model, a story, a map, a schema, a script, or a plan, and serves as a structure for explaining the data and guiding the search for more data.

The data identify or construct the frame, and the frame determines which data are attended to. Neither the data nor the frame comes first; rather, it is an iterative process.

Decisionmaking is to make decisions or plan action scripts to achieve given task goals. The process involves managing goals, planning, re-planning and adapting, evaluating options, and selecting an option as the final decision outcome. This process describes how an experienced operator makes a decision with or without explicit procedures. *Decisionmaking* within an NPP is characterized as involving experts and being largely driven by procedures. Yet, although procedures usually dictate the actions of the operators, operators still maintain a mental model of the situation and plan their course of action while adhering to procedures. That is, they will have an idea of what it is that must 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.

Action is defined as implementing an action intended to achieve a particular goal on the level of a single manual action (such as operating a valve) or a predetermined sequence of manual actions. The action(s) must involve the manipulation of the hardware or software that would consequently alter plant status. The process of *Action* includes initiating the action, executing action steps, and verifying the action outcome. Errors of action execution can be classified into two major forms: slips and lapses. Slips are errors where actions executed are “not as planned.” They typically occur in the performance of largely automatic tasks performed by a skilled individual in familiar conditions, especially when attention is diverted (e.g., because of distraction or preoccupation). Lapses are errors in executing the planned action, such as missing steps of an action or executing the action at the wrong time. Lapses involve failures of memory, where an individual may forget to perform an intended action.

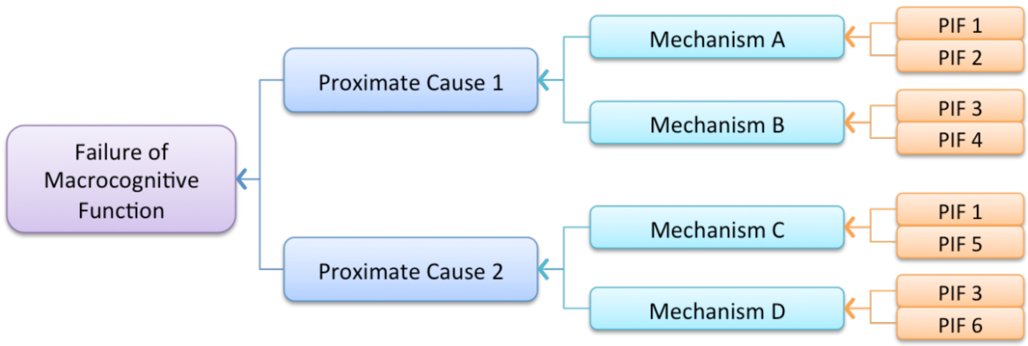
Teamwork is defined as crew interactions with each other to accomplish a task. *Teamwork* typically involves coordination, collaboration, and communication among the crew members. For NPP control room operation, the crew has been trained to work together and crew coordination and collaboration is defined in operating procedures; therefore, the teamwork process mainly involves communication and leadership. NPP control room crews are hierarchical and have a distinct leadership structure. Errors in either communication or leadership can lead to failure of the *Teamwork* function.

Operators typically have to engage in all of these macrocognitive functions to accomplish a task. Some tasks, such as diagnosing an alarm, may involve more detecting and understanding than decisionmaking or action, whereas other tasks, such as implementing a reactor coolant system (RCS) depressurization, rely heavily on action and teamwork. Additionally, the flow of human thought does not follow a linear path through the macrocognitive functions. Rather, there is parallel thought and iterations of macrocognitive functions as operators conduct their work.

Cognitive Framework

One major outcome of the literature review is a synthesis of information about cognitive mechanisms, proximate causes, and PIFs for each macrocognitive function. The other outcome is a cognitive framework that takes all four of these elements—macrocognitive functions, proximate causes, cognitive mechanisms, and PIFs—and organizes them into a tree structure that illustrates how macrocognition may fail and describes the reasons why. Each macrocognitive 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.

The generic structure for each tree in the cognitive framework is shown in the diagram below. 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 to right, the box in columns represents the macrocognitive function, the proximate causes of failure of the function. The cognitive mechanisms associated with each proximate cause, and PIFs that contribute to the failure of each mechanism.



This cognitive framework provides explanation about *why* PIFs are important and *how* PIFs influence human cognition errors. It is important to note that the framework is a tool to identify which proximate causes, mechanisms, and PIFs to consider or investigate for the situation or human failure event (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 influence 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 research.

The content of the framework was developed to apply universally to any HRA methodology. As such, it does not provide guidance for assigning a relative importance to each performance influencing factor, evaluating its degree of goodness or badness, or a methodology for quantification of human error probabilities. Guidance for those elements of the analysis process depends on details of the particular HRA methodology and its associated quantification models.

In summary, this report presents the outcome of an effort to build an up-to-date cognitive basis for HRA. We conducted a literature review to synthesize our understanding of the cognitive aspects of NPP crew behavior in response to plant upsets, based on research in various behavioral science disciplines. We developed a cognitive framework to organize information related to human performance in NPP operations and identify relevant PIFs leading to crew failure. This framework presents the links between the PIFs, cognitive mechanisms, proximate causes of failure, and ultimately the macrocognitive functions.

The information in this report can serve as the technical basis for new HRA methods and a tool for improving existing HRA practices. The structured cognitive framework can assist HRA analysts with making judgments on what can go wrong with human performance and how various performance influencing factors may contribute to errors. The cognitive basis enables analysts to understand and systematically identify the reasons why humans make errors. Lastly, although the cognitive basis was initially developed for improving HRA, it can also support addressing human performance issues identified in human factors applications.

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ACRONYMS AND ABBREVIATIONS

ACRS	Advisory Committee on Reactor Safeguards
ACT-R	Adaptive Control of Thought—Rational
ADS	accident dynamics simulator
AT	Activity Theory
ATHEANA	A Technique for Human Event ANAlysis
BOP	balance-of-plant operator
CAP	corrective action program
CRM	crew resource management
D-I-K	Data-Information-Knowledge
EUT	Expected Utility Theory
GEM	Guidance-Expertise Model
HEP	human error probability
HERA	Human Event Repository and Analysis
HFE	human failure event
HRA	human reliability analysis
HSI	human-system interface
IDA	Information, Decision, Action
IDAC	Information, Decision, Action, Crew
IDHEAS	IntegrateD Human Event Analysis System
LOCA	loss of coolant accident
LTM	long-term memory
LT-WM	long-term working memory
MS	mental state
NDM	naturalistic decisionmaking
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
PIF	performance influencing factor
pMFC	posterior medial frontal cortex
PRA	probabilistic risk assessment
PSF	performance shaping factor
R/M	recognition/metacognition
RCS	reactor coolant system
RCT	Rational Choice Theory

RO	reactor operator
RPD	recognition-primed decision
SA	situation awareness
SACADA	Scenario Authorization, Classification, Analysis, and Debriefing Applications
SAMG	severe accident management guidelines
SG	steam generator
SGTR	steam generator tube rupture
SRM	staff requirements memorandum
SRO	senior reactor operator
SS	shift supervisor
STA	shift technical advisor
THERP	Technique for Human Error Rate Prediction
WM	working memory

1. INTRODUCTION

Many human reliability analysis (HRA) methods are available for use as part of probabilistic risk assessments (PRAs) in modeling risk in nuclear power plants (NPPs). HRA is a two-stage process: qualitative analysis and quantification. Qualitative analysis involves evaluating the scenario or event involved in the analysis, working with pre-defined human failure events (HFEs) and/or identifying and defining new HFEs, and analyzing plant conditions, procedures, operator tasks, and other contextual information associated with the HFEs. The quantification process takes the qualitative analysis as input and estimates the probability of failure of the HFE, referred to as the human error probability (HEP), based on the context and effects of performance influencing factors (PIFs).[1]

However, there is evidence that the results associated with a particular HFE analysis could vary depending on the HRA model/method used, and/or the analyst applying the method (Lois et al., 2009). Because the U.S. Nuclear Regulatory Commission (NRC) frequently uses HRA results and insights to support risk-informed regulatory decisionmaking, the NRC has a vested interest in the quality of HRA and continues to improve the robustness of PRA/HRA through targeted activities (e.g., supporting and endorsing PRA standards developed by professional societies).

In a staff requirements memorandum (SRM), SRM-M061020, to the Advisory Committee on Reactor Safeguards (ACRS), the NRC Commissioners directed the ACRS to “work with the staff and external stakeholders to evaluate the different human reliability models in an effort to propose a single model for the agency to use or guidance on which model(s) should be used in specific circumstances” (2006). The NRC then instituted a research effort in response to SRM-M061020 to address issues related to the robustness of HRA, with a particular emphasis on improving traceability and consistency.

The NRC project team convened expert workshops to identify desirable features for HRA models. The features included a sound underlying technical basis to model human performance, completeness, reliability, repeatability, and transparency (Hendrickson et al., 2012). The team used these features as the criteria against which they examined existing models. The team concluded that, while each model has its strengths, no model meets all the desirable features identified above. Furthermore, evidence accumulated through several studies, including the International Empirical Study (Lois, et al., 2009) as well as from a U.S. domestic empirical study, has shown that all methods have some general limitations contributing to variability in HRA results for the same HFE (Forester et al., in press):

Cognitive Basis. All of the methods have limitations in modeling and quantifying human performance under various conditions. At least part of the variability within a method between analysts can be attributed to a lack of an adequate underlying theoretical basis to guide the analysis, particularly with respect to the cognitive activities associated with understanding complex situations and deciding how to respond.

Qualitative Analysis. The HRA methods need systematic and thorough guidance for performing a qualitative assessment to support HRA quantification (Hendrickson, et al., 2012). The differences in the qualitative analysis required by the different methods (and those performed by different analysts) appear to be a major driver of the variability in the results obtained by the different applications. Improved guidance for performing the qualitative analysis should contribute to improving the consistency of HRA results.

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1. Some HRA methods refer to contextual factors as performance shaping factors (PSFs). The term performance influencing factor (PIF) is used in the IDHEAS HRA methodology, and thus is used throughout this document.

Tie between Qualification and Quantification. Many methods focus on identifying failure mechanisms and the contextual factors that contribute to the mechanisms; these methods generally produce a superior qualitative analysis (rich in content and quality operational stories). However, superior qualitative analysis itself does not necessarily produce HEPs that are more accurate. The information gathered during the qualitative analysis should be used to produce a HEP. However, with some exceptions (such as the Technique for Human Error Rate Prediction (THERP)), many methods have inadequate guidance on how to use the information from qualitative analysis to determine HEPs (i.e., translating the information into HEPs). For example, in empirical HRA studies, some analyst teams had difficulty using the information obtained during the qualitative analysis in an effective way during quantification (c.f., Lois et al., 2009).

PIF Judgments. Different HRA methods identify different PIFs as important to consider (e.g., high versus low workload, adequacy of indications) for a given situation. Yet, the methods generally do not provide justification regarding why and how a PIF contributes to human errors; therefore, it is difficult for HRA analysts to judge the presence and effects of a PIF when quantifying HEPs.

The first limitation, cognitive basis, contributes largely to other limitations. An adequate technical basis is needed to identify the relevant domains of cognitive activity for a given human action, identify potentially important failures and failure modes that are most likely while performing in those cognitive domains, and guide the collection of information that analysts use to perform an HRA. Without a strong cognitive basis, it is unclear what information should be included in qualitative analysis, how analysts should identify such information, and how analysts should use such information for HEP estimation. In addition, PIFs affect human failures by affecting cognitive processes involved in the human failure events. Without a strong cognitive basis, judgments of PIFs and their effects on human failures on a given situation can be arbitrary or solely rely on expert judgment.

Based on this evidence, the NRC staff decided to address SRM-M061020 by developing an integrated HRA method that would incorporate the strengths of the existing methods and develop new features to address the limitations of existing methods. The integrated method is thus referred to as an Integrated Human Event Analysis System (IDHEAS). Among the new features should be an updated technical basis for human reliability, grounding the method in current science. Therefore, the first step of the method development was to develop a technical basis that synthesized the current understanding of human performance and human errors from cognitive sciences and operational experience. The technical basis will serve as the foundation for developing the qualitative analysis guidance and a quantification model for estimating human error probabilities in IDHEAS. We developed the technical basis by performing a comprehensive cognitive literature review, synthesizing the information, and developing a framework to organize the information for use in HRA. This report presents the technical basis we developed, including the psychological framework and literature review results. The use of these outcomes in IDHEAS will be described in separate reports.

1.1 Overview of the Literature Review

1.1.1 Developing a Technical Basis for IDHEAS

We recognize that establishing a solid cognitive foundation for HRA is critical to reduce variability of HRA. Current HRA methods generally use descriptive human behavioral models. Yet, those models are not tied to the mechanisms underlying human errors. A mechanism, by definition, means a natural or established process by which something takes place or is brought about. We used the term mechanism or cognitive mechanism here to refer to the neurophysiological, psychological, or behavioral processes by which human cognitive tasks are accomplished. Therefore, we decided to perform a thorough review of current psychological, cognitive, human factors, and operational research to develop the technical basis for IDHEAS.

Research in the behavioral sciences has accumulated knowledge about the mechanisms underlying human performance, including how human performance may be affected by situational factors. This knowledge should be used to develop the technical foundation for HRA. Such a cognitive basis can guide qualitative analysis, tie information from qualitative analysis to quantitative analysis, elucidate the effects of PIFs on human failure, and define the strength of PIFs with respect to cognitive mechanisms and human vulnerabilities.

However, this information is scattered throughout the broad fields of cognitive psychology, behavioral psychology, neuropsychology human factors, and human performance; even review articles in the literature typically only focus on one narrow aspect of human performance (e.g., attention, situation awareness (SA)) without systematically documenting the available information for the full range of human performance. Moreover, the majority of literature focuses the description of results and conclusions on how humans can successfully perform given tasks without explicitly delineating the conditions under which humans would fail the tasks (i.e., it often needs analysis and inference to identify information about human failures from literature). Therefore, our task was to mine current state-of-the-art behavioral sciences research for information to establish direct links (causal relationships) between performance influencing factors, mechanisms of human cognition, and human performance. Such links would enhance the basis for expert judgment and improve both qualitative and quantitative aspects of HRA.

The use of explicit and causal links allowed us to adapt PRA practices (such as event trees/fault trees to model equipment performance) and apply them in an analogous approach to the qualitative analysis part of HRA. One of the most significant findings of the International HRA Empirical Study (Lois, et al., 2009) is that variability in estimation of HEPs is driven to a great extent by differences in the quality and depth of the qualitative analysis. By adopting a structured causal cognitive framework to inform the qualitative analysis, we aim to enable analysts to appropriately collect information and identify potential failure paths and associated causes and influencing factors, thus reducing inter- and intra-analyst variability. This aim took the literature review a step further—the development of causal linkages in a structured cognitive framework that provides analysts a tool that will assist them in the qualitative analysis process.

1.1.2 Scope and Goals of the Literature Review

Using a systems engineering approach, we first identified the scope, goals, and requirements for the literature review, and then developed an implementation plan to perform the literature review and synthesize the information from the literature. The ultimate goal of the literature review was to develop a technical basis for IDHEAS by providing a profound understanding of human errors in NPP internal, at-power events. This understanding should include the following aspects:

- cognitive tasks in NPP internal, at-power events
- cognitive functions that support the tasks
- cognitive mechanisms underlying the functions
- performance influencing factors that affect the mechanisms

To accomplish this, the specific goals of the literature review were to:

- Identify the proximate causes for failure of cognitive tasks that operators may perform in NPP control rooms that result in negative consequences for plant safety.

- Identify cognitive mechanisms underlying the cognitive function's proximate cause (i.e., identify how and why cognitive errors occur).
- Identify factors that influence human performance and, where possible, identify how those factors affect the chance of failures.
- Develop, based on the literature, a structured cognitive framework that can serve as a psychological foundation for IDHEAS.

We subsequently developed the following requirements for conducting the literature review to achieve these goals.

Requirement 1: Review literature and operational experience relevant to NPP operation.

Because the purpose of the literature review was to improve the technical foundation of HRA for the NPP domain, the information on human cognition identified from the literature review should be relevant to NPP operation. We decided that this requirement included research related to human performance for internal at-power events, which typically involves control room operator performance in response to design-basis initiating events that are part of a PRA. Yet, the psychological foundation developed from the literature review should be as generic and broadly applicable as possible to allow for application outside of control room activities and for events outside the scope of Level 1 design basis events. For example, the cognitive framework should be informative to such applications as event recovery performance that involves activities outside the control room.

Requirement 2: Identify taxonomy of cognitive functions required for performance in NPP operation.

NPP operator activities are predominately driven by cognition; accordingly, one task of the literature review was to identify the cognitive functions that operators use to accomplish NPP operation. Another characterization of NPP operation is teamwork; operating crews are groups of people who are highly trained, supervised, and who work together in a regulated, procedure-driven environment to control the plant. Therefore, we specified that the literature review include both cognition at an individual level and at the crew level, and that the review focus on research related to highly trained or expert personnel rather than novices. Furthermore, the literature review should identify a taxonomy that describes the cognitive functions that mediate operator performance in NPPs. Section 2 defines the cognitive functions (called macrocognitive functions) used in the literature review and cognitive framework.

Requirement 3: Identify information on why and how failure of a macrocognitive function can occur.

To understand why humans make cognitive errors, it is necessary to understand how human cognition successfully operates. In other words, it is important to identify the *mechanisms* by which human cognition operates. Some psychological literature may discuss these mechanisms on a behavioral or descriptive level, while other psychological research may provide a more profound understanding of the contingencies and boundary conditions with which humans can reliably perform a function. Both lines of information are necessary for the specific goals of determining why operators make failures under various situations and explaining how the PIFs affect the chance of failures.

Requirement 4: Identify information about which PIFs are relevant for each type of failure, and why and how the PIFs affect the chance of failures.

Of primary importance for this requirement is to identify the PIFs relevant to a particular cause of failure; for example, an HRA analyst would find it very valuable to have information that allows her/him to narrow down which PIFs to consider when evaluating the likelihood that operators will misdiagnose a situation in a particular HFE under analysis. Regarding how and why PIFs influence the chance of failure, it is desirable that the technical basis should include information addressing the following specific issues:

- how a PIF affects human performance in general (i.e., fatigue increases reaction time)
- how PIFs influence specific task performance (i.e., increasing traffic complexity leads to higher workload for air traffic controllers)
- how PIFs relate to mechanisms (i.e., a sustained high level of stress can impair a human's attention shift to new targets)
- how PIFs affect human errors.

Requirement 5: Produce a structured tool that organizes all of the above information into a cognitive framework that serves as the psychological foundation of the IDHEAS HRA method.

Each of Requirements 1-4 above represents a part of the desired outcome, while Requirement 5 represents the integrated outcome. The task was to sort, synthesize, integrate, and organize information in these different forms from the literature review into a structure that can be used to support the IDHEAS HRA method. Thus, the literature review should connect failures of macrocognitive functions with cognitive mechanisms, and PIFs. However, the information needed to make these connections may not be readily available in the literature. As mentioned previously, research in the areas of cognitive psychology and human performance may not have focused on fully elucidating the relationships between PIFs, cognitive mechanisms, and types of proximate causes. Establishing these links requires analysis, inference, and development based on information available. Due to the limited information, the links can be limited and subjective. Therefore, we determined that we would organize the cognitive framework structure in such a way that it may be updated as new research becomes available and validated or modified for application to HRA. Furthermore, the cognitive framework should be a usable tool with adequate documentation for analysts to employ it in their analyses. The cognitive framework is thus the ultimate product of the literature review.

1.1.3 Literature Review Process

The literature review team conducted the literature review in two major rounds. The first round was exploratory with the purpose to identify the scope of the literature review (i.e., what major models and research domains to include), and to identify a model for organizing the literature into a usable structure. Based on the results of the first round, the literature review team adopted a macrocognitive model from a number of existing cognitive models for structuring the literature review and cognitive framework. The model includes five macrocognitive functions that underlie cognitive tasks. Section 2.2 of this report discusses macrocognition in general and provides an overview of various macrocognitive models; Section 2.4 details the macrocognitive structure used in this approach.

We then commenced the second round of the literature review to identify the causes of failure of human cognition in the macrocognitive functions included in the model. The focus was on identifying the mechanisms, or the cognitive processes, that, in certain circumstances, may fail and lead to proximate causes. We then began organizing the mechanisms obtained from the references included in the review, and began the process of building the cognitive framework. Section 2.5 of this report discusses this process in detail. Table 1-1 provides the search terms and concepts that we included when conducting the literature review.

Table 1-1. Search terms used in literature review.

Search Domain	Search Terms and Concepts		
Cross-Cutting Areas	• Macrocognition - and performance - and team performance • Attention	• Working memory/central executive • Personality theory/individual differences	• Learning • Resilience • Workload/task load/other loads
Detecting and Noticing	• Vigilance • Monitoring • Problem detection • Sensation • Perception	• Pattern processing/matching (context effects, expectancies, complexity, recognition) • Desensitization	• Engagement • Information foraging • Change blindness • Situation awareness
Understanding and Sensemaking	• Situation awareness • Situation assessment • Sensemaking	• Mental model • Frames • Schemas	• Scripts • Mental maps
Decisionmaking	• Complex problem solving • Team problem solving • Planning • Re-planning/adaptation/adaptability	• Naturalistic decisionmaking • Recognition-primed decisionmaking • Cognitive biases • Goal selection	• Prioritization/prioritization errors • Procedure following errors
Action	• Multitasking • Dual tasks • Execution errors • Slips • Lapses	• Performance and contextual errors • Task/action switching • Simultaneous action goals • Automaticity	• Stimulus-response compatibility • Error monitoring and correction • Motor control
Teamwork	• Communication • Teamwork • Team/crew collaboration • Team/crew performance • Team/crew decisionmaking • Team/crew problem detection	• Team/crew problem solving • Team/crew dynamics • Team sensemaking • Team situation awareness • Groupthink • Group collaboration style • Leadership styles	• Team cohesion • Shared resource management • Crew resource management • Group macrocognition • Team cognition • Distributed cognition

1.2 Overview of this Report

The current chapter briefly discusses above the literature review process, boundaries, and scope; the majority of the report focuses on the macrocognitive models, macrocognitive functions, and cognitive mechanisms that achieve the functions. These together comprise the cognitive framework for IDHEAS. This document serves as an introduction to the psychological concepts that relate to human performance in NPPs, and provides users with enough background information to use the cognitive framework (Appendix A and Appendix B). A separate report discusses the development of IDHEAS and instructions for the practical application of the method (Forester, et al., in press).

Chapter 1 describes macrocognition and macrocognitive models and functions. From there, each of the remaining chapters presents literature findings that support each macrocognitive function. Chapter 0 discusses the macrocognitive function *Detecting and Noticing*, Chapter 0 describes *Understanding and Sensemaking*. Chapter 5 reviews *Decisionmaking*, Chapter 6 describes *Action*, and Chapter 7 discusses *Teamwork*. The results of the literature review are summarized in Appendices A and B. Appendix A provides tables that list all of the cognitive mechanisms for failure for each macrocognitive function, and identifies PIFs that influence the cognitive mechanisms and proximate causes of failure, while Appendix B depicts the information from the tables in Appendix A graphically in the cognitive framework diagrams.

Because of limited time and resources, this report, while serving as a generic technical basis for HRA, has several limitations:

1. While the information presented in the report is largely taken from cognitive and psychological literature and therefore it is generic to human performance, the work was directed by the chosen cognitive framework, which in turn was strongly influenced by the assumptions of the IDHEAS method. Review of the cognitive mechanisms was primarily focused on those relevant to control room tasks. Research in psychology, sociology, and human factors of relevance for NPP control room operation that do not fit one or more assumptions have not been covered or only marginally integrated into the framework. This includes research from team decisionmaking, situated cognition, distributed cognition, and cognitive systems engineering.
2. The focus of the report is on cognitive mechanisms of the macrocognitive functions. While the report presents information from the literature on how various performance influencing factors may contribute to proximate causes, the models for performance influencing factors and their relations to various cognitive mechanisms were not thoroughly reviewed. Thus, many factors, especially organizational factors that may enhance human performance and recover human errors were not thoroughly covered in the report.
3. The tables in Appendices A and B delineated the potential relationships between proximate causes, mechanisms, and related PIFs. These tables can serve as useful references for developing HRA methods and practicing HRA. Yet, notice that due to the incompleteness in the literature and limitations in our review, we had to infer many of the relationships in the tables based on our understanding of the existing information. The inferences are considered to be expert judgment and thus have inherent subjectivity.

Overall, the report provides a thorough literature review and technical foundation for human reliability analysis. Moreover, the literature review conducted for each of the macrocognitive functions provides broad coverage of the relevant literature and synthesis of the key points to be drawn from the literature relative to the factors influencing human performance and human reliability. Therefore, the report also serves as a technical basis for research and practice in human factors engineering that is oriented to ensure safety.

2. MACROCOGNITION

2.1 Introduction

Models of human cognition developed circa the 1970s–1980s used a “human as computer” metaphor to describe information processing. Information was input to the mind (or “black box” of the human) through the sensory systems, then the information was processed by the mind and a response was generated. This was also consistent with the behavioral tradition that had dominated experimental psychology to that point, in which the stimulus-response paradigm was the basis of much psychological thought. The “black box” metaphor was used because the cognitive processing could not be seen; therefore, it was hidden from view.

As neural imaging technology and the sophistication of psychological research advanced, scientists began to shed light on the internal workings of the “black box”. It gradually became clear that an input-processing-output information processing metaphor was inadequate to describe the true complexity and dynamics of human cognition. Nevertheless, the information processing perspective of human cognition has been quite popular in applied fields like engineering and human reliability analysis (HRA), as evidenced by the information processing models used in various HRA methods. The simplification of human thought into serial or linear stages made the information processing models very useful for applied purposes. However, we now know that human thought is not entirely serial or linear—a great deal of simultaneous, parallel, and circular processing occurs. Also, information processing approaches cannot adequately account for the creativity, insight, illogical thinking, instinct, and moments of brilliance that people are prone to have (Anderson, 2000).

Models of human cognition have subsequently become more dynamic as a result of this research. Research on human cognition spans many domains such as cognitive psychology, cognitive neuroscience, psychophysics, behavioral science, and human factors. The level of detail at which each research effort addresses human information processing varies from neural responses, cognitive system activities, and behavioral measures. Psychological research has moved on to models that describe human cognition as several systems that work together to process information (Baddeley, 2000; Baddeley & Hitch, 1974; Baddeley & Larsen, 2007). Work done in real-world settings, such as naturalistic decisionmaking and situation awareness (SA), combined with more narrowly focused laboratory research, has done much to elucidate the complexity of human cognition. Particularly for applied research in naturalistic settings, it has become clear that a macrocognitive perspective is imminently more useful for understanding human cognition.

Macrocognition is a term originally coined by Cacciabue and Hollnagel (1995) to describe cognition in real-world settings, rather than in research laboratories. Macrocognition focuses on the nature of human performance “in the field,” where decisions are often very complex and must be made quickly, by domain experts, in risky or high-stakes situations (Klein et al., 2003). Microcognition, on the other hand, is typically the focus of tightly controlled laboratory research, with a goal of elucidating the building blocks that underlie cognition that is more complex. There are a large number of microcognitive models, all focused on different aspects of human cognition and how the brain works. Macrocognition integrates the more narrowly focused microcognition laboratory research findings together into a larger picture that describes what people actually do with their brains in applied, complex settings.

Given that the present project is focused on human cognition in a nuclear power plant domain, using macrocognition as the organizing construct for the literature review and cognitive framework is more appropriate for several reasons:

- It organizes microcognitive models into a manageable set of functions.

- HRA analysts can easily understand macrocognition.
- Macrocognition is useful for predictive analyses of human performance in complex scenarios. For example, it is more appropriate for an analyst to predict crew performance at detecting a critical cue than it is for the analyst to predict whether the operator will pay sufficient attention to an incoming stimulus (cue) that it is drawn into active working memory.
- Macrocognition is detailed enough to synthesize psychological research findings into a structure that yields a coherent understanding of how human cognition functions and what can lead it to fail.
- It integrates state-of-the-art psychology and cognitive science into a foundation for HRA, providing a more advanced technical basis for HRA than previous information processing models.

This chapter provides an overview of several macrocognitive models and then shows how macrocognition was adapted to apply to nuclear power plant (NPP) operations. The second half of the chapter describes the development of a macrocognitive framework for use in HRA.

2.2 Overview of Macrocognition

There are a number of macrocognition models in the literature describing macrocognitive functions (i.e., high level mental activities to accomplish a task or achieve a goal in a naturalistic environment; Letsky, 2007). Each approach divides the spectrum of cognition up into slightly different chunks; however, there is general consensus that the macrocognitive functions relevant to human performance in complex, dynamic, high-risk domains include but are not limited to (Roth, 2010a, 2010b):

- Detecting stimuli and noticing problems (detecting and noticing).
- Understanding information and making sense of situations (understanding and sensemaking).
- Planning responses and making decisions about what to do (planning and decisionmaking).
- Taking action and monitoring effectiveness of the action (action).[2]
- Communicating and coordinating with team members (communication and coordination).

Notice that from the point of view of the individual, team communication and coordination activities could be seen both as resources for achieving other macrocognitive functions or as goals on their own. One could also consider other resources (like memory aids, support tools) in an extra function like “cognitive tools use”. This might be an important addition in a NPP setting where there is extensive use of, for example, operating procedures. On the other hand, from the perspective of a team such as the ones in NPP control rooms, communication, collaboration, and coordination together can be viewed as a macrocognitive function with which the team achieves its task goals.

A key difference between macrocognitive models and traditional information processing models is that macrocognition recognizes that human cognition is not strictly linear or serial, but it also involves a great deal of parallel and cyclic processing. Macrocognitive functions occur in a continuous loop (Roth, 2010b) and overlap (Patterson & Hoffman, 2012). People working in

2. Roth (2010a, 2010b) clarified that most models of macrocognition do not typically include action, but included action in her list of macrocognitive functions based on the history in the NPP HRA community of analyzing action implementation errors.

naturalistic settings typically have to accomplish most or all of these functions, often at the same time (Klein, et al., 2003).

The next two sections review two well-recognized macrocognition models to elucidate how the macrocognitive functions work together to accomplish complex tasks.

2.2.1 Macrocognitive Functions by Klein et al.

Klein et al. (2003) proposed a macrocognition model with an initial set of primary macrocognitive functions and supporting macrocognitive processes[3] (see Figure 2-1) to investigate how cognition actually functions in real world complex tasks. The primary macrocognitive functions included:

- naturalistic decisionmaking, or how experts make decisions in real-world environments
- sensemaking and situation assessment, or how people understand and make sense of the situation
- planning, or how people develop plans for responding to the situation
- adaptation and re-planning, or how people adapt their plans and strategies given the dynamic nature of the situation
- problem detection, or how people detect anomalies or abnormal conditions that need to be addressed
- coordination, or how people coordinate their behavior with others to achieve common goals

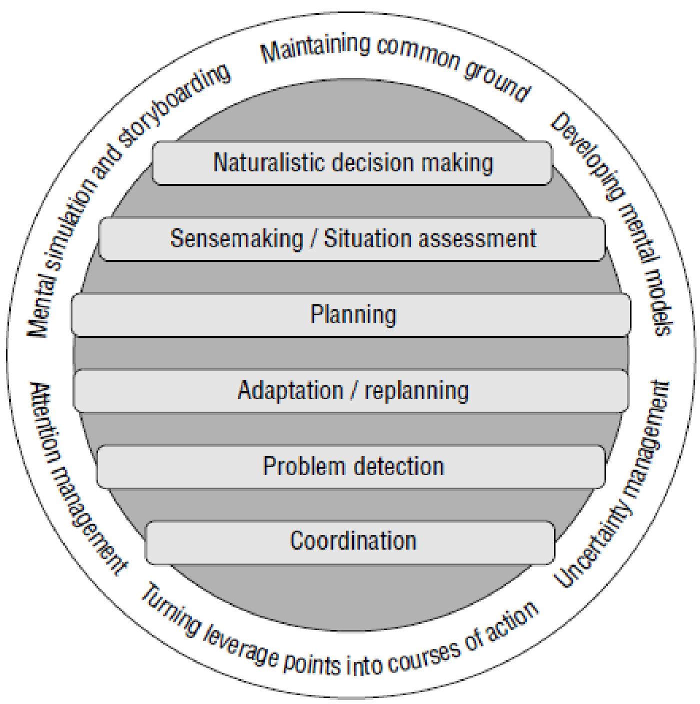

Figure 2-1. Macrocognitive functions and supporting processes for individuals and teams (Klein, et al., 2003).

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3. Klein et al. (2003) expressly stated that they intended this list of primary macrocognitive functions to encourage research at the macrocognitive level rather than to advocate an “official,” validated list.

In Figure 2-1, the blocks in the middle represent the macrocognitive functions; the items in the surrounding circle represent the macrocognitive processes that support the functions. The macrocognitive processes are means for achieving the functions. Notice that all of the functions share all of the macrocognitive processes. Therefore, these functions and processes work together in a continuous loop, with the acknowledgment that some or all of these functions have to occur simultaneously.

At the time when Klein et al. (2003) published their model, they decided that it was premature to attempt to diagram the relationships between the different functions and supporting processes. There is no assumption of serial or linear flow between the functions, nor is there an assumption about which function occurs first. Rather, the flow is dynamic, continuous, and dependent on the situation, with much parallel or simultaneous cognitive activity.

2.2.2 The Overlapping Macrocognitive Function Model

Patterson and Hoffman (2012) adapted the Klein et al. model (2003) for space shuttle missions. They proposed an integrated macrocognitive framework for primary functions, which are the most important functions that a work system must conduct to achieve its primary goals (Patterson & Hoffman, 2012). Patterson and Hoffman identified five primary macrocognitive functions: detecting problems, sensemaking, re-planning, deciding, and coordinating, each of which is described briefly below.

Detecting Problems. The function of detecting problems involves noticing that events may be taking an unexpected turn. This change, whether positive or negative with respect to the goal of the system, requires explanation and may indicate a need to reframe the understanding of the situation (sensemaking) and/or revise ongoing plans (re-planning) or actions.

Sensemaking. Sensemaking involves activities such as collecting, verifying, and integrating information, and making assessments about how the detected information maps onto potential scenarios or explanations. It includes generating hypotheses to consider and potentially revisiting discarded hypothesis when faced with new evidence.

Re-planning. This function involves adaptively responding to changes in the situation or objectives from a variety of sources. It also includes adapting pre-made default plans to the specific situation within a window of opportunity. When default plans are not available or applicable, re-planning involves creating a new strategy for building one or more desired end states or goals. According to Patterson and Hoffman (2012), “this function includes adapting procedures, based on possibly incomplete guidance, to an evolving situation where multiple procedures need to be coordinated, procedures that have been started may not always be completed, or when steps in a procedure may occur out of sequence or interact with other actions” (p. 2).

Deciding. Patterson and Hoffman state that making a decision is a complex activity that is not simply the act of committing to some course of action to reach certain fixed goals (2012). Instead, it is far more complex. It involves a number of questions and issues, some of which are more or less important in different contexts. It might also involve questioning the appropriateness of default courses of action, considering trade-offs in ongoing plan trajectories, or reversing previous decisions or commitments. Patterson and Hoffman view decisionmaking as more often the activity of a team, rather than a single individual; deciding can be a consensus activity involving the accommodation of different positions toward decisions (2012).

Coordinating. According to Patterson and Hoffman, the function of “Coordinating” consists of managing activity, dependencies, and communication across individuals who have roles that may have common, overlapping, interacting, or even conflicting goals (2012).

Patterson and Hoffman developed a representation of the dynamic overlaps and interactions of the five primary functions (see Figure 2-2). They posit that any of the five functions can involve events in the environment, communication between people, or reasoning within an individual. All of the functions are continually ongoing (consider each ring as continuously rotating about its center), and over time, a function overlap more or less with the others functions as they engage or interact with each other. “Coordinating” may be a function that continuously “wraps” the others. As the situation evolves, the work system may increase the emphasis on a particular function, which could be illustrated in Figure 2-2 by increasing the radius of the corresponding circle and altering the overlaps (Patterson & Hoffman, 2012). Thus, Patterson and Hoffman’s integrated framework illustrates that macrocognitive functions are parallel, continuous, interacting, and overlapping.

Figure 2-2 also clearly shows that the macrocognitive functions are not independent of each other. The function of detecting problems, for example, involves the functions of understanding the perceived information, making a decision about whether it is important or relevant, and adapting plans to the new information. Similarly, there are aspects of deciding in all of the other macrocognitive functions, and all of the functions require coordination with other members of the crew. The Patterson and Hoffman model depicts human cognition in a “big picture” view, integrating microcognitive areas together and demonstrating the interrelationships with other areas.

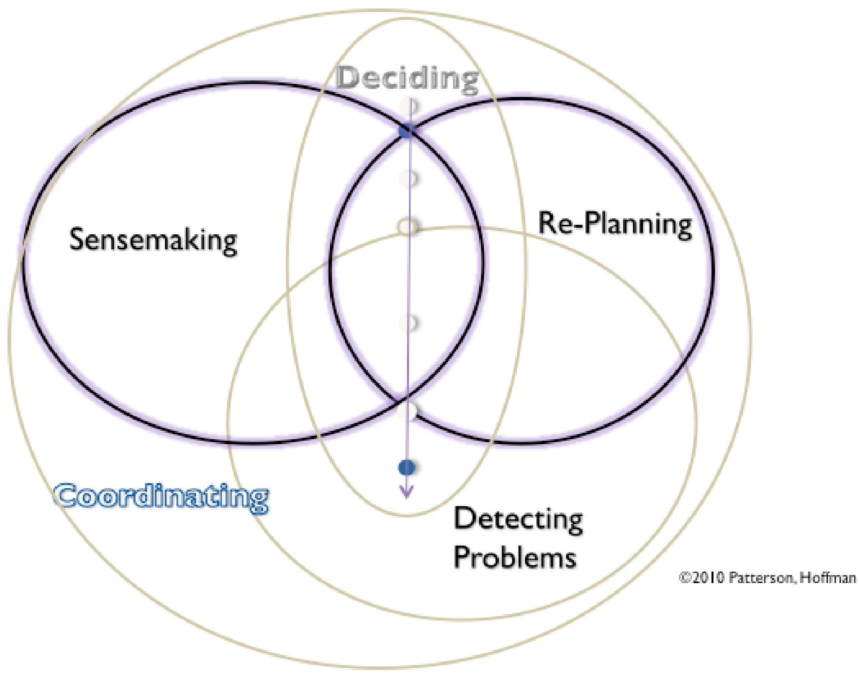

Figure 2-2. The overlapping function model of macrocognition (Patterson & Hoffman, 2012).

Both the Klein model and the Patterson and Hoffman model incorporate “coordination” as the teamwork aspect of macrocognition. Other studies focused more explicitly on team macrocognition (Fiore, Smith-Jentsch, Salas, Warner, & Letsky, 2010; Letsky, 2007; Letsky, Warner, Fiore, & Smith, 2008). For example, Letsky et al. proposed that team coordination is achieved through four stages: knowledge construction, team collaborative problem solving, team consensus, and outcome evaluation. They also identified that team coordination is achieved through verbal and nonverbal communication. In summary, while the authors of the various macrocognitive models intended the main theoretical concepts to apply across domains, they developed their models based on their own experience in specific domains of application. This might result in the subtle differences between the models. Given that these models have no fundamental differences in their capturing the nature of human cognition, we should value all these models and integrate their strengths to come up with a generic cognitive framework for NPP applications.

2.3 Macrocognition for NPP Operations

Nuclear power operations have some aspects in common with aviation and military operations, such as hierarchical command and control, and real-time management of complex interactive systems. However, NPP operations are highly proceduralized. Various types of procedures (e.g., alarm response procedures, abnormal operating procedures, and emergency operating procedures) provide pre-defined goals, criteria to assess conditions and situations, and detail specific actions to be taken in response to abnormal or accident conditions. Additionally, plants have severe accident management guidelines (SAMGs) that provide high-level guidance for the goal of preventing or mitigating radioactive release to the environment, and set functional priorities for optimal management of an accident. In the United States, the general work practice for NPP operators is to adhere to procedural instructions. The unique nature of the nuclear power plant domain tailors a macrocognitive model to the specific features of the nuclear environment. For example, procedure-based operation eliminates many challenging and uncertain aspects in decisionmaking: the team structure and working protocols in the control room do not demand many cognitive aspects of communication and coordination activities.

Several cognitive models have been used in the NPP human factors engineering and HRA domains: Information-Decision-Action (IDA) and Information-Decision-Action-Crew (IDAC), and O'Hara's model of generic operator tasks. These models provide information about the important aspects of human cognition from an NPP perspective. In addition, this report includes a descriptive model of teamwork in NPP control room operations.

2.3.1 IDA and IDAC

The IDA model (Shen & Mosleh, 1996, Smidts, Shen & Mosleh, 1997) is an engineering approximation of human cognition developed for modeling operator performance in the nuclear power plant domain. It provides an error taxonomy for event analysis (Smidts, Shen & Mosleh, 1997). The model applies to environments similar to NPP operations where behavior is influenced by extensive training and requirements to follow procedures. IDA divides human information processing into three main blocks:

- I – Information (collecting information): the operator's perception of plant conditions
- D – Decision (diagnosis and making a decision about what to do): the operator's goals and strategies for handling the situation, as well as memories (including memories of expected plant responses, current activities, related plant symptoms from earlier experience, and knowledge of plant system and operation)
- A – Action (implementing the chosen action): taking action in the plant, based on the decision made in the D phase

IDA's error taxonomy consists of internal errors and external errors. An internal error would be failure of any of the I, D, or A phases. External errors are mismatches between three elements: the plant's needs, procedures, and crew decisions. IDA also accounts for certain PIFs such as time stress that may affect behavior.

In a series of five papers, Chang and Mosleh (2007a, 2007b, 2007c, 2007d, 2007e) expanded and improved upon the IDA model to create a model called IDAC. IDAC is best described as a computer simulation-based cognitive model designed specifically for simulating an operating crew's behavior when responding to abnormal NPP scenarios in the Accident Dynamics Simulator (ADS) simulation environment. ADS includes five functional elements that interact with each other in close frequency to generate multiple scenarios following an initial plant malfunction:

- a plant behavior simulator
- a control room panel simulator
- a crew behavior simulator (i.e., IDAC)
- a hardware behavior simulator (i.e., to model potential hardware failures)
- a simulation sequence controller

IDAC's role in the ADS simulation environment is to probabilistically model potential operators' responses based on up-to-date plant information and available resources (e.g., procedures and memory). The most recent ADS-IDAC implementation can be found in Coyne (2009).

The IDAC crew behavior simulator consists of two functional elements: the cognitive processor and the psychological processor. Together, they interact with memory and procedures to form the IDAC individual cognitive process model, shown in Figure 2-3.

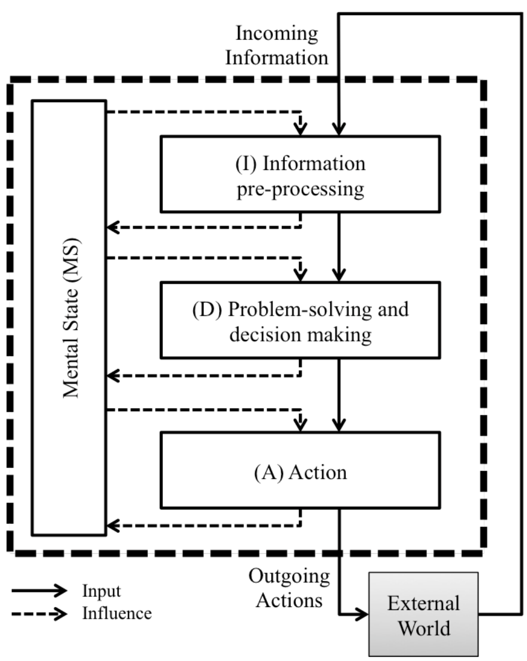

Figure 2-3. IDAC operator cognitive flow model.

The cognitive processor consists of three blocks taken from IDA: Information pre-processing (I), problem solving and decisionmaking (D), and action execution (A). These three blocks dynamically interact with the psychological processor, also known as mental state (MS). Changes in any of the cognitive processor blocks (IDA) may result in changes to mental state, which in turn may affect the subsequent cognitive elements' behavior, as shown in Figure 2-3. Because IDAC assumes a crew operation environment, the "External World" in Figure 2-3 includes the plant, the procedures, and the other crew members. IDAC's Action execution block includes not only physical action taken on the plant but also communication to other crew members. Each of these blocks in the operator cognitive process model is summarized below and discussed in more detail in Chang & Mosleh (2007c).

Information pre-processing (I): Block (I) of the cognitive process model refers to a person's highly automatic process of handling incoming information. This involves information filtering, comprehension and memory, grouping and categorizing, and prioritizing, but stops short of further inference and conclusions (Chang & Mosleh, 2007a, 2007c).

Problem solving and decisionmaking (D): This stage is also referred to in IDAC as "diagnosis and decisionmaking." This block refers to what happens after information perception—what people do with the information they have perceived. This block includes cognitive activities such as "situation assessment," "diagnosis," and "response planning." Information that has been brought to an operator's attention is translated into a problem statement or a goal that requires resolution. The process of resolving a problem or goal involves selection of a method or strategy. Goals may be broken into sub-goals, in such a way that complex problems are broken down into simpler ones, and solved using an appropriate strategy (Chang & Mosleh, 2007a, 2007c).

Action execution (A): Block (A) of the cognitive process model refers to the execution of the action that was decided upon in Block (D). Actions are typically skill-based, highly practiced, and require little cognitive effort (Chang & Mosleh, 2007a, 2007c).

Mental State (MS): The MS block interacts with each of the IDA blocks dynamically. The mental state influences the activities in each of the IDA blocks (e.g., by affecting the filter used in I, or by shaping the choice of strategy in D), and is in turn updated by the results of the activities in each block. The MS block explains how cognitive activity starts and continues, and provides reasons for why a goal is selected or abandoned (Chang & Mosleh, 2007a, 2007c).

The IDAC model takes the classical information processing concept, i.e., framing cognition as a continuous series of IDA loops. IDAC posits a linear, serial flow from I to D to A, and an assumption of success of the previous phase when evaluating any one phase. In other words, when evaluating the D phase, for example, an analyst assumes the information gathered in the I phase is correct, necessary, and sufficient for proper decisionmaking. Otherwise, the error would be in the I phase, not the D phase. Likewise, when analyzing the A phase, an analyst assumes success in both the I and D phases. If an error occurs in action implementation that is due to incorrect decisionmaking, then the error is actually in the D phase, not A.

Additionally, IDAC adds fine-grain information processing by conceptualizing that these IDA loops are nested,[4] as shown in Figure 2-4. What this means is that for any phase of IDA, there are sub-loops of IDA. For example, in the process of perceiving information (I), an operator recognizes information (I-in-I), makes decisions about the relevance of that information (D-in-I), and takes action based on that decision, such as discarding or integrating with other information (A-in-I). Therefore, there are decision elements in the information gathering process. The Nested IDA loop structure would identify the decision related to information gathering that belongs to the high-level I element rather than the D element. This nested structure has the benefit of pinpointing the specific error. IDAC states that this nested structure can continue for as many layers as necessary to decompose complex tasks into simple subtasks (Chang & Mosleh, 2007a).

4. For human failure analysis, IDAC uses the nested I-D-A loop error taxonomy to identify the cognitive root cause that failed a task. A task in PRA typically requires multiple I, D, and A interactions with different levels of granularities within an operator and between operators. Using a single layer of I-D-A for root cause identification has a tendency to blur the scope of each individual cognitive element. IDAC's two-level nested I-D-A loop (see Figure 2-4) intends to clarify the boundaries.

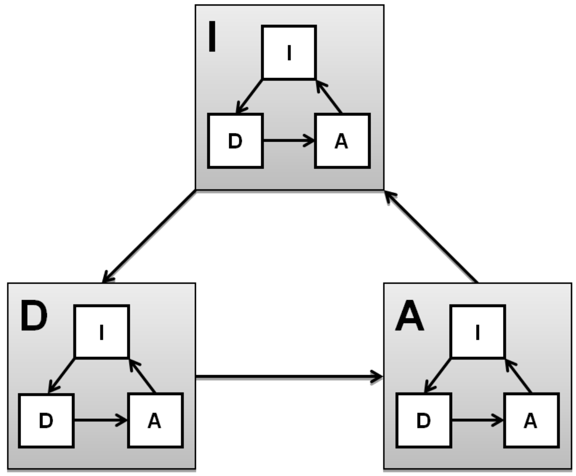

Figure 2-4. Nested IDA structure concept.

A key difference between IDA and IDAC is the crew component (C) of IDAC. IDAC models crew behavior by creating a simplified crew structure with three generic types of operators based on the roles in an NPP crew: the decision maker, action taker, and consultant (Chang & Mosleh, 2007a). These roles can be organized in different crew structures based on the type of crew organization at a plant. Two main features characterize crew interactions: communication and coordination. Communication occurs through formal and informal channels. Roles specify formal communication channels, such as the formal communication between the decision maker and the action taker. IDAC considers all other communication as informal. Crew coordination can be highly dynamic and complex, and is dependent on the culture of the crew. Coordination as modeled in IDAC includes supporting behaviors such as performance monitoring, error correction, and workload and responsibility redistribution (Chang & Mosleh, 2007a).

The IDAC crew model includes crew interactions with the system through actions of individual members. For each member in the crew model, there are:

- defined responsibilities and tasks
- defined formal communication channels
- defined experience and knowledge bases
- individualized psychological and physical characteristics

Crew influences on individual operator response are accounted for through the IDAC team-related performance influencing factors (PIFs) (discussed in Chang & Mosleh, 2007b).

While the simulation aspects of IDAC are not relevant to the present effort, IDAC provides a structure with underlying models of both individual cognition and team behavior of an NPP operating crew. These aspects of the IDAC model make it an appropriate choice for adapting macrocognition to the NPP domain. The next section discusses another NPP-specific model that is also informative to the task of applying macrocognition to NPP operations: O'Hara's model of NPP operator tasks.

2.3.2 O'Hara's Model of NPP Operator Generic Tasks

John O'Hara and colleagues have developed a generic characterization of NPP operator performance that has been applied in many NRC human failure event (HFE) guidance development efforts (O'Hara et al., 2008). This model does not use the term "macrocognition," but it describes the basic categories of operator activities to accomplish control room tasks.

According to O’Hara, operators perform two types of tasks: primary tasks and secondary tasks. Primary tasks include activities such as monitoring plant parameters, following procedures, responding to alarms, and operating equipment (e.g., starting pumps and aligning valves). The secondary tasks of interest are “interface management tasks.” Primary tasks have a number of common cognitive elements: monitoring and detection, situation assessment, response planning, and response implementation. O’Hara referred to these common cognitive elements as generic primary tasks. The generic primary tasks are similar to those macrocognitive functions in the Klein et al. (2003) model. Breakdowns in any of these generic primary tasks can cause a human error. Figure 2-5 shows the diagram of O’Hara’s model. Each of these generic primary tasks is discussed in more detail below.

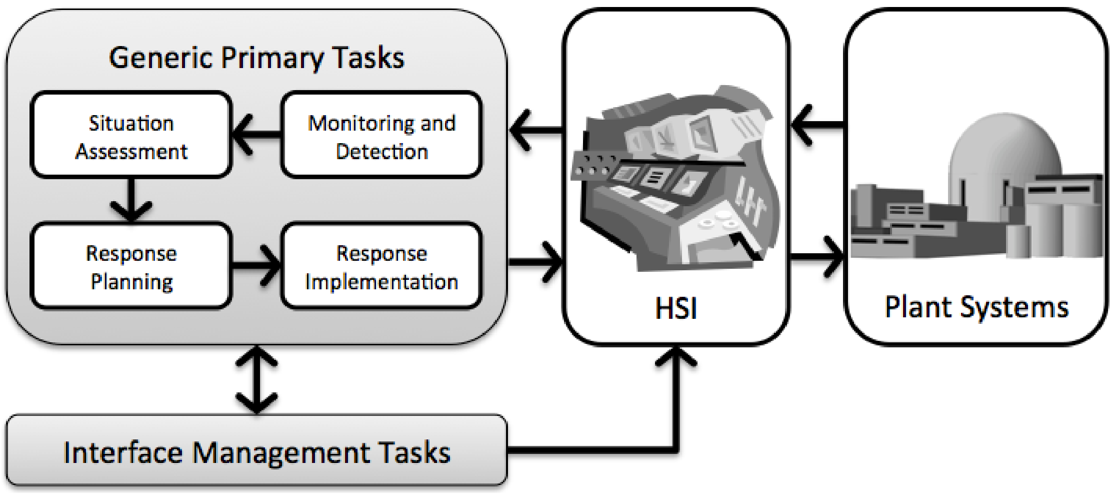

Figure 2-5. O’Hara’s cognitive model of NPP control room operations, adapted from O’Hara et al. (2008).

Monitoring and Detection: According to O’Hara et al. (2008), the task of monitoring and detection involves extracting information from the environment, such as checking the parameters on a control panel, monitoring parameters displayed on a computer screen, obtaining verbal reports from other personnel, and sending operators to areas of the plant to check on system components. From this information, operators determine if the plant is operating as expected. In a highly automated plant, much of what operators do involves monitoring. Detection is the operator’s recognition that something has changed (e.g., a component is not operating correctly), or the value of a parameter has increased or decreased.

Situation Assessment: Situation assessment is the evaluation of current conditions to determine if they are within acceptable limits, or to identify the underlying causes of any abnormalities. Operators actively try to construct a coherent, logical explanation to account for their observations. According to O’Hara et al. (2008), this cognitive activity involves two related concepts: the situation model and the mental model. The mental model consists of the operator’s internal representation of the physical and functional characteristics of the plant and its operation, as they understand it should be. This model rests upon formal education, training, and experience. Situation assessment occurs when operators use their mental model to understand information they obtain from the human-system interfaces (HSIs) and other sources. The cognitive representation resulting from situation assessment is termed the “situation model,” which refers to the understanding that personnel have of the plant’s current situation, (i.e., their current situation model). The alarms and displays serve to generate information supporting situation assessment. The HSIs may provide additional support to situation assessment in the form of operator-support systems.

To construct a situation model, operators use their mental model, i.e., the general knowledge and understanding about the plant and its operation, to interpret their observations and to extract its implications. Limitations in knowledge or in current information may entail incomplete or inaccurate situation models. The mental model consists of the operator's internal representation of the physical and functional characteristics of the plant and its operation as they understand it should be. The mental model rests on formal education, training, and experience.

Response Planning: According to O'Hara et al. (2008), response planning refers to deciding upon actions to resolve the current situation. In general, it involves operators using their situation model to identify goal states and the transformations required to achieve them. The goal state may vary, such as identifying the proper procedure, assessing the status of back-up systems, or diagnosing a problem. To meet their goals, operators generate alternative response plans, evaluate them, and select the one most appropriate to the current situation model. Response planning can be as simple as selecting an alarm response or it may involve developing a detailed plan when existing procedures proved incomplete or ineffective.

In an NPP, procedures usually aid response planning. The need to generate a response plan in real time largely may be eliminated when operators trust that the procedures are suitable to meet the current problem. However, even with good procedures, operators will undertake some aspects of response planning. For example, they still need to (1) identify goals based on their own situation assessment, (2) select the appropriate procedure(s), (3) evaluate whether the procedure-defined actions are sufficient to achieve those goals, and (4) adapt the procedure to the situation, if necessary.

Response Implementation: This entails performing the actions specified by the response plan, which may include such actions as selecting a control, providing control input, and monitoring the responses of the system and processes. Several types of errors are associated with controls. One example is mode errors, a new type associated with digital technology. A mode error occurs when operators take an action thinking the control system is in one mode when actually it is in another. Consequently, the system's response to the action is not what the operator expected.

While the O'Hara et al. model does not describe "coordination" as one of the generic tasks, it does point out the importance of teamwork in NPP operations. As O'Hara et al. (2008) noted:

> *Individual operators typically do not undertake these tasks alone; they are accomplished by the coordinated activity of multi-person teams. Operators share information and work in a coordinated fashion to maintain the plant's safe operation as well as to restore it to a safe state should a process disturbance arise. Crew members may perform a task cooperatively from one location, such as the main control room, while in other cases a control room operator may have to coordinate tasks with personnel in a remote location, such as at a local control station. Important human factors engineering aspects of teamwork include having common, coordinated goals, maintaining shared situation awareness, engaging in open communication, and cooperative planning. Successful teams monitor each other's status, back each other up, actively identify errors, and question improper procedures" (p. 7).*

O'Hara's model suggests that the four generic primary tasks, at least partially, are processed in serial:

Monitoring/Detection→Situation Assessment→Decision and Planning→Action Implementation

O'Hara's model did not address the relationship between the generic primary tasks and how they work together to accomplish complex tasks. The descriptive model of NPP control room teamwork presented next was intended to fill this gap.

2.3.3 Integrating Macrocognition with NPP Model

This chapter discussed three macrocognitive models and three cognitive models used in the NPP domain. We evaluated these models and analyzed their applicability to NPP operator performance. Through the analysis, we decided to adapt the strengths of these models and reconcile them into a single macrocognition model for HRA use. Table 2-1 presents a side-by-side comparison of the models.

Table 2-1. Comparison of the macrocognitive and NPP models.

Model	Roth (2010a, 2010b)	Klein et al. (2003)	Patterson & Hoffman (2012)	Chang & Mosleh (2007a)	O'Hara et al. (2008)
Macrocognitive Functions/ Information Processing Stages/	Detecting/noticing	Problem detection	Detecting problems	Information pre-processing	Monitoring and detection
	Understanding and Sensemaking	Sensemaking/ situation assessment	Sensemaking	N/A	Situation assessment
	Planning /deciding	Planning; Adaptation/ replanning; and Naturalistic decisionmaking	Deciding; Replanning	Diagnosis/problem solving and decisionmaking	Response planning
	Action	N/A	N/A	Action	Response implementation
	Communicating/ coordinating (teamwork functions)	Coordination	Coordinating	Crew coordination and interactions	Crew coordination
Relationship of the Functions/ Stages	Processing occurs in a continuous loop. It can be serial, but it also can start at any function and move in any direction	All the functions are in a dynamic, continuous loop, with many or all of the functions occurring at the same time, depending on the situation	Functions are overlapping and interact dynamically, depending on the situation	Phases are in a serial loop. Cognition flows in a series of IDA loops with nested sub-loops	The main stream of cognitive processing is serial from monitoring/ detection to response implementation

As shown in Table 2-1, a notable difference between the macrocognitive models and the NPP models is that the NPP models assume linear, serial flow, while the macrocognitive models do not. The macrocognitive models acknowledge that human cognition is more complex than what serial information-processing models can account for. As discussed by Roth (2010a, 2010b), Klein et al. (2003), and Patterson and Hoffman (2012), the cognitive process can start in any of the macrocognitive functions and move in any direction, involving parallel and cyclical processing in addition to serial processing.

The nested IDA concept in IDAC recognizes that the cognitive functions are not independent of each other. It is similar to Patterson and Hoffman's overlapping function model in that IDAC recognizes that perceiving information involves some aspects of decisionmaking and action; decisionmaking involves aspects of gathering information, diagnosis, and action; and that taking action involves aspects of detecting information and decisionmaking.

Another difference between the models is in dividing the continuous span of cognition into discrete macrocognitive functions. Roth (2010a, 2010b) identified five functions by combining planning with deciding. Klein et al. identified six functions (2003), and Patterson and Hoffman identified five (2012). Both the Klein et al. model and the Patterson and Hoffman model separated planning or re-planning from decisionmaking, and neither included action. The NPP models, on the other hand, have fewer granularities. IDAC has only four functions, with diagnosis and problem solving combined with decisionmaking instead of standing as a separate function. O'Hara's model only contains four generic primary tasks, though the model does discuss the importance of teamwork.

Despite the differences, there are remarkable similarities between the macrocognitive models and the NPP models, given that they were developed from psychological and engineering perspectives, respectively. The four generic primary tasks plus crew coordination used in the O'Hara et al. model are essentially the same as the functions generalized by Roth, and if one combines planning, re-planning and decisionmaking in the Klein et al. (2003) and Patterson and Hoffman (2012) models, this produces comparable categories, with the exception of action. IDAC has only four functions; however, IDAC combines diagnosis (or forming an understanding of the situation) and problem solving with decisionmaking. If one separates that part out, it produces five functions that look nearly identical on the surface to O'Hara et al. (2008) and Roth (2010a, 2010b).

Several key features were generalized from these models. Primarily, these include an understanding that the macrocognitive functions overlap, and that they dynamically interact with each other in a continuous, non-linear loop, involving parallel and cyclical processing. Given that the purpose of the literature review is to develop a cognitive framework that serves as a foundation for HRA in the NPP domain, and given that both of the NPP models have five functions (having separated diagnosis from decisionmaking in IDAC), we decided to adapt these functions into the macrocognitive model for Integrated Human Event Analysis System (IDHEAS):

- Detecting and Noticing
- Understanding and Sensemaking
- Decisionmaking
- Action
- Teamwork

The next section provides basic definitions of each of these five macrocognitive functions, and subsequent chapters in this report discuss each function in detail.

2.4 The Macrocognition Model for HRA

As discussed in the previous section, we adapted a macrocognition model that consists of five macrocognitive functions as the cognitive framework for IDHEAS. This section first provides brief descriptions of each macrocognitive function, and then describes the relationship between the functions.

2.4.1 Definitions of the Macrocognitive Functions Used in this Approach

Detecting and Noticing

Detecting and Noticing is the process of perceiving important information in the work environment. Emphasized in this macrocognitive function are the sensory and perceptual processes that allow humans to perceive large amounts of information and focus selectively on those pieces of information that are pertinent to present activities.

The cognitive processes associated with *Detecting and Noticing* are those related to the psychological processes of sensation, perception, and attention. Sensation has a large capacity for input, but sensory information can only be retained for a short interval before being replaced by new sensory information (Atkinson & Shiffrin, 1968; Baddeley, 2000; Baddeley & Hitch, 1974). Moreover, a person can only attend to a limited amount of information at a time. Attention determines which pieces of sensed information are processed and enter into the human's awareness. Raw information must be filtered or selected, and meaningful information is processed and extracted for further cognitive processing. When there is too much meaningful sensory information, the individual may not be able to detect and notice all of that information, resulting in sensory overload. Conversely, a lack of salient sensory information may cause important plant information to go undetected or unnoticed.

Understanding and Sensemaking

The macrocognitive function *Understanding and Sensemaking* is the process of understanding the meaning of the information that has been detected. Models and processes that fit into this function include the data/frame theory of sensemaking, situation awareness (SA), interpretation of pieces of information, and integrating multiple pieces of information together into a diagnosis. Cognition in this function ranges from automatic, effortless recognition and understanding to more effortful thinking and deliberate attempts to make sense of multiple pieces of information.

The model used to integrate all of the various approaches to understanding for the purposes of this effort is the data/frame theory of sensemaking (Klein, Moon, & Hoffman, 2006; Klein, et al., 2007). This model is an extension of Neisser's (1967) perceptual cycle theory, in which a person's sampling of the environment updates their cognitive map of the environment, which in turn directs further exploration. The data-frame theory of sensemaking posits that information coming into the sensemaking process is data. This data is integrated with an existing frame, which is a mental representation that serves as a structure for explaining the data and guiding the search for more data (Klein, et al., 2007). The data identify or construct the frame, and the frame determines which data are attended to. Neither the data nor the frame comes first; rather, it is a constant process of moving back and forth from data to frame. This dynamic aspect is the central theme of the model.

This model is ideal for the cognitive framework because it identifies the three primary sources of failure of *Understanding and Sensemaking*: the data (e.g., the operator has the wrong information), the frame (e.g., the operator is using an incorrect system model to understand the situation), or the integration of the two (e.g., new information is not properly integrated with the frame).

Decisionmaking

Decisionmaking involves goal selection, planning, re-planning and adapting, evaluating options, and selection. *Decisionmaking* within an NPP is characterized as involving experts and being largely driven by procedures. NPP control room decisionmaking typically involves routine (unconscious) decisions, such as deciding a piece of information is irrelevant, deciding between two gauges to obtain information from, or deciding to ask a question; it is not limited to making a decision about what action to take in response to the event. 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 must be accomplished and how it 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.

Two models that are particularly useful when examining decisionmaking within an NPP are a recognition-primed decision (RPD) model (Klein, 1993), and an integrated naturalistic decisionmaking model proposed by Greitzer et al. (2010). RPD was primarily developed to explain decisionmaking in stressful situations and under time pressure. The integrated naturalistic model includes concepts from situation awareness theories, and recognition/metacognition. This integrated model well describes the processes an experienced operator goes through in making a decision with or without explicit procedures.

Action

Action is defined as implementing an action on the level of a single manual action (such as operating a valve) or a predetermined sequence of manual actions. The action(s) must involve the manipulation of the hardware and/or software that would consequently alter plant status. It is assumed that the other macrocognitive functions (e.g., *Detecting and Noticing*, *Understanding and Sensemaking*, and *Decisionmaking*) have been carried out successfully.

Operator actions can take the form of individual control actions (e.g., turning a switch to a particular position; turning a pump on or off) or a sequence of actions intended to achieve a particular goal. An example of a sequence of actions is realigning a set of valves to change a flow path. In some cases, all that is required is a single, discrete, control action to achieve the goal. For example, manually tripping the plant generally requires a single button press (or turn of a switch). However, in other cases more sustained control is required. For example, in many situations operators are required to make continuous adjustments to maintain a parameter within a specified set of limits.

Reason (1990) divided errors of execution into two major forms: slips and lapses. Slips are errors where actions executed are "not as planned." They typically occur in the performance of largely automatic tasks performed by skilled individuals in familiar conditions, especially when attention is diverted (e.g., because of distraction or preoccupation). Lapses involve failures of memory, where an individual may forget to perform an intended action. This is often due to a failure in prospective memory—memory for intended actions in the future.

Teamwork

Teamwork is the macrocognitive function that focuses on how people interact with each other to coordinate as the individual or crew works on a task. In the present effort, we are using this macrocognitive function primarily to include coordination, collaboration, and communication between individuals, as well as to address crew interaction issues such as command and control.

This macrocognitive function focuses on the emergent aspects of team coordination to avoid duplicating cognitive functions already described by previous macrocognitive functions. Building on the team sensemaking work of Klein, Wiggins, and Dominguez (2010), these emergent aspects are unique to and only emerge when people work together in teams. For example, even in a team setting, individual macrocognitive functions like *Understanding and Sensemaking* occur in parallel in all team members, such as a crew's response to an alarm annunciation. Given this context of independent parallel processing, the essence of teamwork is the combination of these independent process efforts via communication for purposes of facilitating team coordination. Using communication to combine the individual macrocognitive processes is one emergent aspect of *Teamwork*; the other is leadership. NPP control room crews are hierarchical and have a distinct leadership structure. Errors in either communication or leadership can lead to failure of the *Teamwork* macrocognitive function.

2.4.2 Relationship between the Macrocognitive Functions

The macrocognitive functions described above represent a complete span of NPP operators' cognition when performing complex tasks. Klein's model states that the macrocognitive functions work together in a loop; Patterson and Hoffman's model suggests that the functions are overlapping, while O'Hara's model hinted that at least one of the main streams of information processing is from Monitoring/Detection to Response Implementation (also referred to as *Action*). Each of these models represents one perspective of how the functions work together. All the models acknowledged that these functions relate to and support each other, and they share some common cognitive mechanisms, yet each function is achieved by a unique set of cognitive mechanisms and can lead to unique types of human errors.

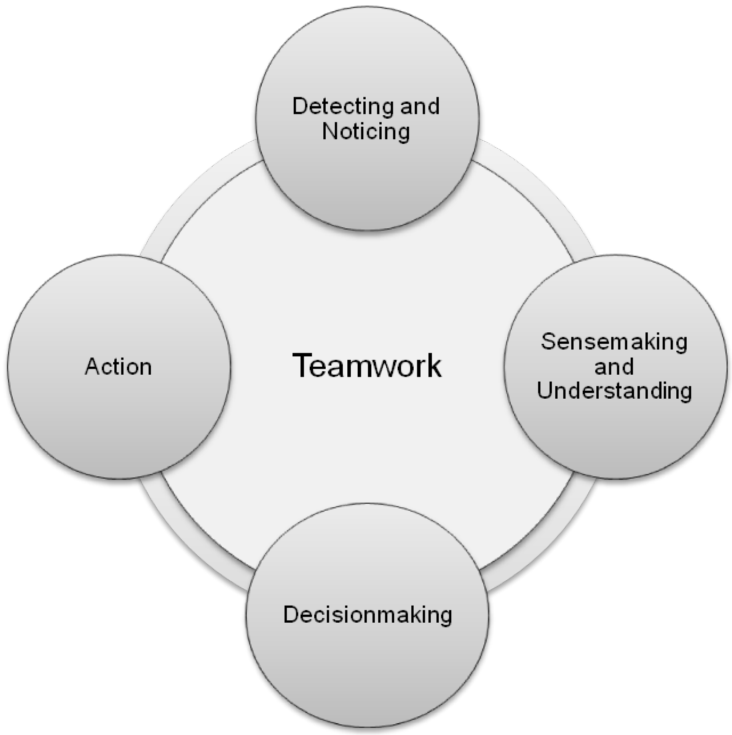

Figure 2-6. The five macrocognitive functions.

Figure 2-6 depicts the relationship among the macrocognitive functions. The functions are parallel and cyclical, and the functions overlap and interact with each other. Each of the macrocognitive functions operates in the context of team interaction. Like the Patterson and Hoffman (2012) model, the representation shown in Figure 2-6 recognizes that each macrocognitive function may involve aspects of the other functions. The figure shows that individual cognitive functions play out in the context of team interaction. We recognized that it is important to consider cognition at the level of the crew. The macrocognitive functions work simultaneously in all operators in the NPP crew, and the crew members must communicate and coordinate with each other to ensure that they make the appropriate response to the plant conditions.

2.5 Development of the Cognitive Framework

This section documents the process we took to transform the literature review into a cognitive framework. The purpose of the cognitive framework is to identify connections between proximate causes, cognitive mechanisms, and influences for the failures. The goal is to identify how failure occurs, (i.e., the cognitive mechanisms for human errors and the context (PIFs) that may activate those mechanisms).

Because the purpose of HRA is to understand human error and predict the likelihood of errors, we structured the literature review and developed the cognitive framework in terms of human failure. This meant that the focus was on identifying information that can explain human error. This required reinterpretation and inferences of the major psychological literature reviewed because many findings in the psychological literature are focused on how to optimize successful human performance. For example, research on attention may discuss factors that are crucial for successful performance solely from the perspective of optimal performance. This does not necessarily explain what can lead to failure of attention. In such cases, we had to interpret, supplement, or make inferences about how the information could apply to failures, based on our expertise and other research.

This section describes the genesis of the cognitive framework, including identification of the cognitive mechanisms, proximate causes, links of the causes and mechanisms with PIFs, and construction of this information into the cognitive framework.

2.5.1 Identification of Cognitive Mechanisms

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

Using this definition, we reviewed the literature in depth to extract knowledge about the macrocognitive functions and then identify the underlying processes and explain how errors or mistakes can occur, or ways in which psychological models would help describe failures. Some models call out specific types of errors. Other models specifically discuss processes that are required for success; transforming this information into a mechanism required framing the description of the process in failure terms. We often added terms such as "not" or "failed to" to the processes that make the functions work.

For example, the following excerpts from Endsley (1995) illustrate a cognitive mechanism for the *Understanding and Sensemaking* function:

> *"Operators of complex systems frequently employ a process of information sampling to circumvent this [attention] limit. They attend to information in rapid sequence following a pattern dictated by the portion of long-term memory concerning relative priorities and the frequency with which information changes…. Working memory also plays an important role, allowing one to modify attention deployment on the basis of other information perceived or active goals…" (p. 41).*
>
> *"Failures in information sampling are commonplace, however, and may result from the lack of an adequate strategy or internal model for directing sampling. Wickens…has also noted that humans have several general failings in sampling, including misperception of the statistical properties of elements in the environment and limitations of human memory (forgetting what has already been sampled)" (p. 55).*

The excerpts describe the process of using a mental model to guide information sampling and direct attention toward important information. However, when an incorrect mental model is used, attention may be directed toward information that is not important and contribute to an incorrect understanding of the situation. Consequently, we identified a cognitive mechanism for failing the *Understanding and Sensemaking* function as, "incorrect, inappropriate, or inadequate frame used to search for, identify, or attend to information." Appendix A lists all of the cognitive mechanisms identified through this process, sorted by macrocognitive function and proximate cause.

2.5.2 Identification of Proximate Causes

Many cognitive mechanisms were identified for each macrocognitive function. A cognitive mechanism can fail to achieve its intended function in different ways. For example, working memory is a mechanism for understanding the situation. Failure of working memory, such as memory overload, can lead to misunderstanding or incomplete understanding of the situation. We identified the outcomes of failure of the mechanisms, and grouped the outcomes into readily identifiable types of failures of the cognitive functions. We refer to these type of failures as proximate causes. Hence, proximate causes are the result of failure of cognitive mechanisms. A proximate cause can be associated with several cognitive mechanisms, and vice versa. Furthermore, one or several proximate causes may lead to human failure.

Whereas cognitive mechanisms are scientific findings described in the literature, the set of proximate causes is merely a classification scheme used to group the cognitive mechanisms. Therefore, there can be different ways to classify the mechanisms. Our goal was to develop a defined set of proximate causes that have distinct non-overlapping definitions, and are observable, identifiable, or inferable in a practical manner. With many rounds of exploration and pilots, we decided to use the major process steps of a macrocognitive function as the framework of proximate causes. For example, per the literature, achieving the *Detecting and Noticing* function requires the cognitive mechanisms of attending to the cue/information and perceiving the cue/information correctly. Therefore, the proximate causes were identified as: cue/information not attended to, cues/information not perceived, and cues/information misperceived. We developed an initial list of proximate causes, then gradually revised the list as we collapsed together items that seemed similar (i.e., that produced similar or overlapping effects).

The set of proximate causes identified is listed below.

- Failure of *Detecting and Noticing*
  - Cues/information not attended to
  - Cues/information not perceived
  - Cues/information misperceived
- Failure of *Understanding and Sensemaking*
  - Incorrect data
  - Incorrect frame
  - Incorrect integration of data, frames, or data with a frame
- Failure of *Decisionmaking*
  - Incorrect goals or priorities set
  - Incorrect pattern matching
  - Incorrect mental simulation or evaluation of options
- Failure of *Action*
  - Failure to execute desired action
  - Execute desired action incorrectly
- Failure of *Teamwork*
  - Failure of team communication
  - Failure in leadership/supervision

We describe the cognitive mechanisms and proximate causes in generic terms from a psychological perspective to ensure applicability over a wide range of situations, including human cognition within and outside of the control room. Yet, since the initial scope of the literature review was primarily limited to cognitive mechanisms that support cognitive activities of NPP operators in internal, at-power events, some cognitive mechanisms that are pertinent to situations outside the scope, such as those supporting dynamic, distributed decisionmaking, were not included in the review. Subsequently, the proximate causes, while a good coverage for NPP internal, at-power events, may not cover the entire operation span of NPP events such as several accident management or low-power shutdown.

2.5.3 Performance Influencing Factors

The circumstances or contextual factors that contribute to human performance in a work environment are referred as to performance influencing factors (PIFs), or performance shaping factors. PIFs can either reduce or increase the likelihood of error. PIFs are commonly used in human reliability analysis (HRA) methods to adjust the human error probability (HEP) depending on the context of the situation, and they are also commonly used to identify root causes of errors and areas for improvement. We defined PIFs as contextual factors (including plant factors) that influence the likelihood that the cognitive mechanisms “activate” and lead to the proximate causes of macrocognitive function failure.

Every HRA method has its own set of PIFs. At present, there is not a standard way of defining PIFs. Groth (Groth, 2009; Groth & Mosleh, 2012) assembled a list of PIFs from a number of HRA methods. The PIFs are sorted into five factors or categories:

- Organization-based factors: factors that are under the control of the organization and include the organization’s attitudes and behaviors that affect human performance.
- Team-based factors: factors related to the team that is working together to achieve a common goal and the quality of their interactions.
- Person-based factors: factors internal to each individual and encompass a person’s state of mind, temperament, and other intrinsic characteristics.
- Situation/stressor-based factors: characteristics of the scenario that are external to the person and to the system, and that are likely to influence human performance. Stressor PIFs are the demands of the situation that the person perceives as tension or pressure that can disrupt or facilitate performance.
- Machine-based factors: factors related to the system as designed by the vendor or manufacturer, including the building structure, mechanical and electrical components, hardware, and software.

Each of these categories consists of many specific factors, as shown in Table 2-2. In our literature review, we identified empirical findings about how cognitive mechanisms may fail under various experimental manipulations or operational contexts. Based on these findings, we used the list in Table 2-2 to make inferences about what PIFs may affect a given cognitive mechanism. The links are summarized in Appendix A.

Table 2-2. Complete PIF taxonomy as organized by Groth & Mosleh (2012).

Organization-Based	Team-Based	Person-Based	Situation/ Stressor-Based	Machine-Based
Training Program • Availability • Quality Corrective Action Program • Availability • Quality Other Programs • Availability • Quality Safety Culture Management Activities • Staffing o Number o Qualifications o Team composition • Scheduling o Prioritization o Frequency Workplace Adequacy Resources • Procedures o Availability o Quality • Tools o Availability o Quality • Necessary Information o Availability o Quality	Communication • Availability • Quality Direct Supervision • Leadership • Team member Team Coordination Team Cohesion Role Awareness	Attention • To Task • To Surroundings Physical and Psychological Abilities • Alertness • Fatigue • Impairment • Sensory Limits • Physical Attributes • Other Knowledge/Experience Skills Familiarity with Situation Bias Morale/Motivation/Attitude	External Environment Conditioning Events Task Load Time Load Other Loads • Non-task • Passive Information Task Complexity • Cognitive • Task Execution Stress Perceived Situation • Severity • Urgency Perceived Decision • Responsibility • Impact o Personal o Plant o Society	HSI • Input • Output System Responses

2.5.4 Creating the Cognitive Framework: Connecting Proximate Causes, Cognitive Mechanisms, and PIFs

One requirement for the literature review was to build a framework that connects failures of macrocognitive functions with proximate causes, cognitive mechanisms, and PIFs. The purpose of such a tool is to identify how failure occurs. For the possible proximate causes of failure of a macrocognitive function, the cognitive framework identifies the potential cognitive mechanisms for human error, and what contexts (PIFs) may activate those mechanisms. We took all four of the elements discussed above—macrocognitive functions, proximate causes, cognitive mechanisms, and PIFs—and organized them into the cognitive framework, a tree structure that illustrates how macrocognition may fail and describes the reasons why. Each macrocognitive function is represented with one tree, yet the tree branches are not necessarily orthogonal to each other. Specifically, we have endeavored to make the proximate causes as independent from each other as possible. The generic structure for each tree in the cognitive framework is shown in Figure 2-7. Starting from the left in the figure, the first box represents the macrocognitive function that the tree is analyzing. Boxes in the next column represent the proximate causes of failure for the function. Each proximate cause is then linked to a number of cognitive mechanisms. Each cognitive mechanism is connected to the relevant PIFs for that mechanism. The flow moves from left to right: for a given cognitive function, the tree allows one to identify the proximate causes of the failure of the function, the cognitive mechanisms leading to the causes, and the PIFs contributing to the causes through the mechanisms. Note that the diagram depicts an ideal situation: a given set of PIFs only contribute to one cognitive mechanism, and a given set of mechanisms only contribute to one proximate cause. In reality, different causes can be associated with some common mechanisms, and the same cognitive mechanism may lead to more than one proximate cause. The same is true for the connections between PIFs and the cognitive mechanisms.

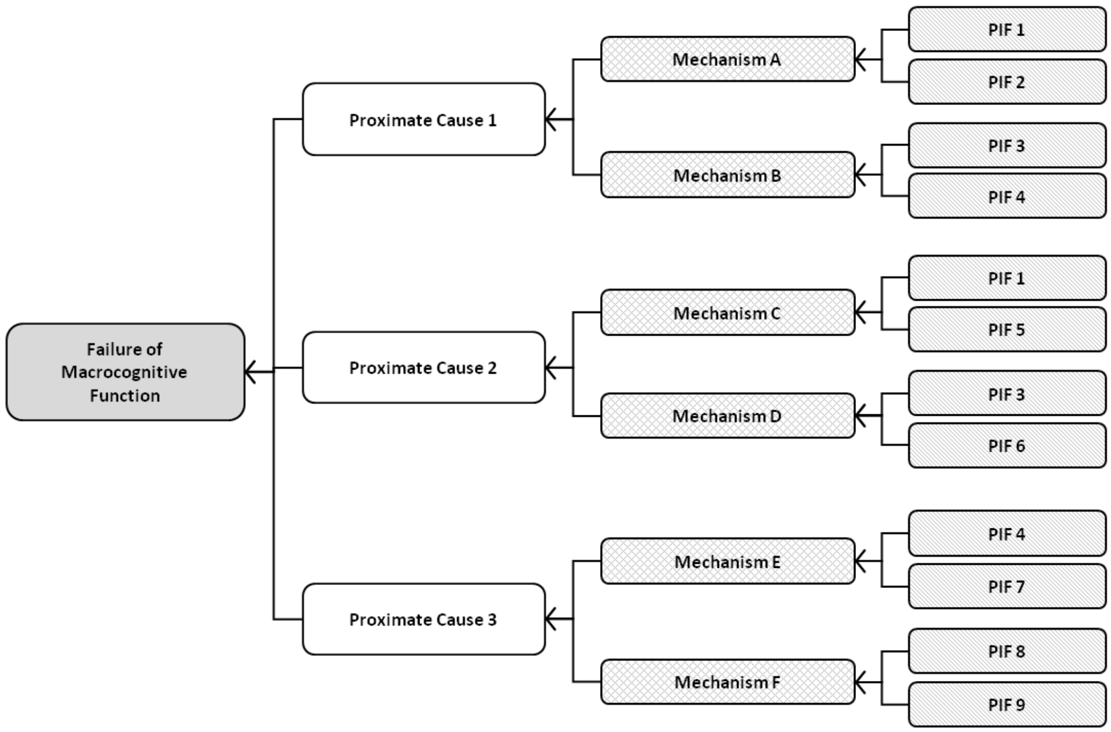

Figure 2-7. Generic cognitive framework: links between PIFs, cognitive mechanisms, proximate causes, and macrocognitive functions.

Each tree of the cognitive framework (in Appendix B) corresponds to a set of detailed tables (in Appendix A) that provide supporting information for the psychological basis of each node in the tree. Together, Appendix A and Appendix B are the outcomes of the literature review: a cognitive framework tool that serves as the psychological foundation for the qualitative and quantitative analysis methodology of the IDHEAS HRA method.

In addition, the cognitive framework can be used more generally to identify causes, mechanisms, and PIFs to consider for any situation involving human error. The framework gives analysts a structured tool, based on psychological research, for identifying the types of factors likely to be relevant for a given human failure event. As a result, the cognitive framework may prove useful to other HRA methods or human factors applications.

An excerpt from Table A.1.1 in Appendix A (the *Detecting and Noticing* macrocognitive function) is shown in

Table 2-3. This excerpt contains two cognitive mechanisms that explain the proximate cause of cues/information not perceived. The tables in Appendix A are organized by macrocognitive function and proximate cause. The first column in each table contains the cognitive mechanism that can lead to the proximate cause. The second column provides a discussion of how the mechanism works. The third column provides an example. Next, the table lists the relevant PIFs for the cognitive mechanism, followed by an explanation of how or why the PIF is relevant. The last column provides references.

Table 2-3. Excerpt from Table A.1.1 listing cognitive mechanisms and PIFs for the proximate cause Cues/information not perceived.

Mechanism	Discussion	Example	Relevant PIF(s)	Explanation	References
Working memory	Broadbent's "filter theory" explains sensory bottlenecks—the alarm might be missed because humans have a limited ability to take in stimulus inputs and perceive them. It is possible to reach sensory bottlenecks, which can result in sensory overload.	Filter theory has direct implications for plant environments like control rooms, where concurrent tasks and multiple simultaneous alarms may lead to sensory overload and cause operators to miss some relevant information.	• Task load	Sensory bottlenecks dictate ability to perceive information.	Broadbent (1958)
Cue content	The human's ability to detect or sense stimuli is a function of how clearly that stimuli is present over and above existing background noise (i.e., the cue's signal to noise ratio).	The cue is not presented to the operator with sufficient strength/energy to distinguish itself from existing background noise such that it activates a sensory response in the operator.	• HSI • Task load • Task complexity • Stress	The signal to noise ratio is too low for the operator to be able to perceive the cue (i.e., distinguish it from noise).	Bustamante (2008)

The two cognitive mechanisms included in the excerpt in

Table 2-3 are working memory and cue content. People have limits to the amount of information they can process at once. Information overload occurs when more information is sent to a person than that person is capable of taking in, or when the person is processing other information and as a result cannot take in anything new (Broadbent, 1958). When this happens, important data may be missed. Because of this, task load is a PIF that can influence the likelihood of information overload occurring.

The cue content cognitive mechanism explains that if the cue is not salient enough to be distinguished from the background noise, it is more likely to be missed (Bustamante, 2008). Therefore, the amount and nature of the output from the HSI is important—is the critical information buried in flashing lights and noise? Workload and stress are also issues, because with increasing task load, complexity, and stress, the amount of mental resources that are occupied with the task increases and leaves less available to attend to cues. With a heavy workload, cues that are not particularly salient, which would normally be noticed in low workload situations, may be missed. Stress is known to cause attentional narrowing (Nikolic, Orr, & Sarter, 2004), or to decrease the amount of information one can attend to. This also can lead to missing a cue if the cue is not particularly salient.

As shown by the example in

Table 2-3, one of the most important developments in the cognitive framework is that there are explicit connections between PIFs, cognitive mechanisms, and proximate causes of failure. Specifically, the tables provide explanation about which PIFs are important and why, provide information about how PIFs influence cognitive errors, and put this information in a simple tool that can inform HRA and other applications.

2.6 Summary

This chapter provided an overview of macrocognition and explained the process we used to identify a macrocognitive model for the IDHEAS HRA method. We reviewed major models of macrocognition and two NPP-specific models. Comparing the models demonstrated that they were largely consistent, though they use slightly different terminology for the same concepts. Furthermore, the models are complementary. We adapted these models into a generalized cognitive framework for use in the IDHEAS HRA method. This framework has five macrocognitive functions:

- Detecting and Noticing
- Understanding and Sensemaking
- Decisionmaking
- Action
- Teamwork

We conducted a review of the behavioral sciences literature related to each of the above macrocognitive functions to identify cognitive mechanisms, causes of failure (proximate causes), and the effects of PIFs. We then organized the information gleaned from the review into tables (Appendix A) and the cognitive framework (Appendix B). Together, the cognitive framework and the accompanying tables form the technical basis for the IDHEAS HRA method, and can also be useful to other HRA methods or human factors applications.

3. DETECTING AND NOTICING

3.1 Introduction

The macrocognitive function of *Detecting and Noticing* refers to perceiving important information in the work environment. *Detecting and Noticing* emphasizes how humans selectively process the large bulk of information that they have sensed and focus on the information that is pertinent to tasks. This chapter first introduces *Detecting and Noticing* as a macrocognitive function in general and its specific involvement in performing nuclear power plant (NPP) tasks. The chapter then summarizes the cognitive mechanisms underlying *Detecting and Noticing*, followed by proximate causes of failure in *Detecting and Noticing*. Lastly, the chapter presents examples from the literature that demonstrate the impact of certain performance influencing factors (PIFs) on the success or failure of the *Detecting and Noticing* function. We generalized the psychological literature findings to provide a cognitive basis of what leads to human failures in detecting and noticing critical task-relevant information. This information is summarized in Appendix A.1.

3.1.1 Sensation and Perception

The cognitive processes associated with *Detecting and Noticing* include sensation, perception, and attention. Sensation, broadly defined, involves the input of environmental stimulus information into the sensory organs. This information may encompass the traditional five senses and may be visual, aural, olfactory (related to smell), gustatory (related to taste), or tactile. Additional sensory information includes proprioception (related to the position of parts of the body), kinesthesia (related to the sensation of motion), equilibrioception (related to the body's balance), chronoception (related to perception of time), thermoreception (related to sense of temperature), and nociception (related to sense of noxious stimuli and pain). For the purposes of nuclear power plant operations, the main sensory modalities are visual and aural, although some consideration is given to tactile inputs.

Perception is the point at which sensory information is first given meaning. Sensory information can be seen as raw input information. Sensation is largely a biological process and holds relatively constant across people. Different normal-sighted individuals, for example, do not sense the color blue differently from each other. However, at the point at which blue is imbued with meaning, that meaning is subject to the cognition of the individual beholding it. Blue may be a favorite color for one individual yet a disliked color for another individual. Moreover, the experience of particular individuals may impact their perception of that color. One individual may have been trained to associate blue with a positive flow condition, while another individual may have no functional associations with the color. Perception is a byproduct of memory—the individual's past experiences and training will affect the meaning associated with a particular perception. Memory infuses sensation with meaning to become perception.

3.1.2 *Detecting and Noticing* across Sensation and Perception

Human cognition is not a strictly serial process of inputting information, giving it meaning, and then making sense of it. Throughout information processing, meaning is created by merging sensory information with cognition and memory. The flow of information is bidirectional, and meaning may be imbued early in the sensory process to enable sensory filtering. As described earlier in Chapter 2, the five macrocognitive functions are overlapping and support each other, yet each function has its own focus and roles in achieving the tasks.

Figure 3-1 illustrates the different focuses of sensation and perception across the *Detecting and Noticing* and *Understanding and Sensemaking* functions. In terms of cognitive processes, cues and information from the environment are initially sensed. At this stage, the environmental cues and information are represented as raw sensory signals. This sensory information is perceived by giving it initial meaning. Essentially the sensory signals are categorized into perceptual objects. As additional meaning is placed on these perceptual objects and they are synthesized, cognition is said to take place. At this stage, the objects are semantic in the sense that they represent meaningful entities that are understood. The progression of information can be seen in the example from spoken speech at the bottom of the figure. Speech is initially sensed as sound waves and encoded neurologically. As meaning is extracted from the raw speech signal, the sound emerges phonetically as /sh/. /sh/ is still a relative abstraction, but it is a meaningful sound or phoneme in the English language. These phases of sensing and perceiving are the areas covered in *Detecting and Noticing*. Additional meaning is attached to the phoneme, and it takes on word or word-like meaning. The sound /sh/ in isolation has a meaning ("Quiet!") in English. As that meaning is deduced, the corresponding phase is captured by *Understanding and Sensemaking*.

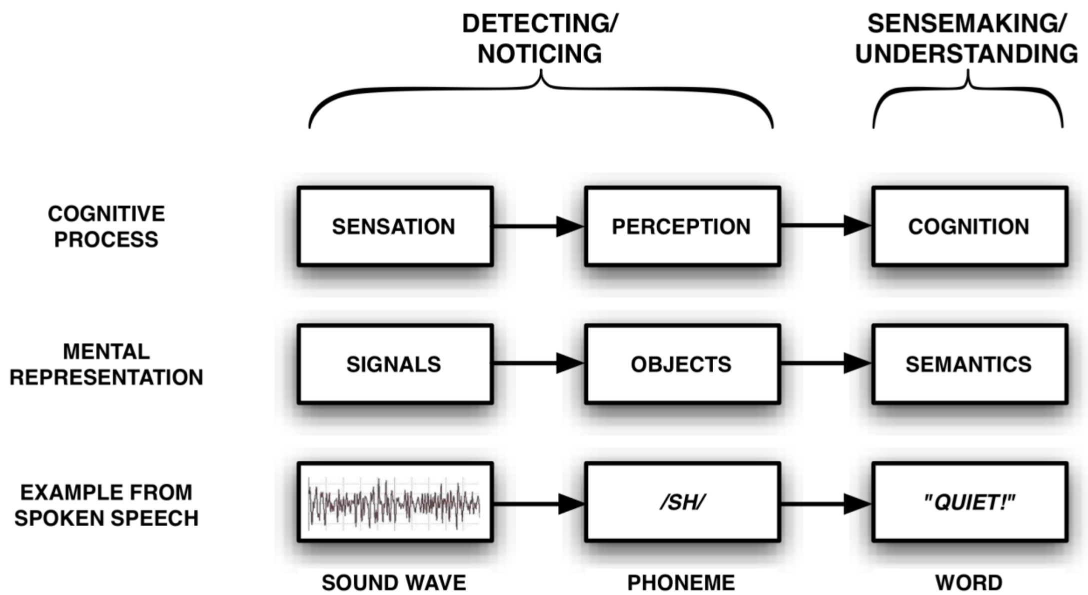

Figure 3-1. The relationship between the macrocognitive functions of Detecting and Noticing and Understanding and Sensemaking.

The relationship between sensation, perception, and cognition can be seen from a biological perspective. The sensory receptors such as the rod and cone cells found within the retina provide the raw sensory input to the visual system. As this information reaches the visual cortex, it is perceived. Finally, as information in the visual cortex travels to the associative cortex, it becomes cognition.

A further example helps to illustrate the distinction between sensation, perception, and cognition. When a control room operator sees an annunciator illuminate, the operator initially senses the light from the light box. In parallel, the operator sees the shapes and forms of the surrounding, unilluminated alarm tiles. Both illuminated and unilluminated alarms contain equal sensory information (although illumination results in higher sensory intensity). However, illuminated and unilluminated alarms do not have equal meaning. The illuminated alarm tile has a different meaning from the unilluminated alarm tiles surrounding it. The operator perceives the illuminated versus unilluminated alarm tiles and associates meaning with them. This semantic difference is the essence of perception. Even though the operator has perceived the "alarmness" of the alarm, he or she still has not made sense of the alarm or understood its explicit meaning. Its perceptual meaning is that it is a lighted light box needing attention—a composite mental representation of feature detection, object recognition, and sensory salience. Its cognitive meaning—imbued with focused sensemaking and understanding beyond the generic representation of perception—is that of a specific alarm, and the operator responds according to the specific alarm.

Sensation has a large capacity for input, but sensory information can only be retained for a short interval before being replaced by new sensory information (Atkinson & Shiffrin, 1968; Baddeley, 2000; Baddeley & Hitch, 1974). Moreover, only a limited amount of sensed information is processed by the brain's information processing systems and enters into the human's awareness or percepts. For this reason, raw information must be filtered or selected and meaningful information is processed and extracted for further cognitive processing. This function is referred to as *Detecting and Noticing*. While sensation is a process that occurs at the biological or hardware level, perception is analogous to control systems where hardware processing can be modulated by software algorithms. When there is too much meaningful sensory information, the individual may not be able to detect and notice all of that information, resulting in sensory overload. In summary, *Detecting and Noticing* represents the process of detecting meaningful signals from a large bulk of information received by the sensory organ.

Literature has broadly suggested the following purposes of *Detecting and Noticing*:

- detecting salient cues in the environment
- detecting changes or new cues onset in the environment
- detecting weak but mission-critical cues from an information-rich environment
- noticing abnormal cues
- searching for specific cues pertinent to a task

These purposes are applicable to operators' tasks in NPPs as well and actually define a significant portion of the operators' monitoring tasks in the main control room (Morray, 1986). NPP operators monitor plant state during normal, abnormal, and urgent operating conditions. The control room provides a series of stimulus cues to the operators—instrumentation and control states, alarms, and written procedures draw the attention of the operators and are detected and noticed accordingly (Vicente, Mumaw, and Roth, 2004). A failure to detect and notice important cues in the control room can lead to delays in diagnosing plant states, misdiagnosis of plant states, or even failure to diagnose plant states requiring response. As such, *Detecting and Noticing* is a crucial part of the control room operators' contribution to plant safety in the main control room.

Mumaw et al. (1994, 2000) reported that monitoring demands in an NPP are often different from those in the types of monitoring tasks that have been examined in laboratory settings. An NPP has thousands of parameters that operators can potentially monitor. Further, monitoring is not the only activity in which power plant operators are engaged; monitoring activity is interweaved with other ongoing responsibilities of managing day-to-day tasks for generating power. Mumaw et al. (2000) performed cognitive field studies to understand NPP operators' monitoring task. They found that what makes monitoring difficult is not the need to identify subtle abnormal indications against a quiescent background, but rather the need to identify and pursue relevant findings against a noisy background. Operators devised proactive strategies to make important information more salient or reduce meaningless change, create new information, and off-load some cognitive processing onto the interface. These findings emphasize the active problem-solving nature of monitoring, and highlight the use of strategies for knowledge-driven monitoring and the proactive adaptation of the interface to support monitoring.

The scope of the literature review was limited to those relevant to monitoring/detecting activities in NPP control rooms during internal, at-power events. We made the following assumptions to the activities: (1) operators always know what to monitor/detect, per their training and procedures, (2) the cue/information to be detected has no uncertainty; that is, operators always know and can recognize the meaning of a cue/information as long as the cue is correctly perceived, and (3) the information is effortlessly used for the next cognitive function, *Understanding and Sensemaking.* These assumptions set forth the broadness of the literature search. As for the levels of details and depth of literature search, the literature reviewed in this chapter excludes psychological literature in a number of well-documented areas in sensation and perception:

- sensory and perceptual impairments such as colorblindness or prosopagnosia (impaired facial recognition), which are presumed not to be relevant to control room operators or operations;
- neuroimaging studies, which provide insights into the neurobiological underpinnings of sensation and perception, but do not typically provide functional accounts of processes that map to proximate causes; and
- psychophysical research, which primarily reviews the intersection of sensation, perception, and the use of psychological scales, which is not a typical control room activity.

It must also be noted that almost no literature on sensation and perception is specific to the domain of nuclear energy. The findings from other domains such a basic psychology, human factors, and aviation psychology must be extrapolated to account for control room phenomena. As such, the examples involved make use of subject matter expertise in psychology and nuclear power operations to generalize the psychological findings. However, sensation and perception are largely invariant across humans and across applications. Sensation and perception occur at the physiological level, and the processes are consistent across domains. Therefore, it has been unnecessary to perform such research specifically for nuclear power applications. Nuclear regulatory guidance on those factors that affect sensation and perception (e.g., lighting levels or font size for readability) has been derived from research in other areas (NUREG-0700; O'Hara, Brown, Lewis, & Persensky, 2002) and the generalization to nuclear has been straightforward and widely accepted.

3.2 Cognitive Mechanisms for *Detecting and Noticing*

3.2.1 Behavioral Aspects of *Detecting and Noticing*

Sensory and perceptual information may be passively detected or actively sought. This distinction is explained through information foraging theory (Pirolli, 2007), stating that sensory and perceptual information gathering is akin to foraging for food. In the wild, organisms alternate between grazing in fruitful patches of food and actively foraging for food. By analogy, humans feed on sensory information in the environment. Humans alternate between grazing information that is readily available and actively foraging for new information. Control room operations alternate between phases when the operator is actively looking for information about key plant parameters and periods where sufficient information can be found within a limited area of focus (Boring, 2011). During a period of passive information grazing, the operator receives salient information that pops out of the scene and captures his or her attention. During a period of active information foraging, the operator seeks information that is important to the task goals.

In NPP control rooms, procedures or knowledge may guide the degree to which operators actively versus passively seek specific information (Massaiu, Hildebrandt, & Bone, 2011). So, this information may guide the operator where to look and it may change "what" information to search for, but it cannot change how the operator senses or perceives that information. For example, experienced control room operators will actively seek specific plant information, whether guided by procedure or based on the operators' plant knowledge. The operators will sense and perceive the same information—the only difference being whether the operators actively seek that information or passively receive it.

3.2.2 Overview of Mechanisms for *Detecting and Noticing*

Figure 3-2 shows a diagram of the cognitive processes underlying the visual *Detecting and Noticing* function. The processes for auditory information follow a very similar pattern.

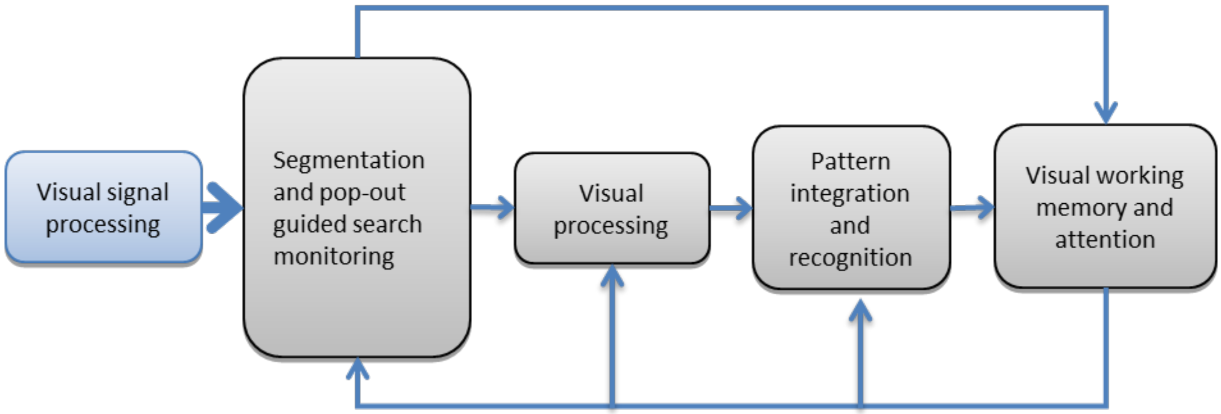

Figure 3-2. Diagram of cognitive processes for the Detecting and Noticing function.

Briefly speaking, visual signals are first sensed by the retina—the sensory organ—and go through some preliminary signal processing (such as enhancing the signal-to-noise ratio) by subcortical neural structures, then reach the primary visual cortex for preliminary visual perceptual processing. From the visual cortex, visual information is processed in two stages: the pre-attentive and the attentive stages. The pre-attentive stage is vision without capacity limits. It captures salient cues/information at once in the whole visual field by segmenting a visual scene and popping out salient stimuli, and the salient information triggers visual attention and is stored in working memory. Next at the attentive stage, visual attention directs the fovea to salient information for detailed visual perception. These cognitive processes are achieved through three major information processing pathways: pre-attentive, bottom-up (stimulus driven), and top-down (memory driven):

- The pre-attentive pathway performs visual segmentation and pop-out of salient stimuli.
- The bottom-up pathway processes visual features of the attended visual area of interest, combines visual features into integrated patterns, and retains visual objects in working memory.
- In top-down processing, the individual strategically directs their attention to current goals and expectations due to experience. This is done through memory. The top-down pathway guides attention to the fovea or searches for the more interesting information and selectively enhances the responses of the visual cortex to specific stimuli (i.e., selective attention).

The micro-cognitive functions involved in these pathways are summarized as follows:

- visual signal processing—sense and pre-process visual signals for perception
- segmentation and pop-out—extract salient information
- visual feature perception—perform preliminary visual analysis of features such as contrast, color, shape, and motion

- pattern and object integration—integrate multi-dimensional visual features into a coherent pattern or object

3.2.3 Cognitive Mechanisms Involved in *Detecting and Noticing*

The psychological literature has reported many cognitive processes or models involved in *Detecting and Noticing*. Those cognitive processes act like software that works on the three pathways delineated in Figure 3-2 to ensure that the *Detecting and Noticing* function is reliably performed. The literature either hypothesized or generalized experimental findings on how various cognitive processes work to achieve the *Detecting and Noticing* function. We grouped the cognitive processes reported by the experimental literature into five categories of cognitive mechanisms. After a representative list of seminal articles and books for *Detecting and Noticing* was identified through the process described earlier in this document, we sorted the references into meaningful clusters of related articles.[5] Table 3-1 lists the references from the reviewed literature that are pertinent to each category of mechanisms. Note that this list of references is, by design, representative but not exhaustive in terms of the psychological phenomena documented in the research literature.

Table 3-1. Key literature according to cognitive mechanisms for Detecting and Noticing.

Cue Content – Salient Process	Vigilance in Monitoring	Attention	Expectation	Working Memory
• Biederman (1987) • Hendy, Farrel, & East (2001) • Hitchcock et al. (2003) • Levi (2008) • Massaro & Cohen (1991) • Nikolic, Orr & Sarter (2004) • Orasanu & Martin (1998) • Phillips (1974) • Pirolli (2007) • Xing (2007)	• Aarts & Pourtois (2010) • Bustamante (2008) • Donald (2001) • Donald (2008) • Eriksen & St. James (1986) • Jones & Endsley (1996) • Lavine et al. (2002) • Lin et al. (2009) • MacLean et al. (2009) • Malcolmson, Reynolds & Smilek (2007) • Mumaw, Roth & Burns (2000) • Pirolli (2007) • Steelman-Allen et al. (2009) • Szalma et al. (2004) • Vicente (2007) • Vicente & Burns (1996) • Vicente, Roth & Mumaw (2001)	• Beck, Levin & Angelone (2007) • Bubić (2008) • Durlach, Kring & Bowens (2008) • Tales, Porter & Butler (2009) • Varakin, Levin & Collins (2007) • Vierck & Kiesel (2008)	• Einhorn & Hogarth (1981) • Klein (1993) • Köhler (1947) • Lipshitz (1993) • Treisman (1991)	• Brewer et al. (2010) • Broadbent (1958) • Caggiano & Parasuraman (2004) • Einhorn & Hogarth (1981) • Endsley (1995) • Kurby & Zacks (2007) • Phillips (1974) • Reicher (1969) • Soliman (2010) • Steelman-Allen et al. (2009)

The categories simply provide a high-level way to organize the many cognitive phenomena related to *Detecting and Noticing*. The categories represent different types of cognitive phenomena. It would be equally possible to categorize the articles differently according to their effects on human performance. These five types of cognitive processes may be viewed as requirements for detection—these are fundamental cognitive mechanisms that allow people to

5. A formal sorting method called *card sorting* was employed. This method is commonly used in human factors to arrive at categories of related concepts.

perceive task-pertinent information in their environment. Each requirement for detection presents the opportunity for failure, which provides explanations behind the proximate causes. The discussion will first focus on the five types of mechanisms required for *Detecting and Noticing*, and then the discussion will address specific opportunities for failure.

The five different categories of cognitive mechanisms for *Detecting and Noticing* as identified in the research literature are as follows:

- *Cue Content – Salient Process.* One area that can greatly affect the operators' *Detecting and Noticing* is the type and quality of cues with which he or she is confronted. Important sensory cues may be of a degraded quality, making it difficult for the operator to detect or notice them. Important cues may also be buried in an overabundance of other cues, making it difficult for the operator to detect the most salient cues. Similarly, the information scene the operator confronts may be complex, requiring considerable effort to find the most salient cues and necessitating higher cognitive functions such as *Understanding and Sensemaking* to glean meaningful cues from the environment. The visual system has segmentation and pop-out functions to detect salient targets. Yet, the content of the cue has to be salient enough to be detected by these functions.
- *Vigilance in Monitoring*. Vigilance is marked by the ability to attend to cues over time in monitoring tasks. An operator's ability to attend to or monitor cues will naturally degrade over time as a byproduct of fatigue. In addition, the operator's attention can be affected by a number of factors, ranging from the operator's workload, which degrades attention more quickly; to stress, which can interfere with the operator's ability to attend.
- *Attention*. Attention is the cognitive process of selectively concentrating on one aspect of the environment while ignoring other things. It has also been referred to as the allocation of processing resources. Attention guides searching for and monitoring the information of interest, focusing visual processing on it, filtering out the unwanted information, and binding visual features into an integrated pattern/object. Salient cues can automatically draw one's attention. Attention plays a crucial role in determining what sensory information is detected/noticed. As such, attention is a central part of perception and one of the areas that determines the success or failure of the *Detecting and Noticing* macrocognitive function. Therefore, attention serves to direct cognitive resources to the most important semantic information. Similarly, when the individual is engaged in tasks requiring high levels of attention (i.e., high workload), the attentional focus may not allow reapportioning of novel sensory information, resulting in missed information.

  An important part of control room operations is being able to detect changes to cues. Typically, salient changes in cues can pop-out of the visual scene and automatically capture one's attention. However, a number of factors can intervene to make change detection difficult. Inattentional blindness describes such a failure. It results when a person fails to detect a meaningful cue in the environment, such as when first gazing at a control board, even when the cue is salient enough. The factors leading to inattentional blindness include not paying attention (e.g., attention is focused on something else), perceptual overload, or memory overload. A phenomenon related to inattentional blindness is change blindness, pursued as a technique to study inattentional blindness. In change blindness, a person will fail to notice that a key cue has changed. Typically, this occurs during a visual saccade, in which the person briefly averts his or her gaze to look at another cue. Upon return to the original cue, the person fails to notice a change because his or her attention was away from the change when it occurred.
- *Expectation.* How operators perceive their environment is subject to certain expectancies and biases. Experience primes the operators to expect certain cues in the environment. In

most circumstances, specific cues are the correct ones, and the result is that such cues are reinforced for greater reliance in the future. However, cues can be deceiving, and operators may come to over-rely on particular cues while missing important contradictory cues needed for proper situation assessment. Perceptual biases result when operators over-rely on specific cues to the detriment of proper perception.

- *Working Memory.* Working memory represents memory held for a very brief period. Such memory is transitory and is constantly refreshed by new sensory information. Working memory represents the focus of attention. As information in working memory is processed, it interacts more directly with long-term memory stores. Information that is not processed or rehearsed in working memory is lost as it is refreshed with new sensory information. Working memory is considered to have a finite amount of information that can be attended to or processed at any given time. As more information is added to this, the ability to maintain items in working memory degrades. Information-rich circumstances may overload the working memory buffer and make it difficult for the operators to maintain information that is important to attend to and process. For example, if an operator is comparing a set point value with an actual value on a component, the ability of the operator to retain the two values in working memory can be greatly hampered if other, salient information from the control room is competing for working memory resources. Likewise, the operator may fail to take in new information into working memory if he or she is otherwise concentrating on specific items in working memory. Information in working memory must be segmented, and errors in segmenting are often a cause of incorrect retention in long-term memory (i.e., incorrect eyewitness testimony, because details of an event have been incorrectly segmented and missing information has been filled in).

There is clearly a degree of interaction between these cognitive mechanisms. For example, perceptual expectations in the form of biases may exacerbate change blindness, or working memory overload can affect attention allocation. Table 3-1 provides a list of the key literature identified for each cognitive mechanism discussed in this section. The specific operator performance effects of these categories are discussed in terms of the proximate causes further below. The literature sources identified in Table 3-1 are referenced at the end of this chapter for further reading in Appendix A-1.

3.3 Proximate Causes for Detecting and Noticing

By our classification scheme, proximate causes correspond to the failure of the major steps of the cognitive processes underlying the *Detecting and Noticing* function. From Section 3.2, we can summarize that the major steps for the function include attending for the pertinent information, perceiving the information, and processing the meaning of the information (through pattern recognition, working memory, etc). Therefore, we identified three proximate causes that correspond to the failure of each step:

- cues and information not perceived
- cues and information not attended to
- cues and information misperceived

Here cue or information refers to information in the environment that is meaningful to task performance. A cue is a stimulus in the environment. A salient cue serves as a direct trigger for a decision or action. Operator may fail to attend to important perceived information, for example. When an individual actively seeks or forages for meaningful stimuli, he or she is looking for cues. Likewise, when specific stimuli are broadcast, such as happens with an alarm, a cue is being pushed to the operator. A cue may take the form of a status indicator, an alarm, or other plant-related details that are meaningful in understanding the status of the plant. Cues may represent textual information such as the numbers on a gauge, the words on an annunciator, or even written procedures. Communication, whether verbal or nonverbal, between individuals can also serve as cues. Cues may also take the form of graphical (non-textual) displays, sounds such as auditory alerts, or even distinct smells (such as the smell of burning wire) that provide indications of the status of the plant.

Note that the definition of a cue in the present context goes beyond visual perception as described in the psychological literature. A cue is a feature of an object that helps the individual give form to the object. For example, depth perception is an important aspect of determining the relative size and position of objects. While some depth information comes from binocular disparity between the images captured between the two eyes, a significant amount of information can be determined by monocular cues. Monocular cues important for depth perception include the texture gradient (there is less detail in objects that are further away), interposition (an object that occludes another is closer), size (objects further away are smaller), linearity (parallel lines converge in the distance), and atmospheric cues (items in the distance tend to be "hazier"). Such features are valid in an ecological context but are seen to be of less importance in the carefully constrained world of the control room. Therefore, cues, as used in this report, refer to salient information about the plant status, such as trend displays, alarms, switch position, and other indicators that help the operator extract meaning about the plant.

A failure of perceiving meaningful cues results in a failure of the subsequent macrocognitive function of *Understanding and Sensemaking*. Here the meaningful cues include all the cues that are needed for understanding. For instance, if a level indicator is miscalibrated, the quality of a cue content is considered as low and the information is not perceived. In fact, if the operators notice that the indicator is not behaving as expected (by comparing with other cues) they might still infer the real level, that is, succeed in *Understanding and Sensemaking*. Therefore, the meaningful cues here include the indicator levels and its behavior or changes. Cues that exist but are not sensed or perceived are assumed not to trigger the operators to respond. The three proximate causes for *Detecting and Noticing* correspond to three processing steps in which cues and information are attended, correctly perceived, and propagated for subsequent *Understanding and Sensemaking*:

- *Cues and information not attended to.* The cues or information may be sensed and perceived but not attended to—in other words, the sensory-perceptual system acts as a filter, and this information is not propagated for further *Understanding and Sensemaking*. For example, during an incident at the plant, a control room operator may be confronted with an alarm flood. The raw sensory cues correspond to the individual alarms that are present, but the operator experiences sensory overload and cannot consciously perceive or process the large number of simultaneous cues. Or, the operator's attention may be focused on a particularly important part of plant recovery and choose not to respond to certain alarms until a more pressing issue is addressed.
- *Cues and information not perceived.* The cues or information may simply be missed, in which case they are not perceived. For example, a control room operator may not notice that an important indicator is trending downward.
- *Cues and information misperceived.* The cues or information may be sensed but misperceived. In other words, the sensed information is tagged with the incorrect meaning. For example, a control room operator may misread a pump as being on when, in fact, it is off.

The proximate causes can be explained in terms of cognitive mechanisms, as seen in Table 3-2. For example, cues can fail to be perceived because of low cue quality. Cues may fail to be attended to because of competing sensory information resulting in too many meaningful cues.

Cues may be misperceived because the cue content is too complex, requiring greater attentional resources than the operator has available at that time.

Table 3-2. Explanations and examples for the proximate causes of the Detecting and Noticing function.

Cognitive Mechanism	Example
Proximate cause: Cues/information not perceived	
[A1] Cue Content	*Cue salience is low and not detected. For example, the operator fails to detect "low" indication because scale of trend display makes subtle changes difficult to see.*
[A2] Vigilance in Monitoring	*Unable to maintain vigilance. For example, the operator is fatigued at the end of the night shift and has difficulty monitoring the plant. Alternatively, the operator must attend to several indications following a plant transient, thereby missing important cues.*
[A3] Attention	*Inattentional blindness—missing something that is in plain sight. For example, the operator may not perceive a plant indicator because it is not the focus of the operator's attention.*
[A4] Expectation	*Mismatch between expected and actual cues. The operator may not notice a plant indicator because he or she is not looking for it. This may occur because of the operator's mindset—if the operator has a particular hypothesis about the plant condition, he or she will look for information to confirm that hypothesis but may not equally look for information to disconfirm it.*
[A5] Working Memory	*Working memory capacity overload. If the operator attends to multiple alarms simultaneously, they may reach a state of information overload in which he or she is focused on a particular alarm panel and may miss additional alarms or indicators elsewhere in the control room.*
Proximate cause: Cues/information not attended to	
[B1] Cue Content	*Too many meaningful cues. For example, during a plant transient, the operator may have multiple simultaneous indications, such as an alarm flood involving hundreds of annunciators, and may not be able to attend to all indicators simultaneously. This mechanism focuses on the content and amount of the information.*
[B2] Vigilance in Monitoring	*Divided attention. For example, if the operator has to respond to multiple simultaneous alarms, the operator may reach a state of so-called information overload or alarm flood in which he or she is unable to attend to additional alarms. Also, the operator may be fatigued at end of night shift and have difficulty monitoring plant. Alternatively, the operator may be stressed, leading to shortened attentional focus. In [A2], operator simply misses important information. Here, the operator is aware of new cues like alarms but cannot attend to or address it.*
[B3] Attention	*Change blindness. For example, the operator may not notice a change in a plant indicator because the operator has missed the prior state of the indicator. In inattentional blindness [A3], the operator misses detecting a change in an indicator that is not his or her current focus. In contrast, change blindness occurs when the operator is focused on monitoring an indicator and simply fails to notice the change.*
[B4] Expectation	*Overreliance on primary indicator. The operator may be monitoring a particular plant indicator to the exclusion of other meaningful indicators that should or need to be monitored. This often occurs because of the operator's mindset—if the operator has a particular hypothesis about the plant condition, he or she will look for information to confirm that hypothesis and may discard information to disconfirm it.*
[B5] Working Memory	*Working memory capacity overflow. This mechanism focuses on the operator's limited working memory capacity. For example, if the operator has to respond to multiple simultaneous alarms, the operator may reach a state of so-called information overload or alarm flood in which he or she is focused on a particular alarm panel and may disregard additional alarms or indicators elsewhere in the control room. The distinction with [A5] involves the extent the operator is aware of information that must be attended to. In [A5], the operator misses information because his or her attention and working memory are elsewhere. Here, the operator is aware of the additional alarms, but simply cannot dedicate resources to processing additional alarms.*

Cognitive Mechanism	Example
Proximate cause: Cues/information misperceived	
[C1] Cue Content	*Cues are too complex. For example, during a plant transient, the operator may have multiple simultaneous indications that have multiple facets or dimensions, and may not be able to attend to all indicators simultaneously. The operator may arrive at the wrong conclusion about the plant state because he or she is unable to interpret the entire cue content.*
[C2] Attention	*Inattentional blindness—The technical term for the phenomenon of missing something that is in plain sight. For example, the operator may misperceive obvious plant information because that information is not the focus of the operator's attention. In this case, the operator may fail to integrate important information that would otherwise be obvious (e.g., changing trends, because the operator is focused on understanding different information). The distinction between [A3] and here deals with how inattentional blindness manifests. The operator may simply not perceive changed but important information in [A3], whereas here they may misinterpret it.*
[C3] Expectation	*Mismatch between expected and actual cues. The operator may be monitoring a particular plant indicator to the exclusion of other meaningful indicators that should or need to be monitored, leading to a misperception of a cue about plant status. This may occur because of the operator's mindset—if the operator has a particular hypothesis about the plant condition, he or she will look for information to confirm that hypothesis and may discard or miss information to disconfirm it.*
[C4] Working Memory	*Memory segmenting error. Information may be parsed or processed incorrectly, leading to a misperception of the plant state. This can occur especially in response to high task load or when the operator is distracted. Based on his or her expectations for the progression of a plant transient, the operator may fill in missing or expected information, leading to the wrong perception.*

3.4 Performance Influencing Factors impacting *Detecting and Noticing*

Cognitive mechanisms are influenced by contextual factors that arise from human interactions with the work environment, as well as the nature of the tasks being performed. Appendix A.1 provides summaries of the relationships between the cognitive mechanisms and performance influencing factors (PIFs) based upon the literature review and authors' inferences. The tables link PIFs and mechanisms for each proximate cause. Selection of appropriate PIFs for a given human failure event (HFE) has been a source of confusion in many human reliability analysis (HRA) methods. The cognitive mechanisms help to delineate the correct PIFs for proximate causes. This delineation becomes especially important in HRA quantification, where different PIFs may lead to different human error probabilities for the same proximate causes. Accounting for the cognitive mechanisms provides the scientific basis for linking the correct PIFs with the proximate causes.

Note that PIFs rarely offer a simple binary (yes/no) effect on triggering proximate causes. The effect of context in triggering degraded performance is not an all-or-nothing effect. Rather, as the contextual factors increase, PIFs serve to drive up the magnitude of the degraded performance. Where sufficient evidence exists in the psychological literature, the cognitive mechanisms described in Appendix A.1 provide justification to account for the effect of the PIFs on the proximate causes.

Much of psychological literature reports inferential statistical results when reporting the results used to test a hypothesis (e.g., F-values for an analysis of variance and p-values for significance testing). In many cases, the inferential statistical results will be presented in an article, but the underlying descriptive statistical results (e.g., mean, standard deviation, or effect size) remain unreported and are simply depicted in a figure. For the purposes of determining the effect of a reported PIF on performance, it is particularly useful to have descriptive statistics that might, for example, reveal that a particular PIF decreased performance by 20 percent. Instead, the exact effect is not reported, making it difficult to extract the precise relationship between the PIF and performance. In such cases, it is necessary simply to report that a particular PIF caused a statistically significant difference in performance. Appendix A.1 lists descriptive statistics when they are reported in the source articles; otherwise, the relationship between a PIF and performance is discussed in general terms as can be derived from the articles.

The psychological literature does not typically refer to its subject matter using the term used in the present document—PIFs. An article may, for example, report results of performance of subjects using different visual display technologies and display design techniques. In this literature review, we may use these results to provide evidence about a 'PIF' pertaining to the human system interface and its effect on human performance. The literature review is thus outcome oriented; that is, studies have been reviewed with the intent of extracting insights about the relationships between the phenomena or subject matter of interest (e.g., display design technology) and the outcome of interest to HRA (e.g., the potential for display design technologies to influence the kinds and likelihood of human errors).

The tables in Appendix A.1 provide a crosswalk between:

- Proximate causes for *Detecting and Noticing*
- Categories of cognitive mechanisms that explain the proximate causes
- Example explanations of the cognitive processes involved in the mechanisms
- PIFs associated with those proximate causes.

The tables are further summarized graphically in cognitive framework diagrams in Appendix B.1. The reader may use these tables and diagrams to determine plausible relations between the proximate causes and PIFs. The value of using the mechanisms becomes apparent in this context, because most proximate causes can be explained through multiple cognitive processes. Without consideration of the cognitive mechanisms presented here, the selection of the most appropriate PIFs can be extremely subjective. The mechanisms account for why a particular PIF is the best fit. Moreover, different PIFs may have different underlying error rates. In other words, the same proximate cause may have different human error probabilities (HEPs) depending on the cognitive processes involved. Understanding the underlying cognitive mechanism is therefore important not only for identifying the most relevant PIFs but also for calculating the correct HEP.

Note that the table provides separate paths for different types of analyses. When performing an analysis for which the proximate causes have been identified, it is appropriate to trace from left to right through the table, starting with the proximate causes and selecting the most appropriate PIFs based on the cognitive mechanism. However, in a prospective analysis, such as when attempting to anticipate potential proximate causes that could happen, the analysis should be performed from right to left, first identifying realistic PIFs and then tracing through the cognitive mechanisms to determine the most likely proximate causes. Alternately, the analyst may consider the mechanism at play for particular operator tasks and use this as the basis for using the table.

3.5 Summary

This chapter summarized the psychological research literature applicable to monitoring and acquiring information in nuclear power plant (NPP) control rooms. This chapter introduced three proximate causes that contribute to the failure of the function and explained the underlying cognitive mechanisms. Finally, this chapter highlighted the various contexts in the form of PIFs that may trigger failures in the cognitive mechanisms. Using this chapter in conjunction with the supplemental information in Appendix A.1 allows the analyst to use insights from psychological literature to complete an accurate and scientifically grounded human reliability analysis related to *Detecting and Noticing*.

Notice that the scope of the literature review was limited to those relevant to activities in NPP control rooms in internal, at-power events. The assumptions made for the scope include that (1) operators always know what to monitor/detect, per their training and procedures, (2) the cue/information to be detected has no uncertainty, and (3) the information is effortlessly used for the next cognitive function, *Understanding and Sensemaking.* For scenarios beyond these assumptions, additional mechanisms and proximate causes may be needed to provide a full coverage of the explanation to the failure.

4. UNDERSTANDING AND SENSEMAKING

4.1 Introduction

Understanding and Sensemaking refers to the process of associating the meaning of the various pieces of information with one's mental models to generate the understanding of the situation in the scenario context. It involves models and processes such as sensemaking, situation awareness (SA), interpretation of pieces of information, and integrating multiple pieces of information together with knowledge into a coherent understanding. This chapter focuses on elucidating the cognitive processes of how people make sense of their environment. We reviewed neurocognitive and psychological experiments and models for how humans understand their environment. This chapter first introduces *Understanding and Sensemaking* as one of the macrocognitive functions; the chapter then presents an overview, at a very high level, of the basic processes involved in making sense of a situation, followed by the description of several influential models of how humans achieve *Understanding and Sensemaking*. Subsequently, the chapter reviews and categorizes a large body of literature on how performance influencing factors (PIFs) may affect sensemaking. Finally, the authors applied the mechanisms reviewed in this chapter to establish links between PIFs and proximate causes to provide understanding of how PIFs affect likelihood of human errors associated with *Understanding and Sensemaking*. The details of the review are summarized in Appendices A and B.

4.1.1 Overview of the *Understanding and Sensemaking* Function

The function of *Understanding and Sensemaking* encompasses the cognitive activities of understanding and making sense of the information that a person has perceived. This ranges from the automatic, unconscious comprehension of words, for example, to the very conscious and effortful thinking, integration of information and diagnosis of a situation. The same psychological processes are involved across the spectrum, but the level of automaticity varies—the immediate, unconscious recognition of information that occurs in perception is automatic, whereas deliberate, conscious understanding of situations has much less automatic processing. Cognitive activity is not one or the other, conscious or automatic, but rather a blending of both, with varying degrees of conscious or unconscious processing depending on the situation (Klein, Phillips, Rall, & Peluso, 2007).

As discussed in Chapters 2 and 3, the boundary between *Detecting and Noticing* function and *Understanding and Sensemaking* function is blurry, as human cognition is a continuous, non-linear process. An analogy from the reading comprehension literature may help distinguish between perception, understanding, and sensemaking. Perception that occurs in the *Detecting and Noticing* function is comparable to recognizing a familiar word—one does not piece together the letters to know the word; the word is simply recognized as a whole (Durso, Rawson, & Girotto, 2007). This process is immediate and automatic. Understanding the meaning of the sentence is comparable to understanding the context-specific meaning of information extracted from the perceptual input. This is less automatic and requires attention, but still does not require extensive effort to process. Integrating the information from a passage of text with word knowledge to form a richer understanding of the text is comparable to integrating information from a situation with knowledge to diagnose the event under way (Durso, et al., 2007). It is a deliberate effort to understand the environment.

To further clarify the difference between *Detecting and Noticing* and *Understanding and Sensemaking*, it is possible to describe *Detecting and Noticing* as involving assigning basic meaning to a stimulus that is not context dependent, but *Understanding and Sensemaking* involves comprehending what the information means in the context of the present situation. For example, identifying an alarm indicator as lit occurs in *Detecting and Noticing*, but assigning the context-specific meaning of failure of a piece of equipment occurs in *Sensemaking*. Another way to differentiate between *Detecting and Noticing* and *Sensemaking* is to consider whether the application of meaning to stimuli is conscious. In perception, a person imbues stimuli with meaning in a largely automatic, unconscious manner. However, in *Understanding and Sensemaking*, applying a meaning to a red light in the context of the situation is conscious and effortful, and people are aware of their thinking process.

To map this analogy to the macrocognitive functions, perception (as in recognizing a word, or as in recognizing an alarm) falls into the *Detecting and Noticing* function. When a person applies a context-specific meaning (such as understanding a sentence, or understanding that an alarm means a particular piece of equipment is malfunctioning) and performs deeper integration with knowledge (such as diagnosing an event), this falls into *Understanding and Sensemaking*. To differentiate between these ends of the spectrum, in this report, we refer to comprehending the context-specific meaning of perceived information as *Understanding*, whereas *Sensemaking* is referred to as the process of integrating the understanding of the pieces of information into a cohesive story or big picture to make sense of the situation based on knowledge and experience.

4.1.2 *Understanding and Sensemaking* with Procedures in the NPP Domain

Sensemaking serves a number purposes or activities beyond simply comprehending stimuli. Klein et al. (2007) list eight purposes of sensemaking:

- Detecting problems (e.g., to determine if a pattern is worth worrying about and monitoring more closely)
- Using clues to learn more about the situation
- Forming explanations
- Using anticipatory thinking to prevent problems
- Projecting future states (e.g., to prepare for them, or, as in Naturalistic Decisionmaking, visualizing the outcome of a potential decision)
- Finding the levers (e.g., to figure out how to think and act in a situation, or to figure out what strategy to employ)
- Seeing relationships (e.g., as when we use a map to understand where we are going)
- Identifying problems (e.g., describing problems in a manner that leads to finding a solution)

All of these purposes are involved in operators' situational assessment in nuclear power plant (NPP) operations. In NPPs, operations are dictated by procedures. Control room operators have detailed procedures for normal, abnormal, and emergency operations. Field operators have procedures for the testing and operation of equipment on the plant floor. Technicians and maintenance personnel have procedures or step-by-step work orders for their maintenance tasks, detailing the work that is to be done. There are also procedures that instruct operators on how to use the operating procedures.

Control room procedures, particularly abnormal and emergency procedures, are designed to be diagnostic and symptom oriented. They are designed to aid operators in diagnosing events, help them understand the situation, and assist them in determining the appropriate course of action to respond to the situation. Utilities design their procedures to reduce the cognitive burden on operators and prevent them from being forced to rely primarily or solely on their knowledge and experience to respond to a plant upset. This is important, as operating experience and research has shown that errors occur more frequently when people are engaged in knowledge-based activity (i.e., they are relying solely on their knowledge and experience, without any rules to guide them) than when people are engaged in rule-based behavior (i.e., people are making decisions with the aid of rules or procedures) (Reason, 1990).

Nuclear power plant operators are qualified and licensed to operate the reactor and associated systems in the plant, yet regulations and plant policies tightly constrain operators to follow emergency procedures in responding to an event. Given this, one may ask why *Understanding and Sensemaking* is still a concern for human reliability analysis (HRA) and this research effort. If the procedures do all the thinking for the operators, then why should we be interested in how operators think?

Two important points provide an answer to this question. First, research with NPP operators has shown that even when they are following procedures in response to an event, operators are still engaging in diagnostic or sensemaking activity. Operators "think ahead of the procedures." Operators use the procedures both as a check to ensure that they meet all critical safety functions and regulatory requirements (Roth, 1997), and as a guide to help them develop their understanding of the event. They anticipate how the event is going to unfold based on their current knowledge, they develop dynamic situation assessments that provide explanations for the symptoms they are observing and identify expectations for additional symptoms they should see if their explanation is correct. If their expectations are violated, they seek additional or alternative factors that can provide an explanation for the plant behavior (Roth, 1997; Vicente, 2007; Vicente, Mumaw, & Roth, 2004; Vicente, Roth, & Mumaw, 2001). This all happens in addition to and parallel to following procedures. Second, there may be instances where the procedures do not match the situation well, and operators will have to engage in sensemaking and diagnosis without the help of procedures.

Operating experience has demonstrated this to be the case. There have been a number of incidents at various NPPs that challenged operators because their procedures did not work for the situation. For example, in an event at the Crystal River 3 NPP (Meyer, 1992), a pressurizer spray valve stuck open during a power increase following a shutdown, causing a slow depressurization. The indication for this valve in the control room showed incorrectly that it was closed. Operators perceived plant behavior as inexplicable, as all they could see was evidence of a depressurization with no indications of problems with the pressurizer or any other reason to explain it. This was primarily a problem with the indication, but the fact that their operating procedures did not help them determine the cause of the depressurization or prompt them to verify that all relevant spray valves were closed compounded the difficulty of the event. Without procedures to guide them, operators did not understand the nature of the situation and made several inappropriate knowledge-based decisions, including increasing power in an attempt to increase pressure and later, after the reactor had automatically tripped, temporarily bypassing engineered safety features. Eventually, a senior shift superintendent made a knowledge-based decision to close the pressurizer spray line isolation valve based on his understanding of the possible causes of reactor coolant system (RCS) pressure leaks, which terminated the leak. As this example shows, procedures do not always provide appropriate guidance for the situation, and operators consequently have to use their knowledge and experience to respond to the event.

Sensemaking does not stop merely because operators are working from procedures. Therefore, for the *Understanding and Sensemaking* function, procedures can be viewed as a source of information, or data, and as an influence on the selection or construction of a mental model. Procedures can greatly reduce the cognitive burden on operators to figure things out when they are well suited to the situation at hand. Procedures may also act as cues or triggers that allow operators faster and easier access to the knowledge they already have that is most pertinent to the situation. Sensemaking activities continue regardless.

Given the discussion above, we made the following assumptions about *Understanding and Sensemaking* in NPP control rooms for internal, at-power events: (1) Operators have mental models of the scenarios, (2) operators have procedures to guide and verify their understanding of the scenarios; and (3) operators' experience and procedures are adequate for them to make a full assessment of plant situations. These assumptions set forth the scope of the literature review for the function.

A High-Level Overview of the Cognitive Mechanisms of *Understanding and Sensemaking*

When reviewing the various models for how humans understand their environment, it is possible to generalize at a very high level the basic processes involved in making sense of a situation (see Figure 4-1). The human sensory systems perceive information from the external world, subject to the various influences that can affect perception as discussed in Chapter 3. The process of perception applies initial, non-context specific meaning, and this new information (i.e., "data" or "percept/perception") is integrated with prior information stored in long-term memory to interpret and make sense of the information; the integration occurs in working memory. These basic processes are dynamic and iterative. At each of these stages, certain PIFs can affect the underlying cognitive processes.

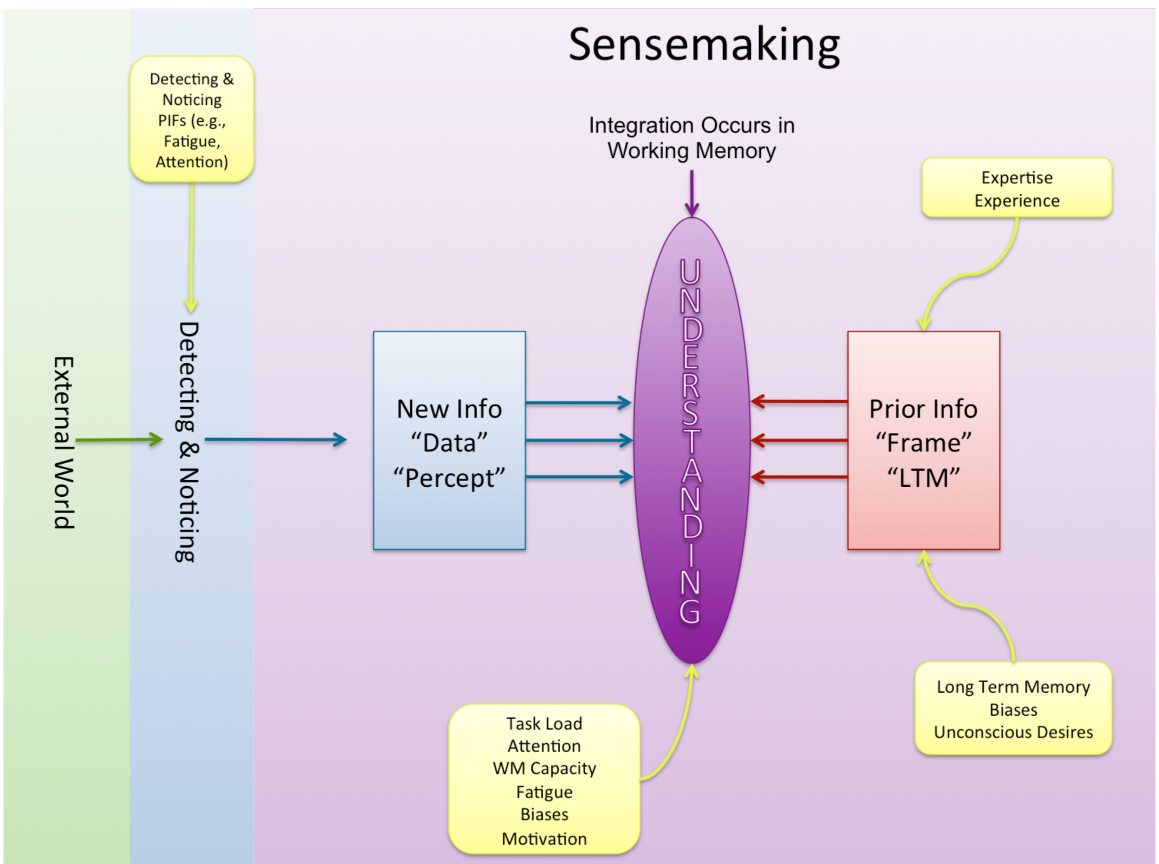

Figure 4-1. High-level overview of sensemaking.

The value of such a high-level overview is two-fold. First, it indicates the process required for sensemaking. Sensemaking requires that:

- the information stored in working memory be processed for understanding;
- an appropriate, effective frame is retrieved;
- the information and frame is correctly and reliably integrated; and
- the integration process is iterated and dynamically updated until the situation makes sense.

Second, the overview indicates points within the sensemaking process where failures can occur.

- The information coming into the sensemaking process may be inaccurate due to:
    - problems with the quality, accuracy, or availability of the information itself, external to the human perceptual process;
    - failures or errors in perception; or
    - decision errors about to which information to attend.
- There may be a problem with the existing knowledge that the new information is being integrated with, as when a person uses an incorrect mental model with which to interpret the information.
- The integration of new information with prior information itself can produce incorrect understanding. Failures can also occur if the integration process is not adequately iterated to achieve the correct understanding, or the process is not updated with dynamic evolving information.

Moving deeper from this high-level overview, research in macrocognition has developed several models of sensemaking that describe the dynamic processes in greater detail. These models are founded on common cognitive mechanisms yet they often focus on different aspects of *Understanding and Sensemaking*, therefore they are typically complementary to each other although they may appear different. To make it easier to understand the commonalities and differences among models, we first summarize the basic concepts and terminologies that are frequently used in the models.

- *Data/information.* What one perceives from the external world. Yet, given that *Understanding and Sensemaking* iterate with perception, the data and information entering the understanding process may have already represented the integration of both the perceived external world and the individual's initial understanding of what were perceived.
- *Long-term memory (LTM).* Knowledge and experience stored in the brain that can be retrieved for use.
- *Working memory (WM).* A process or a mechanism that maintains pieces of information online for immediate use and binds pieces of information together.
- *Mental model.* This term has been used in the literature with different meanings. Sometimes a mental model is referred to as a static representation of something stored and pulled out of long-term memory (e.g., a mental model of how a plant works). The term is also used to mean something that is 'constructed' dynamically to explain the current situation (e.g., there are currently two malfunctions in the plant – one explains why the steam generator (SG) level is increasing and one explains why I have radiation in an auxiliary building). In this report, we refer to a mental model as the static representation.

- *Frame/framing.* The concept of "frame" was introduced by Klein, et al. (2007). A frame encompasses the concepts of a mental representation, a mental model, a story, a map, a schema, a script, or a plan, and serves as a structure for explaining the data and guiding the search for more data. Yet, the concept also has two meanings in the literature. Some use the term "frame" as something static that is pulled out of long-term memory and 'instantiated'. Others used the term "frame" to refer something more active that is 'constructed' to account for the existing evidence—to make sense of the evidence. In this report, we use the term "frame" for the dynamically constructed representation of a person's current understanding of a situation. However, the initial frame in the sensemaking process could be the same as the static, instantiated representation of data stored in the long-term memory. Subsequently, the term "framing" is used to refer the process of constructing a frame. Klein et al. (2007) refer to sensemaking as a process of framing and reframing.
- *Situation awareness.* Endsley developed the situation awareness theory to explain human cognition, where situation awareness is the mental representation derived through a conscious deliberative process to form an understanding of what is going on. It is also often a highly automatic process of situation recognition, using a schema of prototypical situations that is dynamic and ongoing. On the other hand, Endsley believed that sensemaking is characterized as primarily of the conscious deliberative type, and therefore situation awareness encompasses a broader understanding of what is going on than sensemaking does.
- *Situation model.* O'Hara et al., 2008 used the term "situation model" to refer to the active knowledge representation that is constructed dynamically and used to explain symptoms and derive predictions and projections in a particular situation (as opposed to a mental model which was reserved for long-term memory representations). This term is similar to the "frame" concept proposed by Klein et al. (2007).

4.1.3 An Overview of the Dynamic Data/Frame Theory of Sensemaking

Gary Klein and his associates have put forth a model of how people in real-world settings make sense of their environment that they term "a data/frame theory of sensemaking" (Klein, Moon, & Hoffman, 2006; Klein, et al., 2007). Weick (1995) introduced the concept of sensemaking as a primary cognitive function that people must carry out in a variety of natural settings. Sensemaking allows people to question what is known, evaluate what is conjectured, hypothesize and diagnose, and integrate facts with theory (Klein, et al., 2007). Klein et al. have developed a model that is an extension of Neisser's (1967) perceptual cycle theory, in which a person's sampling of the environment updates their cognitive map of the environment, which in turn directs further exploration. Klein et al. assert that sensemaking is a cyclical process that starts when a person or group of people recognize that their current understanding of things is inadequate. This typically happens when people are surprised or when something unexpected occurs. Sensemaking involves not only understanding the meaning of pieces of information, but more importantly, putting together pieces of information to form a complete understanding of the situation. Sensemaking can therefore be defined as a deliberate effort to understand events or situations (Klein, et al., 2007). Figure 4-2 provides a high-level overview of the data/frame theory of sensemaking.

The data/frame theory of sensemaking posits that information coming into the sensemaking process is data (depicted in Figure 4-2 as small green circles of differing shapes and sizes). This data is integrated with an existing frame, which is the current understanding that links data with other elements to explain and describe the relationship of the data with other entities. Figure 4-2 depicts frames as the blue discs into which the green bits of data fit. A frame encompasses the concepts of a mental representation, a mental model, a story, a map, a schema, a script, or a plan, and serves as a structure for explaining the data and guiding the search for more data (Klein, et al., 2007). The data identify or construct the frame, and the frame determines the data to which the person attends. Neither the data nor the frame comes first; rather, it is a constant process of moving back and forth from data to frame. This dynamic aspect is the central theme of the model.

Klein et al. (2007) explain further, "Sensemaking is a process of framing and reframing, of fitting data into a frame that helps us filter and interpret the data while testing and improving the frame and cyclically moving forward to further adapt the frame. The purpose of a frame is to define the elements of the situation, describe the significance of these elements, describe their relationship to each other, filter out irrelevant messages, and highlight relevant messages. Frames can organize relationships that are spatial (maps), causal (stories and scenarios), temporal (stories and scenarios), or functional (scripts)" (p. 119). Section 4.2.1 discusses this model of sensemaking in more detail.

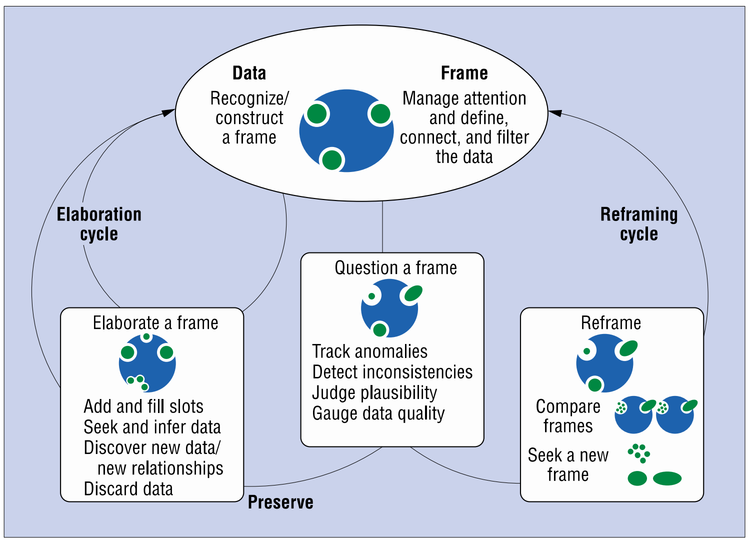

Figure 4-2. The sensemaking process (Klein, et al., 2006).

4.1.4 Working Memory and the Neurological Basis of Sensemaking

Integrating pieces of information in the brain requires working memory, which maintains pieces of information online and associates them. Working memory processes pieces of present information and combines them with the knowledge retrieved from long-term memory. It is limited in the amount of information it can handle at once, because of this people break up information into manageable chunks. Working memory has been referred to as short-term memory in the past because of limitations to how long information can stay active. Recent research has elaborated upon older short-term memory models. The Baddeley model of working memory (2000; 1974) is the model that has received support from psychological and neurophysiological experiments. Working memory has several subsystems or processing buffers that process different types of information: the visuospatial sketchpad handles visual and spatial information, and the phonological loop processes verbal and auditory information. Working memory interacts with long-term memory through the episodic buffer. The central executive controls and directs attention and the flow of information between these systems.

In reviewing the working memory literature over the last 20 years, there seem to be two camps of research when it comes to the limits of working memory. One group of research shows working memory with a limit of about seven to nine chunks of information, whereas other research shows that people have a limit of about four chunks of information that they can keep in working memory. We synthesized this research, and determined that working memory for actively processing information has a different limit than working memory for maintaining information in active consciousness. Working memory has a “maintenance buffer” that keeps active pieces of information that are not being immediately used. The maintenance buffer can hold between about seven to sixteen chunks of information. Information that is actively being used in more complex or effortful thinking is manipulated in a “processing buffer.” This processing buffer has a limit of four chunks of information, plus or minus one (Xing, 2007).

Taking a step back to see how information flows in and out of working memory allows one to see where working memory fits in the larger sensemaking process.

Figure 4-3 provides a high-level illustration of the psychological processes behind sensemaking, based on the neurological organization of the human brain. Again, a discussion of neural structures is too fine a level of detail for HRA purposes, but reviewing the functions that the neural structures perform is instructive to inform readers of the basic processes. Information enters working memory from the sensory systems and/or from long-term memory through the episodic buffer. This information can go into either the maintenance or active processing buffer. The processing buffer also receives input from other neural systems that are related to belief and intention. Information then can be transferred to long-term memory, or moved forward into the areas of the brain that handle decisionmaking. Decisionmaking also influences the information that is kept and processed in working memory.

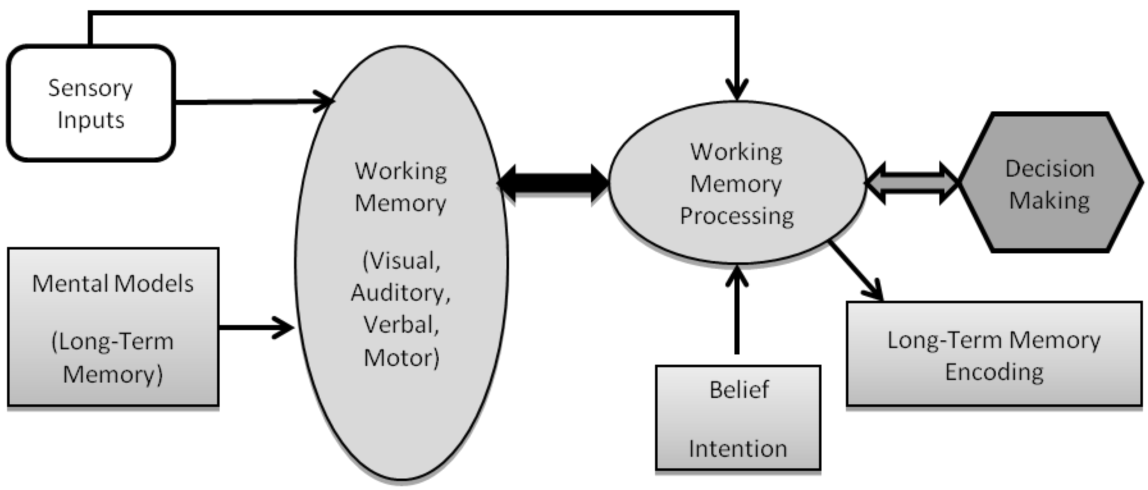

Figure 4-3. Cognitive processes behind sensemaking (Xing et al., 2011).

4.2 <u>Major Cognitive Models of Sensemaking</u>

There are a number of cognitive models related to *Understanding and Sensemaking*. We discuss four of them here. The criteria for selection include:

1. The model is detailed enough to explain how *Understanding and Sensemaking* works and fails.
2. The model focuses on sensemaking of the environment or situation, not on detailed step-by-step cognitive activities such as the ACT-R model (Adaptive Control of Thought—Rational; Anderson, 1993).
3. The model has gained recognition in the cognitive psychology community and has been applied to various applications.

Each of the four models discussed in this chapter explains the processes of *Understanding and Sensemaking*. However, they are each different in their perspective, focus, and intended applications. For example, Klein's model focuses on the dynamic processes of sensemaking, while Endsley's situation awareness model was intended to make the products of the internal processes of sensemaking observable and measurable. Together, these models present a more comprehensive description of sensemaking mechanisms; each model offers some unique perspective on human errors associated with sensemaking. Presented along with the description of each model is a discussion of its strengths and limitations.

The four models describe the psychological aspects of *Understanding and Sensemaking* without addressing the underlying neurocognitive basis for the psychological processes. One critical mechanism for *Understanding and Sensemaking* is working memory. The sensemaking processes described in the four models require working memory to bind or integrate related information together to form the elements of mental representation of the situation and to retain the presentation. Associated with working memory is attention. Attention is needed for execution of information binding and selection. Both working memory and attention have limitations in their resources, capacities, and timing. These limitations are root causes to many human errors. Therefore, following the description of the four psychological models, we also generalize the functionalities of working memory and attention in *Sensemaking* as well as their limitations.

4.2.1 Detailed Discussion of the Data/Frame Theory of Sensemaking

As overviewed previously in Section 4.1.3, the data/frame theory of sensemaking describes the process of how people dynamically compare and integrate incoming data with a frame to understand the situation. Frames are the key structural component to the data/frame theory of sensemaking. A frame is a mental representation, or the current understanding that links data with other elements to explain and describe the relationship of the data with other entities. Other research discusses concepts such as mental representations, situation assessment, mental pictures, mental models, mental maps, stories, schemas, scripts, if-then rules, expectations; the concept of frame encompasses all of these and any other related constructs (Klein, et al., 2007). A frame serves as a structure that explains the data in the environment and guides the search for more data (Klein, et al., 2007). Specifically, the person interprets all perceived information (data) in light of his or her frame, and the frame guides the person to seek out additional data and shapes how the person determines what information is relevant.

For example, an NPP operator has a mental model about the design of the plant, including the layout of the control and indication panels, relationships between the various systems and how they interact, the configuration of the various systems, and the nominal behavior of the plant when it is at power and when it is starting up or shutting down. This mental model of the system is a frame. When the operator starts a shift, she or he participates in a shift briefing in which she or he is informed about any ongoing work, any components or systems that are out for maintenance, etc. The operator then updates his or her frame of the system accordingly. Operators also have frames for the types of events that they are trained to handle. NPP operators must be able to pass training on a number of design-basis events, such as steam generator tube ruptures (SGTR), or a loss of coolant accident (LOCA). These events have certain associated symptoms, such as increasing steam generator level and secondary system radiation alarms for an SGTR event. Through training, operators create mental models (i.e., frames) for these events that pair symptoms with explanations. During an actual event at a plant, operators will compare the symptoms they are observing in the plant to the frames stored in their memory to help them diagnose the event. Operators may also integrate multiple frames, such as considering both the frame for the event in progress with the frame for the current system configuration.

The purposes of sensemaking (problem detection, forming explanations, projecting future states, finding relationships, etc.) imply complexity and a variety of human thinking as one strives to understand the environment. People are active interpreters and constructors of information, and people actively judge what data is relevant and deserves attention. Sensemaking involves more than just deriving inferences from perceived cues (Klein, et al., 2007). Sensemaking involves adductive reasoning, more so than deductive logic (Klein, et al., 2007; Lundberg, 2000). This means that people search for explanations that best account for the symptoms or data they are seeing, rather than looking for data to confirm the conclusion they already have, as they would with deductive logic. Once people have an understanding, they will often attempt to confirm it with the data, but until they have a diagnosis, they are searching for explanations for the data they have (Klein, et al., 2007; Lundberg, 2000).

Klein et al. present seven basic types of sensemaking that they have been able to distinguish in research to date, or seven types of activities that can occur in the sensemaking process, as depicted in Figure 4-4. These are not “stages” that occur in a linear fashion, but rather are types of sensemaking that can occur in the process, depending on the data and frame. It is important to note that there is no start or end in Figure 4-4; the process can start in any of the ovals in the diagram, and sensemaking can proceed through some or all of these activities in one situation, often more than once.

As in Figure 4-2, Figure 4-4 depicts data as the small, variously shaped green circles, and frames as the larger blue circles into which the data pieces fit. In each of the types of sensemaking activities, Klein et al. (2007) lists the ways that the frame drives data collection on the left of the circle, and lists the ways that the data affects the frame on the right of circle. Thus, within each type of sensemaking activity, the data and frame define and update one another, as depicted by the reciprocal arrows in the top oval (although not displayed, Klein et al. assert that the same reciprocal relationship between data and frame exists in each of the sub-types of sensemaking shown in the smaller ovals).

The basic data/frame match is an attempt to connect incoming data with a frame. In Figure 4-4, this is the large oval at the top of the diagram, in which the data fit neatly in the frame. The frame a person uses depends on the available information, the person’s goals, available gallery of frames, and other factors such as workload, fatigue, and motivation (Klein, et al., 2007). Klein et al. posit that the initial matching of data with frame may be automatic and pre-conscious, but overall the sensemaking process is volitional and conscious. Pattern matching can be unconscious or preconscious, whereas comparing different frames tends to be conscious and deliberate (Klein, et al., 2007).

As people continue to operate in the environment, they will elaborate and extend the frame they are using with the new information they learn about the situation. They will not seek to replace the frame if no surprises or unexpected circumstances arise (Klein, et al., 2007). In this type of sensemaking, neither the data nor the frame is rejected. As the person learns more information, his or her understanding gradually deepens and broadens. Figure 4-4 illustrates this with smaller, more finely detailed bits of data in the frame that represent the more nuanced understanding.

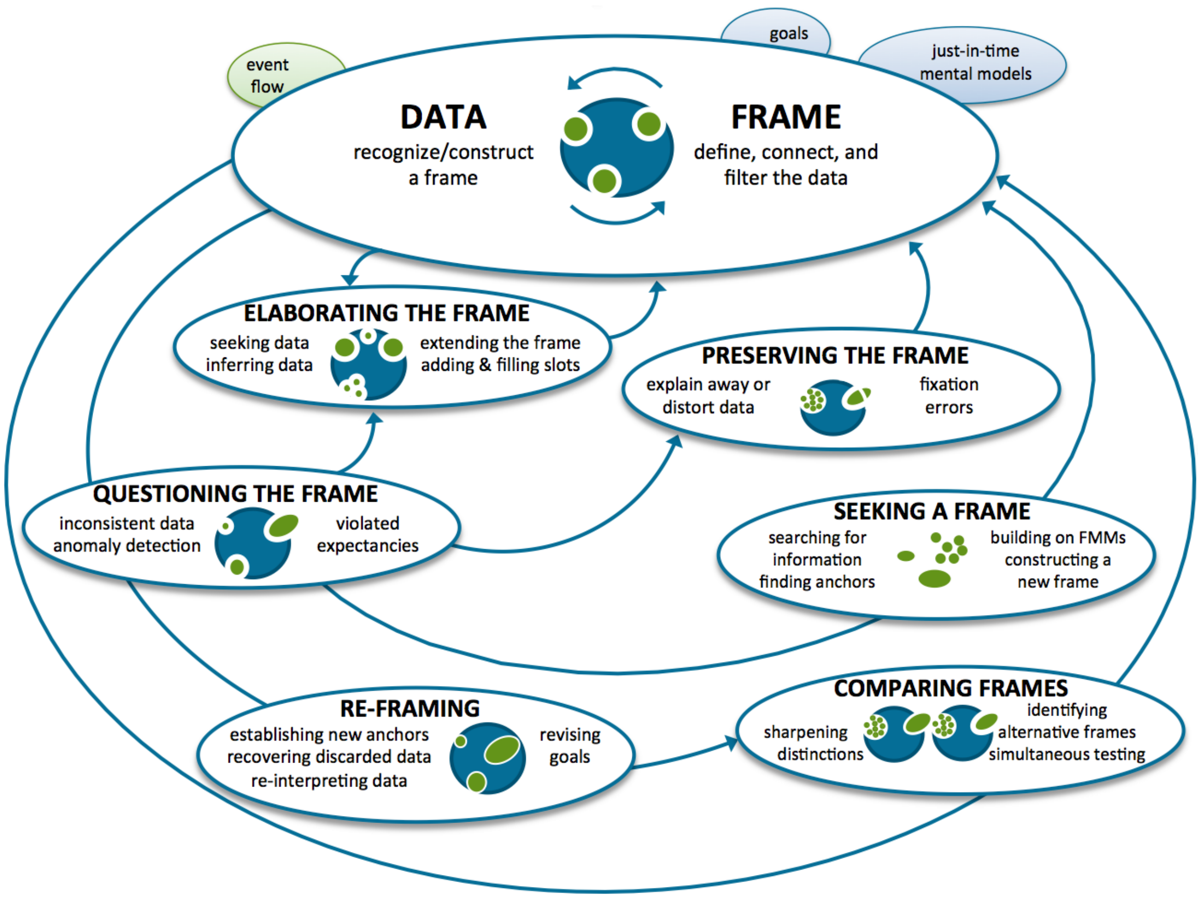

Figure 4-4. A more detailed view of the sensemaking process (Klein, et al., 2007).

However, when something unexpected happens or people are surprised, they begin the process of questioning the frame. Here, people consider data that are inconsistent with the frame in use (shown in Figure 4-4, “questioning the frame”, with a piece of data that does not fit in the frame). It may be the case that the frame is incorrect, the situation has changed, or the inconsistent data are inaccurate, but at this point all that is known is that there is a mismatch. The violation of the expectations provided by the frame leads people to question the accuracy of their current understanding or situation assessment (i.e., the frame) (Klein, et al., 2007).

Sometimes, when questioning the frame, people preserve the frame by discounting or dismissing the data that do not match the frame (depicted in Figure 4-4, “preserving the frame”, by the white line that cuts off the part of the data that does not fit in the frame as a metaphor for ignoring that part of the data). If the data are indeed inaccurate or unreliable, this is appropriate. This is also a potential mechanism for causing error, particularly if the data are indications that the current explanation (i.e., frame) is faulty. Dismissing, ignoring, or explaining away data can lead to problems such as routinizing deviance, accepting inappropriate amounts of risk, or entrenching “knowledge shields” that people use to defend frames in the face of contradictory evidence. These problems can cause fixation errors, wherein people maintain their current frame despite evidence that indicates the frame is incorrect (Klein, et al., 2007). This is a very important class of errors in the control room as showed by human performance simulations of control room operation.

Sometimes it is necessary to deliberately compare multiple frames to figure out what is happening in the situation. This may be the case when the data have more than one plausible explanation. Figure 4-4 depicts "comparing the frames" with two similar frames, with the only difference as the size of the slot for one of the pieces of data. Experts can sometimes evaluate up to three alternative frames simultaneously, as when doctors consider multiple diagnoses for a set of presenting symptoms, and deliberately select frames that allow them to sharpen the distinctions between the diagnoses that are most relevant. They will then search for data that allows them to determine which frame is correct. This approach can be referred to as using a "logical competitor set," in that the person will develop one or two logical competitors to the current frame and use the competitors as a means for identifying critical data that will allow the correct frame to be selected (Klein, et al., 2007).

Reframing occurs when people replace the operating frame with one that better explains the data (shown in Figure 4-4, "re-framing", with a frame in which the data now fit). This new frame then guides the search for data and cues. During reframing, people consider data elements they may have previously discarded so that formerly discrepant information now fits the frame. In this way, reframing sensemaking involves hindsight understanding (Klein, et al., 2007; Weick, 1995).

If people encounter data that make no sense whatsoever, or when they identify a frame as inadequate, people may seek a frame. Figure 4-4 illustrates "seeking a frame" as pieces of data without a frame. People may be able to reframe, as mentioned previously. If a suitable frame is not immediately available, people will have to search for a frame that works, or construct a new frame. This may involve looking for analogies, searching for more data to find anchors that can be used to construct a new frame, and assembling data elements as they build an explanation (Klein, et al., 2007).

All seven of these types of sensemaking activities can occur as people attempt to understand what is going on, and as people compare data with frames, they may move back and forth through the types of sensemaking. Errors made in any one point in the sensemaking process (such as inappropriately preserving a frame) can be recovered if the discrepancy between data and current explanation becomes so large that people have to acknowledge an incorrect frame and search for an accurate frame to replace it with.

In general, Klein's sensemaking model integrates and incorporates decades of research on human cognition. It provides explanation for how humans understand their world, and as such, it can serve as an important part of the cognitive psychological basis for HRA.

4.2.2 The Product of Sensemaking: Situation Awareness

Klein's sensemaking model provides a theoretical description of the sensemaking processes. On the other hand, Endsley's Situation Awareness (SA) model focuses on making those inner processes of sensemaking observable and measurable. The central theme of Endsley's SA model is to classify the momentary product of sensemaking, referred to as situation awareness, into three stages or levels: perception, comprehension, and projection. Associated with this model, Endsley also developed experimental techniques to measure one's SA during task performance. Because of the availability of this technique, SA has been the subject of numerous studies in applied, real-world situations for years. Therefore, SA research is highly relevant to identifying the cognitive mechanisms for error and the contributing factors that can lead to error.

Situation awareness is a term that has become popular in real-world settings and refers broadly to people "knowing what is going on." It is used to indicate people's dynamic understanding of events and situations, and the construct has been applied in many domains, including aviation, air traffic control, power plant operations, military operations, and more. One benefit of SA research is that it allows measurement of an internal process and provides insight into how those internal processes interact with the environment. Additionally, the SA literature provides information about the factors that influence performance.

There are three models of SA that are instructive for examining how sensemaking plays out in real-world settings: Endsley's model of SA, the functional model of orienting activity based on activity theory, and the perceptual cycle theory of SA. Each model is discussed below to identify the key insights into performance that the model provides.

4.2.2.1 Endsley's Model of Situation Awareness

Endsley's model of SA (Endsley, 1995) has received by far the most attention and research. Shown in Figure 4-5, Endsley's model is an information-processing model that describes SA as a product of mental processing (termed situation assessment) that consists of three levels. The first stage, Level 1, consists of perception of the status, attributes, dynamics, and other relevant aspects of objects and information in the task environment, which Endsley refers to collectively as "elements" (Endsley, 1995; Salmon et al., 2008). The information is merely perceived at this point; higher-level processing or comprehension has not yet occurred. Level 1 of Endsley's SA model corresponds to the *Detecting and Noticing* macrocognitive function used in this report; many of the mechanisms identified for *Detecting and Noticing* in Appendix A.1 are based on or drawn from Level 1 of Endsley's model.

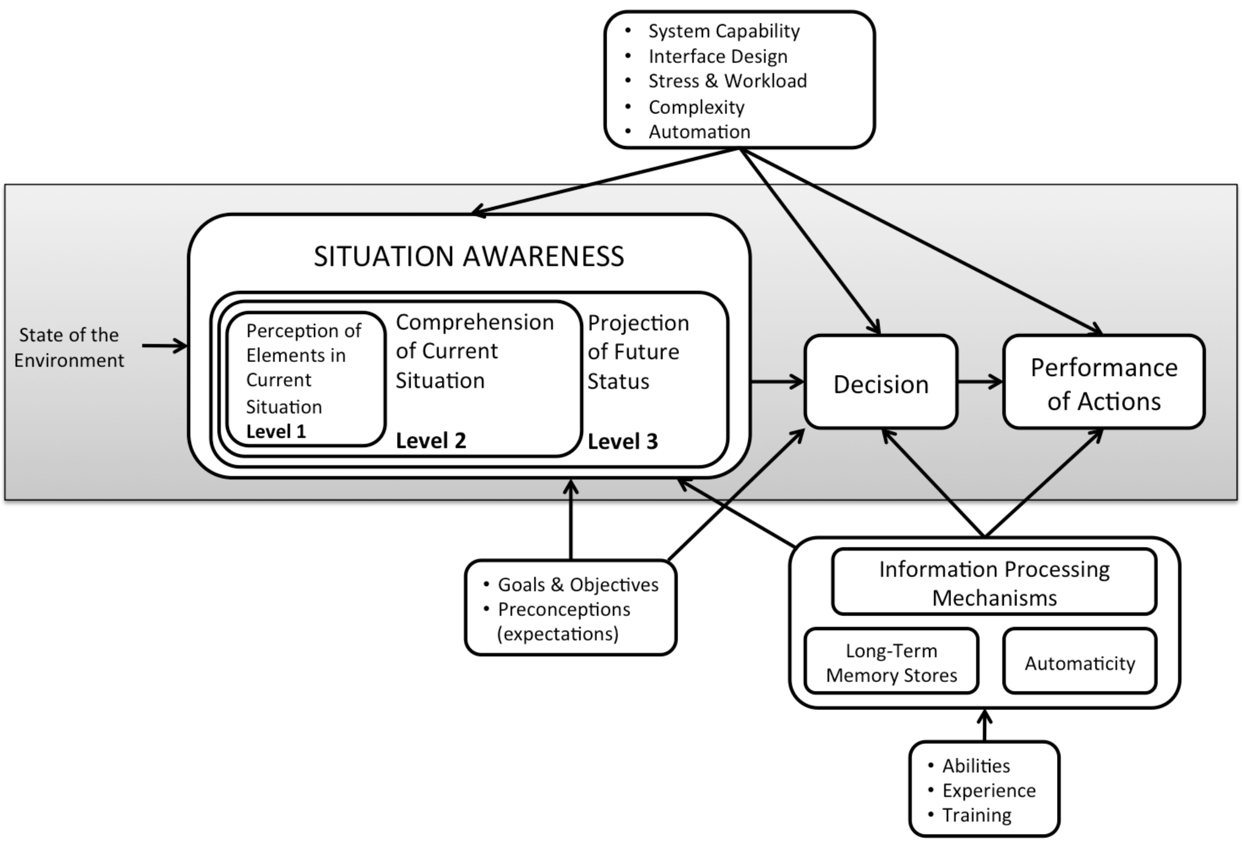

Figure 4-5. Endsley's model of situation awareness.

Level 2 and Level 3 SA correspond to the *Understanding and Sensemaking* macrocognitive function. Level 2 SA involves the comprehension of Level 1 information to understand the relation of the data to the situation (Endsley, 1995; Salmon, et al., 2008). This involves combining, interpreting, storing, integrating multiple pieces of information, and determining relevance of the data to the situation (Endsley, 2000). In Level 2 SA, the operator forms a holistic mental model or picture of what is going on, and attempts to understand objects and aspects of the situation in light of the larger mental picture (Endsley, 1995).

Level 3 SA involves projecting the current understanding of the situation into the future to mentally forecast the future state given currently available information (Endsley, 1995, 2000; Salmon, et al., 2008). This ability to project and anticipate is crucial to subsequent *Decisionmaking*. Level 3 SA is indicative of experience and marks operators who have the highest level of understanding of the situation (Endsley, 2000).

Each of these levels is a product: Level 1 SA is a product of perceptual processes, and Level 2 and Level 3 SA are products of mapping data from Level 1 SA to mental models that facilitate comprehension of current status and projection of future state (Endsley, 1995; Salmon, et al., 2008). Mental models are formed based on knowledge, training, and experience, and are used to direct attention to critical elements in the environment as well as integrating elements together into a coherent picture (Endsley, 1995; Salmon, et al., 2008).

Endsley refers to this process as SA, but it bears remarkable similarity to Klein's (Klein, et al., 2006) sensemaking model. It may be plausible that SA as Endsley describes it is the product of the sensemaking process as Klein et al. describe it.

The application of the SA Model in HRA

Endsley's model is generic and applicable to multiple domains, and the simplicity of the three levels lends itself to easy measurement and extension to training guidelines and system design (Salmon, et al., 2008). The model has also been extended to team SA (Prince & Salas, 2000).

One of the main strengths of Endsley's model is its immense popularity. It has been applied widely in a large number of domains, including but not limited to aircraft pilots, air traffic control, military operations, NASA missions, power plant operations, rail system operations, equipment maintenance, and medicine. This has produced a large body of research, vastly more than research on Klein et al.'s sensemaking model, much of which has elucidated factors that can affect SA, from system design, training, expertise, workload, complexity, stress, automaticity, goals, and individual differences, among others. This is very valuable for the present effort to provide a psychological basis for HRA, as these factors map well to the performance influencing factors examined in HRA and provide information regarding the nature of the effect of these factors on SA.

There are similarities and differences between the SA theory and Klein's framing theory for sensemaking. The framing theory focused on how people work to make sense of the information and situations they find themselves in, largely at the organizational level with respect to explaining organizational accidents or unusual events. In Endsley's view, sensemaking is basically "the process of forming level 2 SA from level 1 data through effortful processes of gathering and synthesizing information, using story building and mental models to find some representation that accounts for and explains the disparate data." (Endsley, 2004, p. 324). Framing theory focuses on forming reasons for past events and diagnosing the causative factors for observed faults; while situation awareness incorporates such assessments as a part of comprehension, it also focuses on understanding how such factors influence other aspects of the situation and projections of the future. Together, both theories provide a comprehensive picture of *Understanding and Sensemaking* and therefore serve as the cognitive basis for the function.

4.2.2.2 Perceptual Cycle Theory of Situation Awareness

Smith and Hancock (1995) take a holistic view of SA, defining it as "adaptive, externally directed consciousness" that is a "generative process of knowledge creation and informed action taking."

Consciousness is the part of an operator's knowledge-building behavior that the operator intentionally manipulates. Situation awareness generates behavior that is directed toward achieving a goal in a specific task environment (1995).

Smith and Hancock's perspective on SA is based on Neisser's (1967) perceptual cycle model. As such, this model has the closest resemblance to Klein's sensemaking model, which is also based on Neisser's perceptual cycle theory. The perceptual cycle theory posits that an agent and the environment continually interact to produce performance: the environment informs the agent, modifying knowledge, which directs the agent's activity in the environment. This in turn samples and potentially alters the environment, which informs and updates the agent's knowledge, and the cycle continues (Neisser, 1967; Smith & Hancock, 1995).

Smith and Hancock argue that the process of obtaining and maintaining SA centers on mental models that contain information about certain situations. These internal mental models facilitate the anticipation of events, direct an individual's attention to cues, and direct their course of action to ensure that the situation continues to conform to expectations as it evolves. Unexpected events prompt additional searches for more information, which then updates the operator's mental model (Salmon, et al., 2008; Smith & Hancock, 1995). Figure 4-6 shows the perceptual cycle model of SA.

The perceptual cycle approach to SA is expressly not merely a snapshot of the person's mental model. Rather, SA guides the process of updating knowledge (Smith & Hancock, 1995). In air traffic control, for example, controllers build mental pictures of the aircraft in their airspace. SA is not the picture, but instead the controller's SA builds the picture (Salmon, et al., 2008; Smith & Hancock, 1995). In this perspective, SA is both process and product. The model provides explanation for how the product—operator's knowledge—is produced by the perpetual cycle of knowledge directing action, sampling the environment, and updating knowledge (Salmon, et al., 2008; Smith & Hancock, 1995).

Adams, Tenney, and Pew (1995) elaborated on the concept of SA as both process and product, "As product, it is the state of the active schema—the conceptual frame or context that governs the selection and interpretation of events. As process, it is the state of the perceptual cycle at any given moment. As process and product, it is the cyclical resetting of each by the other" (p. 89).

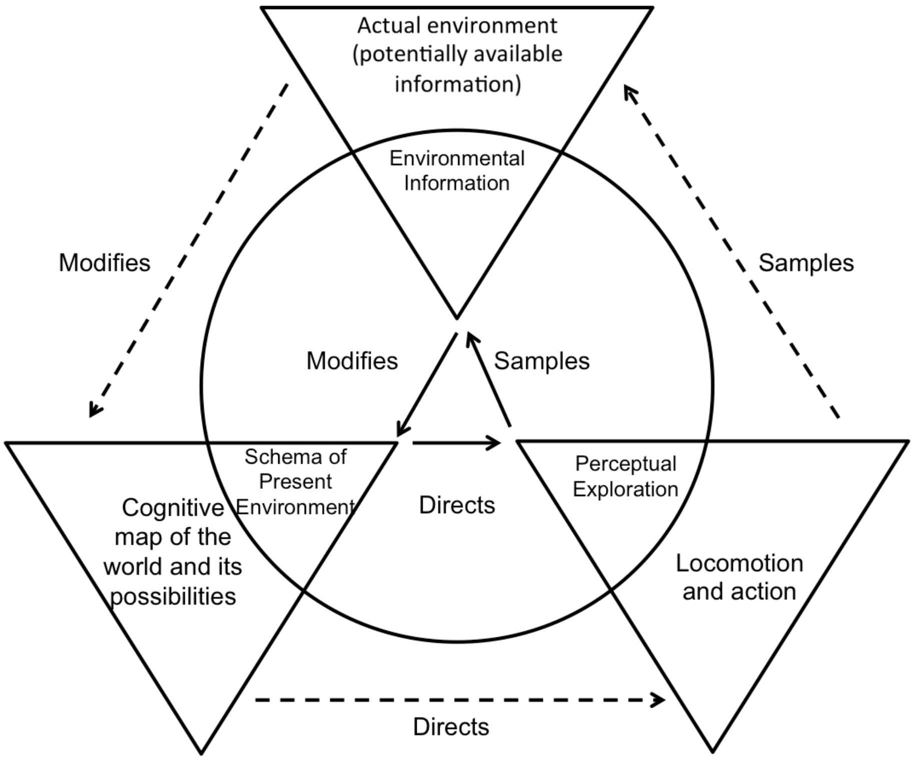

Figure 4-6. The Perceptual Cycle model of situation awareness (Salmon, et al., 2008; Smith & Hancock, 1995).

Strengths and Limitations of the Perceptual Cycle Model of Situation Awareness

A key strength of the perceptual cycle theory of SA is that it is a complete model, providing explanation for both the process and the product of the process. It is based on sound psychological theory (Neisser, 1967), and it showcases the dynamic, non-linear nature of SA (Salmon, et al., 2008). It explains how SA is dynamically obtained, maintained, and updated, and it explains anticipation, or as Endsley describes it, Level 3 SA (Adams, et al., 1995; Salmon, et al., 2008).

Despite the strength of this model, it has two major drawbacks. First, Endsley's model has essentially eclipsed the perceptual cycle model—there has been very little research conducted with this model, and as a result, there is nearly no information available to expand upon the model or identify factors that affect it. This may be due in part to the second major drawback: the nature of this model, its focus on dynamic process and product, makes measuring the construct as defined by the model very difficult (Salmon, et al., 2008). Without a way to measure SA based on the model, conducting research is not feasible.

The key insight from this model for the present purpose of supporting HRA, then, is that the internal mental models are the most important factor for success or failure of SA. The mental model establishes expectations and directs actions in the environment, including which information to sample. This information then integrates with or updates the mental model. If the mental model is not complete or is inaccurate, the person could be looking for information that is objectively unimportant. The model does not describe a way for a person to correct the mental model; in this aspect, Klein's Sensemaking model is more complete.

4.2.2.3 The Functional Model of Orienting Activity (Activity Theory)

The Functional Model of Orienting Activity is a model related to the concept of SA based on Activity Theory (AT), a psychological paradigm developed for the study of work behavior (e.g., Leont'ev, 1977; Platanov, 1982; Vygotsky, 1960, 1978). It assumes a unique human psychology defined by goal-directed behavior (Bedny, Seglin, & Meister, 2000). Activity Theory is an entire psychological paradigm, and as such is too broad to discuss in entirety in this review of sensemaking-related literature. For the purposes of this project, it is more appropriate to provide an overview of the relevant assumptions underpinning the theory and discuss in more detail the application of AT to the concept of SA.

As stated previously, AT assumes that human cognition is goal-directed. Workers go about achieving their goals through a process of psychological reflection—they build an internal model of the situation that is an image, a reflection of reality as they have understood it (Bedny, Karwowski, & Jeng, 2004; Bedny & Meister, 1999; Bedny, et al., 2000). Psychological reflection is a dynamic activity—reflection allows the person to capture changes in the situation and look at it from different perspectives (Bedny, et al., 2004). This allows the mental representation built from the reflection to incorporate multi-faceted sets of features, the nature of the relationships between aspects of the situation, and changes in these over time (Bedny, et al., 2004).

Goals are held as mental images of the ideal or desired state, called an image-goal; the projected outcome of activity is also represented internally as an image (Bedny & Meister, 1999). AT allows for unconscious motives, but states clearly that goals are always conscious (Bedny, et al., 2000). The basic structural components of activity are the image-goal, motives that direct individuals toward the goal, and a system of actions that allow the person to achieve the goal (Bedny & Meister, 1999). Individuals may subjectively form internal goals for the situation, and objectively given goals are still subject to interpretation and acceptance or rejection by the person. Differences between the desired goal and current state are evaluated based on personal significance, which influences how motivated a person is to achieve the goal (Bedny & Meister, 1999).

According to AT, activity consists of three components or stages: orientational, executive, and evaluative. In the orientational stage, people develop a subjective mental model of reality and a dynamic picture of the world that provides a coherent explanation of reality (Bedny & Meister, 1999). This stage can include both mental and external exploration of the world. The orientational stage of AT appears to be a composite of the macrocognitive functions of *Detecting and Noticing* and *Understanding and Sensemaking*.

The executive stage of AT includes decisionmaking and performance of actions (Bedny & Meister, 1999), which maps to the macrocognitive functions of *Decisionmaking* and *Action*. In the evaluative stage, the person assesses the result of the action, which leads to corrective actions. In the macrocognitive model used in the present project, this maps back to *Detecting and Noticing* and *Understanding and Sensemaking*. The remainder of this section will be devoted to the orientational stage, which is a basic component of operator performance, as it involves situation assessment and comprehension, understanding of the current situation, and anticipation of future status (Bedny & Meister, 1999). In this kind of activity, the concept of SA is critical, and the orientational stage has the most relevance for sensemaking. Figure 4-7 shows how individuals accomplish the task of comprehending the meaning of the situation (called gnostic activity) through dynamic reflection of the situation (Bedny & Meister, 1999).

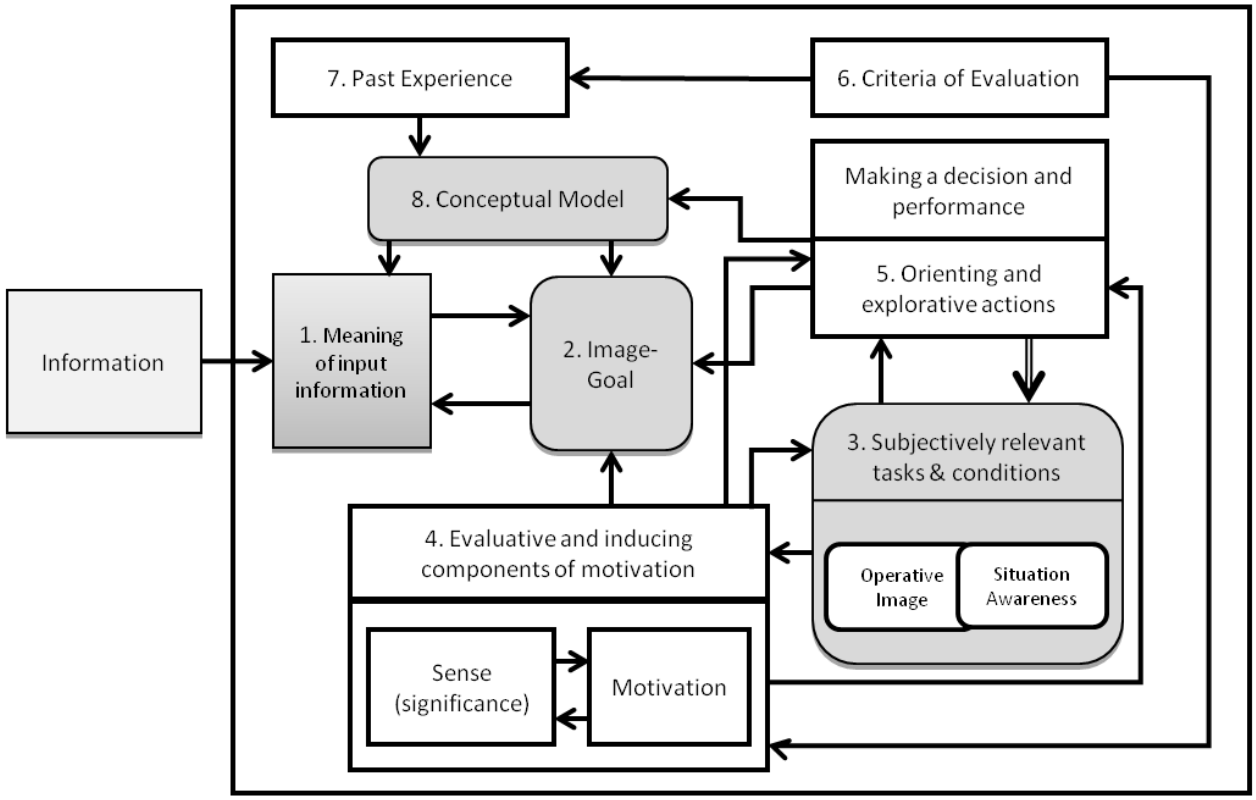

Figure 4-7. The Functional Model of Orienting Activity (Bedny & Karwowski, 2004; Bedny, et al., 2004; Bedny & Meister, 1999).

As shown in Figure 4-7, multiple factors affect the meaning of perceived information (Block 1). To properly interpret the information, the operator must have professional experience (Block 7) and knowledge (Block 8). The goal of the activity, in the form of an image (Block 2) and the components of motivation associated with it (Block 4) also affect the interpretation of the information. There are two aspects of motivation: sense and motivation. Sense refers to the subjective significance of goal attainment, and motivation determines the direction and amount of energy devoted to achieving the goal. Sense and motivation affect the methods of interpretation through the orienting and explorative actions (Block 5) to obtain further information, which feeds back into the image-goal of the desired state (Bedny & Meister, 1999). Block 5 is important in that it shows how the sensemaking process dynamically modifies interaction with the world and how interaction with the world dynamically modifies the understanding of the event (Salmon, et al., 2008).

The other important functional mechanism for dynamic reflection and understanding of the situation is Block 3, subjectively relevant task conditions. This function block includes conceptual and image components of critical features of the environment, based on what is significant to the operator (Salmon, et al., 2008), and provides a dynamic representation of reality that is tightly connected with the concept of SA. Mentally manipulating features of the object or situation and comparing them with the goal accomplish this function. This function interacts with the goal through motivation (Block 4) and orienting actions (Block 5), and can correct the goal, if necessary (Bedny & Meister, 1999).

The manipulation of the operative image can be to a large extent unconscious. But SA, as described in Endsley's model, is part of this function and is very conscious. The operator is also conscious of the aspects of the operative image that overlap with SA (Bedny & Meister, 1999).

Therefore, the “subjectively relevant task information is involved in the dynamic reflection of the situation, and the constant transformation of information on conscious and unconscious levels according to the goals that arise before an operator” (Bedny & Meister, 1999).

Together, the conceptual model (knowledge), image-goal, and subjectively relevant task conditions form the “mental model of reality” that allows operators to generate descriptions of system purpose and design, explain system functioning and observed system state, and prediction of future system status (Bedny & Meister, 1999).

Strengths and Limitations of the Activity Theory Model

Some of the function blocks in the model bear a strong resemblance to performance influencing factors. Operator knowledge and experience have a long history of treatment as performance influencing factors (PIFs) in various HRA methods. The Functional Model of Orienting Activity also explains the importance of personal PIFs such as individual motivation and personal goals, which influence the energy people devote to the task of understanding information and selecting relevant information that is deemed to be critical to the situation for further integration into the mental model and image-goal. A number of HRA methods acknowledge the importance of personal PIFs, but few actually include them in their human performance models. In addition, like Klein’s model, the AT model also recognizes cognition as a series of process cycles rather than a linear process.

Activity Theory does not speak much to the types of errors that can occur within this process, but it does mention that faulty orientation is possible. What is subjectively significant to the individual may not be objectively important to the situation, and if the person focuses on objectively unimportant elements in the dynamic reflection of the event, this can lead to faulty orientation in the situation and distortion of or an inaccurate internal model of reality (Bedny & Meister, 1999). The authors also state that knowledge and experience are necessary to properly interpret information in the situation, which would indicate that if the person does not have the necessary experience, this can lead to problems in formulating the image-goal and interpreting the information correctly.

While AT does provide a more dynamic view of human cognition than Endsley’s three-stage SA model, it is not without a number of limitations. Activity Theory has not been entirely embraced by Western psychologists, and there is consequently a lack of empirical research to support the model (Salmon, et al., 2008). The model has received much less attention than Endsley’s model, and the emphasis on process and product of SA makes the model difficult to use to measure SA. Furthermore, there are logical connections that should exist between function blocks that are not in the model, which calls into question its validity (Salmon, et al., 2008). For example, there is no connection between knowledge or experience (Blocks 8 and 7, respectively) and motivation (Block 4). It makes sense to think that one’s experience and knowledge would influence the information that a person finds personally significant. For example, an operator who has been chastised in training for failing to adequately monitor steam generator levels and promptly identify a steam generator tube rupture (SGTR) may focus on steam generator indications to the detriment of other systems or be more likely to interpret steam generator (SG) level indications as signifying a tube rupture when the situation is actually a different event.

4.2.3 The Proximate Causes for the *Understanding and Sensemaking* Function

Klein’s model delineates the major steps underlying the *Understanding and Sensemaking* function. With the assumptions that NPP operators have developed mental models for scenarios through their training and have procedures guiding and verifying their understanding of scenarios, the key steps to ensure the success of function are acquiring correct and complete data, selecting the right mental model/frame, and integrating the data with the frame to generate situation assessment. Therefore, although failure of *Understanding and Sensemaking* can occur in a number of ways, we can categorize them into the following proximate causes:

- *Incorrect Data.* The data the person is comparing with a frame is incomplete, incorrect, or otherwise insufficient to understand the situation. This may be due to one of the following reasons:
  - the information itself is faulty, external to the person;
  - there are errors in the perceptual process (in which case the failure is in the *Detecting and Noticing* function); or
  - the person attends to inappropriate information, or focuses on inappropriate aspects of the information (e.g., operators are focused on coolant level and overlook rate of change).
- *Incorrect Frame*. The frame used to understand the situation is incorrect, incomplete, or otherwise insufficient to properly interpret the data. In this proximate cause, the mental model in use is not adequate to provide a correct understanding of the situation. This can be due to a number of factors, such as the person does not have the necessary experience to develop appropriate frames, or because the situation seems similar to a different frame. Whatever the reason, the cause of failure of *Understanding and Sensemaking* is that the person is using an inappropriate frame for the situation.
- *Incorrect Integration of Data, Frames, or Data with a Frame.* This refers to errors in integration. The person does not properly integrate pieces of information together, does not correctly match data with a frame, or does not appropriately integrate multiple frames, such as when a person does not properly merge a frame for a system (i.e., a system model) with the frame for the ongoing event (i.e., a situation model). In addition, because sensemaking is a continuous, dynamic process, the person must integrate new data into the frame periodically as the situation evolves. In this proximate cause, the data is correct, the frame is correct, but the integration, matching, or updating process goes awry.

4.2.4 Cognitive Mechanisms for Proximate Causes

One of the important differences between the *Detecting and Noticing* and *Understanding and Sensemaking* functions is the nature of the research that supports and explains the phenomenon. The *Detecting and Noticing* function lends itself to *microcognitive* models that focus on one small slice of the perceptual process. However, when it comes to how people understand and make sense of that perceived information, *micro* models no longer suffice. The manner in which people go about understanding their environment ranges from simple recognition to much more complex and effortful processing. To represent adequately this range of complexity, the models of cognition are consequently at a higher, more complex level. Most of the research reviewed in this effort focused on more *macro* models, such as SA and sensemaking.

As a result, there are not groups or categories of literature outside of the models of sensemaking and SA that provide information on the cognitive mechanisms that can lead to the proximate causes of failure for the *Understanding and Sensemaking* function. We identified the cognitive mechanisms by the models themselves. We cluster the remainder of the literature reviewed in relation to these models by the factor the research examined, which maps well to the concept of performance influencing factors. The remainder of this chapter will be devoted to summarizing the cognitive mechanisms that can lead to the proximate causes and to a discussion of the most relevant PIFs to the *Understanding and Sensemaking* function (Section 4.2.5).

4.2.4.1 Working Memory and Attention

As discussed earlier, memory plays a significant role in the sensemaking process, as the activity of merging perceived information or data with a frame or mental model occurs within working memory. Working memory and attention are the cognitive mechanisms that enable sensemaking to occur. As such, the human sensemaking process is strongly subject to the limitations of working memory. Before discussing the specific mechanisms identified in the cognitive framework for the proximate causes, it is important to overview some important findings regarding memory and SA or sensemaking. Relevant findings in the literature include:

- Working memory span, or the number of chunks one can hold active in memory at once, is correlated with SA performance. People with larger working memory spans tend to develop better SA (Gugerty & Tirre, 2000). The more information a person can work with, the more likely they are to develop a full picture of what is happening.
- Maintaining SA involves the verbal, spatial, and central executive components of working memory, selectively depending on the situation and nature of the task. Tracking a moving object relies on the spatial subsystem, and working memory works to actively support SA through processing and storage in the various working memory subsystems (Johannsdottir, 2005).
- Long-term working memory (LT-WM) refers to the activated area of long-term memory that interacts with working memory as people cognitively process a problem or situation. It serves to extend working memory in a manner that involves skilled use of storage in and retrieval from long-term memory (Cook, 2001; Sohn & Doane, 2004). LT-WM has also been called skilled-memory, in that it refers to memory that is a function of knowledge and experience, and it is a significant mnemonic skill or structure for sensemaking performance (Cook, 2001), as increased efficiency in retrieving information (or frames or mental models) stored in long-term memory is important for sensemaking and SA. LT-WM has been shown to be a skill that operators can use to overcome the limitations of working memory (Jodlowski, 2008).
  - LT-WM capabilities are strongly associated with SA performance in experts: experts with better LT-WM capacity perform better than experts with lower LT-WM capacity. However, for novices, working memory span is more important for SA performance than LT-WM (Sohn & Doane, 2004).
  - Skilled memory or LT-WM may be more applicable to operation of systems in highly familiar conditions and less applicable to managing unexpected catastrophic failures. Expertise is built up by experience and repeated practice of cognitive and perceptual-motor skills. This means that LT-WM is highly beneficial for normal or familiar operations. Yet when operators are faced with unexpected, extreme, unfamiliar, surprising, or otherwise novel events, skilled-memory or LT-WM is less useful, and working memory span is more important to performance (Cook, 2001).
- Situation awareness failures can occur due to insufficient working memory span, or the decay of information in working memory over time. If people do not work to keep information active (e.g., by repeating or revisiting it), it can rapidly fade from memory (Baddeley, 1992; Baddeley & Hitch, 1974; Endsley, Bolté, & Jones, 2003). Endsley states that memory is crucial for SA, as aspects of the situation must be kept and used in memory to produce and maintain SA. Significant errors can result from systems that force operators to rely heavily on their memory (Endsley, 2000; Endsley, et al., 2003; Endsley & Garland, 2000).

Attention is a phenomenon that is strongly related to memory. It is theorized to be the primary duty of the central executive, a component of working memory, to direct and control attention and flow of information in and out of working memory (Baddeley, 1992; Baddeley & Hitch, 1974). Consequently, attention is also a primary factor for sensemaking or SA, as attention to the right or wrong information can make the difference between understanding the situation and not understanding. Relevant findings related to attention include:

- Taxing the central executive with tasks that require attention often impairs working memory performance on problems. Soliman (2010) found that executive function is strongly associated with SA. For people with already low SA, taxing the central executive produced significant performance decrements on executive tasks and on SA, whereas for people with high SA, taxing the central executive did not affect performance on the distractor tasks or overall SA.
- Experienced operators have mental models that inform them of the information they need to attend to and which information to disregard, and experts' search patterns through even complex displays for information can be quite efficient (Durso & Gronlund, 1999; Endsley, 2000).
- Operators tend to make rapid repeated visits to faulty systems with their gaze, rather than looking at the information for a longer duration. This tends to be due to the top-down knowledge and the structured environment, which allows operators to know what information they need to look at and when (Durso & Gronlund, 1999).
- Stressors can narrow the attentional field, or the area of the visual field that operators can attend to (Baddeley & Hitch, 1974). This means that potentially information in the periphery may be neglected, leading to poorer SA (Durso & Gronlund, 1999; Endsley, et al., 2003).

The above section overviewed the important general literature findings for the mechanisms of working memory and attention; the following section will discuss the mechanisms that were developed specifically for the cognitive framework structure.

4.2.4.2 Links between cognitive mechanisms and proximate causes

As stated earlier, the three proximate causes for failure of the *Understanding and Sensemaking* function are:

- Incorrect data
- Incorrect frame
- Incorrect integration of data, frames, or data with a frame

The cognitive mechanisms identified from the literature review provide an explanation of *how* and *why* those causes may occur.

Table 4-1 presents information excerpted from Appendix A.2 to show the cognitive mechanisms that are relevant for each proximate cause. Note that a few of the cognitive mechanisms apply to more than one proximate cause, such as "data not properly recognized, classified, or distinguished."

Table 4-1. Cognitive mechanisms for the proximate causes.

Proximate Cause	Cognitive Mechanism
Incorrect data (incorrect, incomplete, or inadequate information used to understand the situation)	Information available in the environment (including procedures) is not complete, correct, or otherwise sufficient to create understanding of the situation
	Attention to wrong or inappropriate information
	Improper data or aspects of the data selected for comparison with or identification of a frame
	Incorrect or inappropriate or inadequate frame used to search for, identify, or attend to information
	Data not properly recognized, classified, or distinguished
Incorrect integration of data, frames, or data with a frame	Data not properly recognized, classified, or distinguished
	Improper integration of information
	Improper aspects of the frame selected for comparison with the data
	Improper data or aspects of the data selected for comparison with or identification of a frame
	Incorrect or failure to match data or information to a frame or mental model
	Mental manipulation of the information (including projection of future status) is inadequate, inaccurate, or otherwise inappropriate
	Working memory limitations impair processing of information
	Improper control of attention
Incorrect frame (incorrect, incomplete, or improper frame or mental model used to understand the situation)	Incorrect or inadequate frame or mental model used to interpret or integrate information
	Frame or mental model inappropriately preserved or confirmed when it should be rejected or reframed
	Frame or mental model inappropriately rejected or reframed when it should be preserved or confirmed
	Incorrect or inappropriate frame used to search for, identify, or attend to information
	No frame or mental model exists to interpret the information or situation

4.2.5 The Effects of PIFs on *Understanding and Sensemaking*

PIFs influence sensemaking through various means, such as acting on working memory and attention. In building the cognitive framework, we identified experimental findings and inferred links between PIFs and proximate causes via the cognitive mechanisms identified in this literature review.

This section discusses specific literature findings related to PIFs that have been shown to affect *Understanding and Sensemaking*. Consistent with the models of sensemaking and SA, most of the literature about the effects of PIFs falls into the following areas:

- Expertise
- Workload and task complexity
- Quality and availability of information

There is also information about other factors that affect performance such as stress, fatigue, and individual differences. We discuss each of these groups as they relate to PIFs of interest to HRA: training and experience, task complexity and workload, and human-system interface (HSI) and procedures. We present some relevant findings in each of those areas to demonstrate the effects of those PIFs.

4.2.5.1 Training and Experience—Expertise and Goals

Much of the literature reviewed discussed expertise and goals as important influences on sensemaking. However, HRA traditionally concerns itself with *training* and *experience*, because those factors are easier to objectively measure by HRA analysts in the field. For example, it is simpler for an HRA analyst (who is typically not a psychologist) to determine that an operator has successfully passed all qualification training and requalification training, and has 12 years of experience as a reactor operator than to subjectively evaluate whether the operator is an expert in reactivity control. An HRA analyst can more easily identify whether an operator has received training on a particular event than she/he can determine whether that operator has *retained* the knowledge the training was intended to impart. Training and experience are means for building expertise and teaching operators on which goals are relevant and how they should prioritize goals. Training, experience, and expertise are clearly linked; subsequently, when a PIF of expertise is identified by the literature, the PIFs of knowledge/experience/expertise and training are selected in the Appendix A.2 table.

Expertise

One of the primary factors identified repeatedly in psychological and human factors research that affects how well people understand their environment is expertise. Numerous researchers have documented that people with more experience tend to outperform novices (Anderson, 2000; Endsley, 2000, 2006; Endsley & Garland, 2000; Klein, et al., 2007). A large body of research has been conducted to determine why this is the case. It is not always possible in real-world settings to have an expert on hand to assist in determining what is happening, so finding a way to improve novice performance is considered to be of great importance. In the case of plant upset, control room operators have access to expertise in the form of shift technical advisors (STAs), more senior operations personnel, subject matter experts (SMEs), and in the case of major events, an entire technical support center that is designed to provide operators with the expertise and skill they need to control the plant.

What is it about expertise that facilitates such improved performance over novices? On this, both basic laboratory and applied psychological research has provided a large amount of important information. For ease of understanding, the findings related to expertise are grouped in loose categories of Expertise and Frames, Expertise and Interpretation of Information, Expertise and Memory/Attention, Expertise and Problem Solving/Use of Information, and Other Findings.

Expertise and Frames

- Experts and novices use the same reasoning strategies, logic, and abductive reasoning, but experts have a richer repertoire of frames. They have more knowledge and a broader, more detailed set of frames (or models/patterns/information) from which to work. Novices, on the other hand, have a limited knowledge base from which to work (Anderson, 2000; Klein, et al., 2007).

- Experts' mental models are richer in terms of having more detail, more variety, more subtle and finer degrees of differentiation, and more comprehensive coverage of the domain. Experts are more sensitive to the context of the situation (Anderson, 2000; Klein, et al., 2007).
- Experts are more likely to be able to work with multiple frames at once. When faced with data that has more than one explanation, experts can deliberately elaborate two to three frames simultaneously, looking for information that will rule out one of the frames (Feltovich, Johnson, Moller, & Swanson, 1984; Klein, et al., 2007).

Expertise and Interpretation of Information

- Information in the environment is not presented in neat packages of data to people. Instead, expertise is needed to sift through information to select and define what information is important (Klein, et al., 2007).
- Novices are more likely than experts to interpret information that is actually irrelevant as important (Klein, et al., 2007).
- Experts are more prone to question data than novices because they are more familiar with cases of faulty information. This may also mean that experts are more confident in their frames and skeptical of contrary evidence (making them more susceptible to fixation errors) than novices, who are less confident in frames and more sensitive to contrary data (Klein, et al., 2006).

Expertise and Memory/Attention

- Experts have a greater ability to store problem information in long-term memory, store it in a well-structured and organized manner, and to be able to quickly and easily retrieve it. Experts are better able to remember more patterns (or frames) and larger, more complex patterns than novices (Anderson, 2000).
- As people develop expertise in an area, they create more complex chunks of information. People can only process a limited amount of information in working memory at once. One strategy to deal with this limitation is to break information into chunks. This is why telephone numbers are broken up into three chunks—area code, prefix, and four-digit number. People recall the three chunks, not ten digits. Experts' chunks are more complex and structured than novices, so experts can work with more information successfully than novices (Anderson, 2000). Experts are better than novices at organizing information into meaningful units (Doane, Sohn, & Jodlowski, 2004).
- Experts have stored the solutions to many problems in long-term memory, which gives them an advantage over novices who have to tackle each new problem from scratch. This allows experts to focus on more sophisticated and unique aspects of the problem (Anderson, 2000).
- Working memory capabilities are more predictive of novice SA, but long-term working memory is more important for expert SA. For experts with a low working memory span, long-term working memory skills are crucial for successful SA (Sohn, 2000).
- Experts develop automaticity to their cognitive processes as well as to the physical actions for a task. This allows them to devote their cognitive resources and attention to areas that are less routine (Endsley, 2006; Shebilske, Goettl, & Garland, 2000).

Expertise and Problem Solving/Use of Information

- Experts can take advantage of their knowledge base to use redundancies and constraints in a situation to generate expectancies. They can fill gaps in their understanding with assumptions and inferences based on knowledge of similar situations (Klein, et al., 2007).
- Experts are more likely to have a functional understanding of the situation or problem and invoke principles that they can use to solve the problem, whereas novices tend to have a poorer understanding of how to go about solving the problem, even if they know what factors are relevant. They just do not know how to use that information (Chi, Feltovich, & Glaser, 1981; Klein, et al., 2007). Experts are better able to organize their problem solving efforts in a way that is optimally suited to solving the problem (Anderson, 2000).
- Experts show a greater capability for anticipation—to identify what is coming next and what must be done in preparation (Klein, et al., 2007; Klein, Snowden, & Pin, 2011). This is plausibly due to their frames or mental models having more information about the progression of a situation across time, so they know what comes next.
- Experts perceive problems in ways that enable more effective problem solving. They have a richer set of perceptual features for encoding problems (Anderson, 2000).
- Experts are more accurate than novices in determining whether changes in the situation are in accordance with expectations of their mental model (Doane, et al., 2004).
- Experts are more context-dependent than novices, meaning that they are more sensitive to surroundings, circumstance, and the specific aspects of the situation than novices. This makes experts better at classifying situations than novices (Federico, 1995)

Other Findings Related to Expertise

Expertise also has negative aspects. First, a great deal of practice is required to develop expertise in any field (Anderson, 2000), and the acquired expertise can become degraded without reinforced learning over the time. Next, expertise can be quite narrow. Expertise developed in one area may fail to transfer to other domains, even areas that are similar.

Goals

Goals are important to sensemaking for a number of reasons. Sensemaking is a goal-driven process, with the goal being to understand what is going on and respond appropriately (Klein, et al., 2006; Klein, et al., 2007), perhaps to bring an unexpected event under control. In goal-driven processing, a person focuses attention in accordance with the active goals. The operator actively seeks information related to accomplishing the goal, and the goal contributes to interpretation of the data (Endsley, 2000).

Specific findings related to goal selection include:

- For the following reasons, selection of correct or appropriate goals is critical for properly understanding the situation. If a person is pursuing an inappropriate or less important goal, critical information may be missed (Endsley, 2000):
    - The active goals direct the selection of the mental model used for understanding the situation (Endsley, 2000).
    - The goal and associated mental model are used to direct attention, identify and select important information from the environment, and direct scan patterns (Endsley, 2000).
    - People use goals and their associated mental models to interpret and integrate information into a full understanding or comprehension of the situation. "The goal determines the 'so what' of the information" (Endsley, 2000, p. 20).

- Failure to maintain multiple goals has been shown to cause problems in maintaining SA (Endsley, 1995)
- Interpretation of information from the environment depends on the goal of the activity and the motivation behind it, including the significance the operator places on the goal (Bedny & Meister, 1999). If the goal (image-goal) is inappropriate for the situation, then the person may incorrectly interpret the information.

4.2.5.2 Task Complexity—Working Memory and Attention

Complexity refers to the quantity, variety, and intermingled relations of the elements of an object or situation (Xing, 2004). Park and Jung (2007) developed a task complexity measure to quantify the complexity of tasks stipulated in emergency operating procedures in NPPs. The measure consists of five complexity factors: (1) amount of information to be managed by operators, (2) logical entanglement due to the logical sequence of the required actions, (3) amount of actions to be accomplished by operators, (4) amount of system knowledge in recognizing the problem space, and (5) amount of cognitive resources in establishing an appropriate decision criterion. Task complexity contributes to human performance degradation because the increased load demands more cognitive resources such as working memory and attention. With higher task complexity, such as the amount of information that a person has to work with, the person must increase the cognitive resources to maintain and integrate that information.

We treat memory and attention as cognitive mechanisms in the cognitive framework, both of which were discussed in detail in Section 4.2.4.1. Below is a brief summary of certain findings regarding the effects of task complexity on memory and attention, which in turn affect *Understanding and Sensemaking*.

- Situation awareness failures can occur due to insufficient working memory span, which is needed to process complex tasks. Significant errors can result from systems that force operators to rely heavily on their memory (Endsley, 2000; Endsley et al., 2003; Endsley & Garland, 2000).
- Information in working memory decays over time. If the task requires individuals to retain the information for a long period of time before the information is used, it can rapidly fade from memory unless individuals work to keep information active (i.e., by repeating or revisiting it) (Baddeley, 1992; Baddeley & Hitch, 1974; Endsley, et al., 2003). Maintaining a high and accurate level of SA necessitates expending cognitive resources—it requires cognitive workload, which may compete with other parallel cognitive tasks. Heavy concurrent task demands may in turn divert resources from the maintenance of SA.
- Even experienced operators can make errors in the process of prioritizing attention and neglect to attend to certain information, particularly when they have to juggle numerous competing tasks and pieces of information. Distraction due to other tasks or overly salient information is a major contributor to SA errors (Adams, et al., 1995; Endsley, 2000; Jones & Endsley, 1996).

4.2.5.3 Workload—Working Memory and Attention

Workload[6] is another strong influence on sensemaking performance. It is generally referred to as the amount of cognitive or physical tasks an operator must handle in a situation. By this definition, workload is related to task complexity and task load for the time available to perform the task. The more tasks a person has to perform, the more demands on the person's resources to perform the tasks within the given time. Cognitive or mental workload may be conceptualized as a function of the supply and demand of cognitive processing resources, with two main determinants: the task demands (e.g., task difficulty, priority, and situational factors); and the internal supply of attention or cognitive resources available to support processing (e.g., *Detecting and Noticing*, *Understanding and Sensemaking*, planning, and *Decisionmaking*) (Tsang & Vidulich, 2006). Therefore, with higher cognitive workloads, demands on attention, working memory, and long-term working memory are increased, and it becomes more likely that sensemaking or SA will be impaired. Experience may mediate cognitive workload: experienced operators often have learned strategies for managing high workload. For example, teamwork is a way to split high workload among the team members; displays can reduce the load of remembering information; and procedures can reduce the mental workload in assessing situations by assisting operators with diagnosis. Below are listed several important findings related to workload:

- With increasing physical workload, there was a general trend of decreasing SA for perceptual knowledge (Level 1 SA), comprehension (Level 2 SA), and overall SA. However, physical workload did not appear to affect Level 3 SA or cognitive task (a military helicopter loading simulation) performance. Therefore, physical workload appears to affect SA, but this does not necessarily translate to task performance decrements (Perry, Sheik-Nainar, Segall, Ma, & Kaber, 2008).
- Both high and low workload are associated with degraded SA, while sufficient SA is needed for reliable task performance regardless of the workload. This relationship between workload and SA is also mediated by level of expertise. An experienced operator can maintain SA with lower investment of cognitive resources, often due to the schema or mental model used to assist in understanding the situation. However, it is a dangerous trap to assume that a more experienced operator necessarily has a better understanding of the situation; heavy reliance on resource-free mental models may mean that the operator incorrectly interprets or fails to notice an unexpected or surprising event (Wickens, 2001).
- Skill level and expertise moderate the supply of attentional and cognitive resources. A certain level of task demands may impose different levels of workload on an operator, depending on ability and skill level. A high skill level is functionally equivalent to having a larger cognitive processing resource supply (Tsang & Vidulich, 2006). Similarly, external resources, such as cognitive aids, (e.g., notes, procedures, decision support systems), support centers, and teamwork can also moderate the supply of attentional and cognitive resources.
- It takes a careful balancing of workload and SA to ensure that one can maintain SA without excessive workload. While it takes a certain amount of workload to maintain SA, too much workload overwhelms cognitive resources. Strategic management of this balancing act is postulated to be a function of executive control of attention (the central executive component

6. While most research conducted on workload used the phrase "workload," the PIF taxonomy used in the cognitive framework labels workload as "task load." Groth's (2009) taxonomy also calls out time load (the perception of time pressure) and other loads (to catch any other loadings on the person's activities). In this report, the authors use "workload" and "task load" interchangeably.

of working memory), which is a distinct aspect of human cognition that consumes processing resources. Strategic management of workload and attention competes with the other mental processes that generate cognitive workload on the processing resources. However, strategic management can optimize performance by smartly planning and allocating the limited resources to the processes that need the most attention (Tsang & Vidulich, 2006).

4.2.5.4 HSI and Procedures—Quality and Availability of Information

Information quality (e.g., accuracy, structure, and availability) in a situation is important for correct understanding of the situation—the better and more accurate the information available, the better people are able to make sense of it. For information to be considered to be of high quality for *Understanding and Sensemaking*, the information should be well-organized and structured in such a way that it is consistent or compatible with a person's mental model or the frames that the person is using to comprehend the situation. Thus, information from the human-system interface (including procedures) is of crucial importance for properly understanding an event (Endsley, 1995, 2000; Endsley & Garland, 2000; Jones & Endsley, 1996, 2000; Kim, Yoon, & Choi, 1999). Hence, HSI features such as multimodality, visibility of others actions, alarm filtering, overview displays, and memory aids can substantially affect understanding and sensemaking of the information.

- A person is more likely to identify information that is extremely inconsistent with a current schema (or schema-bizarre information) as contradictory. This often leads to recognizing that either the data or the schema is in error, whereas information that is seen as irrelevant to the schema (but is relevant to the objective situation) is simply not noticed, and an incorrect schema persists (Jones & Endsley, 2000).
- System automation can undermine SA by taking the operator out of the loop. If complex, automated systems do not provide operators with enough information to keep them in the loop, operators may struggle to understand what is going on when the automation fails or reaches situations that it is not equipped to handle (Endsley, et al., 2003).
- Highly complex systems make it difficult for people to develop sufficient internal representations of how the systems work. System complexity can slow down the ability of people to take in information (due to the overwhelming amount of information), and it undermines their ability to correctly interpret the information and project what is likely to happen next (Endsley, et al., 2003).
- The "Las Vegas Strip" phenomenon—when systems display flashing lights, moving icons, overuse bright colors, or simply present too much information, information overload can occur. Misplaced salience can also occur when information that is objectively irrelevant (or inaccurate) is physically more salient than important information, drawing operator attention away from needed information (Endsley, et al., 2003). This phenomenon is certainly relevant for *Detecting and Noticing*; it is also relevant for *Understanding and Sensemaking* because it may lead to operators to use inappropriate data in the sensemaking process, or prevent them from finding the necessary information that is buried amongst irrelevant yet overly salient information.

4.2.5.5 Individual Factors—Stress, Fatigue, and Cognitive Style

Research has also shown that certain individual factors affect sensemaking performance. These factors are often referred to as "individual differences," because they vary from person to person. Individual difference factors include such things as personality types, adaptability, ability to handle stress, and approaches to strategic thinking. During an HRA, an analyst typically will evaluate some individual factors, such as stress and fatigue. However, many of these types of variables are not commonly considered in HRA, particularly variables like personality. Primarily, performance based on personality is considered to be something that HRA analysts will not be able to predict. Nevertheless, when one considers performance of the *Understanding and Sensemaking* function, some individual difference findings may prove informative in identifying how sensemaking may fail. Several important findings in the literature related to individual factors are listed below.

- People tend to be less effective in gathering information under stress. They are more likely to pay less attention to peripheral information, become disorganized in their scanning patterns, succumb to attentional tunneling, and make decisions without considering all available information (Endsley, et al., 2003).
- Fatigue can also reduce working memory span and attentional executive control of working memory. If people have to focus on remaining vigilant, they may have less attention resources to use on important information (Endsley, et al., 2003).
- Analytic thinkers (people who view the world as composed of separate elements that can be understood individually and independently) tend to focus on objects and dispositions. Holistic thinkers, on the other hand, are more likely to include context, and focus on the relationships between different objects and context (Lin, 2009). Analytic and holistic thinkers use information differently during sensemaking, with the difference being strongest during initial sensemaking with limited information. Holistic thinkers are more influenced by the type of information presented during initial sensemaking, identify a problem in the situation sooner, and change their sensemaking more than analytic thinkers. With new contradictory information, though, the difference between analytic and holistic thinkers disappears. The information content ultimately influences sensemaking (Lin, 2009).

4.3 Summary

This chapter discussed *Understanding and Sensemaking*, the function by which people make sense of the information in their environment. The chapter presented an overview of four important models that explain how *Understanding and Sensemaking* works, including the data/frame theory of sensemaking (Klein, et al., 2007) and three models of SA (Bedny & Meister, 1999; Endsley, 1995; Smith & Hancock, 1995). The chapter then discussed the proximate causes of and cognitive mechanisms for failure of sensemaking, and identified relevant PIFs that influence the sensemaking process.

Some of the literature reviewed demonstrates a general effect on performance, such as workload, without linking the effect to specific errors. Other research provided information regarding cognitive mechanisms (e.g., working memory), also without linking the mechanisms to specific errors. Therefore, when organizing the literature that was reviewed, we developed a structure that linked PIFs to cognitive mechanisms to proximate causes of failure, links that previously were not identified in the literature in such a manner. This linked structure is the primary product of this literature review effort, and can be found in the detailed tables in Appendix A.2 and the associated tree diagrams in Appendix B.2. Notice that the literature review of this chapter was under the assumptions that operators have mental models/frames for scenarios they work on and there are procedures to guide and verify their understanding of scenarios. Therefore, the review did not explore in depth the mechanisms for how humans achieve understanding and sensemaking for unfamiliar scenarios or without procedure guidance. Also, the review did not address a large body of literature about how humans achieve understanding for data/information with high uncertainties and how humans use team or community expert judgment to assess situations when data is incomplete. These topics should be addressed when using the cognitive framework to analyze human events outside the scope of the assumptions for this function.

5. DECISIONMAKING

5.1 Introduction

Decisionmaking is 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). Researchers have long been interested in understanding how decisions are made and being able to predict the decided upon solutions. Modeling decisionmaking has progressed from the study of how decisions ought to be made to the study of how they are actually made. The study of decisionmaking 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. The decisionmaking process described in this chapter builds on the information and situation assessment completed through the *Understanding and Sensemaking* function (Chapter 0).

Decisionmaking within a nuclear power plant (NPP) is characterized as involving experts and being largely driven by procedures. In recognition of the complex environment inherent in NPP operations, 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 operators still maintain a mental model of the situation and plan their course of action semi-independently of the procedures. That is, operators know the goals that they need to accomplish and how that should be done, and they use 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.

Human reliability analysis (HRA) needs to model the complexity within the NPP environment and the potential for decisionmaking errors despite operators being provided with procedural direction. One HRA method in particular, ATHEANA, provides some guidance in evaluating errors within NPP operations, especially in the response planning phase (NUREG-1624; NRC, 2000). For example, the method provides plausible explanations and error mechanisms to explain why a small or large change in a parameter may be missed or not attended to, such as the control room crew being fixated on another parameter or having apathy or a lack of urgency in responding to the parametric change. To have a better understanding of the type of decisionmaking errors made within an NPP, and to be better able to represent the error within HRA, it is important to understand the thought processes and phases of decisionmaking that lead to errors.

5.2 Historical Background of *Decisionmaking*

Decisionmaking has been studied for many years within the laboratory and in real world settings. Early attempts were based on normative models and had origins in economics, mathematics, and philosophy. These models described the human decisionmaker as directed by “rational” maximizing behavior—in other words, trying to choose the alternative that maximizes gains. These models are often referred to as normative models. Rational choice theory (RCT) was one of the earliest examples and was built on axioms assuming the decisionmaker would act in a consistent manner and would be guided by rational rules (Nicholson, 1995). Models within this paradigm considered either decisions made in an environment of uncertainty or the absence of uncertainty. For example, in the absence of uncertainty, someone looking to purchase a product knows exactly what he or she will get once he or she makes the decision to buy. However, many decisions are made with uncertain outcomes. For example, buying a lottery ticket allows you odds of winning money, but not certainty. One key model proposed to account for decisions under uncertainty was expected utility theory (EUT) (Von Neumann & Morgenstern, 1947).

The primary claim of normative models, that behavior is rational, fails to portray realistic decisionmaking. The set of rules defined by the models has been shown to be violated in numerous studies (Mellers, Schwartz, & Cooke, 1998). For example, the theories posit that the decisionmaker should act in a consistent fashion such that if one alternative is preferred, it should always be preferred; however, research has shown that this is not always the case. Most notably, the existence of cognitive heuristics and biases such as the framing effect (Kahneman & Tversky, 1984) has demonstrated the “irrational” behavior of people. Specifically, the framing effect states that the way in which a problem is worded will influence the decision made. This effect directly contradicts the hypothesis that if one alternative is preferred it will always be preferred as this preference can be swayed based on the description of the problem.

Descriptive models were developed in an attempt to better represent actual decisionmaking behavior. Whereas normative models describe how a decision ought to be made, descriptive models seek to describe how a decision is made. Simon (1959) introduced a transition to more descriptive theories of decisionmaking by describing limitations on the human processing capacity leading to the idea of bounded (limited) rationality. This concept states that the decisionmaker operates via satisficing instead of maximizing when making decisions (Simon, 1955). Therefore, the decisionmaker acts in ways in which the desired outcome is achieved or satisfied, but it may not be in the best optimal way (i.e., outcome is maximized). That is, the decisionmaker finds a solution that meets the desired criteria and is “good enough,” but does not spend the extra time and resources to thoroughly explore each solution alternative to find the best or optimal solution.

To explain some behaviors previously unaccounted for by normative models, Kahneman and Tversky (1979) developed prospect theory, which also falls into the descriptive camp of decisionmaking theories and models. Prospect theory not only accounts for risk seeking and risk aversion (i.e., the idea that some people engage in behaviors for the thrill of the risk [risk seeking] or adapt an overly conservative nature to avoid risk [risk aversion]), the theory also explains loss aversion (Tversky & Fox, 1995). Loss aversion is the phenomenon observed in people’s behavior of being overly sensitive and opposed to losses. That is, the person is more averse to the loss of some amount than they are to a gain of the same amount (i.e., more averse to losing $20 than to gaining $20).

Prospect theory and other descriptive models or theories are often studied in contrived situations involving simple decisions being made by novices. Within these contrived environments, the models have fared well in predicting behavior; however, the models have not been shown to generalize well to environments that are more complex. The descriptive models typically do not adequately explain real-world decisionmaking involving experts in a time-critical situation. The models have been unable to explain the process the decisionmaker goes through in evaluating a situation, reviewing options, and deciding on a course of action in real-world settings.

5.3 Naturalistic Decisionmaking

Naturalistic decisionmaking (NDM) sought to expand the setting in which decisionmaking was examined. NDM departs from the earlier theories of decisionmaking and considers the decisionmaker in a real-world setting in which decisions are typically embedded in a larger task. Researchers in this area focus on studying “time pressure, uncertainty, ill-defined goals, high personal stakes, and other complexities that characterize decisionmaking in real-world settings” (Lipshitz, Klein, Orasanu, & Salas, 2001, p. 332). Several characteristics of NDM diverge from previous representations of decisionmaking. Lipshitz, Klein, Orasanu, and Salas (2001) explain four essential characteristics of NDM models. First, NDM focuses on the cognitive processes that the decisionmaker engages in instead of solely trying to predict the decision that will be made. Second, NDM describes the decisionmaker as judging the applicability of alternative solutions for reaching a goal one at a time instead of in a comparative manner (a versus b), and the search for alternatives is not exhaustive. Third, NDM focuses on experts instead of novice decisionmakers and places a great deal of importance on the context in which the decision must be made. Fourth, alternatives evaluated by the decisionmaker are only those that can be realistically implemented.

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 decisionmaking of experts in stressful situations and under time pressures. A defining feature of RPD is that the decisionmaker does not compare alternative solutions to each other when searching for an optimal solution; instead, the decisionmaker will sequentially go through the list of alternatives until arriving at a sufficient solution. Thus, RPD is based on satisficing (finding a sufficient solution) instead of optimizing (finding an optimal solution).

RPD consists of three phases: situation recognition, serial option evaluation, and mental simulation. The process engaged in by the decisionmaker is represented in Figure 5-1 (Klein, 1993). In the first stage (situation recognition), the decisionmaker assesses the situation and determines if the situation is typical or if he or she has encountered it before. A decisionmaker may rely on relevant cues from the situation, expectancies about how the situation may evolve, and/or stated goals for success in comparing the situation to previously encountered situations. A decisionmaker can respond to a typical situation with typical and known responses. A novel situation, on the other hand, will require new techniques or new applications of known techniques. In the second stage (serial option evaluation), the decisionmaker sequentially reviews alternative solutions to the problem. The solutions that are considered most typical would be considered first. The solutions are evaluated, one at a time, within the third phase as the decisionmaker mentally simulates the implementation of the solution and the outcome. Based on this simulation, the decisionmaker implements the solution as-is, changes it somewhat, or discards it and imagines another solution.

The phases presented by the RPD model can be generalized to represent the phases of decisionmaking within an uncertain, continuously evolving environment. The phases progress through first comparing the currently encountered situation to the mental model and developing goals to be achieved with the decision, next developing alternative solutions for reaching these goals, and finally implementing the solution. The amount of time spent within each phase will depend on the familiarity with the situation as well as the complexity of the situation. The amount of procedural guidance (and other types of decision aids) can also have an impact on the decisionmaking process. This realization is particularly true when considering decisionmaking in an NPP setting.

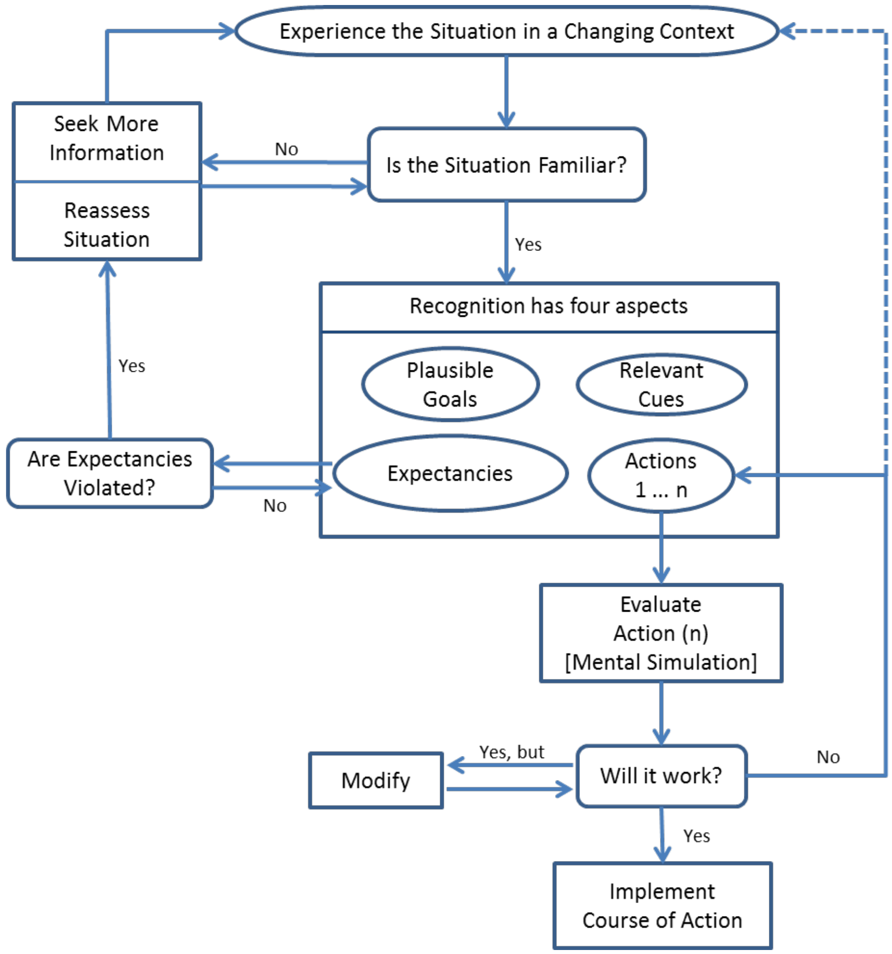

Figure 5-1. Integrated version of recognition-primed decision model (Klein, 1993).

5.4 ***Decisionmaking*** in a Nuclear Power Plant

Although each of the theories and models of decisionmaking discussed in the previous sections has provided insight into the decisionmaking processes, not all of them are useful for our purposes of describing the decisionmaking process undertaken by the operator within an NPP. For instance, normative models are very useful in developing decision aids because they focus on how decisions should be made (Edwards & Fasolo, 2001). However, these philosophies are not useful in helping determine where errors occur in the decisionmaking process employed by NPP operators. That is, the focus on determining where errors may occur in the decisionmaking process must focus on how decisions are actually made and not on how they should be made. For future applications, normative models may serve a role in preventing an error from occurring by aiding the NPP operator in making a decision (i.e., the normative model philosophy is used in constructing the decision aid to be used by the operator).

Descriptive models provide some insight when discussing errors made by NPP operators. However, these models typically focus on studying inexperienced individuals making decisions in laboratory settings where contextual factors play a limited role. These studies have been useful in uncovering decision heuristics that people use in making everyday decisions. These heuristics may be very useful in reducing the cognitive complexity of decisions, but may lead to biasing errors (Tversky & Kahneman, 1974). These biases may still be seen in NPP operations and are useful in this study; however, a broader view of decisionmaking within the NPP environment must be taken to fully understand the types of problems and errors that may be encountered. Researchers only achieved the ability to study people within their environments and account for the environmental and situational impacts on the decision by moving to NDM models. In fact, Zsambok (1997) defines NDM as, “the way people use their experience to make decisions in field settings.” (pg. 4).

NDM provides a good framework for modeling the decisions made by NPP operators. Greitzer, Podmore, Robinson, and Ey (2010) tailored the NDM model to NPP control room operation where decisionmaking is largely directed by procedures. Figure 5-2 shows a reproduction of their model.

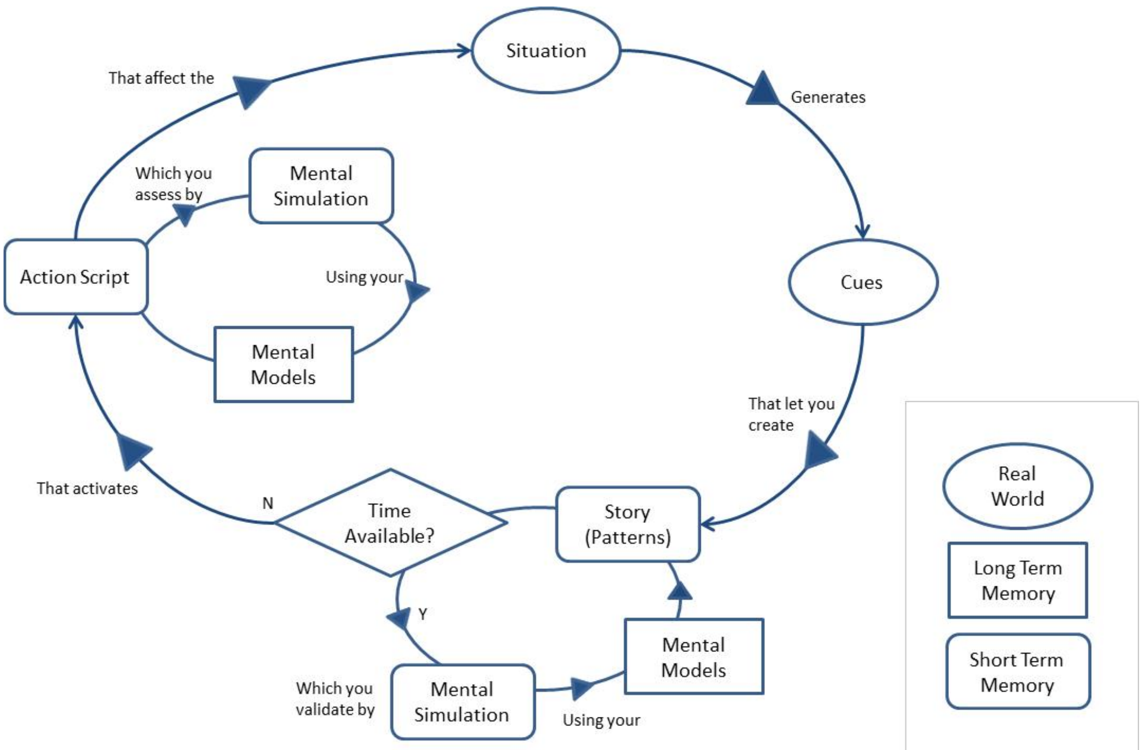

Figure 5-2. Integrated NDM model (Greitzer, et al., 2010).

This integrated NDM model includes concepts from situation awareness (SA) (covered more extensively in Chapter 0 of this document), RPD, and recognition/metacognition (R/M) (Cohen, Freeman, & Thompson, 1997). The initial processing of the cues and formation of the story is done through processes of SA (Endsley, 1997) and early stages of RPD. Chapter 4 of this document covers this process, which sets the groundwork for response planning. It is during the process of *Understanding and Sensemaking* that the person forms the initial mental model characterizing the situation. Following these phases, the person generates alternative options and tests for their applicability to the situation through mental simulations. One feature of this model is its recognition of the continued role of mental models in forming the story of the situation and in selecting an applicable course of action.

R/M (Cohen, et al., 1997) explains how decisionmakers evaluate and improve their situational assessment. Given enough time exists for the evaluation, the decisionmaker will engage in a process of critiquing in which the assessment will be judged based on incompleteness (assessing if the situation is represented completely), unreliability (searching for assumptions made during the assessment that are unreliable or doubtful), and conflict (assessing if there are existing cues that contradict the assessment). The integrated NDM model proposed by Greitzer et al. (2010) includes the idea of critiquing by modeling additional loops of mental simulation during the pattern recognition process.

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 just slightly from either procedural guidance or from previously encountered situations, the operator will have to adapt some 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.

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 operator may evaluate the response plan or action script through mental simulation to evaluate its suitability and then put it into action.

One of the defining features of decisionmaking in an NPP is the dynamic nature of the event. Maintaining appropriate situation awareness of the event, updating the mental model of the situation, and planning the response accordingly are important steps (Murphy & Mitchell, 1986). And these steps continue to occur even in the presence of procedures. During the evolving and dynamic nature of an NPP event, operators were found to follow their procedures, but they also "actively construct a mental representation of plant state and use this mental representation to identify malfunctions, anticipate future problems, evaluate the appropriateness of procedure steps given the situation, and redirect the procedural path when judged necessary" (Roth, 1997, p. 176). So, even with procedures present, the operator's ultimate decision is largely impacted by his or her own cognitive processes.

5.5 Proximate Causes of Failure of *Decisionmaking*

Errors in decisionmaking have been studied in each of the fields reviewed. Descriptive theories have typically focused on the reliance on fallible heuristics and breakdowns in decision processes. However, NDM "generally tries to understand error in a broader context, including insufficient experience." That is, "NDM researchers… are less likely to attribute the error to faulty reasoning strategies, preferring to use the error as an indicator of poor training or dysfunctional organizational demands, or flawed design of human-computer interface" (Lipshitz, et al., 2001, p. 340). Research on errors in NDM has searched for the contextual factors that may contribute to the errors. This focus in NDM makes it a prime candidate for the present effort, as a primary goal for this study is identifying the PIFs that contribute to errors.

We examined the phases or steps of the decisionmaking process where failures were likely to occur. This was performed on the RPD model proposed by Klein (1993, 1998) and the integrated NDM model proposed by Greitzer, Podmore, Robinson and Ey (2010). We conducted a comprehensive review of literature within decisionmaking (including the models discussed in the previous sections) to identify the cognitive mechanisms that lead to errors within these phases and processes. The cognitive mechanisms identified were grouped into three proximate causes according to the major phases in the decisionmaking models.

The proximate causes and relevant cognitive mechanisms identified are the follows:

1. *Incorrect Goals or Priorities Set.* Goals are set as the objectives that the decision should achieve. Goals are the measure for viewing the decision as successful or not. Although goals are formed during any decisionmaking process, they are especially relevant during novel situations when there is no previous experience that 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 in either what goals are set or what priorities are assigned. Cognitive mechanisms include:
    a. Incorrect goals selected. Errors may arise if the operators select the wrong goal to work toward. A variant of this cognitive mechanism is if the operator selects an implausible goal that cannot be achieved.
    b. Incorrect prioritization of goals. Goals may be ordered incorrectly in the operators' mind or given the wrong priority, such that less important goals are addressed first.
    c. Incorrect judgment of goal success. The threshold used by the operator to judge goal success may be incorrectly set too low, or be incorrectly determined as met when it was not.
2. *Incorrect Internal Pattern Matching*. During the *Understanding and Sensemaking* stage, an operator forms a mental model of the current situation. During pattern matching, the operator matches the situation with stored plans, scripts, and stories to judge the typicality of the situation and devise a plan as needed. If the operator judges the situation as being typical, a previous response plan can be used again. If the situation is novel, the operator may find a similar situation that can be adapted to fit the current situation. This proximate cause includes errors that occur during the mental exercise of pattern matching. Cognitive mechanisms include:
    a. Not updating the mental model to reflect the changing state of the system. Events within an NPP may evolve quite quickly, and the operator must update his or her mental model to reflect this dynamic nature.
    b. Fail to retrieve previous experiences. During pattern matching, the operator compares the current situation to previously encountered situations to devise an appropriate response plan. Errors may occur in this recollection process if the operator fails to evoke appropriate previous experiences.
    c. Incorrect recall of previous experiences. Similar to the previous cognitive 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.
    d. 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.
    e. Cognitive biases. Confirmation bias and availability bias may be particularly pertinent to causing errors in this phase of decisionmaking (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 update of the mental model.

3. *Incorrect Mental Simulation or Evaluation of Options.* 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 operator will probably not do an exhaustive test of all proposed solutions, but will choose the first acceptable option. This proximate cause includes errors that occur during the mental simulation or evaluation of options. Cognitive mechanisms include:
    a. Inaccurate portrayal of action. This cognitive 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.
    b. Incorrect inclusion of alternatives. The operator may forget to include some alternatives that should be considered.
    c. Inaccurate portrayal of the system response to the proposed action. This cognitive mechanism manifests in the operator incorrectly predicting how the system will respond to the proposed action.
    d. Misinterpretation of procedures. Response planning within the NPP is done by consulting procedures. An error may occur because either the incorrect procedure selection or inaccurate interpretation or the procedures have complicated logic making them difficult to use and understand.
    e. Cognitive biases. The cognitive biases of overconfidence and the anchoring effect may be especially prevalent for this cognitive mechanism. Overconfidence affects the operator's confidence in the ability of an action to work. Especially if the operator has had previous success with an action, he or she may be overconfident in its ability to work in 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 be biased toward choosing the first action that occurs to him or her, and apply an unsuitable action.

We further identified relevant PIFs for each of these cognitive mechanisms. The figures shown in Appendix B.3 depict the PIFs that the project team identified and how they connect to the proximate causes and cognitive mechanisms. The diagrams in Appendix B.3 serve as graphic summary of the information in the tables of Appendix A.3.

5.6 Summary

This chapter introduced the macrocognitive function of decisionmaking. As defined in this chapter, the process of decisionmaking proceeds after the establishment of the mental model discussed in the previous chapter on *Understanding and Sensemaking*. Yet, this chapter also shows the cyclical nature of the two processes *Decisionmaking* and *Sensemaking*. The chapter presented a historical account outlining the movement of the field and evolution of the research within decisionmaking. The categorization scheme of proximate causes closely resembles models in NDM. The specific cognitive mechanisms outlined are particularly relevant for decisionmaking within the main control room of an NPP during normal or abnormal operations.

Note that the literature review and the proximate causes identified did not address several aspects of decisionmaking (team decisionmaking, distributed decisionmaking, and dynamic decisionmaking) because most control-room decisions are routine and directed by procedures. However, in situations of severe NPP accidents, the decisionmaking process could be very different from the current understanding of normal and event control room operations. This literature review does not address specific decisionmaking considerations in those situations.

6. ACTION

6.1 Introduction

This section addresses errors that can arise in executing physical control actions to achieve a particular goal. From a psychological perspective, such actions are goal-directed motor interactions with the system.

Action errors are often classified as observable errors in human behavior. For example, an early human reliability analysis (HRA) method, the Technique for Human Error Rate Prediction (THERP) (NUREG/CR-1278; Swain & Guttman, 1983), lists the following human errors:

- errors of omission
    - omits entire task
    - omits a step in a task
- errors of commission
    - selection errors
    - error of sequence
    - time error
    - qualitative error

In this context, errors can be the result of failures of any of the cognitive functions associated with detecting stimuli, understanding, planning, or action execution. This chapter deals with the cognitive mechanisms that underlie the failures of attempted execution of a decided upon action plan. These errors are commonly referred to as execution failures or errors of execution (Reason, 1990).

Note that errors of execution, where the individual(s) intended to take the correct action but failed in execution, are distinctly different from instances where the individual(s) had an incorrect intention due to a failure in *Detecting and Noticing*, *Understanding and Sensemaking*, or *Decisionmaking*. Errors of intention are commonly referred to as mistakes (Reason, 1990); mistakes due to failures in one of the other macrocognitive functions are covered in the respective macrocognitive function.

Nuclear power plant (NPP) operators take physical actions on the plant to achieve a particular goal. Physical control actions are performed both by operators within the control room as well as by field operators in the plant itself. In the information, decision, action (IDA) model (Smidts, Shen, & Mosleh, 1997), “action” is defined as “implementing the decided response.” This definition specified whether the response is on the level of executing an entire procedure, executing a procedure step, or executing a single manual action (such as opening a valve). A large portion of the cognitive activities involved in executing a procedure (or procedure steps) include detecting appropriate cues, understanding the situation given those cues and the mental model of the process, and deciding upon the correct response (i.e., the macrocognitive functions reviewed above). For the purposes of this chapter, action is defined as implementing an action on the level of a single manual action (such as operating a valve) or a predetermined sequence of manual actions. The action(s) must involve the manipulation of the human-system interfaces of the plant and would consequently alter plant status. Therefore, physical activities in communication (e.g., giving commands) and collecting information about the plant status are not within the scope of this chapter. Errors in those activities are dealt with in other macrocognitive functions.

NPP operator actions can take different forms:

- Simple actions – One or a few action steps without much mental effort (e.g., turning a switch to a particular position; turning a pump on or off).
- Sequence of actions – A sequence of multiple steps of single, discrete actions to achieve a particular goal. An example of a sequence of actions is realigning a set of valves to change a flow path.
- Control actions – Sustained control of the action human-system interface (HSI) is needed to complete an action. This requires operators to continuously monitor the feedback from the interface and possibly to adjust action steps. For example, operators make continuous adjustments to maintain a parameter within a specified set of limits. Another example is when operators take manual control of auxiliary feedwater to maintain steam generator level between a specified upper and lower bound. In those cases the operators are engaged in continuous manual control that requires close monitoring process parameters. Continuous manual control in NPPs can be particularly challenging because of the complex process dynamics that are involved.
- Long-lasting actions – Actions that take many hours or days to achieve an intended goal, such as the actions in NPP shutdown operations or some ex-control actions. Performing steps or sequences of steps of the action require monitoring and evaluating plant status to ensure that the conditions or requirements for the steps are met.
- Non-procedural actions – Actions that operators do not have procedures or haven't been trained to perform. While this is rare in internal, at-power events, they are anticipated in many ex-control room actions and severe accidents beyond emergency-operating procedures.

We focus the literature review on the cognitive mechanisms of the first three types of actions because they are pertinent to NPP internal, at-power events. Although the mechanisms are generic to humans and are, therefore, applicable to all kinds of human actions, the long-lasting and non-procedural actions involve additional cognitive mechanisms that are not covered in this chapter.

6.2 Cognitive Mechanisms of *Action* Failure

This section provides an overview of cognitive mechanisms of action execution and the associated limitations and vulnerabilities. Appendix A.5 presents in detail the specific mechanisms for *Action* failure as well as the links between the proximate causes, underlying cognitive mechanisms, and relevant performance influencing factors (PIFs).

6.2.1 Overview of Psychological Causes of *Action* Errors

Reason (1990) presented a detailed psychological analysis of the psychological causes of errors of execution. He divided errors of execution into two major forms: slips and lapses. According to Reason (1990), "Slips and lapses are errors which result from some failure in the execution and/or storage of an action sequence, regardless of whether or not the plan which guided them was adequate to achieve its objective."

Slips are errors where actions executed are "not as planned." They typically occur in largely automatic tasks performed by a skilled individual in familiar conditions, especially when attention is diverted (e.g., because of distraction or preoccupation).

A "capture error" is a common type of slip where a more frequently performed behavior "takes-over" when a similar but less familiar action is intended. Capture errors are most likely to occur when the intended action (or action sequence) involves a slight departure from the more routinely performed action, and the action sequence is relatively automated and, therefore, not monitored closely by attention. A paradigmatic example is the case where a person intends to go to the store and the route begins the same way as her routine drive to work, but deviates at a later point. In those cases, automatic processes may inappropriately override intentional, controlled processes, and the person may find herself driving all the way to the work site rather than to the store.

A closely related psychological cause of errors of execution is negative transfer. This occurs when people are highly trained on a task that requires a particular response action and then are required to perform a different action response under very similar conditions. A paradigmatic example is learning to drive on the right side of the road and then having to drive in a different country where you are required to drive on the left side of the road.

Situational factors that can contribute to slips are instances that violate stimulus—response compatibility principles. Wickens and Hollands (2000) describe a number of important dimensions of stimulus response compatibility including:

- Location compatibility. This involves the mapping between physical location of a control and the location of the corresponding display of the value being controlled. Humans have an intrinsic tendency to move toward the source of stimulation. Controls located next to the relevant display will be less error prone. If the controls and displays (e.g., corresponding dials or meters) are organized in a non-intuitive manner that violates location compatibility (for example, if two controls are spatially crossed with their corresponding displays), errors are more likely to occur.
- Movement compatibility. This involves the mapping between the direction of movement of the control and the corresponding value being controlled. When an operator moves a position switch, rotary, or sliding control, movement compatibility defines the set of expectancies that an operator will have about how the display will respond to the control action. For example, an operator would expect that moving a switch up will cause the corresponding display value to go up. Violations of movement compatibility are more likely to result in error.
- Population stereotypes. This involves whether mappings are consistent with expectations based on experience and conventions. Mappings that are inconsistent with population stereotypes (e.g., if red is used for "go" and green for "stop") will be more error prone.
- Modality compatibility. This involves mapping the modality of the stimulus and modality of the response required. If the stimulus is in the auditory modality, performance is better when a vocal response is required than a manual response. In contrast, when the stimulus is visual, then the response is faster and more accurate if the required response involves manual pointing than a vocal response.

Another important psychological cause of execution errors is memory lapses. Lapses involve failures of memory, where an individual may forget to perform an intended action. This is often due to a failure in prospective memory—memory for intended actions in the future. Examples of lapses include instances where operators may forget to perform a specific step, may lose their place in a procedure, or may forget to perform an entire sequence of steps. Lapses most often arise when interrupted in the process of performing a task.

A common, well-studied type of memory lapse is a "post-completion" error, where an individual terminates a task prematurely and forgets to perform the final step(s) that occurs after the main goal of a task has been completed. A classic example of this is forgetting to take out the original from a copier, once the copies have been made. Post completion errors are a particular problem in maintenance tasks, where personnel may omit one or more steps involved in reassembling a piece of equipment and placing it back in service, once the main objective of the maintenance task has been accomplished. Post-completion errors have been well studied by psychologists and a number of theoretical models have been developed to explain the psychological mechanisms that produce them (e.g., Altmann & Trafton, 2002; Byrne & Bovair, 1997).

Mode errors are a form of error that shares elements of slips as well as lapses. They refer to situations where an operator loses track of what mode a system is in, where a given action will have different consequences in different modes of the system. An example is pressing the accelerator of a car to move forward when the transmission is in the “reverse” mode. Mode errors are a well-recognized problem of major concern in automated cockpits, which have various modes of autopilot control (Sarter & Woods, 1995). They can arise in NPP control rooms as well. For example, instances where actions will be blocked from having their intended effect in certain system modes due to complex interlocks. If the displays do not effectively communicate the mode of the system and the fact that there are interlocks preventing the action from having its intended consequence, then the operator may not realize that the intent of his or her action has not been accomplished.

A final psychological cause of execution errors relates to problems in manual control of continuous processes. The term “manual control deficiencies” has been used to refer to psychological causes of problems in manual control of a continuous process. In NPP, operators are often required to control dynamic systems to make them conform within certain time-space trajectories (e.g., increasing or decreasing steam generator level to a particular target value at a certain rate).

Morray (1997) provides an overview of the human performance issues associated with manual process control. Wickens and Hollands (2000) provide a concise summary of the psychological literature on manual control tasks and the factors that contribute to manual control deficiencies. They point out that there are three situational factors that can contribute to the challenges associated with a manual control task. These are:

- The dynamics of the system itself—how it responds in time to the forces applied (i.e., whether there are response lags or shrinks and swells that complicate the ability to control the parameter)
- The process change that is required (i.e., the desired trajectory of the system)
- The display of information concerning the desired and actual state of the system (i.e., whether the information required to control the process is available to the operator and how the information is displayed).

Wickens and Hollands (2000) summarize the human information processing limitations that influence the likelihood of manual control deficiencies. These include processing time, information transmission rate, predictive capabilities, processing resources, and compatibility.

Problems in manual control can lead to system instability, with excessive oscillations (overshooting and undershooting target values and trajectories) with the result that critical parameter limits may be inadvertently exceeded (e.g., steam generator (SG) level may exceed reactor trip set points).

6.2.2 Overview of *Action* Execution in the Brain

Neurophysiological Substrate for Action

To produce planned, goal-directed movements, a cognitive system must be capable of running mental processes, which virtually simulate action sequences aimed at achieving a goal. The mental process either attempts to find a feasible course of action compatible with a number of constraints (internal, environmental, task specific, etc.) or selects it from a repertoire of previously learned actions, according to the parameters of the task. Multiple brain cortical regions are involved. These regions are connected in a network. Figure 6-1 outlines the major pathways in the network: the hierarchy pathway, automaticity, and feedback.

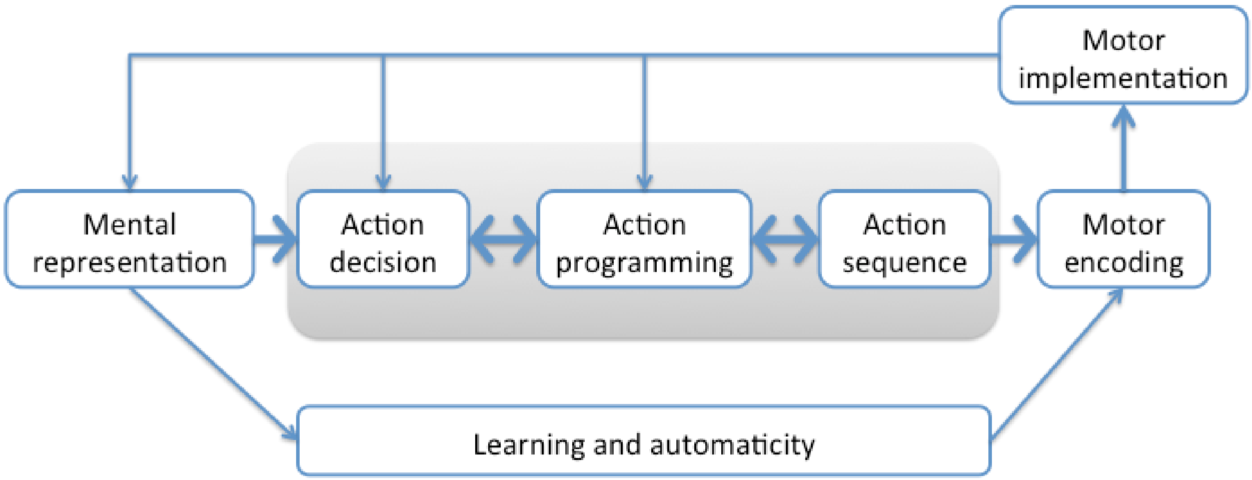

Figure 6-1. Pathways for motor execution.

Hierarchy Pathway. The hierarchy pathway involves movement programming, storing, and sequencing, and movement execution. Programming an action into a single movement or a series of movement commands is done mainly in the forward portion of the frontal lobe. This part of the cortex receives information about the movement goals and decides which set of motor organs (e.g., body, hands, or head) to be involved and how to achieve the required movements. Often an action consists of a sequence of movements in a given order and timing. The cortical network first programs the movement commands and then stores the commands in the network via working memory (in supplementary movement field of the frontal lobe), and executes the commands in the programmed order and timing. Movement commands are processed in the motor cortex, which sends signals to motor neurons to activate specific motor organs for movement execution.

Automaticity Pathway. Action automaticity is the ability to implement actions without occupying the brain with the low-level details required, allowing it to become an automatic response pattern. It is usually the result of learning, repetition, and practice. The sequence of actions appropriate to solve a problem often must be discovered by trial and error and recalled in the future when faced with the same problem. Many routine tasks are performed almost automatically, but such actions may become invalid if the environment changes, at which point individuals need to switch behavior by overcoming automatic actions that are otherwise triggered automatically. Such behavioral switching can occur either retroactively based on error feedback or proactively by detecting a contextual cue.

Sensory Feedback. Human goal-directed behavior depends on multiple neural systems that monitor and correct for different types of errors. To ensure that all of these movements are precise and coordinated, the nervous system must constantly receive sensory information from the outside world and use this information to adjust and correct the movements. According to closed-loop accounts of motor control, movement errors are detected by comparing sensory feedback to an acquired reference state. Differences between the reference state and the movement-produced feedback results in an error signal that serves as a basis for a correction.

Capacity Limits of the Neural Substrates that Perform Action Execution

The following are some capacity limits in the brain network for action implementation reported in the literature:

- Action Programming. The cortical areas for programming action (frontal motor field and lateral intraparietal cortex) can only program one action at a time (Andersen & Buneo, 2002). Therefore, if a task requires simultaneous action goals, the action programming can interfere with each other, resulting in loss of one action, incomplete action programming (e.g., missing a movement step or making the wrong movement order), or transposing movement steps in two action sequences.
- Cost of Switching. Complex jobs require frequent shifts between cognitive tasks—a change of task by requiring subjects to switch frequently among a small set of actions. A performance switch cost is observed such that switching to a new task results in a slower and more error-prone execution of the actions. The actions are substantially slower and, usually, more error-prone immediately after a task switch. Resolution and protection from interference by previous actions explain part of the switching cost. The aspects of the task set, including task variations, task-set overlap, and task-set structure, and modalities of the actions are related to action error rates caused by task switching.
- Coarse Motor Ending. Movement commands for an action generated in the action programming areas coarsely encode the direction and amplitude of the movement. Precise programming of the movement commands is achieved by continuous sensorimotor integration.
- Delayed Actions and Action Sequencing. If an action is programmed but is not executed immediately, the commands for such delayed actions or action sequences are maintained through working memory. Therefore, delayed actions and action sequences are subject to all of the capacity limits of working memory, such as the number of items that can be stored, the duration of the action commands can be maintained without attention reinforcement, and the vulnerability to disruptions. Errors of omission typically occur as the result of excessive demands on working memory.
- Automaticity. Although developing automaticity greatly reduces the demands for the brain action network to program detailed movements, the automaticity is limited to the scope of the learning and training environment. Such actions become invalid when the environment is changed.

Modulators in the Neural Substrate for Action Execution

Reaching or exceeding the capacity limits of cognitive processes can result in errors. However, in working with complex control systems, operational personnel often have to perform tasks that demand cognitive resources exceeding their capacity limits, yet they still need to perform the tasks reliably. Fortunately, the human brain has many mechanisms (referred to as modulators) that allow human information processing to cope with the limits. Moreover, humans develop and intentionally use various strategies to reliably perform complex tasks. Hence, human errors occur when the task demands reach or exceed some cognitive limits and the corresponding modulators or coping strategies are not effective.

The brain has many modulating processes to cope with the limits in the hierarchy action pathway. The following are some modulators reported in the literature:

Executive Control. Unlike a purely reactive system where the motor output is exclusively controlled by the actual sensory input, a cognitive system must be capable of running mental processes that virtually simulate action sequences aimed at achieving a goal. The lateral prefrontal cortex is critically involved in broad aspects of executive behavioral control. Neurons in this area take part in selecting attention for action and in selecting an intended action. Furthermore, the lateral prefrontal cortex is involved in the implementation of behavioral rules and in setting multiple behavioral goals. This area is responsible for strategic planning of macrostructures of event-action sequences.

Switching Control. There are control processes that reconfigure mental resources for task switching. This "switch cost" is reduced, but not eliminated by an opportunity for preparation. Advance preparation reduces task-switching cost through a preparatory control mechanism. Advance task preparation can reduce the task error rate to rates seen in non-switch trials.

Sensory Inputs in Action Programming. Errors of commission often occur because of failures to detect stimulus deviance. Precise and continuous sensory inputs make adjustments to motor functions to enhance action correctness and accuracy. Also, movement programming has been shown to be optimized when the participant is permitted to see his or her hand resting on the starting base prior to movement initiation.

Error-Monitoring and Correction. Goal-directed actions depend on multiple neural systems that monitor and correct for different types of errors, especially errors in delayed or sequences of actions. The frontal error system assesses high-level errors (i.e., goal attainment), whereas the posterior error system is responsible for evaluating low-level errors (i.e., trajectory deviations during motor control). The posterior medial frontal cortex (pMFC) is assumed to monitor performance problems and to interact with other brain areas that implement the necessary adaptations such as attentional focusing. Upon the occurrence of errors, the pMFC selectively interacts with perceptual and motor regions and thereby drives attentional focusing toward task-relevant information and suppresses the perceptual activities encoding action-irrelevant stimulus features.

Automaticity Control. The frontal cortical areas play executive roles in automaticity switching. The anterior cingulate cortex acts retroactively and the pre-supplementary motor area acts proactively to enable switching. The lateral prefrontal cortex reconfigures cognitive processes constituting the switched behavior. The subthalamic nucleus and the striatum in the basal ganglia mediate these cortical signals to achieve behavioral switching. The network enables switching by first suppressing an automatic unwanted action and then boosting a controlled desired action.

The Effects of PIFs on Modulators – How the Brain Fails to Reliably Execute Goal-Directed Actions

Although the capacity limits in the hierarchy pathway of action implementation are generally stabilized in the normal adult brain, the effectiveness and efficiency of the modulator are subject to an individual's intention, experience and strategies of activating the modulators, and individual factors such as fatigue, stress, and drug/alcohol abuse. This is particularly true for the control mechanisms. The modulators are also affected by environmental constraints and an individuals' mental condition. Cognitive and neurophysiologic studies have demonstrated many instances where the effectiveness of modulators was impaired by various factors (i.e., the PIFs). Below are some examples:

- Sleep deprivation impairs error detection and error correction (Hsieh, Tsai, & Tsai, 2009).

- Anxiety impairs error monitoring and correction (Aarts & Pourtois, 2010).
- Higher stress levels are associated with errors of commission (Helton, Head, & Kemp, 2011).
- Using memory aids can reduce the likelihood of errors of omission. According to Reason (2002), conspicuity, contiguity, content, context, and countability of the memory aids are important in reducing omission errors.

6.2.3 Summary of Cognitive Mechanisms Underlying *Action* Failures

Many cognitive mechanisms for action implementation have been revealed in neurophysiological and psychological studies. We summarize the mechanisms into three processes: control selection, cognitive aspects of action control, and motor or physiological aspects of manual execution. The table in Appendix A.5 presents detailed descriptions of the mechanisms grouped into the three processes. Here we briefly describe each process and the related mechanisms.

Control Selection. Many errors in execution are associated with unintentional failure of initiating the action or initiating the wrong action. The underlying neurophysiological mechanisms of control selection include the effectiveness of monitoring and evaluating parameters required to initiate the action and the use of feedback to detect and correct the erroneous outcomes of action steps.

- principles of response selection and compatibility (Proctor & Van Zandt, 2008; Wickens & Hollands, 2000)
- population stereotypes in control coding (Swain & Guttman, 1983)
- error monitoring and correction (Wickens, Lee, Liu, & Becker, 2004).

Cognitive Aspects of Manual Execution. The execution of an action plan can fail due to many cognitive factors. The underlying mechanisms are described in the cognitive limits of "delayed actions and action sequencing." In brief, maintaining an action plan requires working memory and attention, which are vulnerable to their resource limits and interference.

- interference (Kiesel et al., 2010; Reason, 2008)
- memory limitations (Baddeley, 1992; Dodhia & Dismukes, 2009; Reason, 2008)
- attention (Proctor & Van Zandt, 2008; Wickens & Hollands, 2000)
- stimulus response compatibility (Proctor & Van Zandt, 2008; Wickens & Hollands, 2000)
- error monitoring and correction (Wickens, et al., 2004).

Motor/Physiological Aspects of Manual Execution. An action plan can fail to be executed correctly due to many physiological factors and factors related to motor functions. The underlying neurophysiological mechanisms are described in the cognitive limit of "coarse motor encoding." That is, motor commands for an action generated by the action control mechanism only coarsely encode the direction and amplitude of the movement; precise motor execution is achieved by continuous sensorimotor integration that requires sensory feedback. In addition, the motor execution system can become automatic through training and learning; the autonomous movements occur without action control. Yet, such automaticity can introduce execution errors, as described in the cognitive limit of "Automaticity." The psychological factors affecting the motor and physiological aspects of manual execution are listed below:

- automaticity control
- negative transfer and habit intrusion (Reason, 2008)

- population stereotypes in operation of controls (Swain & Guttman, 1983)
- motor learning (Schmidt & Bjork, 1992)
- stimulus response compatibility (Proctor & Van Zandt, 2008; Wickens & Hollands, 2000)
- error monitoring and correction (Hsieh, et al., 2009; Wickens, et al., 2004)
- manual control deficiencies (Wickens, et al., 2004).

6.3 Identification of Proximate Causes

Given that the two major phases of action execution are initiating the intended action and executing the action, we identified the following two proximate causes for *Action* failure:

- *Failed to take planned action*. These are errors of omission. Only those omissions associated with action execution are considered. For example, failing to take an action because of a failure in decisionmaking would be an omission that is dealt with in Chapter 5 of this review.
- *Executed the planned action incorrectly.* This proximate cause includes errors in the outcomes of the action, such as selecting the wrong control or turning a switch to the wrong position. Actions that are carried out too slowly, too quickly, too soon, or too late are also captured by this proximate cause. It is important to note that manual execution of most actions in the control room and in the plant do not require precise (approximately seconds or milliseconds) timing.

Most existing HRA methods have accumulated state-of-practice information that classified action errors at an objective, observable level, such as the manual control failure modes from THERP (NUREG/CR-1278; Swain & Guttman, 1983) and the action error classification scheme developed as part of the ongoing U.S. Nuclear Regulatory Commission (NRC) HRA simulator data collection effort (Roth, Chang, & Richards, 2011). The proximate causes identified in this report should correspond and cover those error types in HRA methods. We reviewed those error taxonomies to better comprehend and articulate the proximate causes.

Action Failure Modes in THERP

The following list of failure modes is taken from the manual control section (Chapter 13) in THERP (NUREG/CR-1278; Swain & Guttman, 1983). As discussed in Section 6.1, it is often unclear which macrocognitive function failed to lead to an action error. For example, an operator could press the wrong button because he misdiagnosed a problem or because he got it confused with another button. This list of failure modes is appropriate for capturing the type of failures that would occur in the action execution:

- selection of wrong control
- incorrect operation of the control
- inadvertent operation of control by unintentional contact.

Action Error Classification in the HRA Simulator Data Collection scheme

The NRC developed an error classification scheme to categorize operator errors from simulator exercises. The scheme is referred to as Scenario Authorization, Classification, Analysis, and Debriefing Applications (SACADA). The scheme classifies action errors into the following types:

- Failed to take required action (did not attempt action)
- Incorrect timing

a. Delayed in initiating action
b. Performed action too slowly (behind the event)
c. Initiated action prematurely
d. Other

- Executed desired action incorrectly

a. Omitted one or more steps
b. Incorrect order of steps
c. Incorrect position (e.g., turn switch to wrong position)
d. Action prevented because of interlock
e. Manual control problem (e.g., overshot, undershot)
f. Other

- Executed undesired action (from perspective of what plant needs or requires)

a. Blocked a needed function from initiation (e.g., an engineered safety system)
b. Stopped or turned off a needed function (e.g., an engineered safety system)
c. Unnecessary initiation of a function (e.g., manual trip)
d. Other

All the above error types can be classified into one of the two proximate causes.

6.4 Summary

This chapter reviewed the cognitive mechanisms underlying action execution and identified two proximate causes for failure of the *Action* function. The chapter also briefly described how some PIFs may affect the cognitive mechanisms. We further mapped the mechanisms to one of the two proximate causes (note that in some cases a single cognitive mechanism could serve as an explanation for both of the proximate causes). We also inferred links between PIFs and the cognitive mechanisms. Appendix A.5 describes the details of these mechanisms and how they relate to the proximate causes and PIFs.

Notice that the scope of literature review in this chapter is limited to cognitive mechanisms and PIFs related to simple, sequences, or control actions in NPP internal, at-power events in which operators are well-trained to perform the actions with detailed procedures. We did not review the literature on additional mechanisms and PIFs relevant to long-lasting or non-procedural actions, or those that operators were not trained for. Such actions may require cognitive mechanisms in addition to the ones reviewed in this chapter.

7. TEAMWORK

7.1 Introduction

The vast majority of the technology used to control critical and complex systems, such as nuclear power plants (NPPs), requires teams or groups because the cognitive (and physical) requirements for operating these systems far exceed the abilities of a single person. As such, it is important to understand the cognitive basis of teamwork in human reliability analysis (HRA). *Teamwork* is the macrocognitive function that focuses on how people interact with each other to coordinate as the individual or crew works on a task. In this chapter we discuss how teamwork functions in NPPs and the unique features of team macrocognition as an emergent process. We then review major models and theories of teamwork, followed by a description of the key components of teamwork in NPPs, and identification of the cognitive mechanisms and proximate causes of failure of the *Teamwork* function. We focus the review on research findings that explain why *Teamwork* can fail (and succeed), and research that models aspects of performance that are unique to teams as they work to accomplish a common task or goal.

7.1.1 Teamwork in NPP Control Rooms

Salas, Dickinson, Converse, and Tannenbaum (1992), defined a team as "a distinguishable set of two or more people who interact dynamically, interdependently, and adaptively toward a common and valued goal/object/mission, who have each been assigned specific roles or functions to perform, and who have a limited life span of membership" (p. 4). Salas, Cooke, and Rosen (2008) elaborated on this definition by adding, "Teams are social entities composed of members with high-task interdependency and shared and valued common goals (Dyer, 1984). They are usually organized hierarchically and sometimes dispersed geographically; they must integrate, synthesize, and share information; and they need to coordinate and cooperate as task demands shift throughout a performance episode to accomplish their mission" (p. 541).

A crew of operators in an NPP is a specialized case of a team, having unique roles and responsibilities for individual members, and a clearly defined and expected approach to the conduct of operations. In the United States, commercial NPPs are required to have a minimum of three crewmembers on shift in the control room any time the plant is in operation: a senior reactor operator (SRO) and two licensed operators, one of which is assigned for the shift as the reactor operator (RO) and the other as the balance-of-plant operator (BOP). [7] The standard operating model for NPP crews has a hierarchical command structure (i.e., the SRO is in charge), and a clear division of primary responsibilities. The SRO is responsible for directing the operation of the nuclear reactor, and primarily directs the RO and BOP to manipulate the controls of an NPP. The RO manages the controls for the reactor core, and the BOP manages the balance of plant controls. The SRO is also responsible for analyzing complex plant conditions and evolutions to provide proper operations focus and ensure error-free performance, investigating off-normal system/plant status to diagnose and correct problems, and ensuring the completion of assigned activities.

The successful operation of an NPP requires effective *Teamwork*. For instance, crew members play an important 'back-up' role for each other—they both formally (formal peer checks) and informally assist in catching and recovering from errors made by others. Team situation awareness is fundamental to these roles. NPP crew members also actively contribute to decisionmaking. For example, in a properly functioning crew there are 'hold-points' before

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7. The three-operator crew model is used only as a simplified example for purposes of discussion. Most U.S. plants employ more than the minimum three-person crew for an individual control room as defined by 10 CFR 50.54(m). Typically, in addition to the three operators, there is a Shift Supervisor (SS) and a Shift Technical Advisor (STA).

major decision points (e.g., when transitioning to a new procedure; or about to take major action) where the supervisor announces his/her current understanding of the situation and what he/she has decided and solicits agreement/objection. Empirical investigations have also illustrated the importance of *Teamwork* in NPP operations. A study by Roth, Mumaw, and Lewis (1994), followed up with another study by Lang, Roth, Bladh, and Hines (2002), showed that the NPP crew's cognitive activities, which are the basis for team performance, are strongly related to successful NPP safety performance, particularly for emergency situations.

7.1.2 The Emergent Aspect of Teams

In a team setting, individual macrocognitive functions like *Detecting and Noticing* and *Understanding and Sensemaking* are often occurring in parallel by all team members. For example, in cases such as an alarm annunciation in an NPP control room, it is highly likely that all three crewmembers (e.g., the SRO, RO, and BOP) will engage, independently and in parallel, in the *Detecting and Noticing* and *Understanding and Sensemaking* functions.[8] The combining of individual macrocognitive processes that are occurring in parallel is the emergent aspect of teams. For teams to function in a coordinated fashion, the parallel processes must be merged and some emergent "group process" must ultimately occur that determines how the group proceeds. The merging of these parallel processes provides additional chances for human error and opportunities for recovery as team members interact and coordinate activities.

A number of researchers have recognized this emergent aspect of team cognitive processing. Roth, Multer, and Raslear (2006) noted that, "An area of growing consensus in the literature on teamwork is the importance of shared contextual knowledge in supporting coordination and facilitating work. Effective performance depends on shared information about both the situation and the other team members. This includes mutual knowledge and beliefs about the current situation, each other's goals, and current and future activities and intentions. Various labels have been used to denote this shared contextual knowledge, including *shared mental models* (Cannon-Bowers, Salas, & Converse, 1993); *team cognition* (Espinosa, Lerch, & Kraut, 2004), *common ground* (Clark & Brennan, 1991; Klein, Armstrong, Woods, Gokulachandra, & Klein, 2000; Klein, Feltovich, & Woods, 2005); *shared situation awareness* (Endsley, Bolté, & Jones, 2003), and *shared work space awareness* (Gutwin & Greenberg, 2004)" (p. 968).

This chapter's general focus is on the aspects of team performance that emerge because individuals are working together toward a common goal. The way this emergent aspect is distinguished from the other macrocognitive functions is by describing how and when the emergent team aspects of the *Teamwork* function become manifest within the continuously iterating evolutions of the other macrocognitive processes.

7.2 Models and Theories on *Teamwork*

7.2.1 Research on NPP Crews

Our review identified three different groups of researchers studying NPP crew behaviors, performance, and/or coordination. Roth (1997) and Vicente, Roth, and Mumaw (2001) performed field studies of NPP crews, and showed that operators often work outside of their narrowly prescribed roles as a way to try to improve their holistic understanding of the situation and improve their overall performance. According to this research, there may be cases where a

8. An exception to this parallel processing may be when a particular teammate is explicitly directed to engage in a different cognitive activity or task, given some predefined or organizationally mandated roles, responsibilities, or authorities (e.g., conduct of operations).

crewmember made a decision or took an action that was not strictly identified as being within his or her purview, but did so because he or she was attempting to:

- Enhance information extraction by increasing the salience of important indicators and reducing the background “noise.”
- Create new information.
- Offload some of the cognitive processing onto the interface (e.g., creating external aids and reminders for monitoring).

Research by Massaiu, Hildebrandt, and Bone (2011) on NPP crews in a simulator at the Halden Reactor Project produced complimentary findings to Roth (1997) and Vicente, Roth, and Mumaw (2001). From their research, they developed the Guidance-Expertise Model (GEM) of NPP control room crews in emergency response situations. GEM specifies that crews use two cognitive control modes during emergencies:

- Narrowing (where the crew is focused on the steps in the emergency procedure)
- Holistic (self-initiated cognitive activities like additional monitoring and developing team situation awareness (SA)).

GEM also posits that the control modes are affected by external PIFs, such as the quality of the emergency procedures, and internal PIFs, such as the quality of the crew’s teamwork. Interestingly, the authors also reveal that the outcome behaviors in the GEM model are not errors. Rather, they are generic types of crew activity that typically impact the performance of tasks.

Carvalho, Vidal, and de Carvalho (2007) and Carvalho, dos Santos, and Vidal (2006) also performed field studies of NPP crews, and showed that communication, shared cognition, and plant culture can affect crew coordination, and ultimately plant safety. Their analyses showed that communication was key in developing a shared understanding of the situation among the crewmembers (i.e., shared cognition), such that the correct decisions and courses of action could be taken. Perhaps more importantly, they showed that this emergent process is messy, in that:

- The communication process can iterate numerous times.
- It is not always possible to predict how many iterations it will take for a shared understanding to be created.
- Numerous cultural factors, including the leadership style of the SRO and the plant’s safety culture can affect communication and the process of forming a shared understanding, which other research (i.e., Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000) has shown is key to effective *Teamwork*.

The findings of these three groups of researchers make it clear that people are remarkably adaptable and do not always strictly follow the rules. This phenomenon persists despite intensive training, and despite the fact that the conduct of operations has been continually updated to address issues related to *Teamwork* based on years of operational experience. Reason (2008) and Hollnagel (2009) have both pointed out that this phenomenon can be both a detriment and a benefit to safety, depending on the circumstances. For example, in the behaviors described above by Roth (1997) and Vicente, Roth, and Mumaw (2001), it is possible that the crews’ coping strategies enhance performance as intended, or they may unintentionally cause an error. Crews may make errors of omission or commission when employing strategies to reduce background “noise”, creating new information, or offloading cognitive information to an external aid. In the context of GEM, crews may inappropriately engage in the “narrowing” cognitive control mode because of poor quality emergency procedures, which may then lead to an error of omission, such as failing to detect new information being presented on an auxiliary display. Crews may also inappropriately engage in the “holistic” cognitive control mode because of an unfamiliar upset condition, and consequently make an error of omission, such as failing to execute a key step in the emergency procedure. The research by Carvalho and his colleagues suggest that a poor safety culture and time pressure can lead to truncated communication among the NPP crew, resulting in an incorrect shared understanding of the situation that leads to errors in decisionmaking and/or action.

7.2.2 Team Errors: Definition and Taxonomy by Sasou and Reason (1999)

Traditionally, literature related to error analysis or error management has focused on individuals making errors. Yet in large complex systems most people work in teams or groups. Sasou and Reason (1999) have attempted to address this gap by developing a taxonomy to characterize different types of team errors. The error taxonomy has two main parts. The first part defines four error types: independent individual errors, dependent individual errors, independent shared errors, and dependent shared errors. Individual errors are made by a single team member without involvement from any other member of the team. Shared errors are errors that are shared by some or all of the team members, regardless of whether or not they were in direct communication. Individual and shared errors are further subdivided into two categories: independent and dependent. Independent errors occur when all available information is correct, whereas dependent errors occur when some part of the information is inappropriate, absent, or incorrect.

The second part of the taxonomy defines the error recovery process. The three error recovery processes are: failure to detect, failure to indicate, and failure to correct. The first step in recovering errors is to detect their occurrence. If the team does not notice the error, they will have no chance to correct them. Actions based on those errors will be executed. Once detected, the recovery of an error will depend upon whether team members bring it to the attention of the remainder of the team. This is the second barrier to team error making. An error that is detected but not indicated will not necessarily be recovered and the actions based on those errors are likely to be executed. The last barrier is the actual correction of errors. Even if the remainder of the team notices and indicates the errors, the people who made the errors may not change their minds. If they do not correct the errors, the actions based on those errors will go unchecked.

Sasou and Reason tested the utility of their definitions and error taxonomy by reviewing events that occurred in the nuclear power industry, aviation industry, and shipping industry. Their review also included an analysis that determined the relationship between the team errors they defined and PIFs. The relationship between their error taxonomy and PIFs (referred to as performance shaping factors (PSFs)) is shown in Figure 7-1.

The key information to take away from this research is that they identified many PIFs that can influence failure of the *Teamwork* macrocognitive function. The SRO mismanaging the time to engage in a course of action, leading to the crew experiencing time pressure is an example of deficiencies in resource/task management. The PIF excessive professional courtesy can contribute to the appearance of unanimous agreement in the social phenomenon of groupthink, and other social pressures like “not rocking the boat” to get along. These social pressures can lead to the failure to indicate the presence of an error and/or failure to correct an error.

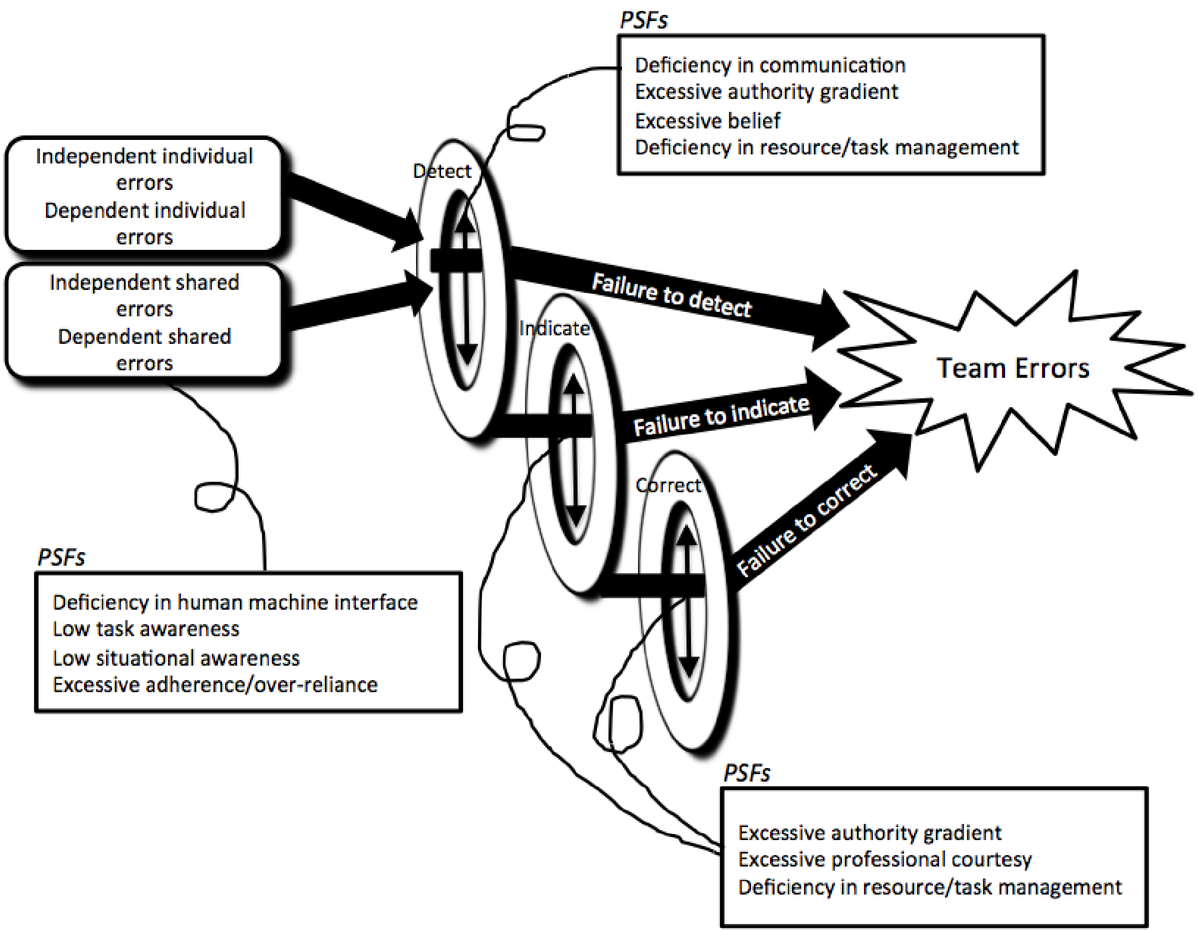

Figure 7-1. Sasou & Reason error taxonomy with mapping to PSFs.

7.2.3 Crew Resource Management

Crew Resource Management (CRM) is a training program created for the aviation industry that attempts to improve crew coordination and flight deck management (Helmreich, 1999). It focuses on team and managerial aspects of flight operations, which are complimentary components to the technical, "stick and rudder" aspects of flight. As Helmreich and Foushee (1993) put it, "CRM includes optimizing not only the person-machine interface and the acquisition of timely, appropriate information, but also interpersonal activities including leadership, effective team formation and maintenance, problem-solving, decisionmaking, and maintaining situation awareness" (p. 4).

CRM is an input-process-output model, whereby inputs are antecedent characteristics of individuals, groups, and the organizational/operational environment that are posited to influence the performance of the team. The 1993 chapter by Helmreich and Foushee describes the model for CRM in detail, so this information is not repeated here. The key information to take away from the research on CRM is that many of the factors they identified as affecting aviation crew performance are relevant to NPP crew performance, and translate into performance influencing factors (PIFs) that can explain why the *Teamwork* function may fail. CRM identifies group composition, organizational culture, and regulatory requirements as "crew performance input factor" PIFs that can affect crew performance. As an example of group composition, if the crew has not logged many hours together and/or is very inexperienced, they may not communicate effectively, which can lead to a breakdown in *Teamwork*.

Similarly, many of the "crew and mission performance functions" in the CRM model describe the nature and quality of the emergent psychological mechanisms of team performance, including communication skills, leadership, planning, prioritization, and coordination of tasking. For example, if the SRO's leadership style is highly autocratic, he may disregard contradictory information that the BOP or the human-system interface (HSI) is presenting, leading to an incorrect decision. Figure 7-2 shows the some of PIFs that have been identified by CRM.

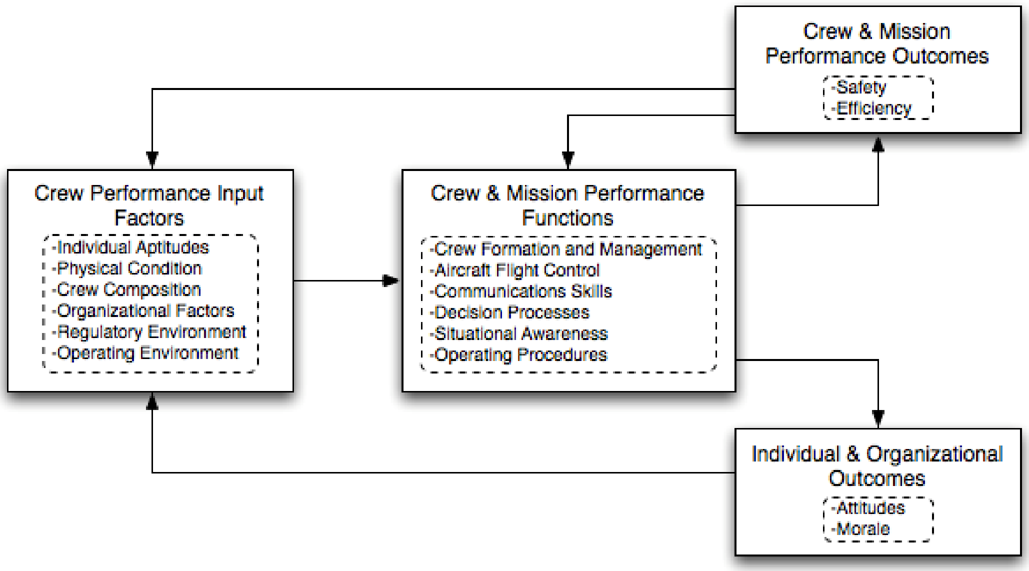

Figure 7-2. The CRM input-process-output model of crew performance.

7.2.4 Team Sensemaking

Team sensemaking is defined as the process by which a team manages and coordinates its efforts to explain the current situation and to anticipate future situations, typically under uncertain or ambiguous conditions. Team sensemaking is very similar to individual sensemaking, but Klein, Wiggins, and Dominguez (2010) argue that in many ways, it is more critical than individual sensemaking, because team sensemaking poses additional emergent coordination requirements and has additional ways for sensemaking to break down. They argue team sensemaking is more difficult to accomplish, and it may be a larger contributor to accidents than failures at the individual level.

Like individual sensemaking, Klein, Wiggins, and Dominguez (2010) describe team sensemaking as a process by which teams reconcile data with their existing frames (i.e., mental models of the situation). The steps for team sensemaking are:

- Identifying a frame to give meaning to the data deemed important enough to be captured.
- Questioning the appropriateness of the frame identified, given the data captured.
- Preserving and elaborating on the original frame, or re-framing by comparing frames or creating a new frame.

An emergent feature of team sensemaking is that the team must decide how to work together as they try to make sense of their situation. Individual team members are engaged in their own internal sensemaking process, but ultimately the team must decide on how the different individual sensemaking processes will be reconciled. Furthermore, the emergent team process of reconciling individual sensemaking applies to all steps of team sensemaking—identifying, questioning, and then preserving/elaborating or re-framing.

The general strategies in which teams work together are hierarchical, collaborative, and opportunistic. For example, if the team is using a hierarchical strategy when identifying a frame, then the team leader will decide the official conclusion. The collaborative strategy involves using consensus to make a team decision. The opportunistic strategy gives everyone on the team the same rank and responsibility for detecting problems and prescribing corrective actions. This reconciliation/resolution process is a unique feature of teams, because individuals will be going through their individual sensemaking processes in parallel, and these parallel processes must eventually be merged and/or narrowed down to one output.

The researchers elaborated on this emergent concept by developing a set of "behavioral markers" for team sensemaking, which are specific examples of the general strategies teams can employ for each step of the sensemaking process, and can serve as the basis for inferring PIFs that could affect team sensemaking. Table 7-1 lists the behavioral markers.

Table 7-1. Team sensemaking behavioral markers (Klein, Wiggins, and Dominguez, 2010).

Team Sensemaking Step	Behavioral markers
Identifying a frame	Team formulates criteria or rules used to identify the frame A team member announces the frame Team collaborates to identify the frame
Questioning a frame	Appoint a team member to play devil's advocate and raise doubts about the suitability of the frame Team creates rules or tripwires to alert them that the frame may be unsuitable Team members voice and discuss what might go wrong using the current frame
Preserving and elaborating a frame	Team discusses and rejects anomalous data as transient signals or otherwise insignificant The team's data synthesizers direct the activities of the data collectors to seek new data to verify the frame The team's data synthesizers and data collectors collaborate to discover new relationships that preserve or extend the frame
Reframing: comparing frames	Team compares frames and votes for one Team forges consensus on which frame is most appropriate Leader announces, which frame is most appropriate
Reframing: creating a new frame	Individual suggests a frame and it is adopted, modified, or rejected as the team compares frames Team speculates on data and suggests causal beliefs; leader or a team member combines viewpoints into a frame Team collaborates to synthesize competing frames

7.2.5 Macrocognition in Teams

Letsky and colleagues (Fiore, Smith-Jentsch, Salas, Warner, & Letsky, 2010; Letsky, 2007; Letsky, Warner, Fiore, & Smith, 2008) have been the main developers of the concept of team macrocognition (Figure 7-3). This model of team collaboration (i.e., *Teamwork*) was developed based on military research, and it identifies macrocognitive processes that are specific to the types of teams that are often seen in military work: asynchronous, distributed, multi-cultural, and hierarchical. The model includes four major team collaboration stages (knowledge construction, collaborative team problem solving, team consensus, and outcome evaluation and revision), and details the macrocognitive and metacognitive processes that relate to those stages.

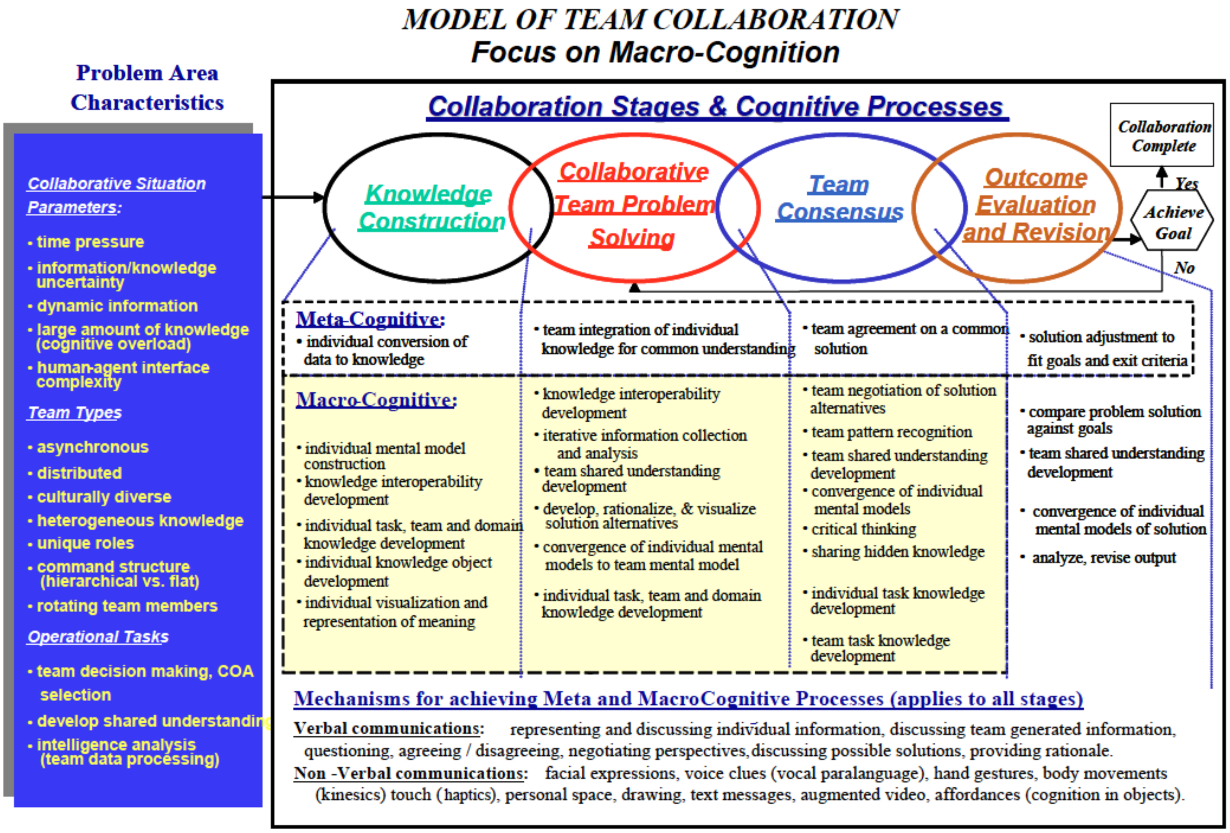

Figure 7-3. Macrocognitive model of team collaboration (Letsky, et al., 2007).

Although this model is certainly relevant to the present research effort, it was not designed with NPP operations in mind. Nuclear power operations are highly proceduralized, which provide predefined goals and decisions dictated by the procedures. There is, for example, little recognition-primed decisionmaking when operations are governed by procedures. However, there are aspects of this model that can apply to the NPP domain. For instance, it is important to note that this model has strong theoretical ties to the psychological literature, and like the work of Klein, Wiggins, and Dominguez (2010) on team sensemaking, the model touches on the idea that there is an emergent aspect to *Teamwork*.

Fiore et al. (2010) documented that team cognition "draws on four general categories of research: externalized cognition, team cognition, group communication and problem solving, and collaborative learning and adaptation" (p. 205). Team externalized cognition is the study of when, how, and why a team uses tools and decision aids such as maps, procedures, or computers to help visualize and conceptualize complex problems, and contributes to the understanding of team macrocognition with respect to how teams use technology to assist in their coordination. The research on team cognition or shared cognition augments the model of team macrocognition by providing insights into how teams communicate information and generate a common understanding of the situation, task, and/or problem. The research on group communication and problem solving is the study of how team dynamics and group processes can affect the assumptions the team makes about the situation, task, and/or "problem space" (similar to the findings in groupthink). The research on collaborative learning and adaptation provides insights into how teams work together to create new knowledge, which is one feature that differentiates *Teamwork* from an individual working in isolation.

Specifically, within the team macrocognition model, the knowledge building process is considered an emergent process in that each individual on the team is involved in their own independent process of collecting Data and converting that data into Information, and ultimately Knowledge (referred to as the D-I-K process). As Figure 7-4 shows, parallel individual processes called “individual knowledge building processes” merge together and become the “team knowledge building processes.”

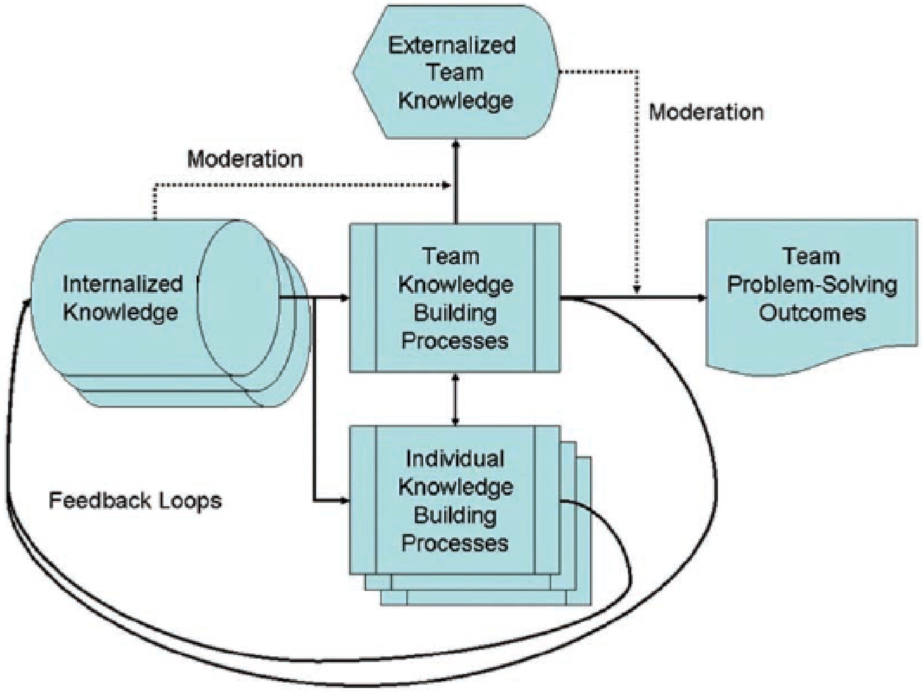

Figure 7-4. Knowledge building process within team macrocognition (Fiore, Rosen, et al., 2010).

It is also interesting to note that the D-I-K process bears a rough resemblance to the macrocognitive framework presented in this document, in that both describe cognitive processes where by external stimuli are received as inputs that are processed to facilitate a behavioral response. The key difference is that D-I-K describes the functional outcomes of the process, as data becomes knowledge, whereas the macrocognitive framework presented in this document describes the process in terms of psychological constructs.

7.3 Cognitive Mechanisms and Proximate Causes of Failure of *Teamwork*

Multiple studies have attempted to identify the important characteristics of an effective team. For example, O’Hara and Roth (2005) investigated the importance of team performance in NPPs and the role of technology in supporting and/or disrupting teamwork. Salas et al. (2005) identified team characteristics like ‘mutual performance monitoring’, ‘backup behavior’ and ‘adaptability.’ Furthermore, Paris, Salas and Cannon-Bowers (2000) summarized the skills required for effective teamwork from multiple domains into 10 teamworking behaviors: adaptability, shared situational awareness, mutual performance monitoring, motivating team members/team leadership, mission analysis, communication, decisionmaking, assertiveness, interpersonal relations, and conflict resolution. O’Conner et al. (2008) classified teamwork functions for NPP crews into five categories: building situation awareness, team-focused decisionmaking, communication, collaboration, and coordination. The first two categories are goals of teamwork, whereas the latter three categories are basic teamwork functions. Characterizing teamwork as consisting of communication, collaboration, and coordination provides a useful framework for modeling the key components of teamwork in NPP operations.

- *Communication* is concerned with the exchange of any information between different team members. Communication includes assertiveness (i.e., communicating ideas and observations in a manner which is persuasive to other team members) and exchanging information clearly and accurately between team members (O'Conner et al., 2008). The failure to exchange information and coordinate actions is one factor that differentiates between good and bad team performance (Driskell and Salas, 1992).
- *Coordination* applies to team members organizing their joint activities to achieve a goal. In particular, NPP operations team members must support the other members of the team as required and monitor their own and others' workload. O'Conner et al. (2008) use coordination to refer to temporal relationships among activities. Coordination includes reacting flexibly to changing requirements of a task or situation, giving help to other team members in situations in which it was thought they need assistance, and prioritizing and coordinating tasks and resources.
- *Collaboration* refers to the manner in which members of a team are working together. O'Conner et al. (2008) characterize the elements of collaboration as leadership (directing and coordinating the activities of, and motivating other team members, assessing team performance, and establishing a positive atmosphere), cooperation (two or more team members working together on a task which requires meaningful task interdependence without any leadership), and followship (cooperating in the accomplishment of a task as directed by a more senior team member).

Theoretically, the proximate causes for failure of *Teamwork* can be attributed to the three basic teamwork processes identified by O'Conner et al. (2008): communication, collaboration, and coordination. However, failures that are unique to the macrocognitive function of *Teamwork* in control room settings and independent of each other can be more simply grouped into two categories: communication and leadership (which is one of the elements in collaboration). Failures in coordination (adaptability, supporting behavior, and team workload management) can be attributed to either failures of communication or leadership. In addition, the cooperation and followship elements of collaboration are less relevant for NPP control room operations during at-power events given the highly structured and proceduralized environment. Therefore, we focus on two key proximate causes of failure of *Teamwork* in the NPP control room: communication and leadership.

7.3.1 Communication

Communication is ubiquitous in *Teamwork* because every aspect of coordination and team performance depends on communication, either in real-time or during prior planning stages. In identifying the key communication-related cognitive mechanisms underlying the *Teamwork* function, we considered the fact that there are, in the simplest case, two different people involved in the communication process: the source of the communication (sender), and the target of the communication (receiver). Both the source and target of the communication can commit either errors of omission or errors of commission. Finally, in the simplest case, the communication process (or cycle in "three-way communication") needs to occur only one time. When these concepts are combined, the following basic cognitive mechanisms can be identified:

- Source error of omission (sender does not communicate information).
- Source error of commission (sender communicates wrong information).

- Target error of omission (receiver does not detect or notice communication, or receiver does not comprehend information).
- Target error of commission (receiver is listening to the wrong source, or receiver is listening for wrong information).
- Incorrect timing of communication (e.g., delayed, premature, communicated too slowly).

Lee, Ha, and Seong (2011) performed an analysis of communication errors using a derivation of the Cognitive Reliability and Error Analysis Method (CREAM) (Hollnagel, 1998) and developed a very similar set of communication error types. Their nine communication error types, shown in Table 7-2, are organized by error mode, and focuses on the source/sender and message content errors, but not on target/receiver errors.

Table 7-2. Communication error types (Lee, Ha, and Seong, 2011).

Error Mode	Error Type
Timing (too early, too late, omission)	Message is sent at the wrong time Message is not sent at all
Acoustic feature (uncommon)	Message is sent with an uncommon acoustic feature
Channel (wrong direction, wrong route)	Message is sent to the wrong place or person Message is sent through an inadequate route
Contents (wrong terminology, unexpected contents for receiver, unrelated contents)	Message production is inadequate Message content is inappropriate for the receiver Message content is wrong
Sequence (jump forward, repetition, reversal)	Message content is inconsistent with other information

There are numerous PIFs that can influence team communication. Groth & Mosleh's (2012) taxonomy of PIFs, discussed in Chapter 2, included team-based factors, such as team coordination, team cohesion, and role awareness. Each of these PIFs can influence the cognitive mechanisms related to communication in a team setting. For example, a lack of team coordination may adversely affect the timing of communication. Similarly, a lack of role awareness may result in either a source or target error of omission, because the crew member is not aware of his or her responsibilities for communicating information or receiving information from other crew members. Additional types of PIFs that can affect team communication include social or environmental factors (e.g., time pressure, team dynamics, excessive authority gradient), and individual differences (e.g., knowledge/experience, risk perception, excessive professional courtesy). Appendix A.5 provides more detail on how each of the communication cognitive mechanisms ties to various PIFs and is explained by various theories and models in psychology. For example, a source error of omission could be due to team cohesion (Helmreich & Foushee, 1993), social pressure (Zajonc, 1965), or groupthink (Janis, 1972, 1982), just to name a few PIFs and their psychological bases.

Complexities of Communication

In addition, communication in NPPs rarely involves only the simplest case of one sender and one receiver. A NPP control room has at least three crewmembers. Moreover, if communication is occurring outside of the control room, there may be more than three individuals involved, and it is important to note that the growth of opportunities for communication errors is geometric as additional individuals become involved in the communication process.

However, in the more complicated instances of communication involving more than two individuals, the cognitive mechanisms do not fundamentally change. The extent and severity of the *consequences* of communication errors may become increasingly more complicated as the number of individuals involved increases. Some example consequences include an individual failing to have an updated understanding of the situation (when everyone else has the correct updated understanding of the situation), multiple individuals having the same incorrect understanding of the current situation, or multiple individuals having different incorrect understandings of the current situation.

7.3.2 Leadership

In the context of this chapter, leadership includes the management of the emergent team process, which is likely to manifest itself multiple times during an operating shift. That is, individual macrocognitive functions like *Detecting and Noticing* and *Understanding and Sensemaking* are regularly occurring in parallel by all team members when a crew is on duty, and leadership is required when it is necessary to combine these independent processing efforts in order to facilitate *Teamwork.*

At a minimum, leadership involves making decisions, supervising direct reports, communicating, and managing the emergent *Teamwork* processes. Given this minimal definition, the cognitive mechanisms for leadership mirror these aspects. The cognitive mechanisms for leadership include:

- Decisionmaking failures.
- Failure to verify that the RO, BOP, and/or other operator have correctly performed their responsibilities.
- Failure to consider information communicated by an individual.
- Failure to iterate the communication process sufficiently.

Leadership decisionmaking works in the same way as other individual decisionmaking processes. As such, PIFs related to decisionmaking are discussed in Chapter 5 as part of the *Decisionmaking* macrocognitive function. In the context of *Teamwork*, leadership decisionmaking can affect how parallel processes are combined by the team to develop a shared understanding of the situation, make a decision, and proceed to take actions based on that decision.

For supervision failures, the relevant PIFs include time pressure, organizational influences (team composition, role definitions, operating philosophies, etc), and individual differences in leadership style. For example, time pressure may cause the SRO to rush through his or her responsibilities and he or she decides to skip the task of performing a second check (Helmreich & Foushee, 1993). Another example is the SRO's leadership style could be more "hands off," and so instead of micromanaging, the SRO decides not to perform a second check of a routine action (Massaiu, et al., 2011).

An example of failure to consider information communicated by an individual is when the SRO ignores or discounts information the RO or BOP is communicating because of poor team cohesion (Helmreich & Foushee, 1993). Leadership style can also serve as a PIF for this cognitive mechanism. For example, an overly autocratic SRO who is unwilling to consider the RO's and BOP's perspectives may create a large power distance gap between the crew members, such that they are unwilling to challenge the SRO with contrary information

(Helmreich & Foushee, 1993). On the other hand, an important aspect of the SRO leadership is to discount unsound hypotheses from other operators, and terminate unfruitful discussions.

The combining of parallel processing efforts is usually done through communication, which can be a highly iterative process (Carvalho, et al., 2007). Communication among team members is rarely a one-time event, and team leaders can have a strong influence on how much the communication process iterates to develop a shared understanding of the situation, make a decision, or take action. The amount of iteration needed can depend on the complexity of the event and the degree of divergence between crew members' parallel processing efforts. In instances where the crew is engaged in understanding an event that they have not trained on recently, communication is likely to be highly iterative. An example of leadership failure to iterate the communication process would be if the SRO cuts off debate with the RO and BOP prior to having a sufficient understanding of the actual situation.

7.4 Summary

This chapter summarized the psychological research literature relevant to teamwork in NPP operations. We focused on two key proximate causes that contribute to failure of the *Teamwork* function: communication failures and errors in leadership. Each proximate cause encompasses a number of cognitive mechanisms that explain how the *Teamwork* function can fail. It is clear from this review that there are many different researchers who have studied team performance (c.f., Roth, 1997; Carvalho, Vidal, and de Carvalho, 2007; Sasou and Reason, 1999; Salas, Cooke, and Rosen, 2008; Klein, Wiggins, and Dominguez, 2010; Letsky et al., 2007). Each of these researchers approached the study of team performance from a different perspective, and provided insights into a variety of PIFs that can influence the failure of *Teamwork* in NPP operations. Appendix A.5 contained additional information about linkages between these PIFs and cognitive mechanisms.

The scope of this review focused on communication and leadership as proximate causes because those aspects of *Teamwork* were deemed relevant to crew interactions in NPP control rooms during at-power events. However, we noted that teamwork can also involve elements of coordination and collaboration. There may be unique aspects of coordination or collaboration that are not covered by the proximate causes of communication and leadership and, therefore, should be considered in the future when modeling activities outside the control room. Another limitation in this chapter is that it focused on an individual's contribution to teamwork, without specifically addressing many team-level characteristics. Thus, some mechanisms identified in this chapter are already covered under the mechanisms for other macrocognitive functions (e.g., under the 'failure of leadership' mode, the mechanism 'failure to consider information communicated by an individual' is equivalent to 'information not attended to' in the *Detecting and Noticing* function). In general, the team functions highlight some additional error mechanisms for a specific individual (the leader) and classes of recoverable communication errors. As a result, organizational factors that influence team performance are not explicitly included as PIFs. Examples include openness and democracy of team, procedure compliance policy, and prescribed communication protocols. There may be an opportunity to expand the scope of this review in the future to include more complete coverage of team-level and organization-level characteristics that influence macrocognition.

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Appendix A
Cognitive Mechanism Tables

This appendix contains detailed information about the behavioral and cognitive sciences literature reviewed to establish a psychological foundation for human reliability analysis. The purpose of these tables and the related cognitive framework diagrams in Appendix B is to map out the cognitive mechanisms and performance influencing factors (PIFs) that explain why a macrocognitive function may fail.

Section A-1 contains the cognitive mechanism tables for failures of *Detecting and Noticing.*

A-1.1 Cue/information not perceived

A-1.2 Cue/information not attended to

A-1.2 Cue/information misperceived

Section A-2 contains the cognitive mechanism tables for failures of *Understanding and Sensemaking.*

A-2.1 Incorrect data

A-2.2 Incorrect integration of data, frames, or data with a frame

A-2.3 Incorrect frame

Section A-3 contains the cognitive mechanism tables for failures of *Decisionmaking.*

A-3.1 Incorrect goals or priorities set

A-3.2 Incorrect internal pattern matching

A-3.3 Incorrect mental simulation

Section A-4 contains the cognitive mechanism tables for failures of *Action.*

A-4.1 Failure to take required action (action not attempted)

A-4.2 Execute desired action incorrectly

Section A-5 contains the cognitive mechanism tables for failure of *Teamwork.*

A-5.1 Failure of team communication

A-5.2 Error in leadership/supervision

Each section in this appendix provides a brief review of the macrocognitive function, proximate causes of failure of the function, and associated cognitive mechanisms. The sub-sections are organized by proximate cause, and include a table listing the cognitive mechanisms for each proximate cause.

The first column in each table lists the cognitive mechanisms. The second column includes a discussion and explanation of each mechanism. The third column provides a real-world example of the mechanism. The fourth column lists the PIFs that have been identified as relevant to the mechanism. The fifth column provides additional discussion of why the PIF is relevant. The last column contains the literature sources referenced in the row. Sometimes there is more than one row dedicated to each mechanism; this represents different literature sources that highlight different aspects of the mechanisms.

This appendix should be used in conjunction with the cognitive framework diagrams in Appendix B. The diagrams are a graphical summary of the information in these tables.

A-1. DETECTING AND NOTICING

This section of Appendix A contains the cognitive mechanism tables for the *Detecting and Noticing* macrocognitive function. *Detecting and Noticing* is the process of perceiving important information in the work environment. This macrocognitive function emphasizes the sensory and perceptual processes that allow humans to perceive large amounts of information and focus selectively on those pieces of information that are pertinent to present activities.

Detecting and Noticing represents the process of detecting meaningful signals from a large bulk of information received by the sensory organ. Sensory information can only be retained for a short interval before being replaced by new sensory information. Moreover, a person can only attend to a limited amount of information at a time. When there is too much meaningful sensory information, an individual may not be able to detect and notice all of that information, resulting in sensory overload. Conversely, a lack of salient sensory information may cause important plant information to go undetected or unnoticed. When meaningful cues fail to be sensed or perceived it automatically results in a failure of the subsequent macrocognitive function of *Understanding and Sensemaking*.

Chapter 3 discusses *Detecting and Noticing* in more detail.

In general, failure of the *Detecting and Noticing* macrocognitive function means that the person does not have the necessary information, or has incorrect information, to appropriately respond to the situation. Without the correct information, the operator is likely to have an incorrect diagnosis of the situation, and is likely to make incorrect decisions about how to respond to the situation. In these cases, however, the root failure is in *Detecting and Noticing*. Three proximate causes have been identified as potentially leading to this failure. Those proximate causes and cognitive mechanisms are:

1. Cue/Information not perceived (Table A-1.1)
    a. Cue content
    b. Vigilance in monitoring
    c. Attention
    d. Expectation
    e. Working memory
2. Cue/Information not attended to (Table A-1.2)
    a. Cue content
    b. Vigilance in monitoring
    c. Attention
    d. Expectation
    e. Working memory
3. Cue/Information misperceived (Table A-1.3)
    a. Cue content
    b. Vigilance in monitoring
    c. Attention
    d. Expectation
    e. Working memory

A-1.1 Cue/Information Not Perceived

This table contains the cognitive mechanisms for the Cue/Information Not Perceived proximate cause. When this is the cause of *Detecting and Noticing* failure, the cue or information may simply be missed, not seen, or not heard, in which case it is not perceived. For example, a control room operator may not notice that an important indicator is trending downward. This proximate cause can be explained by the following cognitive mechanisms:

1. Cue content: Cue salience is low and not detected. For example, the operator fails to detect "low" indication because scale of trend display makes subtle changes difficult to see.
2. Vigilance in monitoring: Unable to maintain vigilance. For example, the operator is fatigued at the end of the night shift and has difficulty monitoring the plant. Alternatively, the operator must attend to several indications following a plant transient, thereby missing important cues.
3. Attention: Inattentional blindness—missing something that is in plain sight. For example, the operator may not perceive a plant indicator because it is not the focus of the operator's attention.
4. Expectation: Mismatch between expected and actual cues. The operator may not notice a plant indicator because he or she is not looking for it. This may occur because of the operator's mindset—if the operator has a particular hypothesis about the plant condition, he or she will look for information to confirm that hypothesis but may not equally look for information to disconfirm it.
5. Working memory: Working memory capacity overload. If the operator attends to multiple alarms simultaneously, they may reach a state of information overload in which he or she is focused on a particular alarm panel and may miss additional alarms or indicators elsewhere in the control room.

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Attention	Change blindness is failure to detect changes in the visual environment due to limitations of working memory. Change blindness is inability to predict the level of missed information and an overconfidence that the visual environment has been perceived correctly. Experiment 1 of this study looked at the effect of intentional search on change blindness. If participants were deliberately/intentionally looking for differences, they were significantly more likely to detect changes in the environmental than if they were not specifically looking for changes.	An operator actively looking for changes in the environment/ instrumentation is more likely to detect such a change than an operator who is not actively looking for changes.	• Intention (motivation) • HSI	Participants who were intentionally looking for changes in the environment had 91% accuracy in detecting changes in the environment, while participants who were incidentally but not specifically looking for changes had 38% accuracy.	Beck, Levin & Angelone (2007)
Attention	The potential for change detection failure during the monitoring of a military digital situation awareness map was investigated.	If an operator is monitoring a complex group of indicators, the disappearance of a	• HSI	The ability to detect changes is dependent on the context of surrounding information. If only a	Durlach, Kring & Bowens (2008)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	Participants were asked to monitor the map for icon appearance or disappearance. A change accompanied by two other changes was detected 69.3% of the time, while the same change occurring alone was detected 79.6% of the time. When three changes occurred simultaneously, all three were detected only 37% of the time. Detection of icon appearance was superior to detection of icon disappearance.	single indicator will be perceived better than if a group of indicators disappears.		single item was changed in a simplified display, it was detected 79.6% of the time. If three changes occurred simultaneously, information context was lost, and the changes were detected only 37% of the time. Change detection varied as a function of whether information was added or deleted. Change detection performance was significantly higher for added items than for deleted items.	
Attention	Change detection was monitored as a function of visual mismatch negativity, a negative reflection in the visual event-related potential evoked by infrequent deviant stimuli. The study found that automatic change detection continued despite high workload. However, as the frequency of the change was increased, the sensitivity of the brain to the change decreased.	If an operator sees a frequent change, he or she may become desensitized to it. This effect is seen in nuisance alarms.	• HSI	Increasing frequency of visual mismatch results in a decreased brain response to change.	Tales, Porter & Butler (2009)
Attention	Change detection exists as a method of testing human perception through rapid presentation of alternating images. Across three experiments, this paper offers insights on the optimal presentation for rapid presentation of alternating images. It was found that increasing the number of presentations strengthens the ability of participants to detect changes, as does maintaining an alternating source-target order for presenting images. While primarily a methodological improvement study, the article highlights the importance of training to improved change detection.	Because of training, an operator may learn to detect changes in indications more quickly than without training.	• HSI	Color and position of changes did not vary significantly in time to detect, but presence differences (appear versus disappear) were quickest to be detected. Training on change detection significantly decreased detection time.	Vierck & Kiesel (2008)
Attention	This experiment reviewed the performance of participants for change detection across different situations. The primary situational distinction involved top-down versus	An operator who employs an active search strategy guided by attentional focus is more likely to detect changes to instrumentation than	• HSI: Type of cue salience • Motivation: Type of strategy used to detect changes	Those participants employing a top-down strategy were 9% more accurate at change detection than those relying on bottom-up cues. Top-down	Bubić (2008)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	bottom-up processes. Top-down here is defined as a cue specifically requiring attentional selection, while bottom-up is defined as a salient cue that does not require specific attentional mechanisms to draw focus. The results showed that change detection was more effective when relying on a top-down strategy of focused attention than when relying on salient cues from the environment.	one who relies on the salience of the instrumentation cues.		participants were also on average .74 seconds faster at change detection than bottom-up participants.	
Attention	If a person's attention is locked onto a particular location or object, then the onset of signals in different locations is less likely to attract attention.	Operator focuses on a specific indicator and misses additional information elsewhere on the panel.	• Attention	Perceptual focus determines what is perceived	Nikolic, Orr, & Sarter (2004)
Vigilance in monitoring	In this model, vigilance or sustained attention is resource demanding and effortful, and humans have only a limited amount of “attentional resources.” As attentional resources are used, stress levels can increase over time because the requirements to remain vigilant are unrelenting. Once those attentional resources are depleted, our ability to maintain attention or be vigilant is compromised.	When attentional resources are depleted, or being used for other tasks, even a clearly presented cue may not be perceived.	• All of the PIFs listed under the category "Personal PIFs"		Szalma et al. (2004) MacLean et al. (2009) Davies & Parasuraman (1982)
Vigilance in monitoring	Attention as a psychological construct (a construct is a hypothetical explanatory variable which is not directly observable) is a key aspect of detect/ notice. External stimulus or stimuli that attract our attention also tends to guide our visual gaze (e.g., a flashing light; even a loud noise tends to cause us to look in the direction from which the sound emanated).	A cue such as flashing light, even a loud noise tends to cause us to look in the direction from which the sound emanated. However, when the stimuli does not have sufficient "activation energy" that exceeds a biologically determined threshold that triggers a sensory response in us, we fail to perceive the cue.	• HSI	The external stimulus or stimuli must have an "activation energy" that exceeds a biologically predetermined threshold for detecting/noticing/sensing objects in the world around us, causing our attention to focus on that stimulus.	Lavine et al. (2002)
Vigilance in monitoring	The presence of a demanding central task effectively narrows or "tunnels" the functional field of view, making it more difficult to extract information from the periphery.	When an operator is engaged in a cognitively demanding task, he is less likely to notice cues that are in the periphery of his visual focus.	• Task load	Refers to visual cues. Mental workload (anything that loads the central executive) creates attentional narrowing.	Nikolic, Orr, & Sarter (2004)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Vigilance in monitoring	The sympathetic response is the action to mobilize the body's resources under stress to induce the fight-or-flight response. It is what causes people to become more anxious under stressful conditions.	1. Not being sufficiently stressed causes an operator to not have sufficient attentional resources at the ready to perceive cues. 2. Too many cues being presented simultaneously causes one to be over-stressed, and in this highly anxious state, an operator may not perceive a critical cue amongst the multitude of other cues	• Stress	Depending on the magnitude of the sympathetic response, an individual may not be sufficiently stressed, or over-stressed. Not being sufficiently stressed may lead to the cue not being perceived. Being over-stressed, for example, by an alarm flooding situation, may lead to a critical cue not being perceived.	Aarts & Pourtois (2010)
Vigilance in monitoring	In this experiment, the interaction of the central executive (related to working memory) and situation awareness was explored. Participants for low, medium, and high situation awareness were given a driving task. Participants with low situation awareness performed significantly worse at tasks involving the central executive. When taxing the central executive with increased workload, the low situation awareness group committed significantly more driving errors than the high situation awareness group. The driving errors were related to cue detection, primarily in the form of detecting information too late to respond properly in the driving simulator, resulting in a simulated impact or road departure.	Operators may have different levels of situation awareness, and individual operators' situation awareness may be impacted by external factors such as stress. For low situation awareness, the operators' ability to detect relevant cues is particularly diminished when there is high workload.	• Task load	Individual difference in situation awareness. Beyond that, a task involving increased workload in working memory/central executive will result in significant decrease in performance on detection-related tasks.	Soliman (2010)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Vigilance in monitoring	Humans are remarkably adaptable. Humans can cope with the constraints of their environment through strategically adapting their behavior to maximize their success (survivability). In the context of NPPs, operators implement 3 strategies to facilitate their task performance (e.g., monitoring). They (a) enhance information extraction by increasing the salience of important indicators and reducing the background "noise," (b) create new information, and (c) offload some of the cognitive processing onto the interface (e.g., creating external aids and reminders for monitoring).	Operators may (a) enhance information extraction by increasing the salience of important indicators and reducing the background "noise," (b) create new information, and (c) offload some of the cognitive processing onto the interface (e.g., creating external aids and reminders for monitoring).	• Morale/ motivation/ attitude	If any of the 3 strategies the operators use fail, it can lead to a cue not being perceived.	Mumaw et al. (2000) Vicente et al. (2001) Vicente et al. (2007)
Vigilance in monitoring	Szalma et al. (2004) showed that the interaction of factors such as sensory modality and workload (time on task) affect stress levels differentially. Stress can either be exacerbated or attenuated depending on how the factors interacted with each other.	Observers became more stressed over time, with evidence of recovery in the auditory but not the visual condition toward the end of the watch.	• Stress • Task load	As stress and workload increase, ability to perceive or attend cues decreases	Szalma et al. (2004)
Vigilance in monitoring	Perceptual Control Theory (PCT) states that people act on their surroundings, the environment, so as to control the effects the environment is having on them. In PCT, organisms generate actions affecting the environment near them, thus altering the environment and creating or changing experiences at many levels in the way desired by the organism. PCT relates to the findings from Mumaw et al. (2000), Vicente et al. (2001), and Vicente (2007) in that what they describe as the key "adaptable" behaviors operators engage in, namely: (a) enhance information extraction by increasing the salience of important indicators and reducing the background "noise," (b) create new information, and (c) offload some of the cognitive processing onto the interface, are all examples of the operator attempt to exert more control on their	Operators may (a) enhance information extraction by increasing the salience of important indicators and reducing the background "noise," (b) create new information, and (c) offload some of the cognitive processing onto the interface (e.g., creating external aids and reminders for monitoring).	• Morale/ motivation/ attitude	If any of the 3 strategies the operators use fail, it can lead to a cue not being perceived.	Powers (1973) Hendy et al. (2001) Mumaw et al. (2000) Vicente et al. (2001) Vicente et al. (2007)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	environment so as to improve their performance (or minimize the likelihood of committing an error)				
Vigilance in monitoring	Failure to perceive the status, attributes, and dynamics of relevant elements in the environment.	Distractions by other relevant tasks, an overall high level of workload, distractions by unrelated situations/tasks, vigilance problems, or overreliance on automation.	• Attention (to task and to surroundings) • Physical & psychological abilities • Task load • Non-task loads	Decrease in perception due to PIFs	Endsley (1995)
Vigilance in monitoring	The relationship between workload and vigilance is similar to that of stress and attention.	1. Tasks too low in complexity cause an operator to not be engaged in the task and have sufficient attentional resources at the ready to perceive cues. 2. Tasks too high in complexity may cause an operator to not perceive a critical cue amongst the multitude of other cues	• Task complexity	Depending on the task's complexity, an individual may not be sufficiently engaged to perceive to the cue, or over-worked.	Donald (2001) Liu et al. (2009)
Vigilance in monitoring	Hitchcock et al. (2003) found a main effect for type of automated warning cue: correct detection of critical signals was best with warning cues of 100% reliability and progressively poorer as warning cue reliability decreased to 80%, 40%. Correct detection performance was worst with no automated warning cue.	Operators are less likely to detect warning cues that are unreliable.		Refers to visual cues. Warning cues that are highly reliable lead to significantly better operator performance than warning cues that are unreliable or unavailable.	Hitchcock et al. (2003)
Vigilance in monitoring	The relationship between workload and vigilance is similar to that of stress and attention.	1. Not having sufficient workload causes an operator to not be engaged in the task and have sufficient attentional resources at the ready to perceive cues. 2. Too many cues being presented simultaneously causes one's workload to be too high, and in this state, an operator may not perceive a critical cue amongst the multitude of other cues		Depending on the amount of work being loaded on to the operator, an individual may not be sufficiently engaged to perceive the cue, or over-worked.	Donald (2001) Liu et al. (2009)
Cue content	The context in which the target cue is displayed influences the likelihood of	If the cue that operators need to attend to is the same	• HSI	Refers to visual cues. Cues surrounded by other dynamic	Nikolic, Orr, & Sarter (2004)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	detection. Specifically, targets embedded in same-color or dynamic displays were the most difficult to detect (targets in color AND dynamic displays had marginally worse detection rates). The detection rate for the color-dynamic displays was 32 percentage points lower than the control, and 20 percent lower than mono-static displays. The combination of color and motion surrounding the target cue had the most detrimental effect on detection performance. Note that this study involved identifying target cues in peripheral vision when the participant was engaged in a cognitively demanding primary task.	color as irrelevant information in the same display, or if it is embedded in other dynamic indicators, they are less likely to notice the cue.		information, such as moving dials or indicators also in the same color as the target cue are less likely to be noticed when the person is attending to another task. The poor detection performance may be the result of masking by surrounding moving display elements, the color similarity between target and background, or a combination.	
Cue content	The SEEV model is based on the plausible assumption that four factors drive the acquisition of visual information: the salience (S) of events that might capture attention; the effort (E) required to redirect attention from one location to another (i.e., visual saccade, head rotation), which will inhibit information access; the expectancy (E) that a given location in the visual field will contain information; and the value (V) of information to be obtained at that location for the task or tasks at hand.	The four criteria/factors in this model must be met in order for a cue to be perceived. In particular, the salience of the cue is critical for perception to occur.	• HSI	If the cue is not presented to the operator with sufficient strength/energy to distinguish itself from existing background noise such that it activates a sensory response in the operator, the operator may not perceive it.	Steelman-Allen et al. (2009)
Cue content	The consistency, predictability, distinctiveness, and interpretability of the signal affect vigilance.	1. If the cue is not consistently presented, the operator may not perceive it. 2. If the cue is unpredictable, the operator may not perceive it. 3. If the cue is not presented to the operator with sufficient strength/energy to distinguish itself from existing background noise such that it activates a sensory response in the operator, the operator may not perceive it.	• HSI	Cue qualities (consistency, predictability/reliability, and strength) affect perception	Donald (2001) Liu et al. (2009) MacLean et al. (2009)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Cue content	The human's ability to detect or sense a stimuli is a function of (1) how clearly that stimuli is present over and above existing background noise (e.g., the cue's signal to noise ratio), and (2) the extent to which the human is willing to accept an error of omission versus an error of commission.	The cue is not presented to the operator with sufficient strength/energy to distinguish itself from existing background noise such that it activates a sensory response in the operator.	• HSI • Workload • Task complexity • Stress	The signal to noise ratio is too low for the operator to be able to perceive the cue (i.e., distinguish it from noise)	Bustamante (2008)
Cue content	Whether the signal is successive (serial) or simultaneous, and whether it is sensory or cognitive affects vigilance.	1. If cues are presented serially, but there is not adequate time to perceive each one before the next is presented can cause the operator to not perceive the cue. 2. If two cues are presented simultaneously, the operator may not be able to perceive both.	• HSI	Cue presentation order affects perception	Donald (2001) Liu et al. (2009)
Expectation	Expectations of a particular type of signal, such as onsets, offsets, or color changes, will increase the likelihood of that particular cue to capture attention. In other words, visual onsets per se do not necessarily capture attention. Instead, the likelihood of detection depends on the match between a person's active attention control settings and properties of the appearing signal.	Operator expects a particular indicator and misses a contrary indication elsewhere on the control panel.	• Training, experience, bias	Refers to visual cues. Training/experience leads to expectations or bias about the type of cues to watch for.	Nikolic, Orr, & Sarter (2004)
Expectation	Van Zoest et al. (2007) found that people are able to complete a search much faster if they had a prior look at the display (i.e., they are able to complete an interrupted search faster than starting a new search). Rapid resumption of the search is based on target pre-processing and hypothesis formation in the last look before locating the target.	Operators know what information they are looking for, and they know where it is located, because they are well-trained on the control panel layout. However, in diagnosing a problem, they may perform a visual scan of control boards. Scanning without interruptions results in quicker diagnosis.	• Experience/ Training	Refers to visual cues and scanning.	Van Zoest (2007)
Working memory	Broadbent's "filter theory" explains sensory bottlenecks—the alarm might be missed because humans have a limited ability to take in stimulus inputs and perceive them. It is possible to reach	Filter theory has direct implications for plant environments like control rooms, where concurrent tasks and multiple simultaneous alarms may trigger sensory	• Task load	Sensory bottlenecks dictate ability to perceive information.	Broadbent (1958)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	sensory bottlenecks, which can result in sensory overload.	overload and lead to missing information.			
Working memory	Suggests that sensory information is held in very short-term memory. If that sensory information is not attended to, it will be lost.	The implication is that plant information may be lost if the operator does not attend to it. If the cue is not presented in sufficient (strength/length/salience) for the operator to register it, it is lost.	• HSI, hardware failure (e.g., bulb burned out upon illuminating)	Strength, length, and salience of cues affect ability to perceive.	Neisser (1967)
Working memory/Vigilance in monitoring	An experiment is presented that demonstrates the effect of working memory on vigilance. Using a visiospatial monitoring task, participants were given either a task that taxed visiospatial working memory or nonspatial working memory. Over a 20-minute period, vigilance decreased significantly for the task using visiospatial working memory but not for the nonspatial working memory.	If an operator must maintain visual information in working memory and monitor visual indicators, the overlap of working memory and perception will result in a high workload, leading to mental fatigue and decreased vigilance.	• Task load	There was a significant interaction of working memory type on vigilance. Vigilance decreased significantly over time for a type match between information in working memory and perceptual cues. In other words, a large degree of overlap resulted in working memory interference and increased workload, decreasing the amount of time the operator could maintain vigilance.	Caggiano & Parasuraman (2004)

A-1.2 Cue/Information Not Attended To

This table contains the mechanisms for the Cue/Information Not Attended To proximate cause. When this is the cause of *Detecting and Noticing* failure, the cues or information may be sensed and perceived but not attended to—in other words, the sensory-perceptual system acts as a filter, and this information is not propagated for further *Understanding and Sensemaking*. For example, during an incident at the plant, a control room operator may be confronted with an alarm flood. The raw sensory cues corresponding to the individual alarms are present, but the operator experiences sensory overload and cannot consciously perceive or process the large number of simultaneous cues. Or, the operator's attention may be focused on a particularly important part of plant recovery and choose not to respond to certain alarms until a more pressing issue is addressed.

1. Cue content: Too many meaningful cues. For example, during a plant transient, the operator may have multiple simultaneous indications, such as an alarm flood involving hundreds of annunciators, and may not be able to attend to all indicators simultaneously. This mechanism focuses on the content and amount of the information.
2. Vigilance in monitoring: Divided attention. For example, if the operator has to respond to multiple simultaneous alarms, the operator may reach a state of so-called information overload or alarm flood in which he or she is unable to attend to additional alarms. Also, the operator may be fatigued at end of night shift and have difficulty monitoring the plant. Alternatively, the operator may be stressed, leading to shortened attentional focus. In vigilance in monitoring for Cue/Information Not Perceived, the operator simply misses important information. Here, the operator is aware of new cues like alarms but cannot attend to or address it.
3. Attention: Change blindness. For example, the operator may not notice a change in a plant indicator because the operator has missed the prior state of the indicator. In inattentional blindness for Cue/Information Not Perceived, the operator misses detecting a change in an indicator that is not his or her current focus. In contrast, change blindness occurs when the operator is focused on monitoring an indicator and simply fails to notice the change.
4. Expectation: Overreliance on primary indicator. The operator may be monitoring a particular plant indicator to the exclusion of other meaningful indicators that should or need to be monitored. This often occurs because of the operator's mindset—if the operator has a particular hypothesis about the plant condition, he or she will look for information to confirm that hypothesis and may discard information to disconfirm it.
5. Working memory: Working memory capacity overflow. This mechanism focuses on the operator's limited working memory capacity. For example, if the operator has to respond to multiple simultaneous alarms, the operator may reach a state of so-called information overload or alarm flood in which he or she is focused on a particular alarm panel and may disregard additional alarms or indicators elsewhere in the control room. The distinction with working memory for Cue/Information Not Perceived involves the extent the operator is aware of information that must be attended to. In working memory for Cue/Information Not Perceived, the operator misses information because his or her attention and working memory are elsewhere. Here, the operator is aware of the additional alarms, but simply cannot dedicate resources to processing additional alarms.

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Cue content	The consistency, predictability, distinctiveness, and interpretability of the signal affect vigilance.	If the cue is difficult to interpret and repeatedly presented, the operator may not attend to the next time the signal is presented.	• HSI	Cue qualities (consistency, predictability/reliability, and strength) affect perception	Donald (2001), Liu et al. (2009), MacLean et al. (2009)
Vigilance in monitoring	Szalma et al. (2004) showed that the interaction of factors such as sensory modality and workload (time on task) affect stress levels differentially. Stress can either be exacerbated or attenuated depending on how the factors interacted with each other.	Observers became more stressed over time, with evidence of recovery in the auditory but not the visual condition toward the end of the watch.	• Stress • Workload	As stress and workload increase, ability to perceive or attend cues decreases	Szalma et al. (2004)
Vigilance in monitoring	Fatigue impairs our higher-level cognitive processes and our ability to perceive stimuli.	When the operator is fatigued, they may not attend to cues being presented	• Fatigue	Fatigue impairs our higher-level cognitive processes and our ability to attend to stimuli.	Donald (2001); MacLean, et al., (2009)
Vigilance in monitoring	The SEEV model is based on the plausible assumption that four factors drive the acquisition of visual information: the salience (S) of events that might capture attention (Yantis, 1993); the effort (E) required to redirect attention from one location to another (i.e., visual saccade, head rotation), which will inhibit information access (Wickens, 1993); the expectancy (E) that a given location in the visual field will contain information (Senders, 1964); and the value (V) of information to be obtained at that location for the task or tasks at hand (Sheridan, 1970).	The four criteria/factors in this model must be met in order for a cue to be attended to. Salience of the cue is a necessary, but not sufficient criteria for attending to the cue. Furthermore, any one of the remaining criteria/factors on its own can be responsible for the operator failing to attend to the cue.	• All of the PIFs listed under the category "Personal PIFs"	1. If the cue is presented in such a way that it is difficult for the operator to change/move their focus of attention to it, the cue may not be attended to. 2. If the operator's expectancy for the cue and the presentation of the cue do not match, the operator may not attend to the cue. 3. If the operator believes the cue does not add value to their understanding of the system and/or situation, they may not attend to the cue.	Yantis (1993), Wickens (1993), Senders (1964), Sheridan (1970), Steelman-Allen et al. (2009), Wickens et al. (2003)
Vigilance in monitoring	Whether the signal is successive (serial) or simultaneous, and whether it is sensory or cognitive affects vigilance.	1. If cues are presented serially, but there is not adequate time to attend to each one before the next is presented can cause the operator to not attend to the cue. 2. If two cues are presented simultaneously, the operator may not be able to attend to both.	• HSI	Cue presentation order affects perception	Donald (2001); Liu, et al. (2009)
Vigilance in monitoring	Whether the signal is coming from a single source or multiple sources affect vigilance. The	1. Operators may not be able to attend to all signals/cues	• HSI	1. Operators' vigilance is related to attention, and as a general rule, tasks requiring split	Donald (2008), Xing (2007), Levi (2009)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	complexity of information being presented on a display affects performance. Visual crowding creates an information-processing bottleneck for recognizing (perceiving) objects in peripheral vision.	coming from multiple sources. 2. Operators may not be able to attend to all signals/cues coming from a cluttered display. 3. Operators may not attend to cues from displays that are in their peripheral vision.		attention can lead to cues/information not being attended to. 2. Cues coming from cluttered displays may not be salient enough for the operator to attend to them. 3. In crowding, the cue's target and flank features are detected independently and, when both fall within the "integration field", they are merged into a percept that is often described as jumbled or indistinct.	
Vigilance in monitoring	The relationship between workload and vigilance is similar to that of stress and attention.	1. Workload being too low to keep the operator engaged causes an operator to not have sufficient attentional resources at the ready to attend to cues. 2. Too many cues being presented simultaneously causes the operator's workload to be too high, and in this state, an operator may not attend to a critical cue amongst the multitude of other cues.	• Workload	Depending on the amount of work being loaded on to the operator, an individual may not be sufficiently engaged to attend to the cue, or over-worked.	Donald (2001), Liu, et al. (2009)
Vigilance in monitoring, Cue content, Attention	The human's ability to detect or sense, and then attend to a stimuli is a function of (1) how clearly that stimuli is present over and above existing background noise (e.g., the cue's signal to noise ratio), (2) the extent to which the human is willing to accept an error of omission versus an error of commission, and (3) the human's attentional capacity at the time the cue is presented.	1. An operator that has responded frequently to false alarms may choose not to attend to a subsequent alarm. 2. The cue is presented with sufficient strength/energy to distinguish itself from existing background noise, but it is not presented long enough for the operator to attend to it.	• HSI • Workload • Task complexity • Stress • Fatigue	1. The operator has changed the threshold to which he/she is willing to accept an error of commission because the system's signal to noise ratio is so low that the probability of false alarms is unacceptably high. 2. Operator misses cue—it is perceived but not attended to before the cue disappears.	Bustamante (2008)
Expectation	Confirmation bias: People tend to seek out evidence that confirms their current position and to disregard evidence that conflicts with their current position.	Operator seeks information to confirm his or her mental model of plant condition.	• Bias • HSI	The greater the congruence between environmental cues and mental model (information being sought), the more the information will be attended to.	Einhorn & Hogarth (1978)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Working memory	Research demonstrates the effect of cue relevance for high and low working memory conditions on formulating the intent to complete an action that cannot be completed immediately. A high focal task is one that provides readily detectable cues that reinforce the planned action, whereas a low focal task is one that does not readily reinforce the action. According to the working memory model, high focal tasks should require minimal working memory because the perceptual cues reinforce memory. Participants with high and low working memory capacity performed equally well on the high focal task, but participants with a low working memory capacity performed much better for focal tasks than for nonfocal tasks. This finding confirmed the theory that low cue focality was affected by working memory capacity.	An operator who is monitoring several plant states concurrently will be cued on appropriate tasking if the instrumentation reinforces the action required. Otherwise, additional working memory will be required to attend to the instrumentation, and both instrumentation cues and follow on tasking may be missed.	• HSI • Workload	Participants with low working memory capacity saw a 20% performance decrement for nonfocal cues.	Brewer (2010)

A-1.3 Cue/Information Misperceived

This table contains the mechanisms for the Cue/Information Misperceived proximate cause. When this is the cause of *Detecting and Noticing* failure, the cues or information may be sensed but misperceived. In other words, the sensed information is tagged with the incorrect meaning. For example, a control room operator may misread a pump as being on when, in fact, it is off. Or, the operator may mis-read an indicator by transposing the numbers.

1. Cue content: Cues are too complex. For example, during a plant transient, the operator may have multiple simultaneous indications that have multiple facets or dimensions, and may not be able to attend to all indicators simultaneously. The operator may arrive at the wrong conclusion about the plant state because he or she is unable to interpret the entire cue content.
2. Vigilance in monitoring: Degraded focus. The operator may have high workload, high fatigue, or high stress, which can cloud judgment and diagnosis, leading to a misinterpretation of a cue about plant status. Alternately, during a period of sustained high workload involving a high focus of attention, vigilance in scanning, detecting, or monitoring degrades to the point where operators misperceive available cues.
3. Attention: Inattentional blindness. The technical term for the phenomenon of missing something that is in plain sight. For example, the operator may misperceive obvious plant information because that information is not the focus of the operator's attention. In this case, the operator may fail to integrate important information that would otherwise be obvious (e.g., changing trends, because the operator is focused on understanding different information). The distinction between Attention for Cue/Information Not Perceived and here deals with how inattentional blindness manifests. The operator may simply not perceive changed but important information in Cue/Information Not Perceived, whereas here they may misinterpret it.
4. Expectation: Mismatch between expected and actual cues. The operator may be monitoring a particular plant indicator to the exclusion of other meaningful indicators that should or need to be monitored, leading to a misperception of a cue about plant status. This may occur because of the operator's mindset—if the operator has a particular hypothesis about the plant condition, he or she will look for information to confirm that hypothesis and may discard or miss information to disconfirm it.
5. Working memory: Memory segmenting error. Information may be parsed or processed incorrectly, leading to a misperception of the plant state. This can occur especially in response to high task load or when the operator is distracted. Based on his or her expectations for the progression of a plant transient, the operator may fill in missing or expected information, leading to the wrong perception.

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Attention, Working memory, Cue content	Template-matching theory accounts for the perceptual match between a stimulus and a pattern in memory. Items in memory serve as templates to which stimuli are compared.	The theory accounts for the difficulty operators may have in mapping the HSI—or a specific plant configuration—to a mental template. The theory also accounts for misreading indicators when there is a mis-map between the stimulus and the mental template.	• HSI	Proper cue perception depends on the degree the information being perceived matches previously experienced information	Phillips (1974)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Vigilance in monitoring	The sympathetic response is the action to mobilize the body's resources under stress to induce the fight-or-flight response. It is what causes people to become more anxious under stressful conditions.	Under high stress, an operator may misperceive a cue. For example, a pilot mistaking the out of fuel light with the intercom light.	• Stress	The stress response being caused by the autonomic nervous system can interfere with higher level cognitive processing of information. In effect, the autonomic response overrides rational thinking	Aarts & Pourtois (2010)
Vigilance in monitoring	Fatigue impairs our higher-level cognitive processes and our ability to perceive stimuli.	When the operator is fatigued, they may misperceive cues being presented.	• Fatigue	Fatigue impairs our higher-level cognitive processes and our ability to perceive stimuli correctly.	Donald (2001), MacLean, et al. (2009)
Vigilance in monitoring	The SEEV model is based on the plausible assumption that four factors drive the acquisition of visual information: the salience (S) of events that might capture attention (Yantis, 1993); the effort (E) required to redirect attention from one location to another (i.e., visual saccade, head rotation), which will inhibit information access (Wickens, 1993); the expectancy (E) that a given location in the visual field will contain information (Senders, 1964); and the value (V) of information to be obtained at that location for the task or tasks at hand (Sheridan, 1970).	Failing to meet any one of the four criteria/factors in this model can lead to a cue being misperceived.	• All of the PIFs listed under the category "Personal PIFs"	1. If the cue is not presented to the operator with sufficient strength/energy to distinguish itself from existing background noise such that it activates a sensory response in the operator, the operator may misperceive it. 2. If the cue is presented in such a way that it is difficult for the operator to change/move their focus of attention to it, the cue may be misperceived. 3. If the operator's expectancy for the cue and the presentation of the cue do not match, the operator may misperceive the cue. 4. If the operator believes the cue does not add value to their understanding of the system and/or situation, they may misperceive the cue.	Yantis (1993), Wickens (1993), Senders (1964), Sheridan (1970), Steelman-Allen et al. (2009), Wickens et al. (2003)
Vigilance in monitoring	Whether the signal is coming from a single source or multiple sources affect vigilance. The complexity of information being presented on a display affects performance. Visual crowding creates an information-processing bottleneck for recognizing (perceiving) objects in peripheral vision.	1. Operators may misperceive some signals/cues coming from multiple sources. 2. Operators may misperceive signals/cues coming from a cluttered display. 3. Operators may misperceive cues from displays that are in their peripheral vision.	• Attention • HSI	1. Operators' vigilance is related to attention, and as a general rule, tasks requiring split attention can lead to cues/information being misperceived. 2. Operators may misperceive cues from cluttered displays that are not salient enough. 3. In crowding, the cue's target and flank features are detected independently and, when both fall within the "integration field," they are merged into a	Donald (2008) Xing (2007), Levi (2009)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
				percept that is often described as jumbled or indistinct.	
Cue content	This study used multi-dimensional (up to ten dimensions) visual icons to test whether participants could accurately detect the state of the various dimensions (binary) of the icons. They found that as the number of dimensions increased, sensitivity (number of correct hits per number of times the dimension was present) decreased exponentially (no specific numbers provided, but from the trend graph, it appears that sensitivity dropped from 100% to about 95% as the number of dimensions increased from 0 to 10).	As the complexity of the cue increases, the less likely operators are to correctly identify crucial aspects of the cue.	• HSI	Refers to visual cues. The quality and amount of information provided in the cue has an effect on whether the cue will be accurately detected. Specifically, the more complex the cue, the less likely operators are to correctly recognize specific parts of the cue.	Repperger et al. (2007)
Cue content	Feature-integration theory. Counterpart to feature analysis and recognition-by-components theory. The theory posits that people must pay attention to a stimulus before they can synthesize its features into a pattern. The implication is that if the person does not attend to an object, they may not perceive relevant features necessary to understand it. It links attention and workload with perception.	The theory accounts for errors such as misreading indicators in busy control rooms due to distraction or high workload.	• HSI • Attention	Proper cue perception depends on paying proper attention to those cues.	Treisman (1991)
Cue content	Gestalt Principles. (1) Elements close together organize into perceptual units. Objects that can form a continuum will tend to be perceived in this manner. Offers possibility that control room elements, especially instrument clusters, may be misgrouped and misperceived. (2) Objects are seen as a whole, even if parts are missing or occluded. (3) Wrong control activated: Elements close together organize into perceptual units. Objects that can form a continuum will tend to be perceived in	1. Operators can misread instruments among other instruments. 2. Has implications especially for disconnected information sources or for discrete sampling situations, affording possibility of misreading information. (Applies primarily to advanced HSIs.) 3. Offers possibility that control room elements, especially controls, may be misgrouped and misperceived. Can identify wrong control among other controls. 4. This property of	• HSI	None provided	Köhler (1947)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	this manner. (4) Rather than perceive parts of an object, the object is perceived as a whole—the whole object automatically "emerges" from the parts during perception. (5) Multistable perception explains that when there is ambiguous information present in the environment, a person may cycle between two interpretations of what the cues represent. While certain optical illusions such as the Rubin vase are often used to demonstrate this phenomenon, it more broadly represents the opportunity for confusion in the perception of objects when there is ambiguity present. (6) Reification explains how objects are formed based on partial information. Since the mind seeks to recognize the environment in terms of objects, the mind may construct objects even when only partial information is available to support that object percept.	Gestalt psychology explains how operators may form an incorrect picture of a situation by automatically forming an overall percept from environmental cues without decomposing individual cues. 5. Given the high number of cues present in control room I&C, ambiguous instrument cues are a distinct possibility. The operator's response to such ambiguity in terms of shuffling between interpretations can lead to misreading the instruments and to delay in taking appropriate actions. 6. This tendency to construct objects can lead to over-generalizations or over-simplifications of environmental cues and may result in filling in missing information according to operator expectations.			
Cue content	The consistency, predictability, distinctiveness, and interpretability of the signal affect vigilance.	1. If the cue is not consistently presented, the operator may misperceive it. 2. If the cue is unpredictable, the operator may misperceive it. 3. If the cue is not presented to the operator with sufficient strength/energy to distinguish itself from existing background noise such that it activates a sensory response in the operator, the operator may misperceive it.	• HSI	Cue qualities (consistency, predictability/reliability, and strength) affect perception	Donald (2001), Liu et al. (2009), MacLean et al. (2009)
Cue content	The human's ability to detect or sense a stimuli is a function of (1) how clearly that stimuli is present over and above existing background noise (e.g., the cue's signal to noise ratio), and (2) the extent to	1. An operator that has responded frequently to false alarms may misperceive a subsequent alarm as another false alarm when it is in fact a real alarm.	• HSI • Workload • Task complexity • Stress • Fatigue • Fitness for duty	1. The operator has changed the threshold to which he/she is willing to accept an error of commission because the system's signal to noise ratio is so low that the probability of false	Bustamante (2008)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	which the human is willing to accept an error of omission versus an error of commission.	2. The operator is fatigued or under high stress and does not correctly perceive the cue (which may or may not have a clear signal)		alarms is unacceptably high. 2. When fatigued or under high stress, cognitive abilities are hindered. For example, the stress response can interfere with higher level cognitive processing.	
Cue content	Collaboration affects visual search (i.e., vigilance/attentional) performance.	Operators working together on a visual search task are less likely to correctly detect targets and make false alarms (compared to operators performing the task side by side, but not collaboratively). Working collaboratively tends to make the operators more conservative, which can lead them to misperceive a cue.	• Team PIFs	Effects of team dynamics on team search	Malcolmson, et al. (2007)
Cue content, Vigilance in monitoring	The relationship between workload and vigilance is similar to that of stress and attention.	When task complexity is too high, an operator may misperceive a cue. For example, a pilot mistaking the out of fuel light with the intercom light.	• Task complexity	Task complexity being too high can interfere with higher level cognitive processing of information.	Donald (2001), Liu et al. (2009)
Cue content, Vigilance in monitoring	The ability to monitor tasks effectively (i.e., maintain vigilance) is affected by the amount of information presented and the number of displays it is presented in.	An operator may have difficulty monitoring plant status indicators that are distributed across multiple panels. (In practice, related functions are grouped on panels, but during a plant transient involving multiple symptoms, the operator may need to monitor multiple areas.)	• HSI	As the number of displays increases, the number of errors of commission the operator makes increases. Participants committed errors of commission only 1-2% of the time when there was only one split screen, regardless of how frequently or infrequently the signal was presented. Participants committed errors of commission 16-17% of the time when there were 16 split screens and the signal was presented at a rate of 1 time every 30 seconds. The error of commission rate dropped to 7-8% when the signal rate was 1 time every 60 seconds, and generally improved the more infrequently the signal was presented.	Lin et al. (2009)
Expectation	Verbal communication misunderstood: Accounts for how we recognize words better than individual sounds,	Accounts for hearing wrong word (either hear it wrong because expecting something else in that context or	• All of the PIFs listed under the category "Personal PIFs"	Verbal (word) salience can affect proper perception	Reicher (1969)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	but we may perceive the incorrect word depending on the context. Sentence context fills in missing information, but it can also prime the wrong word.	hear it wrong because sounds that make up word are not clearly audible).	• External Environment		
Expectation	Verbal communication misunderstood: People fill in missing speech sounds based on context.	Accounts for hearing wrong word (either hear it wrong because expecting something else in that context or hear it wrong because sounds that make up word are not clearly audible).	• Task load	Verbal (word) salience can affect proper perception; missing information may be inserted based on context	Warren (1970)
Expectation	Fuzzy Logic Model of Perception. Verbal communication misunderstood: General theory that suggests we combine context and features to perceive speech and objects. The boundaries categorically distinguishing objects are fuzzy, causing ambiguity in many cases.	For example, the McGurk-MacDonald effect explains how visual and auditory information are integrated (e.g., if a visual /ga/ is combined with an auditory /ba/, the combination is perceived as /da/). The effect generalizes to other areas where there is a visual-auditory mismatch and can lead to misinterpretation of communications.	• Task load	Verbal (word) salience can affect proper perception; missing information may be inserted or falsely categorized based on context	Massaro and Cohen (1992)
Working memory	As new information is perceived, it is segmented into events. Event segmenting occurs automatically and helps define information to be processed in working memory or the intersection points for accessing and comparing to working memory.	If an operator encounters a novel situation, the operator may not segment information about the situation properly, resulting in an incorrect mental model of the situation, potentially increasing the likelihood of misperceived cues.	• Experience/ training	Segmenting for familiar activities is at a coarser level than for novel activities. Segmenting will require greater working memory, or segmenting may occur at false boundaries for novel activities.	Kurby & Zacks (2007)

A-2. UNDERSTANDING AND SENSEMAKING

This section of Appendix A contains the cognitive mechanism tables for the *Understanding and Sensemaking* macrocognitive function. The macrocognitive function *Understanding and Sensemaking* is the process of understanding the meaning of the information that has been detected. Cognition in this function ranges from automatic, effortless recognition and understanding to more effortful thinking and deliberate attempts to make sense of multiple pieces of information. Sensemaking allows people to question what is known, evaluate what is conjectured, hypothesize and diagnose, and integrate facts with theory (Klein, Phillips, Rall, & Peluso, 2007).

The model used to integrate all of the various approaches to understanding for the purposes of this effort is the data/frame theory of sensemaking (Klein, Moon, & Hoffman, 2006; Klein, et al., 2007). This model is an extension of Neisser's (1967) perceptual cycle theory, in which a person's sampling of the environment updates their cognitive map of the environment, which in turn directs further exploration. The data-frame theory of sensemaking posits that information coming into the sensemaking process is data. This data is integrated with an existing frame, which is a person's current understanding that links data with other elements to explain and describe the relationship of the data with other entities. A frame encompasses the concepts of a mental representation, a mental model, a story, a map, a schema, a script, or a plan, and serves as a structure for explaining the data and guiding the search for more data (Klein, et al., 2007). The data identify or construct the frame, and the frame determines which data are attended to. Neither the data nor the frame comes first; rather, it is a constant process of moving back and forth from data to frame. This dynamic aspect is the central theme of the model.

Chapter 4 discusses *Understanding and Sensemaking* in more detail.

In general, failure of the *Understanding and Sensemaking* macrocognitive function means that the person has an incorrect understanding of the situation. In other words, she or he has an incorrect mental model of what is happening. When this occurs, the operator is unlikely to make appropriate decisions in response to the situation, but the root of this error is in the *Understanding and Sensemaking* macrocognitive function. The literature review identified three proximate causes as potentially leading to this failure. Those proximate causes, along with their cognitive mechanisms, are:

1. Incorrect data (Table A-2.1)
    a. Information available in the environment (including procedures) is not complete, correct, or otherwise sufficient to create understanding of the situation
    b. Attention to wrong or inappropriate information
    c. Improper data or aspects of the data selected for comparison with or identification of a frame
    d. Incorrect or inappropriate or inadequate frame used to search for, identify, or attend to information
    e. Data not properly recognized, classified, or distinguished.
2. Incorrect integration of data, frames, or data with a frame (Table A-2.2)
    a. Data not properly recognized, classified, or distinguished
    b. Improper integration of information
    c. Improper aspects of the frame selected for comparison with the data

d. Improper data or aspects of the data selected for comparison with or identification of a frame
e. Incorrect or failure to match data or information to a frame or mental model
f. Mental manipulation of the information (including projection of future status) is inadequate, inaccurate, or otherwise inappropriate
g. Working memory limitations impair processing of information
h. Improper control of attention.

3. Incorrect frame (Table A-2.3)
   a. Incorrect or inadequate frame or mental model used to interpret or integrate information
   b. Frame or mental model inappropriately preserved or confirmed when it should be rejected or reframed
   c. Frame or mental model inappropriately rejected or reframed when it should be preserved or confirmed
   d. Incorrect or inappropriate frame used to search for, identify, or attend to information
   e. No frame or mental model exists to interpret the information or situation.

A-2.1 Incorrect Data

This table contains the mechanisms for the Incorrect Data proximate cause. When this is the cause of *Detecting and Noticing* failure, the data the person is comparing with a frame is incomplete, incorrect, or otherwise insufficient to understand the situation. This may be due to the information itself being faulty, external to the person, errors in the perceptual process (in which case the failure is in *Detecting and Noticing*), or the person attending to inappropriate information, or focusing on inappropriate aspects of the information (e.g., operators are focused on coolant level and overlook rate of change). This proximate cause can be explained by the following mechanisms:

1. Information available in the environment (including procedures) is not complete, correct, or otherwise sufficient to create understanding of the situation
2. Attention to wrong or inappropriate information
3. Improper data or aspects of the data selected for comparison with or identification of a frame
4. Incorrect or inappropriate or inadequate frame used to search for, identify, or attend to information
5. Data not properly recognized, classified, or distinguished.

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Information available in the environment (including procedures) is not complete, correct, accurate, or otherwise sufficient to create understanding of the situation	The quality, accuracy, structure, and availability of information in the situation—the better and more accurate the information available, the better people are able to make sense of it. This means that information from the human-system interface is of crucial importance for properly understanding an event. This also includes issues with the procedures, specifically the procedure formatting, having simple or complex logic, being difficult to read and follow. It also includes issues of vagueness or lack of specificity.	If operators do not have the right information, they will be less likely to have an accurate understanding of what is going on. For example, in an event at the Crystal River 3 nuclear power plant, a pressurizer spray valve stuck open during a power increase following a shutdown, causing a slow depressurization. The indication for this valve in the control room showed that it was closed. The plant behavior was perceived as inexplicable, as all they could see was evidence of a depressurization with no indications of problems with the pressurizer or any other reason to explain it. Their operating procedures did not help them determine the cause of the problem or prompt them to verify that all relevant spray valves were closed. Without information from the plant indicators or procedures to guide them, operators did not understand the nature of the situation and made several inappropriate knowledge-based decisions.	• HSI output • System complexity • Situation dynamics or complexity • Procedure availability, quality • Quality and availability of information	1. The quantity and quality of the information provided by the system interface is of critical importance. The “Las Vegas Strip” phenomenon—when systems display flashing lights, moving icons, overuse bright colors, or simply present too much information, information overload can occur, as well as misplaced salience, when information that is objectively irrelevant (or inaccurate) is physically more salient than important information, drawing operator attention away from needed information. Furthermore, the framing effect shows that aspects of information presentation can affect interpretation of the information. 2. Highly complex systems make it difficult for people to develop sufficient internal representations of how the systems work. System complexity can slow down the ability of people to take in information (due to the overwhelming amount of information), and it undermines their ability to correctly interpret the information and project what is likely to happen next. 3. If the situation or information in the environment is too complex or changing	Durso et al. (2007) Endsley (1995) Endsley (2000) Endsley (2006) Endsley, Bolté et al. (2003) Endsley & Garland (2000) Jones & Endsley (1996) Jones & Endsley (2000) Kim et al.(1999) Meyer (1992) Salmon et al. (2008) Smith & Hancock (1995) Tversky & Kahneman (1981)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
				too rapidly, then it will be beyond the operators' cognitive abilities to process. 4. If the information available from the environment, including from the procedures, is not correct, appropriate, or sufficient for the person to adequately update his/her knowledge, then they are less likely to understand what is going on. 5. Information that is very inconsistent with the current understanding of the situation is more likely to be identified as contradictory and often leads to recognizing that either the data or the frame is in error, whereas information that is seen as irrelevant to the frame (but is objectively relevant to the situation) is simply not noticed, and an incorrect frame persists. 6. System automation can undermine situation awareness by taking the operator out of the loop. If complex, automated systems do not provide operators with enough information to keep them in the loop, operators may struggle to understand what is going on when the automation fails or reaches situations for which it is not equipped to handle.	
Attention to wrong/ inappropriate information	This mechanism refers to the problem when attention is on the wrong information, due to bottom-up issues such as information salience. Specifically, this refers to the problem that occurs when particularly "loud" or salient information that is objectively incorrect or irrelevant catches the operator's attention. This attention capture diverts operators' attention away from the information that is relevant and important to the situation. This also includes issues such as accidentally gathering the wrong information, like getting information from Train A instead of Train B.	If operators are attending to inappropriate information, they may misclassify the situation. For example, when faced with a large number of alarms, operators may miss one important alarm (such as a RCP seal temperature alarm) because they are focusing on other alarms.	• Cue salience • HSI Output	1. Misplaced salience, when information that is objectively irrelevant (or inaccurate) is physically more salient than important information, can draw operator attention away from needed information. 2. The information that is sampled in the environment feeds into and updates the operators' frame/mental model. If the information provided by the interface is incorrect, so will the operators' understanding of the situation be incorrect.	Adams et al. (1995) Endsley, Bolté et al. (2003) Klein (1993) Lipshitz (1993) Salmon et al. (2008) Smith & Hancock (1995)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Improper data/aspects of the data selected for comparison with/ identification of a frame	This mechanism refers to the situation where the operator focuses on the wrong information, or wrong parts of the information. This is less a bottom-up issue of cue salience capturing attention, but instead describes the situation when operators have a frame or mental model about what is happening, but because of the way information initially presented itself, focus on inappropriate data. This can also occur due to operators placing too much subjective significance on information that is objectively unimportant.	If operators focus on one indicator to the exclusion of others, they may not fully understand the situation. For example, if operators focus on RCS level but do not account for the *rate of change* in level, they may misunderstand the urgency of the situation.	• Knowledge/ experience/ expertise • Training • HSI Output, Situation dynamics	1. Having insufficient knowledge and experience can lead operators to selecting an incorrect or inadequate model of the situation, focus on inappropriate aspects of the frame to understand the situation, and come up with an incorrect understanding of the information. Experts are better able to make use of their mental models to impose form on sensory data in real time. 2. Training is a method for developing knowledge and experience. If training does not provide operators with the necessary information or practice, knowledge will suffer. 3. The initial one or two key data elements that present themselves in the situation often serve as anchors for developing understanding. These anchors elicit the initial frame, and we use that frame to search for more data elements, which in turn elaborate that frame or anchor a new frame. If the first few pieces of information are misleading or spurious, understanding will suffer.	Bedny & Meister (1999) Durso et al. (2007) Klein et al. (2007)
Incorrect/ inappropriate/ inadequate frame used to search for, identify, or attend to information	This refers to when the operator has an incorrect frame or mental model for the situation, which directs their attention toward information that is not objectively important. This, in turn, further perpetuates the incorrect understanding of the situation. This can occur because of habit intrusion, in which the habitual frame interferes with the ability to attend to non-habitual information; expectations for how the situation will unfold; the goals the operator has in the situation, including goals of personal significance to the operator (such as saving face or not being perceived as wrong); a lack of	For example, people tend to seek out evidence that confirms their current position or mental model and to disregard evidence that conflicts with their current position, a phenomenon known as confirmation bias.	• Knowledge/ experience/ expertise • Training	1. Having insufficient knowledge and experience can lead operators to selecting an incorrect or inadequate model of the situation, focus on inappropriate aspects of the frame to understand the situation, and come up with an incorrect understanding of the information. Experienced people use their knowledge base to develop expectancies about situations. Experts are more likely to be able to work with multiple frames at once. When faced with data that has more than one explanation, experts can deliberately elaborate two to three frames simultaneously, looking for information that will rule out one of the frames. Experts are more prone to question the data, and are also more confident and skeptical in the face of contradictory information. 2. Training is a method for developing knowledge and experience. If training does not provide operators with the	Bedny & Meister (1999) Einhorn & Hogarth (1981) Endsley (1995) Endsley (2006) Feltovich et al., (1984) Klein et al. (2007) Niesser (1976) Salmon et al. (2008) Smith & Hancock (1995)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	relevant training, knowledge, or experience; or knowledge, training, or experience predisposing the operator to an incorrect frame for the situation. NOTE: This can also lead to not checking information frequently enough. If the frame doesn't specify checking information often enough, then important parameters may not be checked with adequate frequency.			necessary information or practice, knowledge will suffer.	
Data not properly recognized, classified, or distinguished	This mechanism refers to classification or categorization of information at the recognition level, before the information is more deeply or consciously processed. Once a scene is identified (perceived), top-down influences from existing knowledge on identification of aspects of the situation begin. Operators can get the "gist" of a situation very quickly, and that "gist" may be inaccurate if information has not been properly classified. If information is improperly categorized (e.g., as irrelevant or oversimplifications), then operators will not make proper use of the information, and understanding will suffer. This misclassification can occur due to misperceiving the information (see *Detecting and Noticing*), or misinterpreting the information based on existing knowledge.	For example, if a particular alarm has a history of sounding spuriously, operators may be likely to dismiss it as a false alarm if it activates in the case of a real problem. Another example is the case of operators misreading procedures. Crews attend to the procedures while performing actions. During this time the crew will judge whether the strategies embodied in the procedures are appropriate to the situation. The crew may make a mistake and inappropriately misjudge the procedures as inapplicable due to misreading the procedures.	• Knowledge/ experience/ expertise • Training • HSI Output • Procedure quality	1. Generally, novices or less experienced people tend to be less certain about the relevance of pieces of information, and are more ·likely to interpret information that is noise in the situation as important signals. Insufficient expertise or knowledge of critical cues in the environment may prevent very fine classifications of incoming data. 2. Training is a method for developing knowledge and experience. If training does not provide operators with the necessary information or practice, knowledge will suffer. 3. The manner in which information is presented can affect how it is interpreted. For example, the framing effect shows that word choices, colors, images, and other aspects of presentation can all greatly affect resulting interpretation 4. If procedures are of poor quality, such as being difficult to follow, being inaccurate, or failing to prioritize important steps, they may be more likely to cause misunderstanding.	Durso et al. (2007) Endsley (1995) Klein (1993) Klein et al. (2007) Lipshitz (1993) Roth (1997) Tversky & Kahneman (1981)

A-2.2 Incorrect Integration of Data, Frames, or Data With a Frame

This table contains the mechanisms for the Incorrect Integration of Data, Frames, or Data with a Frame proximate cause. This refers to errors in integration that lead to failure of the *Understanding and Sensemaking* macrocognitive function. The person does not properly integrate pieces of information together, does not correctly match data with a frame, or does not appropriately integrate multiple frames, such as when a person does not properly merge a frame for a system (i.e., a system model) with the frame for the ongoing event (i.e., a situation model). In addition, because sensemaking is a continuous, dynamic process, the person must integrate new data into the frame periodically as the situation evolves. In this proximate cause, the data is correct, the frame is correct, but the integration, matching, or updating process goes awry. This proximate cause can be explained by the following mechanisms:

1. Data not properly recognized, classified, or distinguished
2. Improper integration of information or frames
3. Improper aspects of the frame selected for comparison with the data
4. Improper data or aspects of the data selected for comparison with or identification of a frame
5. Incorrect or failure to match data or information to a frame or mental model
6. Mental manipulation of the information (including projection of future status) is inadequate, inaccurate, or otherwise inappropriate
7. Working memory limitations impair processing of information
8. Improper control of attention.

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Data not properly recognized, classified, or distinguished	As information is perceived, more meaning is applied to it. This is the blurry boundary between *Detecting and Noticing* and *Understanding and Sensemaking*. This mechanism refers to classification or categorization of information at the recognition level, before the information is more deeply or consciously processed. Once a scene is identified (perceived), top-down influences from existing knowledge on identification of aspects of the situation begin. Operators can get the "gist" of a situation very quickly, and that "gist" may be inaccurate if information has not been properly classified. If information is improperly categorized (e.g., as irrelevant or oversimplifications), then operators will not make proper use of the information, and understanding of the situation will suffer.	For example, if a particular alarm has a history of sounding spuriously, operators may be likely to dismiss it as a false alarm if it activates in the case of a real problem. Another example is the case of operators misreading procedures. Crews attend to the procedures while performing actions. During this time the crew will judge whether the strategies embodied in the procedures are appropriate to the situation. The crew may make a mistake and inappropriately misjudge the procedures as inapplicable due to misreading the procedures.	• Knowledge/ experience/ expertise • Training • HSI Output • Procedure quality	1. Generally, novices or less experienced people tend to be less certain about the relevance of pieces of information, and are more ·likely to interpret information that is noise in the situation as important signals. Insufficient expertise or knowledge of critical cues in the environment may prevent very fine classifications of incoming data. 2. Training is a method for developing knowledge and experience. If training does not provide operators with the necessary information or practice, knowledge will suffer. 3. The manner in which information is presented can affect how it is interpreted. For example, the framing effect shows that word choices, colors, images, and other aspects of presentation can all greatly affect resulting interpretation 4. If procedures are of poor quality, such as being	Durso et al. (2007) Endsley (1995) Klein (1993) Klein et al. (2007) Lipshitz (1993) Roth (1997) Tversky & Kahneman (1981)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	This misclassification can occur due to misperceiving the information (see *Detecting and Noticing*), or misinterpreting the information based on existing knowledge.			difficult to follow, being inaccurate, or failing to prioritize important steps, they may be more likely to cause misunderstanding.	
Improper integration of information	As people process information into understanding, they assemble or integrate pieces of information together and map it to existing knowledge. If they put the information together improperly, they can come to incorrect or inadequate conclusions about the situation. They may develop an incorrect holistic picture from the separate perceived elements, producing an inappropriate mental model or frame for the situation.	For example, if operators are dealing with one faulted system, they may have difficulty handling a subsequent secondary faulted system, and integrating the information about the second system into the mental model for handling the situation.	• Attention, working memory capacity • Knowledge/ experience/ expertise	1. People can only process so much information at once. Errors in understanding can occur due to insufficient working memory span, or the decay of information in working memory over time. 2. Experts have a richer repertoire of frames and a much stronger understanding of context. Experts are better able to make use of their mental models to impose form on sensory data in real time. Experts have greater skill in producing inferences. This can be seen in the inferences of the values of variables during monitoring, in the use of covert variables in the building-up of a representation during diagnosis and in the use of inferential strategies during executive control. Experts are better at organizing information into meaningful units.	Baddeley (1992) Baddeley & Hitch (1974) Cellier, Eyrolle, & Marine (1997) Doane et al. (2004) Durso et al. (2007) Endsley et al. (2003) Sternberg & Davidson (1986)
Improper aspects of the frame selected for comparison with the data	When comparing information with the active frame, it is possible for people to focus on inappropriate parts of the frame for the evaluation of the data.	For example, a frame may have "default" and "exception" values, such as a rule that "Scenario X has symptoms of A, B, and C, EXCEPT when variant Y occurs, and then the symptoms of A, B, D, and E are relevant." An error can occur if the person focuses inappropriately on either the default or the exception values.	• Knowledge/ experience/ expertise	Having insufficient knowledge and experience can lead operators to selecting an incorrect or inadequate model of the situation, focus on inappropriate aspects of the frame to understand the situation, and come up with an incorrect understanding of the information. Experts are better able to make use of their mental models to impose form on sensory data in real time.	Durso et al. (2007) Endsley (1995)
Improper data/aspects of the data selected for comparison with/identification of a frame	This mechanism refers to the situation where the operator focuses on the wrong information, or wrong parts of the information. This is less a bottom-up issue of cue salience capturing attention, but instead describes the situation when operators have a frame or	If operators focus on one indicator to the exclusion of others, they may not fully understand the situation. For example, if operators focus on RCS level but do not account for the *rate*	• Knowledge/ experience/ expertise • Training • HSI Output	1. Having insufficient knowledge and experience can lead operators to selecting an incorrect or inadequate model, focus on inappropriate aspects of the frame to understand the situation, and come up with an incorrect understanding of the information. Experts	Bedny & Meister, (1999) Durso et al. (2007) Klein et al. (2007)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	mental model about what is happening, but because of the way information initially presented itself, focus on inappropriate data. This can also occur due to operators placing too much subjective significance on information that is objectively unimportant.	*of change* in level, they may misunderstand the urgency of the situation.		are better able to make use of their mental models to impose form on sensory data in real time. 2. Training is a method for developing knowledge and experience. If training does not provide operators with the necessary information or practice, knowledge will suffer. 3. The initial one or two key data elements that present themselves in the situation often serve as anchors for developing understanding. These anchors elicit the initial frame, and we use that frame to search for more data elements, which in turn elaborate that frame or anchor a new frame. If the first few pieces of information are misleading or spurious, understanding will suffer.	
Incorrect or failure to match data/ information to a frame/mental model	When evaluating the information available in a situation, people may fail to match the information to a frame or mental model, or they may make an incorrect match. This may be due to overexplanation, or finding connections that don't actually exist, or to failing to recognize that the data matches a particular frame.	For example, a situation may be misinterpreted by the crew and the procedures are, therefore, deemed inappropriate. Crews will follow the procedures while responding to an event. During this time the crew will judge/decide whether the strategies embodied in the procedures are appropriate to the situation. The crew may make a mistake either due to a misinterpretation of the situation or due to misreading the procedures.	• HSI Output • Knowledge/ experience/ expertise	1. If operators are focused on other, overly salient information and neglect relevant but less salient information, they may not map the important information to a frame. 2. People are explanation machines. People will employ whatever tactics are available to help them find connections and identify anchors. This means that people may find connections between all sorts of pieces of information, even those that aren't actually connected. Experts are better able to work with the information; they have a richer repertoire of frames, and are less likely to find pseudocorrelations.	Anderson (2000) Chi, Feltovich, & Glaser (1981) Endsley (1995) Klein et al. (2007) Roth (1997)
Mental manipulation of the information (including projection of future status) is inadequate, inaccurate, or otherwise inappropriate	People don't just put pieces of information together; they mentally manipulate, transform, and turn the information around in their heads. This includes projecting the current status into the future to imagine how things will play out, engaging in hypothetical postulation, and abstracting, simplifying, or combining information to better make sense of it. If this mental transformation is done improperly, for example, if information is overly	Overly optimistic estimations of the amount of time one has to work with can lead to problems in responding appropriately to an event.	• Knowledge/ experience/ expertise • Training	1. To ensure the proper interpretation of information by the operator, the operator must have professional experience and knowledge. Having insufficient knowledge and experience can lead operators to selecting an incorrect or inadequate model of the situation, focus on inappropriate aspects of the frame to understand the situation, and come up with an incorrect understanding of the information.	Bedny & Meister (1999) Cellier et al. (1997) Durso et al. (2007) Endsley (1995) Klein et al. (2007)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	simplified, or if projection of future status is overly optimistic or conservative, or if the mental manipulation focuses on inappropriate aspects of the situation, then an incorrect understanding of the situation can develop. NOTE: This can also lead to not checking information frequently enough.			Experts have greater skill in anticipating. This can be seen in the gathering of anticipated cues during monitoring and diagnosis, in the preventive rather than reactive processing of disturbances and in better predictions of process evolution. 2. Training is a method for developing knowledge and experience. If training does not provide operators with the necessary information or practice, knowledge will suffer.	
Working memory limitations impair processing of information	Only a limited amount of the situation can be processed at one time due to limited cognitive capacity.	Operators dealing with multiple alarms, multiple system faults, or multiple tasks may have difficulty keeping everything in memory. This will impair processing and understanding of the situation.	• Situation complexity • Working memory capacity • Experience/ knowledge/ expertise • Training • HSI output • Workload	1. If the environment is well structured, then brief samples can take advantage of redundancies in the world. If it is unstructured, or the operator does not have the experience to take advantage of the structure, then situation awareness will be impaired. 2. Working memory span, the number of chunks of information one can hold active in memory, is correlated with situation awareness performance. People with larger working memory spans tend to develop better situation awareness. The more information a person can work with, the more likely they are to develop a full picture of what is happening. 3. Experts' chunks are more complex and structured than novices, so experts can work with more information successfully than novices. 4. Training is a method for developing knowledge and experience. If training does not provide operators with necessary information or practice, knowledge will suffer. 5. Significant errors can result from systems that force operators to rely heavily on their memory. 6. Maintaining understanding requires expending cognitive resources, which may compete with other parallel cognitive tasks. Heavy	Anderson (2000) Cook (2001) Durso et al. (2007) Endsley (2000) Endsley, et al. (2003) Endsley & Garland (2000) Gugerty & Tirre (2000) Wickens (2001)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
				concurrent task demands may in turn divert resources from the maintenance of situation awareness. This relationship between workload and understanding can also depend on expertise: an experienced operator can maintain understanding with less investment of cognitive resources, often due to their richer mental models. However, a more experienced operator does not necessarily have a better understanding of the situation; heavy reliance on resource-free mental models may mean that the operator incorrectly interprets or fails to notice an unexpected event.	
Improper control of attention	People limited amounts of attention. There is only so much information a person can attend to at once. Problems in attention control can manifest by failing to maintain attention to multiple tasks, goals, or pieces of information.	Procedures often require attention to multiple goals, for example, continuous action steps that must be carried out in parallel with other steps. Or, when operators are dealing with multiple faults, multiple systems, they may have difficulty properly maintaining attention on the appropriate items.	• Knowledge/ experience/ expertise • Cue salience/HSI output • Stressors • Workload	1. Experienced operators have mental models that inform them of the information they need to attend to and which information to disregard. Expert's search patterns through even complex displays for information can be quite efficient. However, even experienced operators can make errors in the process of prioritizing attention and neglect to attend to certain information, particularly when they have to juggle numerous competing tasks. 2. Stressors can narrow the attentional field, or the area of the visual field that operators can attend to. This means that potentially information in the periphery may be neglected, leading to poorer situation awareness 3. Maintaining a high level of understanding requires expending cognitive resources, which may compete with other parallel cognitive tasks. Heavy concurrent task demands may in turn divert resources from the maintenance of situation awareness. Expertise can reduce workload due to use of richer mental models, but reliance on less resource-intensive mental models may introduce other errors.	Adams, Tenney, & Pew (1995) Baddeley & Hitch (1974) Cook (2001) Durso & Gronlund (1999) Endsley et al. (2003) Jones & Endsley (1996) Wickens (2001)

A-2.3 Incorrect Frame

This table contains the mechanisms for the Incorrect Frame proximate cause. When this is the cause of *Detecting and Noticing* failure, the frame used to understand the situation is incorrect, incomplete, or otherwise insufficient to properly interpret the data. In this proximate cause, the mental model in use is not adequate to provide a correct understanding of the situation. This can be due to a number of factors, such as the person does not have the necessary experience to develop appropriate frames, or because the situation seems similar to a different frame. Whatever the reason, the cause of failure of *Understanding and Sensemaking* is that the person is using an inappropriate frame for the situation. This proximate cause can be explained by the following mechanisms:

1. Incorrect or inadequate frame or mental model used to interpret or integrate information
2. Frame or mental model inappropriately preserved or confirmed when it should be rejected or reframed
3. Frame or mental model inappropriately rejected or reframed when it should be preserved or confirmed
4. Incorrect or inappropriate frame used to search for, identify, or attend to information
5. No frame or mental model exists to interpret the information or situation.

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Incorrect or inadequate frame/mental model used to interpret/ integrate information	This mechanism refers to instances in which the person is using an incorrect, incomplete, or otherwise inadequate frame or mental model to understand the situation. This includes having an inappropriate goal for the situation, as goals are frames or parts of frames that indicate how things should happen or the ideal end state. This can occur if the person selects the wrong frame, if habit intrusion interferes with the selection of an appropriate frame, or if a subjectively important goal takes precedence over objectively important goals. Frames or mental models can be inadequate in a number of ways, including but not limited to: • The frame may be insufficient to integrate the information or determine which cues are actually relevant. • The frame may have inaccurate uncertainty features, which makes projection unreliable.	An example is the availability cognitive bias. People believe those values or items which are easier to retrieve from memory, or occur more frequently in memory, are more likely to occur. Items that are easier to retrieve from memory include those that the person is more familiar with, things that have been recently thought of, things that are frequently thought of. An example of this in NPP domain: operators who have been trained heavily on a particular event may diagnose a different event with similar symptoms as the event they have recently trained on. Another example is what is known as a “mode” error: operators believe that a particular system is operating in a particular mode, such as in automatic, or on standby, when it is not. They may then not recognize information that suggests the system is not operating correctly.	• Knowledge/ experience/ expertise • Training • Motivation	1. To ensure the proper interpretation of information by the operator, the operator must have professional experience and knowledge. Lack of experience can influence the options available to the decision maker in deciding upon a course of action or in the evaluation of the options. Experts’ mental models are richer in terms of having more detail, more variety, finer degrees of differentiation, and more coverage of the domain. Experts are also more sensitive to the context of the situation. Experts are more prone to question data than novices because they are more familiar with cases of faulty information. This may also mean that experts are more confident in their frames and skeptical of contrary evidence (making them more susceptible to fixation errors) than novices, who are less confident in frames and more sensitive to contrary data. Experts	Anderson (2000) Bedny & Meister (1999) Durso et al. (2007) Endsley (1995) Feltovich, Johnson, Moller, & Swanson (1984) Klein (1998) Klein et al. (2006) Klein et al. (2007) Tversky & Kahneman (1981)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	• The model may not be sufficiently developed to support projection. • Operators may have an adequate mental model for the situation (e.g., they may know what event is in progress), but an inadequate mental model of the system, plant configuration, system dynamics, or subtle dependencies, that may lead to errors in responding the situation.			are more likely to be able to work with multiple frames at once. When faced with data that has more than one explanation, experts can deliberately elaborate two to three frames simultaneously, looking for information that will rule out one of the frames. 3. Training is a method for developing knowledge and experience. If training does not provide operators with necessary information or practice, knowledge will suffer. 4. The higher the level of motivation or the more intense the motivation, the more mental and physical effort the person expends directed toward the achievement of that goal.	
Frame/mental model inappropriately preserved/ confirmed when it should be rejected/ reframed	When faced with data from the situation that does not match the frame or mental model, people go through a process of questioning the data and/or the frame. Eventually, they either reframe or they reject the data as inaccurate, spurious, or faulty and confirm their existing mental model. This mechanism refers to the case when people inappropriately reject the data and persist in an incorrect frame or mental model. Persistence in an inappropriate mental model may be difficult to overcome, because new information is interpreted in light of the model and is susceptible to confirmation bias.	Operators actively generate situation assessments that include possible explanations for the set of symptoms they observe. They then form expectations with regard to additional symptoms they should observe if their explanation is correct. These expectations are an example of a “frame” that may then be inappropriately confirmed or rejected. For example, if a particular alarm has a history of sounding spuriously, operators may be likely to dismiss it as a false alarm if it activates in the case of a real problem.	• Knowledge/ experience/ expertise • Trust in the data source	To ensure the proper interpretation of information by the operator, the operator must have professional experience and knowledge. Experts are more prone to question data than novices because they are more familiar with cases of faulty information. This may also mean that experts are more confident in their frames and skeptical of contrary evidence (making them more susceptible to fixation errors) than novices, who are less confident in frames and more sensitive to contrary data.	Anderson (2000) Bedny & Meister (1999) Endsley (1995) Klein et al. (2006) Klein et al. (2007) Roth (1997)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Frame/mental model inappropriately rejected/ reframed when it should be preserved/ confirmed	When faced with data from the situation that does not match the frame or mental model, people go through a process of questioning the data and/or the frame. Eventually, they either reframe—say the data is correct and the model is wrong, and switch to a different model—or reject the data and confirm their existing mental model. This mechanism refers to the case when people inappropriately reframe by rejecting a correct mental model and failing to recognize faulty data. Instead, they change to a new, incorrect model of the situation. When the frame is rejected (e.g., their expectations are violated), operators will search for additional or alternative factors to explain the observed system behavior.	Operators actively generate situation assessments that include possible explanations for the set of symptoms they observe. They then form expectations with regard to additional symptoms they should observe if their explanation is correct. These expectations are an example of a "frame" that may then be inappropriately confirmed or rejected.	• Knowledge/ experience/ expertise	To ensure the proper interpretation of information by the operator, the operator must have professional experience and knowledge. Experts are more prone to question data than novices because they are more familiar with cases of faulty information. This may also mean that experts are more confident in their frames and skeptical of contrary evidence (making them more susceptible to fixation errors) than novices, who are less confident in frames and more sensitive to contrary data.	Anderson (2000) Bedny & Meister (1999) Endsley (1995) Klein et al. (2006) Klein et al. (2007) Roth (1997)
Incorrect/ inappropriate/ inadequate frame used to search for, identify, or attend to information	This mechanism refers to the situation when the operator has an incorrect frame or mental model for the situation, which directs their attention toward information that is not objectively important. This then further perpetuates the incorrect understanding of the situation. This can occur because of habit intrusion, in which the habitual frame interferes with the ability to attend to non-habitual information, expectations for how the situation will unfold, the goals the operator has in the situation, including goals of personal significance to the operator (such as saving face or not being perceived as wrong), a lack of relevant training, knowledge, or experience, or	For example, people tend to seek out evidence that confirms their current position or mental model and to disregard evidence that conflicts with their current position, a phenomenon known as confirmation bias.	• Knowledge/ experience/ expertise • Training	1. Having insufficient knowledge and experience can lead operators to selecting an incorrect or inadequate model of the situation, focus on inappropriate aspects of the frame to understand the situation, and come up with an incorrect understanding of the information. Experienced people use their knowledge base to develop expectancies about situations. Experts are more likely to be able to work with multiple frames at once. When faced with data that has more than one explanation, experts can deliberately elaborate two to three frames simultaneously, looking for information that will rule out one of the frames. Experts are more prone to question the data, and are also more confident and skeptical	Bedny & Meister (1999) Einhorn & Hogarth (1981) Endsley (1995) Endsley (2006) Feltovich et al. (1984) Klein et al. (2007) Niesser (1976) Salmon et al. (2008) Smith & Hancock (1995)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	knowledge, training, or experience predisposing the operator to an incorrect frame for the situation. NOTE: This can also lead to not checking information frequently enough—if the frame doesn't specify checking information often enough, then important parameters will not be checked with adequate frequency.			in the face of contradictory information. 2. Training is a method for developing knowledge and experience. If training does not provide operators with the necessary information or practice, knowledge will suffer.	
No frame/mental model exists to interpret the information/ situation	This mechanism refers to the case where the operator has no mental model or frame for the situation. This can be due to insufficient experience or training, or it can be due to the sheer bizarreness of the situation. In the absence of an appropriate mental model, people will often fail to solve a new problem, even though they would have to apply the same logic as that used for a familiar problem.	This is likely rare, but may occur if the plant and the procedures do not provide the necessary information for operators to identify a model and make a diagnosis. An example is an event at the Crystal River 3 NPP, a pressurizer spray valve stuck open during a power increase following a shutdown, causing a slow depressurization. The indication for this valve in the control room showed that it was closed. The plant behavior was perceived as inexplicable, as all they could see was evidence of a depressurization with no indications of problems with the pressurizer. Their operating procedures did not help them determine the cause of the problem or prompt them to verify that all relevant spray valves were closed. Without information from the plant indicators or procedures to guide them, operators did not understand the nature of the situation and made several inappropriate knowledge-based decisions. When someone with more expertise joined the event response, that person was able to recognize the likelihood of a stuck open valve from knowledge, and thus the crew was able to terminate the event.	• Experience, knowledge, expertise • Training • Situation complexity • HSI output, availability and quality of information	1. To ensure the proper interpretation of information by the operator, the operator must have professional experience and knowledge. Having insufficient knowledge and experience can lead operators to fail to understand the situation. 2. Training is a method for developing knowledge and experience. If training does not provide operators with the necessary information or practice, knowledge will suffer. 3. If the situation or information in the environment is too complex changing too rapidly, then it will be beyond the operators' cognitive abilities to process. 4. If the information available from the environment, including from the procedures, is not correct, appropriate, or sufficient for the person to adequately update his/her knowledge, then they are less likely to understand what is going on.	Bedny & Meister (1999) Durso et al. (2007) Endsley (1995) Klein (1998) Meyer (1992)

A-4. DECISIONMAKING

This section of Appendix A contains the cognitive mechanism tables for the macrocognitive function of *Decisionmaking. Decisionmaking* involves goal selection, planning, re-planning and adapting, evaluating options, and selection. In IDHEAS decisionmaking can refer to things such as deciding a piece of information is irrelevant, deciding between two gauges to obtain information, or deciding to ask a question. It is not limited to making a decision about what action to take in response to an event.

Decisionmaking within a nuclear power plant (NPP) is characterized as involving experts and being largely driven by procedures. 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 must be accomplished and how it 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.

Two models that are particularly useful when examining *Decisionmaking* within an NPP are a recognition-primed decision (RPD) model (Klein, 1993), and an integrated naturalistic decisionmaking model proposed by Greitzer et al. (2010). RPD was primarily developed to explain decisionmaking in stressful situations and under time pressure. The integrated model includes concepts from SA, RPD, and recognition/metacognition. This integrated model seems to work well in identifying the process an experienced operator goes through in making a decision, even in the presence of procedures.

Chapter 5 discusses *Decisionmaking* in more detail.

In general, failure of the *Decisionmaking* means that a wrong decision has been made about the nature of the event, whether information is relevant, what the response should be, or what action should be taken. In other words, an inappropriate response plan has been constructed. The literature review identified three proximate causes as potentially leading to this failure. Those proximate causes, along with their cognitive mechanisms, are:

1. Incorrect goals or priorities set (Table A-3.1)
    a. Incorrect goals selected
    b. Missing a goal
    c. Incorrect prioritization of goals
    d. Incorrect judgment of goal success
2. Incorrect pattern matching (Table A-3.2)
    a. Not updating the mental model to reflect the changing state of the system
    b. Fail to retrieve previous experiences
    c. Incorrect recall of previous experiences
    d. Incorrectly comparing the mental model to previously encountered situations
    e. Cognitive biases
3. Incorrect mental simulation or evaluation of options (Table A-3.3)
    a. Inaccurate portrayal of action
    b. Incorrect inclusion of alternatives
    c. Inaccurate portrayal of the system response to the proposed action
    d. Misinterpretation of procedures
    e. Cognitive biases

A-4.1 Incorrect Goals or Priorities Set

This table contains the mechanisms for the Incorrect Goals or Priorities Set proximate cause. When this is the cause of *Decisionmaking* failure, the operator is working toward an inappropriate goal, or has goals improperly prioritized. Goals are set as the objectives that the decision should achieve. Goals are the measure for viewing the decision as successful or not. Although goals are formed during any decisionmaking 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 in either what goals are set or what priorities are assigned. Failure mechanisms include:

1. Incorrect goals selected. Errors may arise if the operators select the wrong goal to work toward. A variant of this failure 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 addressed first.
4. Incorrect judgment of goal success. The threshold used by the operator to judge goal success may be incorrectly set too low, or be incorrectly determined as met when it was not.

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	1. Procedures may mislead the operator to believe the initial situation is changing slower than it really is. 2. Experience with this type of 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. 3. 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)
Incorrect goals selected	During goal setting, the operator may select implausible goals not realizing they cannot be achieved given the state of the system.	The operator has chosen a goal to reach success, but there is not enough time to enact all the necessary actions to achieve that goal.	• Knowledge/ Experience/ Expertise • Time load • Training	1. Experience with this particular situation is lacking and, therefore, the operator does not have an accurate sense of how long implementing actions and seeing results will take. 2. There may not be enough time to allow the operator to	Jenkins, Stanton, Salmon, Walker, & Rafferty (2010) Klein (1993) Lipshitz (1993)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
				implement the solution as planned. 3. Training may be lacking on the manner in which the action should be implemented and on the situation in general, and therefore, the operator wastes time in implementing the solution and may have an inaccurate estimate of time available.	
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	1. Procedures may be poorly written or have complicated logic such that the crew does not fully understand the seriousness of the situation. 2. 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. 3. Training may be infrequent and the operator does not know how to balance the priorities appropriately. 4. System responses may be difficult to understand or misleading causing the operator to misunderstand the seriousness of the situation. 5. The crew or operator may have an incorrect assessment of the impact of the decision and value the continued viability of the plant more.	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	1. Training may be incomplete in how to prioritize goals and what systems should be recovered first and what actions should be performed first. 2. 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.	Amendola, Bersini, Cacciabue, & Mancini (1987) Kasbi & de Montmollin (1991) Rouse (1983) Reason (1997)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Incorrect prioritization of goals	The operator or crew may not know how to devote their time and resources to the problem and waste precious time trying to prioritize the goals.	The crew must decide whether it is more important to chase down the cause of the problem being observed (e.g., why is feedwater low) or respond to the situations being created by the problem (e.g., the need to secure more feedwater).	• Training • Procedures • Resources	1. Training may not direct the team to understand how to approach a situation and prioritize the goals correctly. 2. Procedures may be misleading or unclear as to which goal should be accomplished first. Procedures also often represent scenarios in a linear fashion. 3. Resources may be limited such that the crew cannot attend to both goals simultaneously.	Espinosa-Paredes et al. (2008) Orasanu (1993) Patrick, James, & Ahmed (2006)
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	1. Procedures may be written poorly such that it is hard for the operator to determine when success has been achieved. 2. Training on determining a value for a parameter may be lacking such that the operator is unsure if success has been achieved. 3. 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 et al. (2004)

A-4.2 Incorrect Internal Pattern Matching

This table contains the cognitive mechanisms for the Incorrect Internal Pattern Matching proximate cause. When this is the cause of *Decisionmaking* failure, the operator has mapped the situation to an inappropriate mental model. During the *Understanding and Sensemaking* macrocognitive function, an operator forms a mental model of the current situation. During pattern matching, the operator compares this mental model to previously encountered situations to judge the typicality of the situation and help in devising a plan. If the operator judges the situation as being typical, a previous response plan can be used again. If the situation is novel, the operator may find a similar situation that can be adapted to fit the current situation. This proximate cause includes errors that occur during the mental exercise of pattern matching. Cognitive mechanisms include:

1. Not updating the mental model to reflect the changing state of the system. Events within an NPP may evolve quite 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 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 decisionmaking (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 mental model.

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Not updating the mental model to reflect the changing state of the system	An operator may become fixated on the problem presented by the system and not observe how the system is changing and, therefore, not update the response plan to account for the changes in the system.	An inadequate monitoring strategy is employed by the team.	• Procedures • Training • Knowledge/ Experience/ Expertise	1. An operator may become fixated on the procedures to the point that the plant is not being monitored closely. 2. The crew has not been trained on what an adequate monitoring strategy should be and how often they should check various readings and plant states.	Burns (2000) Murphy & Mitchell (1986) Patrick et al. (2006) Shappell & Wiegmann (2000)
Fail to retrieve previous experiences	An operator may fail to retrieve an applicable previously encountered scenario.	The previously encountered scenario occurred (or was trained on) so long	• Training • System responses	1. Training is not offered frequently enough so that these relevant cases are	Burns (2000) Shappell & Wiegmann (2000)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
		ago, that it is no longer memorable.	• Knowledge/ Experience/ Expertise	fresh to the memory of the operator. 2. The system responses may be ambiguous enough that the operator doesn't recognize the situation as being one that was encountered before.	
Incorrect recall of previous experiences	A previous encountered scenario may be recalled incorrectly either because the situation isn't remembered right or the responses used in the previous situation are not recalled correctly.	An operator is pressed for time and quickly does a mental comparison, but given the time stress, the operator does not correctly recall the previously encountered situation.	• Training • Knowledge/ Experience/ Expertise • Time load	1. Training may either be incomplete and does not include the relevant previously encountered situation, or the training is infrequent and the relevant factors about the previously encountered situation are forgotten. 2. Experience by the operator may be lacking such that he or she hasn't had previous experiences to compare to the current situation. 3. If there is not much time, a comprehensive review may not be possible and the operator may incorrectly recall details about the previously encountered scenario.	Cacciabue et al. (1990) Klein (2008)
Incorrectly comparing the mental model to previously encountered situations	The comparison may be incomplete and compare only some of the situation to the mental model. For instance, the comparison may have terminated early.	The comparison to previously encountered situations may terminate early due to time pressure felt by the operator.	• Time load • Knowledge/ Experience/ Expertise • Training • Attention to task	1. Time load may pressure the operator into making a decision too quickly and terminating the comparison prematurely. 2. Experienced operators are more likely to quickly recognize a typical situation or one that has been encountered previously. Therefore, if the operator lacks experience, he or she may spend too long in searching for a similar previous experience and run out of time. 3. Training may not correctly prepare the operator for comparing the context to the mental model. 4. The operator may be distracted such that his/her attention to the task of mental simulation is incomplete and the task ends premature.	Greitzer et al. (2010) Lipshitz et al. (2001)
Incorrectly comparing the mental model to previously	The mental model may be correct and the previously encountered scenario may be remembered correctly, but an error may occur in the comparison of the two.	Due to time pressure, the operator may simply make a mistake in the comparison and therefore, not	• Training • Time load • Task complexity	1. Training may not correctly prepare the operator for comparing the context to the mental model.	Greitzer et al. (2010) Hoc & Amalberti (2005)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
encountered situations		consider the situation typical when it is or think it does match a previously encountered scenario when it does not.		2. Time load may pressure the operator into making a decision too quickly and the operator therefore makes a mistake during the simulation. 3. The task, context, or mental model may be so complex that the operator makes a mistake in doing the comparison.	
Cognitive Biases	The confirmation bias states that people tend to seek out evidence that confirms their current position and to disregard evidence that conflicts with their current position.	An operator may recall a previously encountered situation that he or she judges to be very similar to the current situation. The operator will tend to find evidence supporting this view and ignore evidence that would prove against the view.	• Time load • Training	1. As time pressure increases, the operator feels more pressure to form a response plan. Therefore, the operator is likely to run with the first similar situation recalled even if it is not that similar. 2. Training may not be frequent enough to keep multiple previously encountered situations fresh in the mind of the operator.	Einhorn & Hogarth (1978) Klein (1998) Milkman, Chugh, & Bazerman (2009)
Cognitive Biases	The retrievability/imaginability/ or availability bias states that the ease with which an item can be brought out of memory will influence the value assigned to the memory. People tend to believe and proceed forward with those items that are easier and quicker to retrieve from memory.	The first remembered previously encountered scenario is likely to be judged by the operator as being at least somewhat similar to the current situation.	• Training • Knowledge/ Experience/ Expertise	1. Training may have been limited so that the operator is not familiar with a large number of previous scenarios to compare against the present situation. 2. The operator may not have much experience and, therefore, is biased toward thinking everything is similar to one of the limited situations he or she does have experience with.	Lipshitz et al. (2001) Tversky & Kahneman (1974)

A-4.3 Incorrect Mental Simulation or Evaluation of Options

This table contains the cognitive mechanisms for the Incorrect Mental Simulation or Evaluation of Options proximate cause. When this is the cause of *Decisionmaking* failure, the operator has engaged in incorrect projection of a possible course of action, or has unrealistically evaluated the options. 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 operator will probably not do an exhaustive test of all proposed solutions, but will choose the first acceptable option. This proximate cause includes errors that occur during the mental simulation or evaluation of options. Cognitive mechanisms 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 forget to 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 making them difficult to use and understand.
5. Cognitive biases. The cognitive biases of overconfidence and the anchoring effect may be especially prevalent for this failure mechanism. Overconfidence affects the operator's confidence in the ability of an action to work. Especially if the operator has had previous success with an action, he or she may be overconfident in its ability to work in 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 be biased toward choosing the first action that occurs to him or her, and apply an unsuitable action.

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Inaccurate portrayal of action	During the mental simulation of applying a multi-step action, the operator may forget one or more critical steps of the action. Therefore, the mental simulation does not accurately predict what the situation's response to the action would be.	An operator dismissed an action thinking it would not work. However, it did not work because the operator forgot the action had a second step done after monitoring the system.	• Knowledge/ Experience/ Expertise • Training • Time load	1. Experience is limited in applying this action, so the operator forgot all the steps involved. 2. Training on the action is limited, and therefore, the operator does not understand the action and does not realize multiple steps are included. 3. Time pressure is increasing and this additional pressure causes the operator to make a mistake in the mental simulation and leave a step out of the action.	Klein (1993) Lipshitz (1993) Orasanu & Martin (1998)
Inaccurate portrayal of action	The operator may make a mistake during the mental simulation and not correctly	The operator incorrectly performed math in his or her	• Memory load	If the action or response is very complex, it requires the operator to	Klein (1993) Lipshitz (1993)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	predict the outcomes from taking the proposed action(s).	mind and thought a certain pressure would be needed to solve the problem when in fact that pressure was too low.		keep a lot in mind. The working memory has limited capacity; therefore, the operator may forget pieces or misrepresent the outcome of the proposed actions.	Murphy & Mitchell (1986) Rasmussen (1983)
Inaccurate portrayal of action	An error may occur if the operator does not realize an action must be implemented in stages of steps. Therefore, the operator does not accurately portray how the action would play out.	A continuous action step that requires monitoring and feedback from the system while implementing the action may be imagines wrong during the evaluation of the action as an option.	• Knowledge/ Experience/ Expertise	Experience may be lacking in understanding plant responses and the need to control the plant in stages/steps followed by monitoring the change.	Gonzalez, Lerch, & Lebiere (2003) Greitzer et al. (2010)
Incorrect inclusion of alternatives	The construction of the response plan may be incorrect because wrong responses are included.	Wrong actions may be included because the response of the previous situation to the actions was not recalled correctly and the operator thought the action had been successful when it was not.	• Training • Knowledge/ Experience/ Expertise	1. Training may be incomplete and the operator is unable to recognize the similarity to previously encountered scenarios or recall the previous scenarios. 2. Experience is lacking in dealing with NPP operations, and therefore, the operator lacks understanding regarding how the plant will react to certain actions and recognizing similarity to previously encountered scenarios.	Cacciabue et al. (1990) Clemen (2001) Greitzer et al. (2010)
Incorrect inclusion of alternatives	The construction of the response plan may be incorrect because responses that should be included are not.	For example, the operator ran out of time for conducting the mental simulation and had to go forward with the best alternative presented at the time. Experience will help the operator learn to do a directed search and simulation of relevant course of action instead of a random and exhaustive search.	• Training • Time load • Knowledge/ Experience/ Expertise	1. Training may be incomplete such that similar previously encountered situations (either encountered by this plant or at other plants) are not trained well enough so that the operator can bring up the appropriate responses when needed. 2. The operator is pressed on time and there is not enough time to perform a more complete mental simulation and compare against more previously encountered scenarios. 3. Experience may be lacking in being familiar with previous scenarios encountered by NPPs, and in recognizing a similar situation.	Cacciabue et al. (1990) Gonzalez et al. (2003)
Inaccurate portrayal of the system	Incorrect judgment of time needed to implement the solution.	Especially in a novel situation in which the operator is imaging the impact of	• Procedures • Training	1. Procedures may not have sufficient clarity or detail to help the operator in such a novel situation.	Klein (1993) Lipshitz (1993) Mumaw, Swatzler, Roth,

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
response to the proposed action		proposed actions on the situation, the operator may not have a correct sense of the time needed to implement the solution.	• Knowledge/ Experience/ Expertise	2. Training may be lacking on similar situations to help the operator have a better estimate of how the system will progress and how much time is available. 3. Experience may be lacking on similar situation that would help the operator make a better prediction of the progression of the plant state and a more accurate estimate of the time remaining.	& Thomas (1994) Shappell & Wiegmann (2000)
Inaccurate portrayal of the system response to the proposed action	The operator or crew may incorrectly judge the amount of time available to implement the solution. The misjudgment may be either thinking there is more time available than there actually is or thinking there is less time available and artificially imposing a time constraint.	A supervisor may impose time pressure on the crew to resolve an issue. If the crew is stressed from time pressure, they are more likely to make mistakes such as taking shortcuts with the procedures and not fully evaluating outcomes from proposed solutions.	• Training • Knowledge/ Experience/ Expertise	1. Training on the situation was not detailed enough to give the operator a realistic sense of how much time would be available to implement a solution. 2. Experience is lacking with this particular scenario, and therefore, the operator does not have a realistic sense of how much time is available.	Klein (1993) Lipshitz (1993) Orasanu & Martin (1998) Shattuck & Miller (2006)
Inaccurate portrayal of the system response to the proposed action	During the mental simulation, the operator may fail to include a problem likely to occur within the system with the application of the action.	Especially for creative solutions applied to novel situations, it is difficult for the operator to imagine all that might go wrong with certain actions.	• Knowledge/ Experience/ Expertise • Training	1. Experience may be lacking, and therefore, the operator is faced with a novel situation. 2. Training on the situation may be lacking.	Klein (1993) Lipshitz (1993) Orasanu & Martin (1998)
Misinterpretation of procedures	Response planning within the NPP is done by consulting the procedures and being directed by them. An error may occur because the wrong procedures are being used for addressing the situation or the procedures are difficult to understand in terms of what actions should be included in the decision set.	A complex situation arises with multiple alarms and multiple operations being required. The operator and crew may be overwhelmed and unsure what procedure is correct for responding to the issues.	• Procedures • Training • Time load • System responses	1. The procedures may be written poorly and are difficult for the operator to use. 2. Training on the use of the procedures, or how to switch between procedures, or how to use multiple procedures may be poor or too infrequent. 3. Time may be compromised if the operator has to spend much time trying to determine which is the appropriate procedure. 4. If the system responses are ambiguous or overly complex, it can mislead the operator into using the wrong procedure.	Cacciabue et al. (1990) Mumaw et al. (1994) Roth (1997)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Cognitive biases	The operator may be overconfident in the ability of an action to work. (overconfidence bias)	Due to an operator's previous success with a certain response plan, the team employs the same response plan without fully realizing the differences between the situations and the likelihood of the actions failing.	• Training • Knowledge/ Experience/ Expertise	1. Training may be lacking on this particular situation, and therefore, the operator does not fully understand and accurately predict the response of the situation to the proposed action. 2. Experience may be lacking with other forms of this type of situation, and therefore, the operator does not understand the subtly of the differences and the impact those differences can have on the success rate of the proposed solution.	Klein (1998) Milkman et al. (2009) Murphy & Mitchell (1986) Orasanu & Martin (1998)
Cognitive biases	The anchoring effect occurs because people are biased toward the first option they see or the first judgment they make.	A wrong action may be chosen just because it was the first one imagined	• Training • Knowledge/ Experience/ Expertise • Time load	1. Training is lacking on the situation to understand appropriate response. 2. Experience is lacking on the situation to understand the appropriate response. 3. Time pressure is leading the operator to make a quick selection, and therefore, the operator is biased to one of the first actions imagined.	Milkmanbet al. (2009) Orasanu & Martin (1998) Tversky & Kahneman (1974)

A-5. ACTION

This section of Appendix A contains the cognitive mechanism tables for the macrocognitive function of *Action.* As discussed in Section 2.2.3 above, *Action* is not listed as a macrocognitive function in either the Klein et al. (2003) or Patterson & Hoffman (2012) models. However, for the purposes of human reliability analysis (HRA), it is important to consider performance of the actual task. It is necessary to be able to predict pressing the wrong button or turning the wrong dial, for example. Therefore, the current model includes the macrocognitive function of *Action*.

When considering the scope of *Action*, it was necessary to define the level of action implementation that is included in the function. A large portion of the cognitive activities involved in executing a procedure (or procedure steps) includes detecting appropriate cues, understanding the situation given those cues and the mental model of the process, and deciding upon the correct response (i.e., the macrocognitive functions reviewed above). For the purposes of this effort, *Action* is defined as implementing an action on the level of a single manual action (such as operating a valve) or a predetermined sequence of manual actions. The action(s) must involve the manipulation of the hardware and/or software that would consequently alter plant status. Therefore, communication (e.g., giving commands) and collecting information about the plant status are not within the scope of this function, as they are encompassed in *Teamwork*. It is assumed that the other macrocognitive functions (e.g., *Detecting and Noticing*, *Understanding and Sensemaking*, and *Decisionmaking*) have been carried out successfully.

Operator actions can take the form of individual control actions (e.g., turning a switch to a particular position; turning a pump on or off) or a sequence of actions intended to achieve a particular goal. An example of a sequence of actions is realigning a set of valves to change a flow path. In some cases, all that is required is a single, discrete, control action to achieve the goal. For example, manually tripping the plant generally requires a single button press (or turn of a switch). However, in other cases more sustained control is required. For example, in many situations operators are required to make continuous adjustments to maintain a parameter within a specified set of limits.

Reason (1990) presented a detailed psychological analysis of the psychological causes of errors of execution. He divided errors of execution into two major forms: slips and lapses. According to Reason (1990) “Slips and lapses are errors which result from some failure in the execution and/or storage of an action sequence, regardless of whether or not the plan which guided them was adequate to achieve its objective.” Slips are errors where actions executed are “not as planned.” They typically occur in the performance of largely automatic tasks performed by a skilled individual in familiar conditions, especially when attention is diverted (e.g., because of distraction or preoccupation). Lapses involve failures of memory, where an individual may forget to perform an intended action. This is often due to a failure in prospective memory—memory for intended actions in the future.

Chapter 6 discusses *Action* in more detail.

In general, failure of the *Action* macrocognitive function means that the implementation of a correct chosen action was omitted or done incorrectly. The literature review identified two proximate causes as potentially leading to this failure. Those proximate causes, along with their cognitive mechanisms, are:

1. Failure to take required action (did not attempt action) (Table A-4.1)
    a. Working memory failure
    b. Prospective memory failure

    c. Divided attention

2. Executed desired action incorrectly (Table A-4.2)
    a. Error monitoring and correction
    b. Dual task interference
    c. Task switching interference
    d. Negative transfer/habit intrusion
    e. Automaticity control
    f. Mode confusion
    g. Population stereotypes
    h. Motor learning
    i. Recognition errors
    j. Stimulus response compatibility
    k. Manual control issues
    l. Continuous control deficiencies

A-5.1 Failure To Take Required Action (Action Not Attempted)

This table contains the cognitive mechanisms for the Failure to Take Required Action (Action Not Attempted) proximate cause. When this is the cause of *Action* failure, the operator neglects to implement the chosen action. This is an error of omission. In the *Action* macrocognitive function, only omissions associated with action execution are considered. For example, failing to take an action because of a failure in decisionmaking would be an error dealt with in the *Decisionmaking* macrocognitive function. This proximate cause can be explained by the following mechanisms:

1. Working memory failure
2. Prospective memory failure
3. Divided attention

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Working memory failure	Working memory has a limited capacity, and the more information that must be kept online to complete a task, the more likely it is that an error will be committed due to working memory failure Information can be combined into chunks to increase the amount of information that can be stored in working memory. Researchers generally agree that the typical span of working memory is 7±2 chunks.	An operator must remember a sequence of 10 predetermined actions specified in a procedure. By the time he gets to Action 8, he has forgotten the remaining actions in the sequence.	• Task load • Non-task load • Knowledge & experience	1. Task demands and non-task demands influence the amount of information that must be kept in working memory. 2. Experts are able to construct more complex chunks allowing for them to make use of greater amounts of information in working memory.	Anderson (2000) Baddeley (1992) Doane et al. (2004) Reason (2008)
Prospective Memory Failure	Once an action plan has been decided upon, execution of that plan may fail due to forgetting (also known as a failure of prospective memory). Actions that are planned to be carried out at some point in the future require that an operator recognize a cue that signals that action and have successfully stored the action plan in long-term memory for retrieval	An operator intends to activate a system as specified by a procedure step, but before he does, he is interrupted by the shift supervisor to complete another task. When he returns to the procedure, he has still not activated the system, but he continues on with the procedure as though he has.	• Task load • Non-task load • HSI	1. High task demands and interruptions make forgetting-the-plan more likely 2. Salient cues from the HSI or routine reminders may help to reduce failures of prospective memory	Dohdia & Dismuskes (2009) Reason (2008) Reason (2002)
Divided attention	Performance is degraded on tasks when attention is divided among two or more tasks (Proctor and van Zandt, 2008).	An operator must monitor one parameter continuously while executing procedure steps. The actions specified in the procedure steps may be overlooked if attention is captured by the monitoring task.	• Task load • Non-task load	Task demands affect the degree to which attention has to be divided among tasks.	Proctor & van Zandt (2008)

A-5.2 Execute Desired Action Incorrectly

This table contains the cognitive mechanisms for the Execute Desired Action Incorrectly proximate cause. When this is the cause of *Action* failure, the operator executes the chosen action incorrectly. This is an error of commission. This proximate cause includes errors of selecting the wrong control and qualitative errors such as turning a dial too much or turning a switch to the wrong position. Actions that are carried out too slowly, too quickly, too soon, or too late are also captured by this proximate cause. It is important to note that manual execution of most actions in the control room and in the plant do not require precise (approximately seconds or milliseconds) timing. This proximate cause can be explained by the following mechanisms:

1. Error monitoring and correction
2. Dual task interference
3. Task switching interference
4. Negative transfer/habit intrusion
5. Automaticity control
6. Mode confusion
7. Population stereotypes
8. Motor learning
9. Recognition errors
10. Stimulus response compatibility
11. Manual control issues
12. Continuous control deficiencies.

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Error monitoring and correction	When executing a motor response, error monitoring and correction depends on appropriate feedback from the system. Errors may occur if feedback regarding control state is delayed or missing	An operator may unintentionally duplicate an action if feedback that the action was carried out by the system is delayed.	• HSI • Fatigue • Anxiety	1. The degree to which the HSI provides appropriate and timely feedback will affect error monitoring and correction. Errors may occur if feedback regarding control state is delayed or missing. 2. Sleep deprivation impairs error monitoring and correction. 3. Anxiety impairs error monitoring and correction.	Wickens (2004) Hsieh et al. (2009) Aarts & Purtis (2010)
Dual task interference	Execution of one task may interfere with aspects of a second task due to “crosstalk” between the two tasks. This interference can occur in cognition or in coding the motor response.	An operator intends to activate a system as specified by a procedure step, but before he does, he is interrupted by the shift supervisor to complete another task. When he returns to the procedure, he has still not activated the system, but he continues on with the procedure as though he has.	• Task load • Non-task load • HSI	1. Task load and non-task load will influence the degree to which operators must perform multiple tasks. 2. Interference from one task to another depends on the similarity in modality of the two tasks. For example, two tasks requiring vocal responses would introduce more interference than one requiring a vocal response and the other requiring manual tracking. The modalities of the required cues and responses are influenced by the HSI.	Reason (2008) Wickens (1976)
Task switching interference	Switching between two tasks can result in interference of the two tasks. This	An operator is delayed in taking an action because he	• Task load	1. Task load and non-task load will determine the amount of task switching that must be done.	Kiesel et al. (2010)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
	interference can occur in cognition or in coding the motor response.	took too long to realize he needed to switch.	• Non-task load • HSI	2. Preparation for task switching (e.g., if a cue is provided prior to a switch to a secondary task) can reduce the interference, but not eliminate it, this can be accomplished via a cue or signal from the HSI.	
Negative transfer/habit intrusion	Highly practiced responses may interfere with the desired response if the current situation demands an alternative. Repetition may also temporarily produce the same effect.	As part of normal operation, an operator almost always opens Valve A and closes Valves B & C, but the current task requires him to open Valves B & C and close Valve A. He accidentally opens Valve A like he always does.	• Task load • Training program • Knowledge and experience	1. High task demands may narrow attention such that negative transfer is more likely 2. The training program will affect the types of tasks that are highly practiced 3. Individual knowledge and experience will dictate the degree to which certain tasks are habitual.	Reason (2008)
Automaticity control	Well practiced sequences of actions often become automated. Automaticity on a primary task is defined as the ability for an individual to complete both a primary and secondary task without a performance decrement to the primary task. When an automatic motor sequence must be changed or stopped due to a novel situation, the automatic process may be difficult to interrupt and/or control. Controlling an automatic sequence can occur based on feedback from the system or based on a contextual cue in the environment.	An operator must carry out a sequence of actions multiple times per day, so he can do it without thinking. However, this particular time, one of the actions failed because a system was not available. Because he was operating on "autopilot," he did not detect this and finished the sequence.	• Training program • Knowledge and experience • Task load • HSI	1. Training programs and individual knowledge and experience will affect the degree to which actions are automated 2. High task demands can narrow attention such that operators do not notice environmental or contextual cues that signal they need to respond differently 3. The HSI may not provide appropriate cues (or they may not be sufficiently salient) for operators to stop an automatic response	Poldrack et al. (2005)
Population stereotypes	Population stereotypes dictate the expectancies of certain control behaviors (e.g., one expects that when a valve is turned counterclockwise, flow will increase). Violating population stereotypes can lead to errors.	A control is typically turned counterclockwise to increase a value; however, the HSI is designed so that you turn it clockwise to increase the value.	• Training program • HSI • Knowledge and experience • Stress	1. The training program and individual knowledge and experience will influence the expectancies of control behaviors (thus affecting the population stereotypes). 2. The HSI should be designed such that controls and displays do not violate population stereotypes 3. Even with extensive training, these violations are difficult to overcome 4. In high stress situations, operators may revert back to their original expectations.	Swain & Guttman (1983)
Mode confusion	If controls (or displays) operate in different modes, it may lead to mode confusion. Errors may be more severe if the controls accomplish drastically different things in the different modes.	Mode A activates a system and Mode B prints information about that system. The current mode is not conspicuously indicated and an operator who intends to activate	• HSI • Knowledge and experience	1. If the HSI is designed such that displays and/or controls operate in multiple modes, it may lead to mode errors. Some major factors that contribute to mode errors are user expectations, user knowledge and sensing of triggering events. The HSI can influence sensing of triggering events (for mode	Degani et al. (1999)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
		the system fails because it is actually in Mode B.		switches) by making conditions or events conspicuous to users. If mode changes and the conditions that cause them are not conspicuously indicated by the HSI, mode errors are more likely to occur. 2. User expectations and user knowledge are influenced by knowledge and experience.	
Motor learning	Retention of motor skills can is influenced by several factors associated with practice including amount of practice, practice schedule (i.e., distributed versus massed and random versus blocked).	An operator performs a sequence of actions incorrectly because he has not practiced the sequence in training for over a year.	• Training program	The training program will influence how well motor skills and sequences are retained. Distribution of practice (i.e., spreading training sessions out over time) leads to better retention of motor skills.	Schmidt & Bjork (1992).
Recognition errors	Misidentification of objects such as controls can lead to errors.	Two controls that do drastically different things look similar and are located side-by-side.	• HSI	The method of control coding in the HSI (e.g., location, color coding, labeling, shape coding or size coding) will affect the likelihood that the right control is selected. The coding scheme selected for the HSI should be consistent with user expectations and conventions.	Reason (2008) Proctor & van Zandt (2008) Wickens et al. (2004) Wickens & Hollands (2000)
Stimulus response compatibility	The relationship between the stimulus (e.g., a display) and the desired response (e.g., a control action) affects the likelihood of failure of that action.	An operator increases a value that he meant to decrease because the control was a lever that when pressed down actually increased the value.	• HSI	If the HSI is designed such that controls and/or displays violate compatibility principles, then it may increase the likelihood of errors. Major compatibility factors include location compatibility and movement compatibility.	Wickens et al. (2004) Proctor & van Zandt (2008)
Manual control issues	The type of control (keyboard, selector switch, button, etc.) as well as specific aspects of the design of that control (the surface or size of a button, the resistance of a knob, etc.) has an impact on the likelihood of committing an error. See Procter & van Zandt (2008) or Wickens et al. (2004) for in-depth discussion of controls.	An operator turns a dial farther than he intends to because the dial does not have enough resistance and is too easily turned.	• HSI	The degree to which human factors principles have been incorporated into the HSI will affect the likelihood of errors due to controls.	Proctor & van Zandt (2008) Wickens et al. (2004)
Manual control issues	Human physiology (build, strength) has limitations that should be accommodated by the design of the workplace. See Proctor and van Zandt (2008) for more detail.	An operator is unable to open a valve because he does not have the strength required to open the valve.	• HSI • Workplace adequacy	1. The HSI should be designed to accommodate human limitations 2. Obstructions and distractions in the environment (e.g., a wet floor) may affect the likelihood of errors	Proctor & van Zandt (2008)
Continuous control deficiencies	When an operator must take continuous manual control of a process (e.g., keeping a system parameter within a prescribed set of limits), human information processing limits and system complexities may lead to errors.	An operator overshoots a system parameter due to unpredictable shrinks and swells.	• System dynamics • HSI	1. Complex system dynamics (such as shrinks and swells) may contribute to manual control deficiencies, making errors more likely. 2. Feedback and indications from the HSI may exceed human information processing limits.	Wickens & Hollands (2000)

A-6. TEAMWORK

This section of Appendix A contains the cognitive mechanism tables for the macrocognitive function of *Teamwork*. *Teamwork* is the macrocognitive function that focuses on how people interact with each other to coordinate as the individual or crew works on a task. In the present effort, this function was used to represent coordination, collaboration, and communication between individuals, as well as to address crew interaction issues such as command and control.

It is important to note that this function only encompasses the emergent aspects of team coordination to avoid duplicating cognitive functions already described by previous macrocognitive functions. Building on the team sensemaking work of Klein, Wiggins, and Dominguez (2010), these emergent aspects are unique to and only emerge when people work together in teams. For example, even in a team setting, individual functions like detecting/noticing and sensemaking occur in parallel in all team members, such as a crew's response to an alarm annunciation. Given this context of independent parallel processing, the essence of teamwork is the combination of these independent process efforts via communication for the purpose of facilitating team coordination. Using communication to combine the individual macrocognitive processes is one emergent aspect of teams; the other is leadership. NPP control room crews are hierarchical and have a distinct leadership structure. Errors in either communication or leadership or supervision can lead to failure of the *Teamwork* function.

Chapter 7 discusses *Teamwork* in more detail.

In general, failure of the *Teamwork* function means that the team fails to properly resolve the independent and parallel individual macrocognitive functions. In other words, the crew members do not share the same understanding of the situation or what decisions have been made. This can lead to poor team performance and errors in individual macrocognitive functions. The literature review identified two proximate causes of failure of this function. Those proximate causes, along with their cognitive mechanisms, are:

1. Failure of team communication (Table A-5.1)
    a. Source error of omission
    b. Source error of commission
    c. Target error of omission
    d. Target error of commission
    e. Incorrect timing of communication.
2. Errors in leadership/supervision (Table A-5.2)
    a. Decisionmaking failures
    b. Failure to verify that the RO, BOP, and/or other operator have correctly performed their responsibilities
    c. Failure to consider the information communicated by an individual
    d. Failure to iterate the communication process sufficiently.

A-6.1 Failure Of Team Communication

This table contains the cognitive mechanisms for the Failure of Team Communication proximate cause. When this is the cause of *Teamwork* failure, key information is not properly shared or distributed among the crew members, and as a result, the entire team does not share a mental model of the situation, or errors may be made when taking action in response to an event. This proximate cause can be explained by the following cognitive mechanisms:

1. Source error of omission. The sender of the communication does not communicate the information.
2. Source error of commission. The sender communicates wrong information.
3. Target error of omission. The receiver of the communication does not detect or notice the communication, or does not comprehend the communication (*Understanding and Sensemaking*-related error).
4. Target error of commission. The receiver of the communication is listening to the wrong source, or is listening for wrong information (listening biased by preconceptions).
5. Incorrect timing of communication. The communication is, for example, delayed, premature, or communicated too slowly.

Mechanism	Discussion	Example(s)	Relevant PIF(s)	PIF Explanation	References
Source error of omission	In any instance of communication in a crew, there are at least two people involved. There is the person sending or transmitting the information (i.e., source), and the person receiving the information (i.e., target). This mechanism is the instance where the source should communicate information to the target(s), but does not.	The SRO has information about the overall state of the NPP system that affects what the BOP is doing with just the turbines, but the SRO does not communicate that information to the BOP. (The reasons why are the PIFs) The RO is hesitant to speak up because: • The SRO has an autocratic leadership style and/or • Social pressures to not be a "squeaky wheel" and/or • He has been wrong too frequently in the past The BOP does not speak up because: • He has an incorrect understanding of the situation • His risk perception of the situation is incorrect • He is unaware of his roles and responsibilities, and/or assumes that someone else will speak up.	• Time pressure • Deficiency in resource/task management • Leadership style • Team cohesion, Social pressure, Groupthink • Knowledge/ experience • Risk perception • Role awareness • Physical or psychological impairment • Training, communication protocol • Confidence in the information to be communicated • Assumption of target's knowledge (misplaced trust in target's knowledge)	1. Time pressure causes the SRO to rush through his responsibilities and he forgets to communicate to the rest of the team. 2. The SRO's leadership style could discourage operators from communicating "bad news," or challenging the SRO's beliefs. 3. The operators could feel social pressure to get along and "not rock the boat" too much by being a "squeaky wheel." 4. The operators could feel social pressure to not "cry wolf." 5. The BOP does not deem and/or understand that the information he needs to communicate is important and/or relevant to reducing the overall CDF. 6. The BOP is unaware that communicating a piece of information to the SRO is part of his roles and responsibilities. 7. The SRO is physically impaired and/or psychologically fatigued and is unable to transmit information. 8. The SRO assumes the RO knows what to do, and does not communicate the instruction.	Helmreich & Foushee (1993) Sasou & Reason (1999) Janis, I. (1972, 1982) Latané, Williams, & Harkins (1979) Massaiu, Hildebrandt, & Bone (2011) Carvalho et al. (2007) Lee et al. (2011)
Source error of commission	This mechanism is the instance where the source transmits the wrong information to the target, or transmits the correct information to the wrong target.	The SRO inadvertently transmits the wrong information to the RO and/or BOP. The BOP communicates the	• Time pressure • Deficiency in resource/task management • Task complexity	1. Time pressure causes the SRO to rush through his responsibilities and he inadvertently transmits the wrong information to the target, or transmits incomplete information, or	Helmreich & Foushee (1993) Sasou & Reason (1999) Klein (2001)

Mechanism	Discussion	Example(s)	Relevant PIF(s)	PIF Explanation	References
	This mechanism also includes communicating information that is not complete, specific enough, vague, overly simplified, done in a confusing way or otherwise insufficient, in addition to being incorrect or inadequate.	correct information, but transmits it to the RO instead of the SRO.	• Knowledge/ experience	transmits information in a confusing way, etc. 2. The complexity of the task causes the SRO to get confused as to what information he should transmit next, and he inadvertently transmits the wrong information, or transmits incomplete information, or transmits information in a confusing way, etc. 3. An upset condition that the crew has not trained on in over a year occurs, and the BOP lacks experience to know that he should have communicated with the RO instead of the SRO.	Massaiu, Hildebrandt, & Bone (2011) Carvalho et al. (2007) Lee et al. (2011)
Target error of omission	This mechanism has multiple psychological explanations. One explanation is where the source has transmitted information with sufficient strength that it could be detected or noticed by the target, but the target did not detect or notice that the information had been communicated. Another explanation is where the target has detected that the source has sent information, but the target is unable to comprehend the information. Another explanation is that a noisy environment (e.g., alarm annunciations) can interfere with, disrupt, or garble the information signal from the source to the target, causing the target to either not *Detecting and Noticing* or comprehend the information.	The RO did not *Detecting and Noticing* what the SRO has instructed him to do. Broadly speaking, comprehension or sensemaking can fail because of bad data, an incorrect mental model/frame, or poor integration of data with the mental model. The target failing to comprehend information communicated to him could be because of any and all of these sensemaking failures, though in this example we assume the data/information sent from the source is good.	• See *Detecting and Noticing* PIFs • See sensemaking PIFs for incorrect mental model/frame • See sensemaking PIFs for poor integration of the data with the mental model • Noisy environment/proximity of source to target • Distraction rich environment • Communication equipment malfunction • Task load	1. The RO does not *Detecting and Noticing* a communication from the SRO because the SRO did not get the RO's attention first. 2. The RO does not correctly comprehend the information sent by the SRO because he has a mental model that leads him to interpret the information differently than intended. 3. A noisy environment can interfere with the information signal being communicated. 4. An environment with lots of distractions can lead to the RO to attend to another stimulus when the information is transmitted. 5. A target already engaged in a complex task requiring his or her focused attention and does not *Detecting and Noticing* the information transmitted.	Klein et al. (2010) Helmreich & Foushee (1993) Sasou & Reason (1999) Massaiu, Hildebrandt, & Bone (2011) Carvalho et al. (2007) Roth (1997) Vicente et al. (2001) See *Detecting and Noticing* references. See Sensemaking references
Target error of commission	This mechanism has multiple explanations. One explanation is there are two or more sources of information sending information to the target, and the target is listening to the wrong source. Another explanation is the target's preconceptions of what information he thinks he should receive next	The BOP is expecting to receive information from the SRO, when in fact it is the RO that he needs to listen to for the correct information. The RO is expecting the SRO to transmit some information (because of his experience has created a preconceived notion of what should happen next), but the SRO	• Role awareness • Knowledge/ experience • See sensemaking PIFS for poor integration of the data with the mental model • Task load	1. An upset condition that the crew has not trained on in over a year occurs, and the BOP does not remember that the roles of the SRO and RO change in this upset condition, and that he needs to listen to the RO for information he normally gets from the SRO. 2. A target already engaged in a complex task requiring his or her focused attention and incorrectly processes	Klein et al. (2010) Helmreich & Foushee (1993) Massaiu, Hildebrandt, & Bone (2011) Carvalho et al. (2007) Roth (1997) Vicente et al. (2001)

Mechanism	Discussion	Example(s)	Relevant PIF(s)	PIF Explanation	References
	biases what he is listening for, and as a consequence listens for the wrong information, or misinterprets the information transmitted.	actually transmits information that is different from the RO's expectations. Yet when the RO receives the SRO's communication, the RO assumes the information is consistent with his preconceptions, and misinterprets the information transmitted. This is a kind of sensemaking error – specifically a data and frame integration error.		and takes action on information that was intended for a different target.	See Sensemaking references
Incorrect timing of communication (e.g., delayed, premature, communicated too slowly)	This mechanism describes the instances where the source correctly transmits information, the target correctly receives (i.e., detects and comprehends) the information, but the timing of the communication is incorrect.	The SRO communicates a command designed to mitigate an upset condition from occurring with insufficient lead time to prevent the initiating event.	• Time pressure • Knowledge/ experience	1. Time pressure causes the SRO to lose track of the moment in time (i.e., he loses situation awareness) when he needs to communicate a command to the BOP. 2. An upset condition that the crew has not trained on in over a year occurs, and the BOP forgets that he needs to communicate a critical piece of information within 20 minutes of the initiating event.	Helmreich & Foushee (1993) Carvalho et al. (2007) Lee et al. (2011) See Sensemaking references.

A-6.2 Error in Leadership/Supervision

This table contains the cognitive mechanisms for the Error in Leadership/Supervision proximate cause. When this is the cause of *Teamwork* failure, the crew fails to work in a coordinated fashion, or as a cohesive team. There may be supervisory or team management problems, such as the leader not facilitating group discussion, or failing to identify and correct an operator error. This failure mode can be explained by the following mechanisms:

1. Decisionmaking failures. This is covered in the *Decisionmaking* function.
2. Failure to verify that the RO, BOP, and/or other operator(s) or staff has correctly performed their responsibilities.
3. Failure to consider the information communicated by an individual.
4. Failure to iterate the communication process sufficiently.

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
Decisionmaking failures	The hierarchical leadership and supervision model used in NPPs dictates that the person in charge makes the final decisions, monitors the performance of the other crewmembers, and controls the deliberation/discussion processes among the team. Thus, one kind of error in leadership/supervision is making a bad decision.	The SRO decides to trip the plant when other options existed to achieve success	• See decisionmaking PIFs	See *Decisionmaking*	Massaiu, Hildebrandt, & Bone (2011) See Decisionmaking references
Failure to verify that the RO, BOP, and/or other operator(s) or staff has correctly performed their responsibilities.	The SRO failing to perform his oversight duties is another kind of error in leadership/supervision.	The SRO does not perform a second check of an action that the RO and/or BOP was directed to complete.	• Time pressure • Leadership style • Safety culture	1. Time pressure causes the SRO to rush through his responsibilities and he decides to skip performing his second check. 2. The SRO's leadership style could be more "hands off" (not micromanage), so he decides not to perform his second check of a routine action.	Helmreich & Foushee (1993) Massaiu, Hildebrandt, & Bone (2011) Carvalho et al. (2007) Carvalho et al. (2006)
Failure to consider information communicated by an individual.	Another kind of error in leadership/supervision is when the SRO does not consider information communicated from the RO and/or BOP during the resolution of the *Detecting and Noticing* and/or sensemaking phases of the team working together.	The SRO correctly detects/notices, and comprehends information communicated to him from the RO and/or BOP, but does not take it into consideration.	• Time pressure • Leadership style • Team dynamics • Safety culture	1. Time pressure causes the SRO to truncate the discussion before the RO or BOP can communicate additional information to him. 2. The SRO's leadership style could be highly autocratic, which leads him to disregard any information communicated to him from others.	Helmreich & Foushee (1993) Massaiu, Hildebrandt, & Bone (2011) Janis (1972, 1982) Carvalho et al. (2006)

Mechanism	Discussion	Example	Relevant PIF(s)	PIF Explanation	References
				3. The SRO could believe RO (and/or BOP) "cry wolf" too frequently, so he ignores their input.	
Failure to iterate the communication process sufficiently.	Another kind of error in leadership/supervision is more team communication could help diagnose the cause of the upset condition and what the correct course of action is, but the SRO truncates the communication.	The SRO cuts off debate among the crew about what corrective actions to take.	• Time pressure • Leadership style • Knowledge/ experience • Safety culture	1. The SRO truncates the discussion because an action must be taken immediately. 2. The SRO's leadership style and prior experience could lead him to believe that he already understands what is causing a particular upset condition and what to do about it, when in fact the cause of the upset condition is different.	Helmreich & Foushee (1993) Massaiu, Hildebrandt, & Bone (2011) Janis (1972, 1982) Carvalho et al. (2006)

Appendix B
Cognitive Framework Diagrams

This appendix contains the cognitive framework diagrams that the project team built based on the literature review. As discussed in Section 2.4, the literature review focused on identifying the mechanisms that can lead to human error. These cognitive mechanisms were organized and sorted into the cognitive framework structure shown in this appendix and the supporting tables in Appendix A.

This appendix should be used in conjunction with the tables in Appendix A. The diagrams in this appendix are a graphical depiction and summary of the information in the tables in Appendix A, and the tables provide explanation and support for the analyst when using the cognitive framework diagrams.

The generic cognitive framework is shown in Figure B-1 below. The macrocognitive functions are shown in purple. The proximate causes of the failure of a function are in blue. The mechanisms behind the proximate causes of failure are shown in turquoise, and the PIFs that influence those mechanisms are shown in orange. The entire framework spans numerous pages; for ease of use, they are broken down by macrocognitive function and proximate cause.

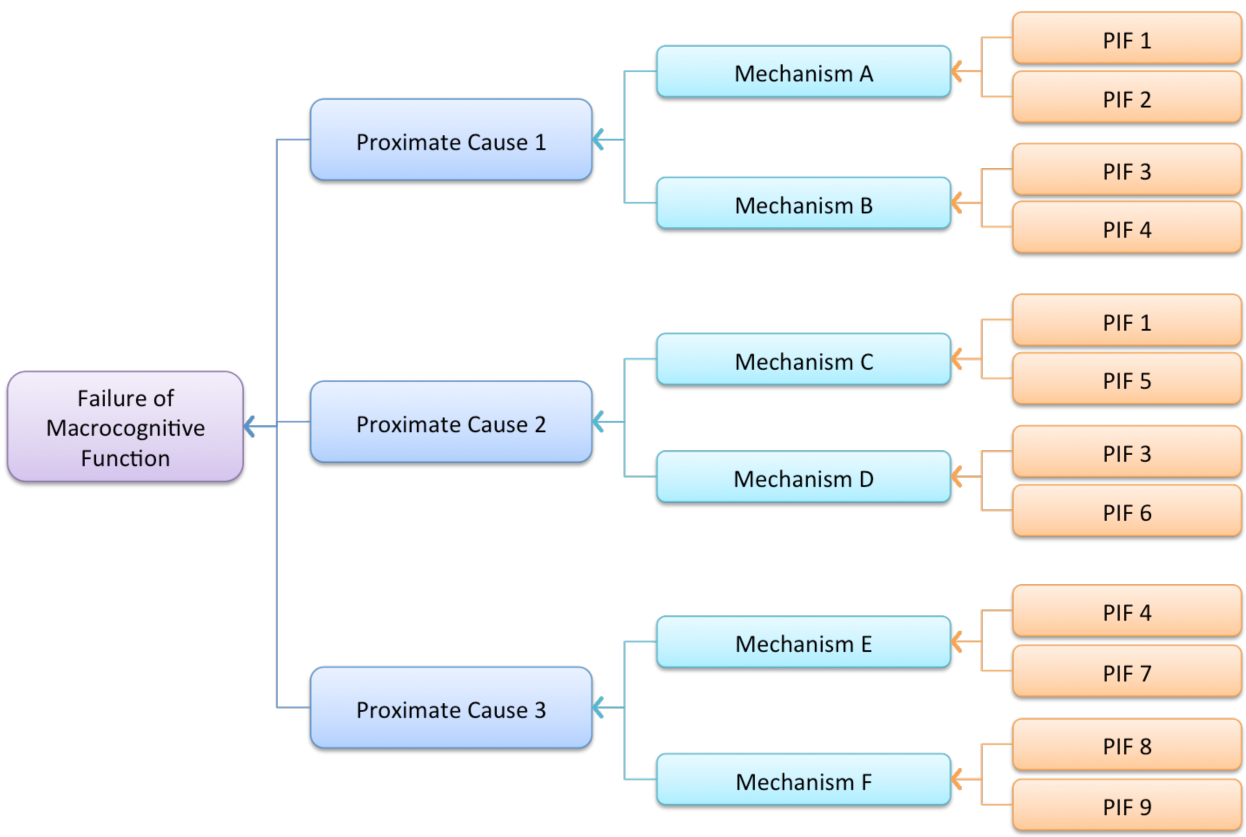


Figure B-1. Generic cognitive framework.

Section B-1 contains the cognitive framework trees for *Detecting and Noticing.* The diagrams are divided by proximate cause:

B-1.1 Cue/information not perceived

B-1.2 Cue/information not attended to

B-1.2 Cue/information misperceived.

Section B-2 contains the cognitive framework trees for *Understanding and Sensemaking.* The diagrams are divided by proximate cause:

B-2.1 Incorrect data

B-2.2 Incorrect integration of data, frames, or data with a frame

B-2.3 Incorrect frame.

Section B-3 contains the cognitive framework trees for *Decisionmaking.* The diagrams are divided by proximate cause:

B-3.1 Incorrect goals or priorities set

B-3.2 Incorrect internal pattern matching

B-3.3 Incorrect mental simulation.

Section B-4 contains the cognitive framework trees for *Action.* The diagrams are divided by proximate cause:

B-4.1 Failure to take required action (Action not attempted)

B-4.2 Execute desired action incorrectly.

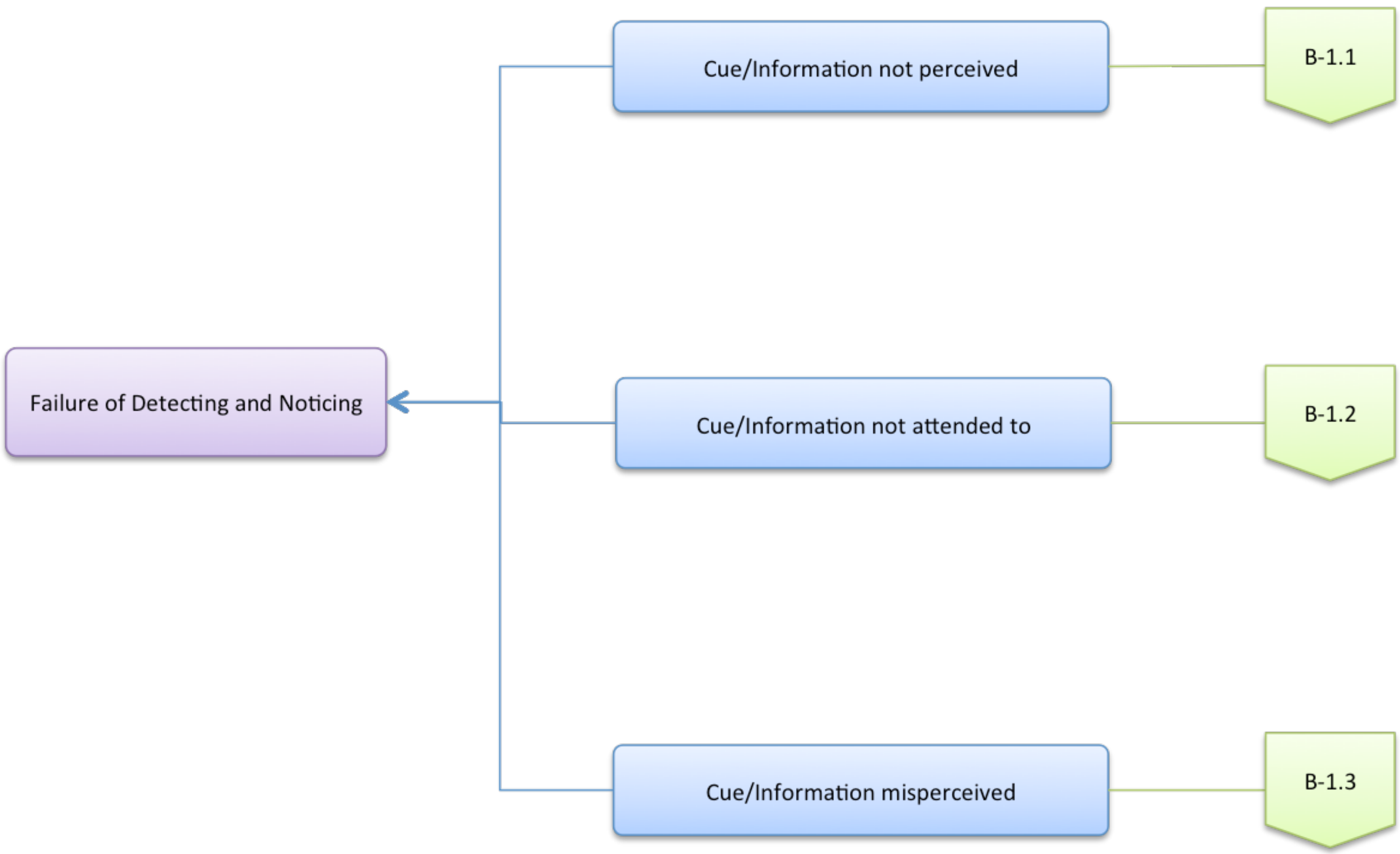
Section B-5 contains the cognitive framework trees for *Teamwork.* The diagrams are divided by proximate cause:

B-5.1 Failure of team communication

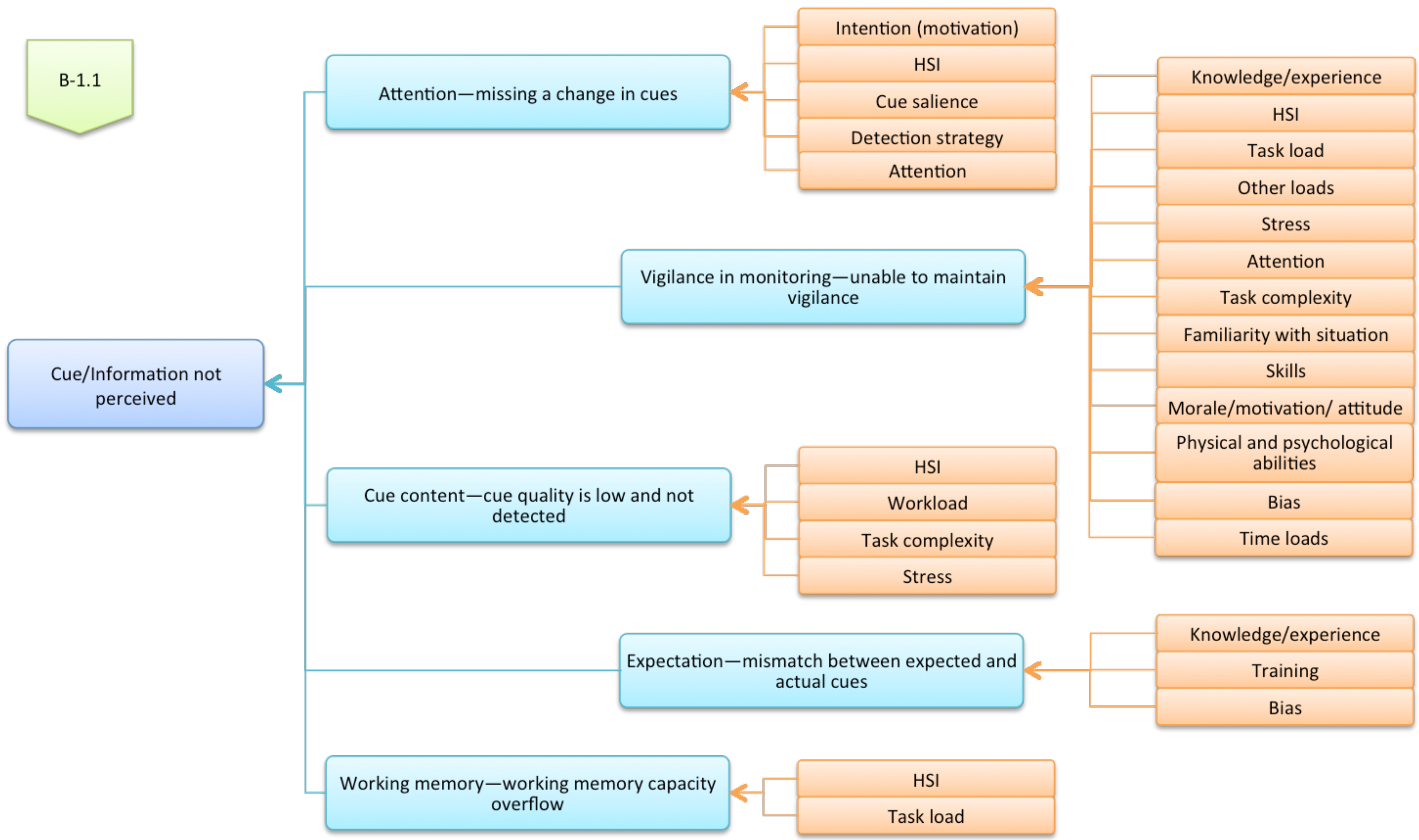
B-5.2 Error in leadership/supervision.

Note that in some of the trees, the mechanisms are not in the same order as they are in the tables in Appendix A; this is due to the need to make the tree fit on one page and has no bearing on the content.

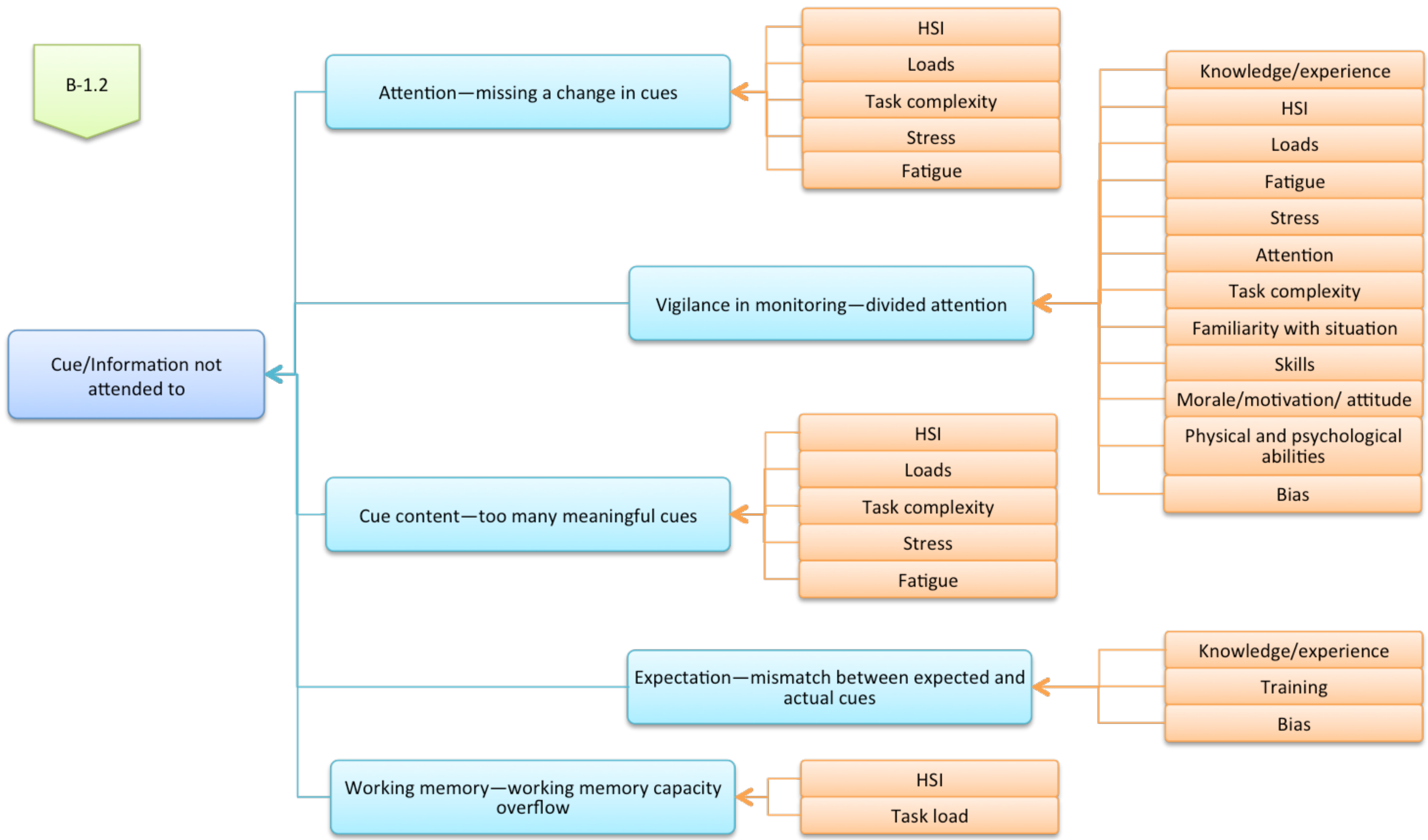
B-1. DETECTING AND NOTICING FRAMEWORK



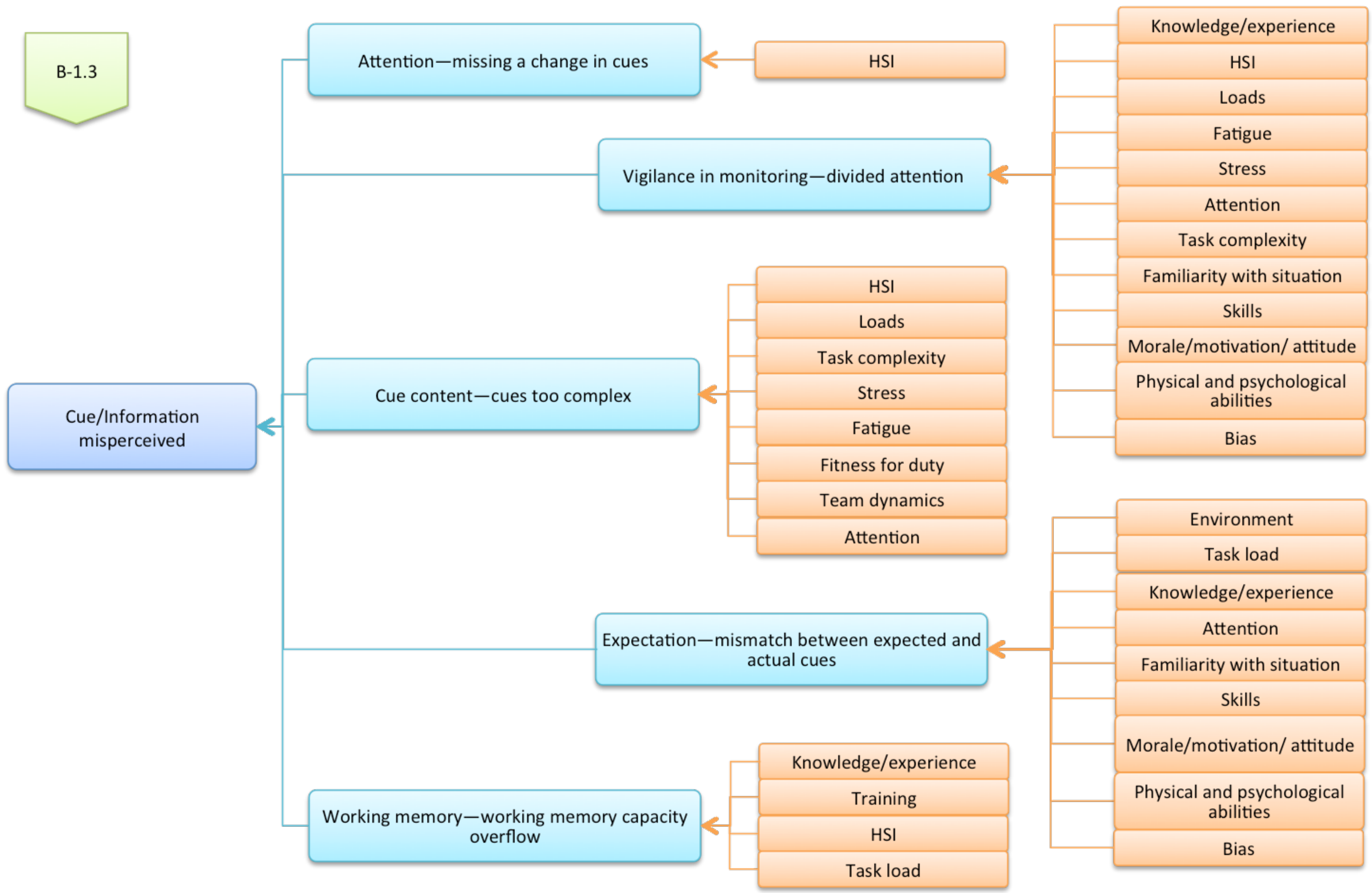
B-1.1 Cue/Information Not Perceived



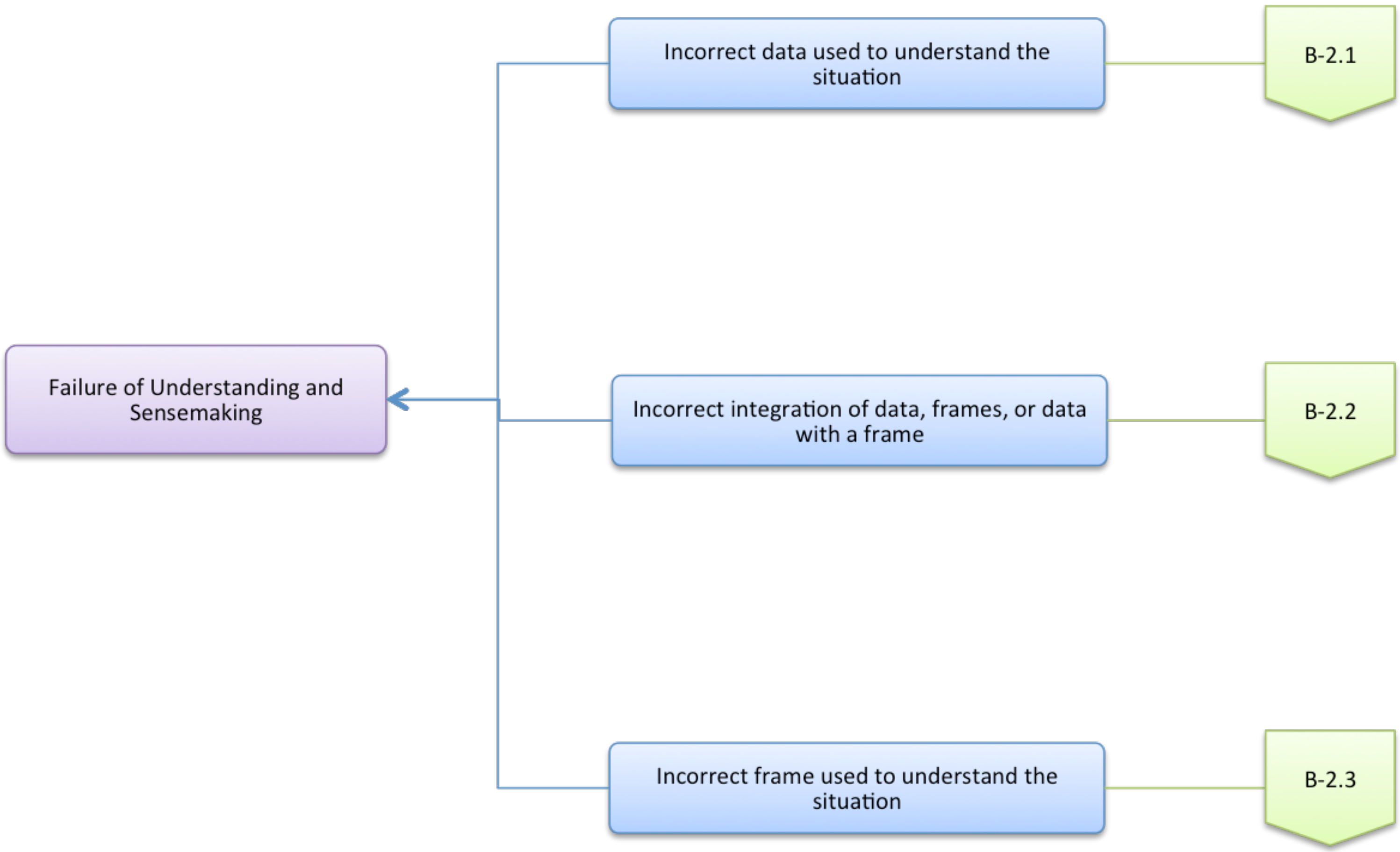
B-1.2 Cue/Information Not Attended To



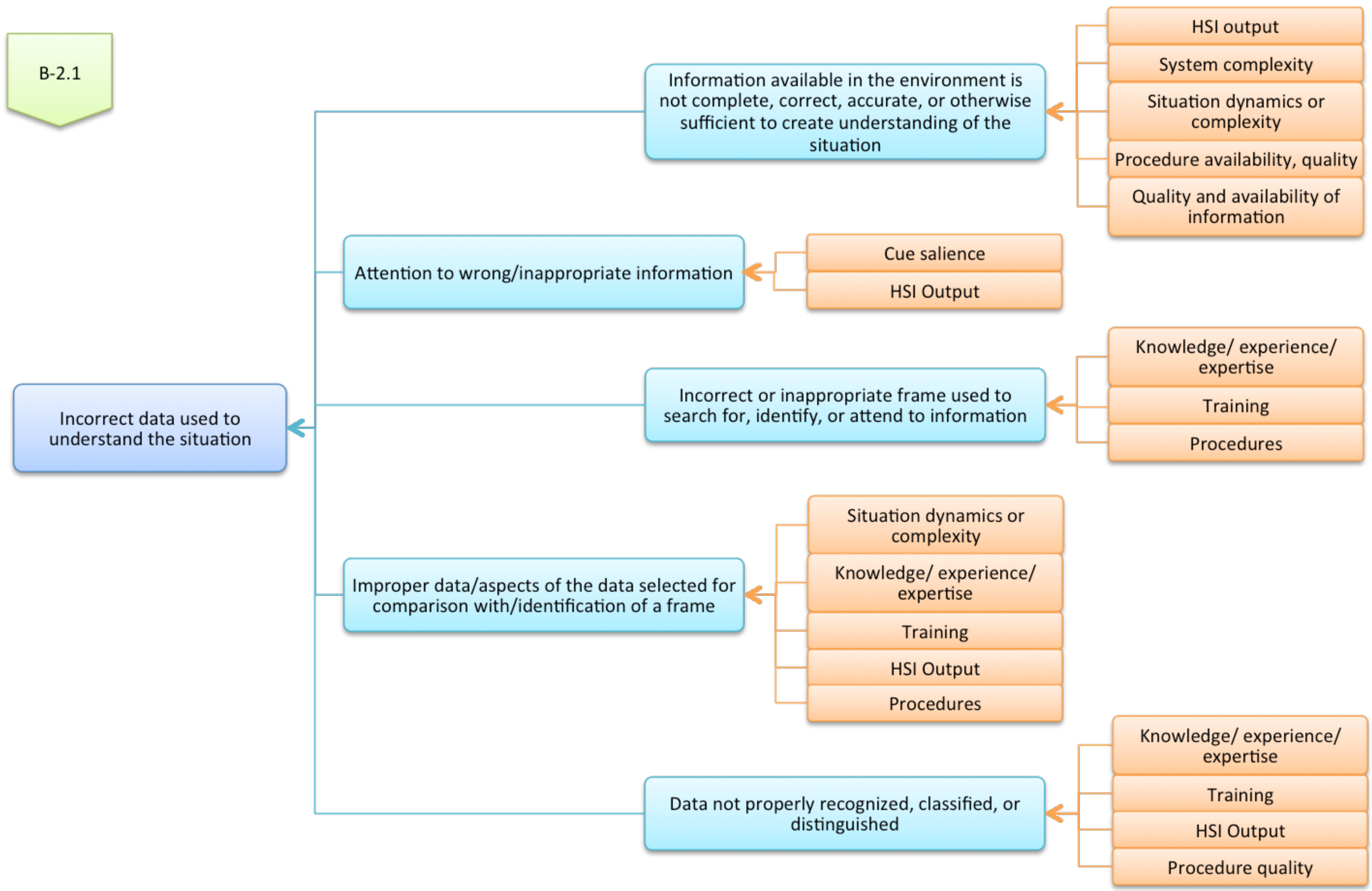
B-1.3 Cue/Information Misperceived



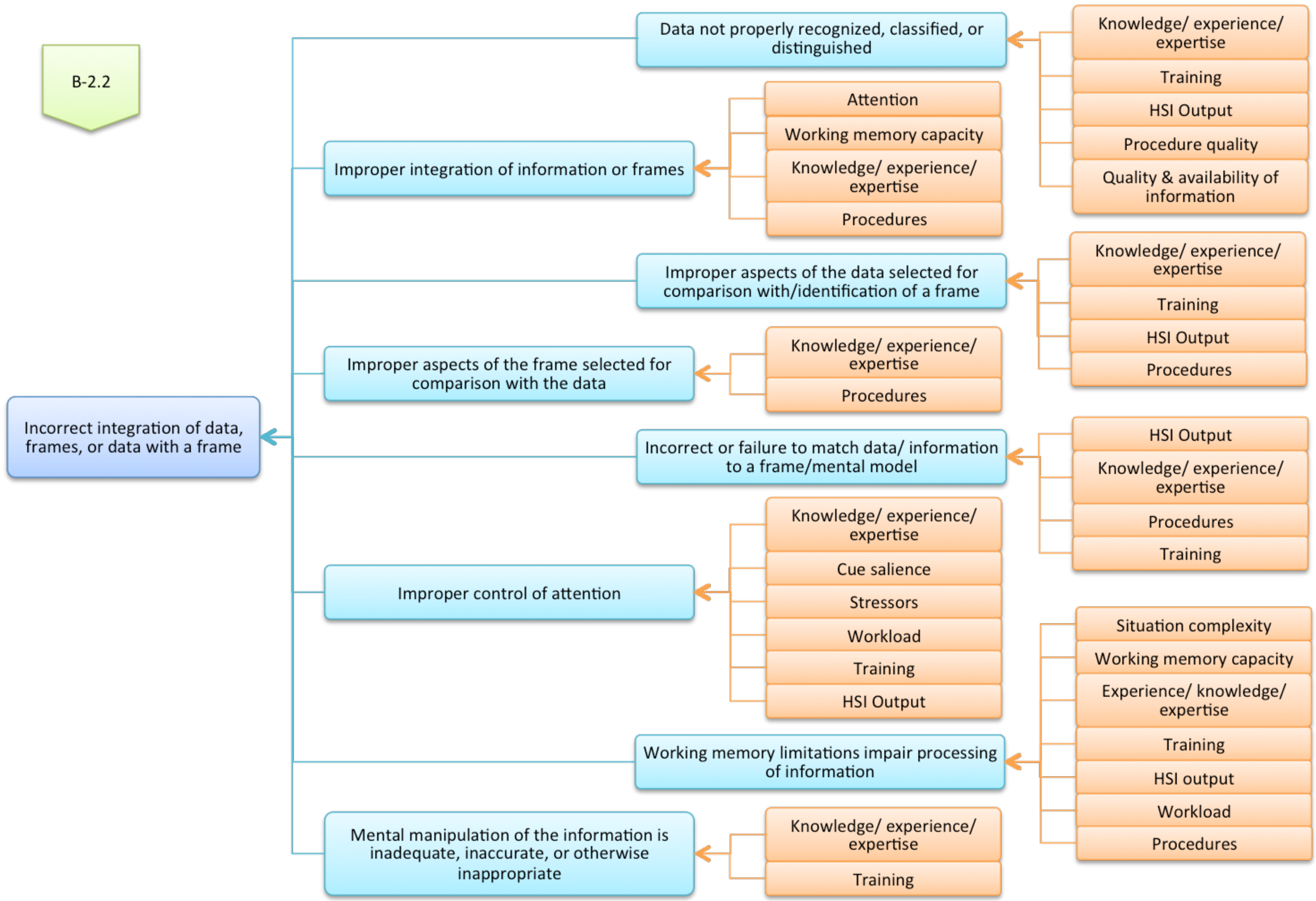
B-2. Understanding and Sensemaking Framework



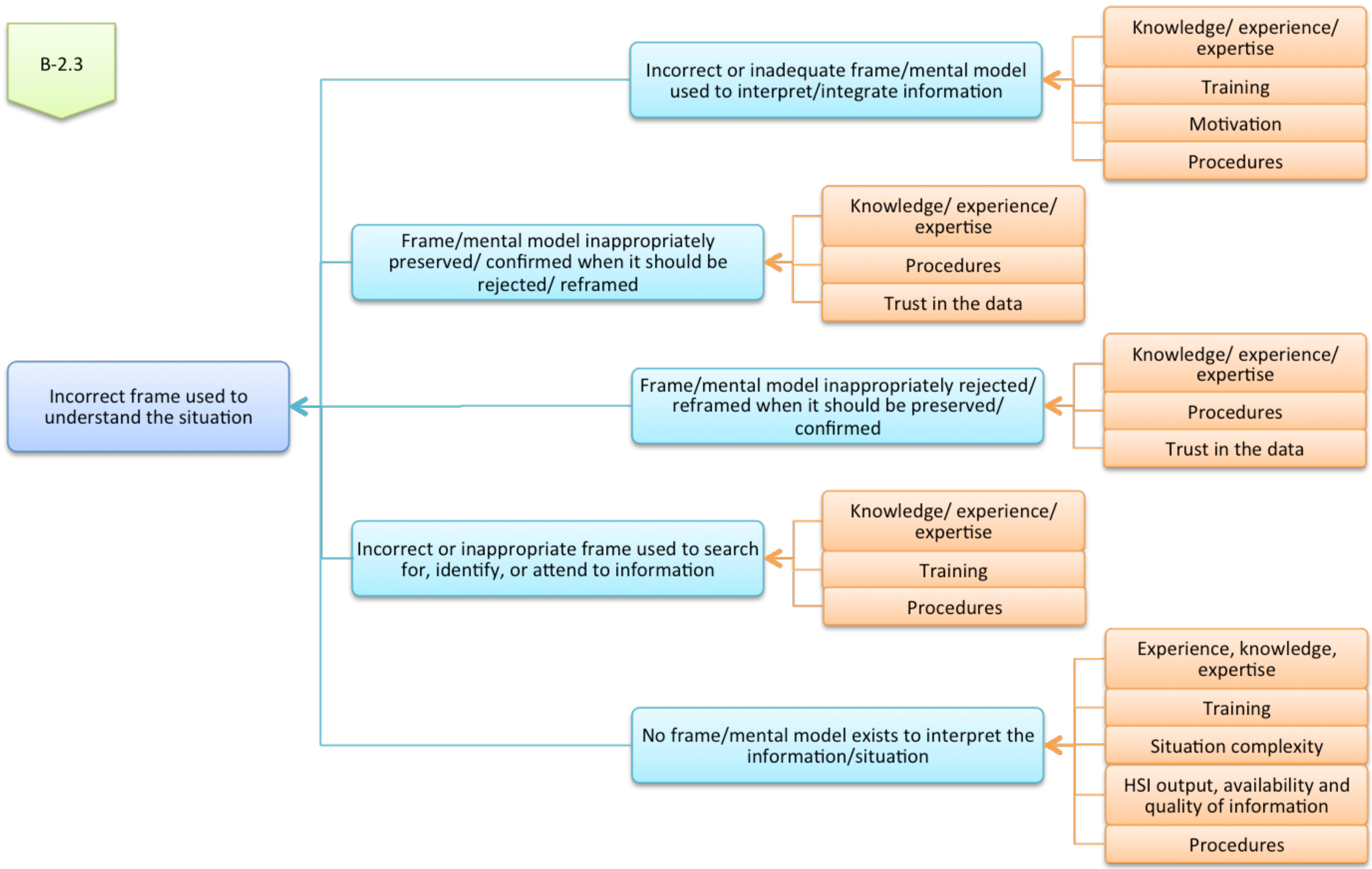
B-2.1 Incorrect Data



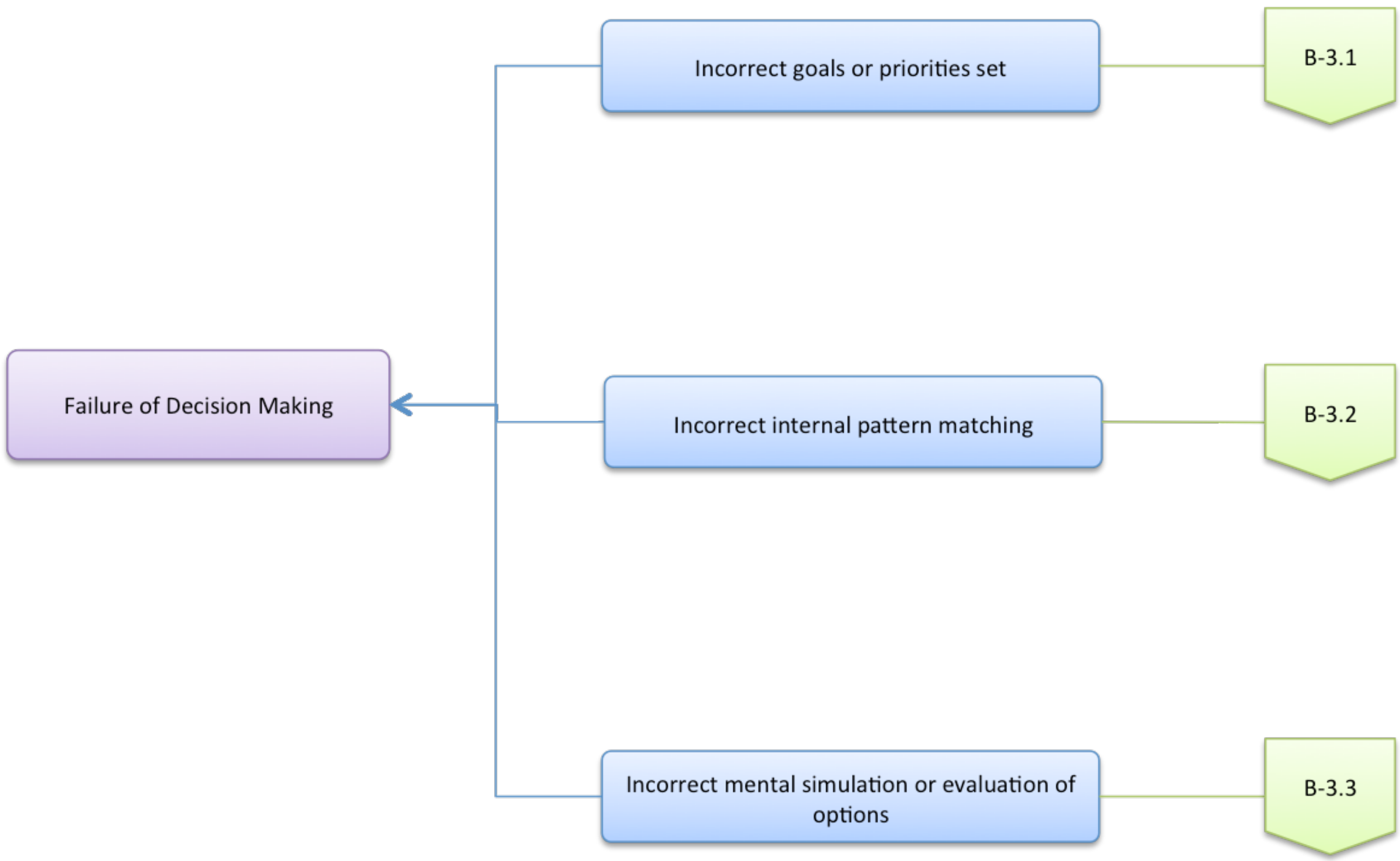
B-2.2 Incorrect Integration



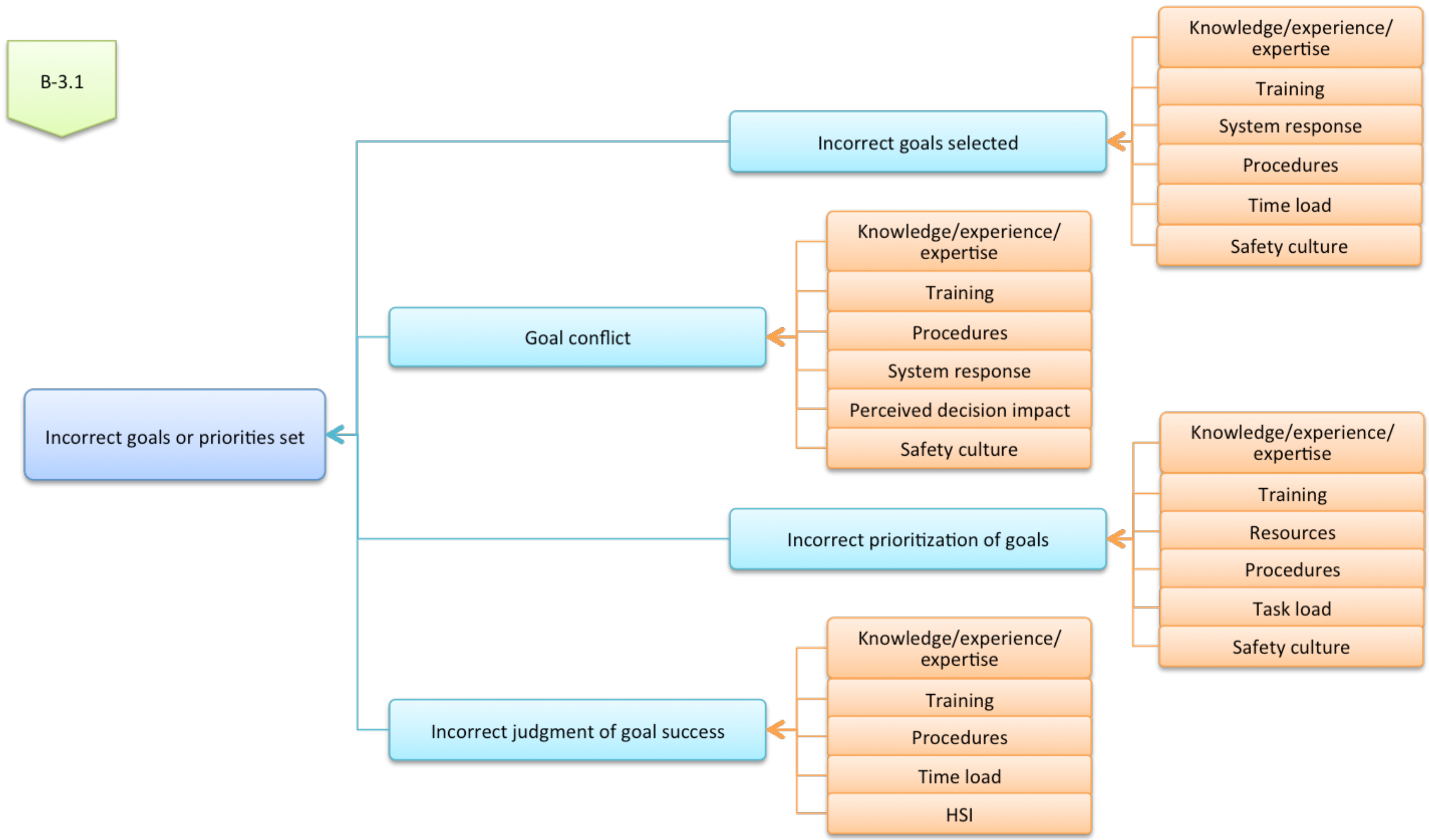
B-2.3 Incorrect Frame



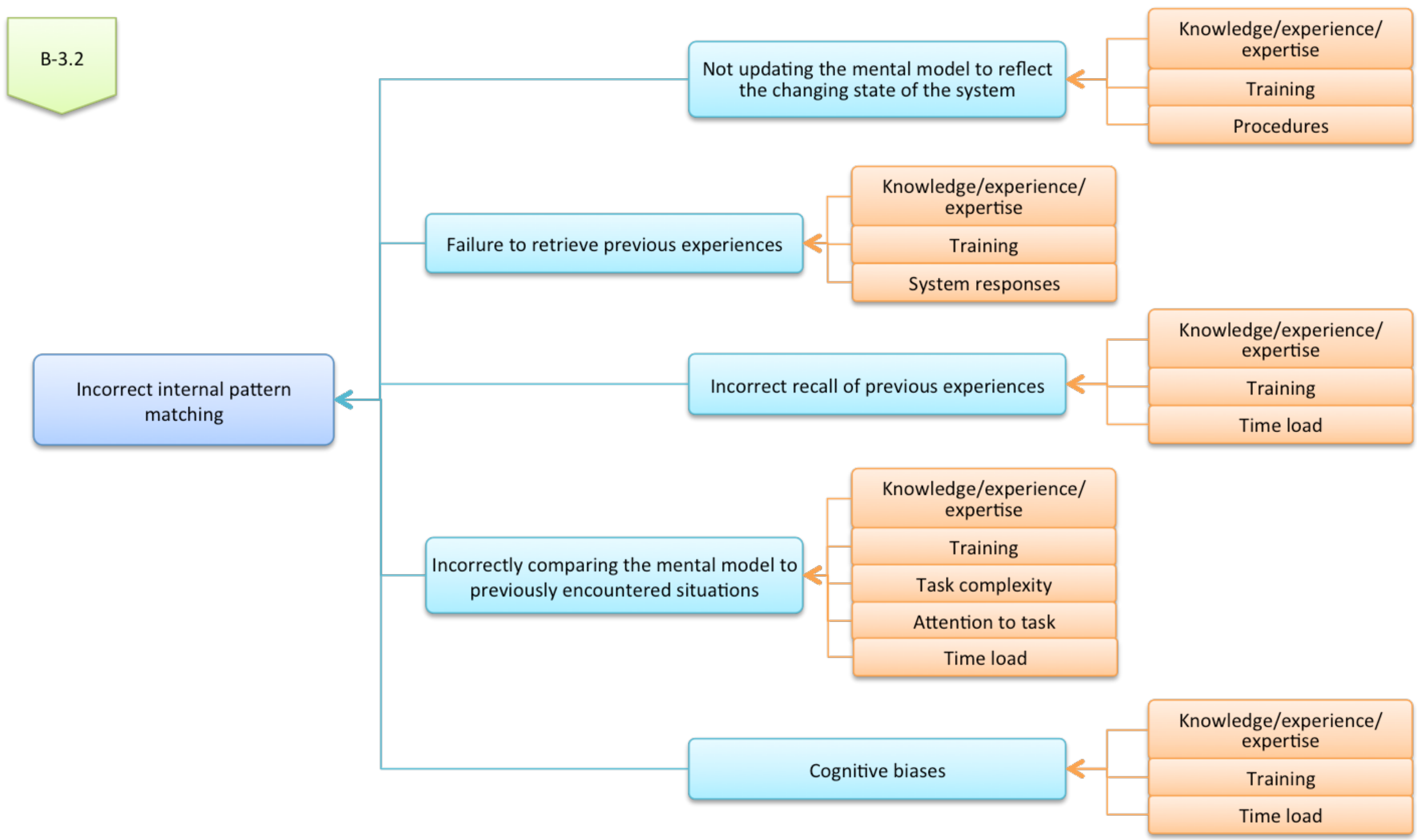
B-3. Decisionmaking Framework



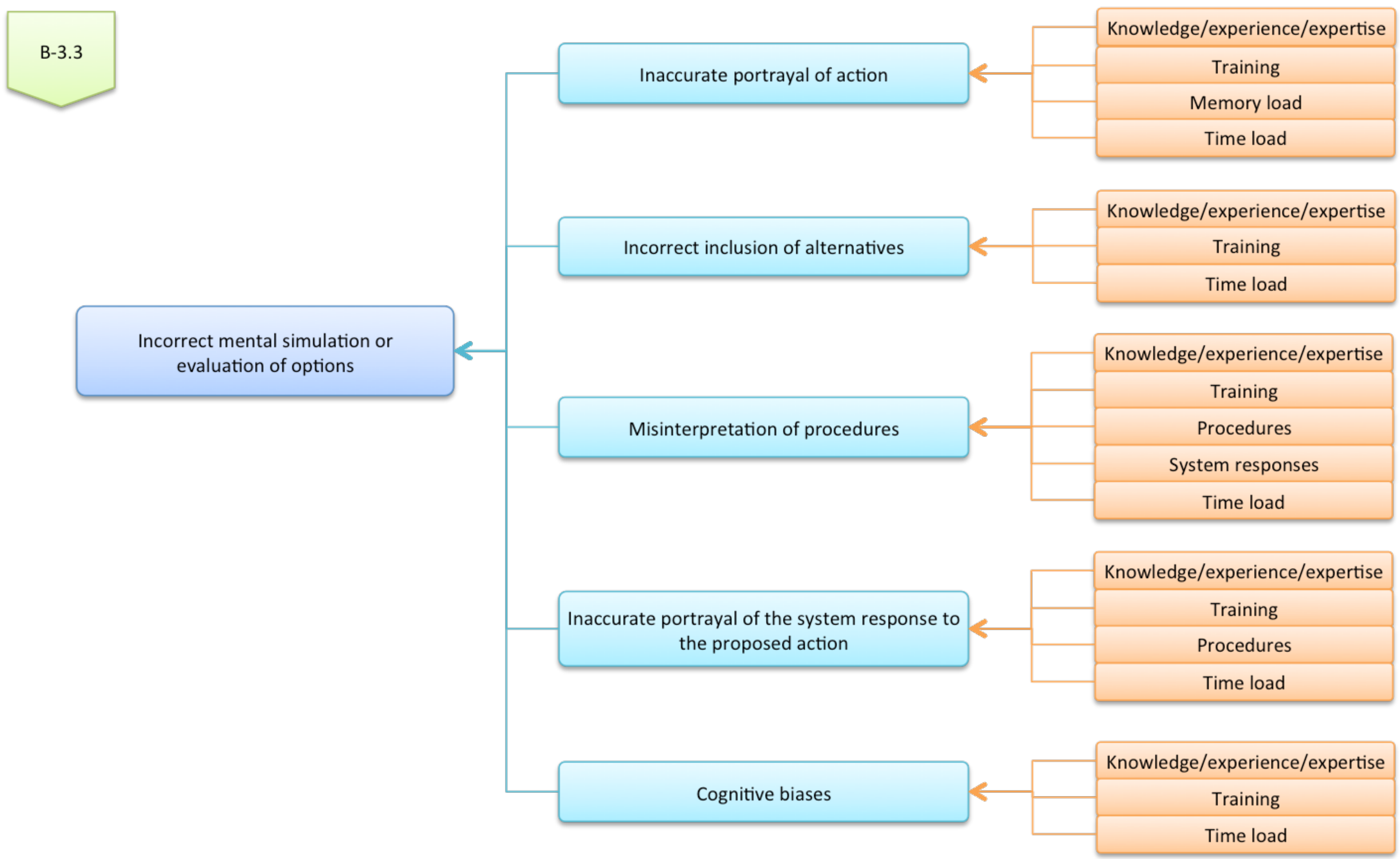
B-3.1 Incorrect Goals or Priorities Set



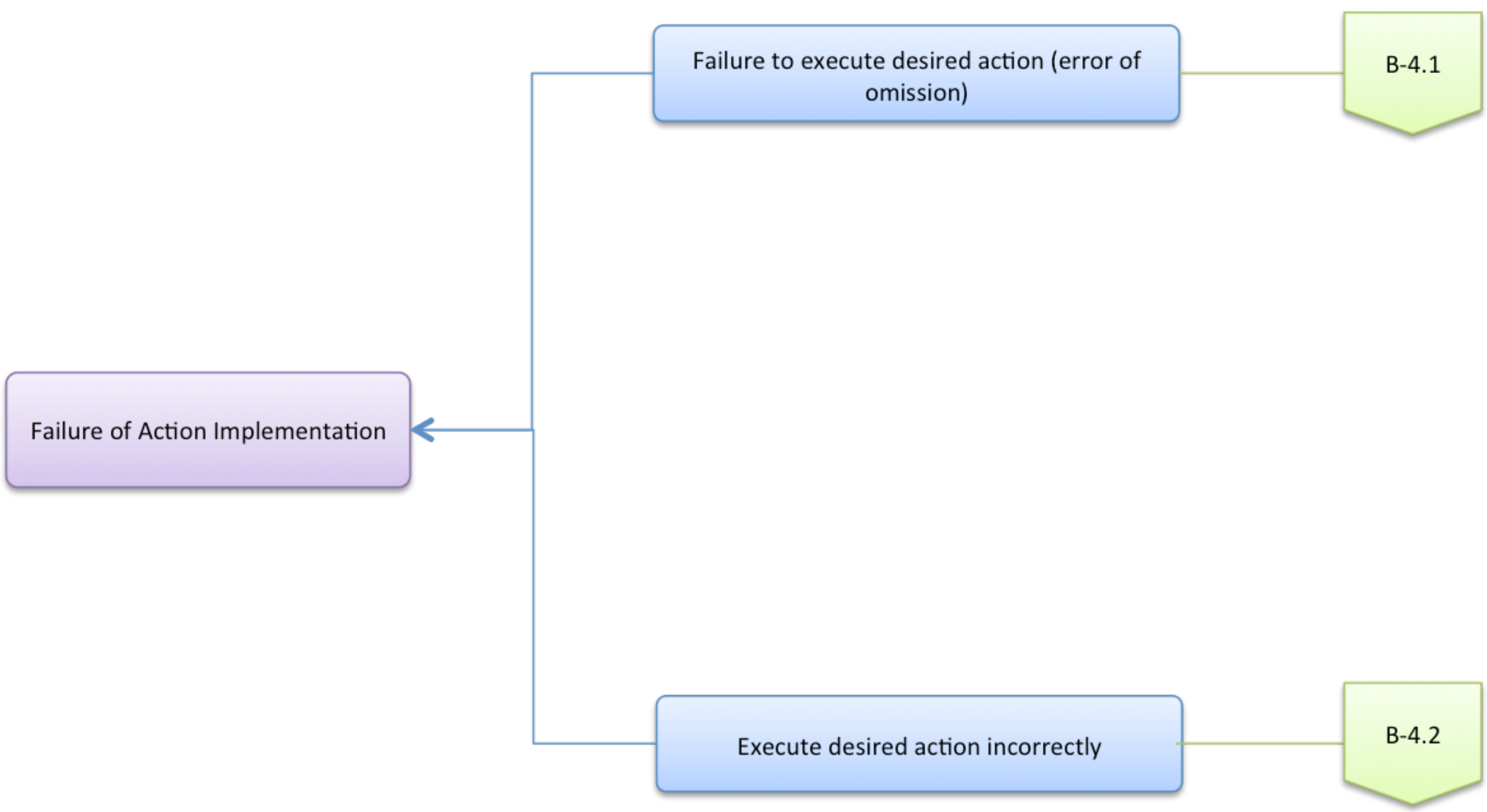
B-3.2 Incorrect Pattern Matching



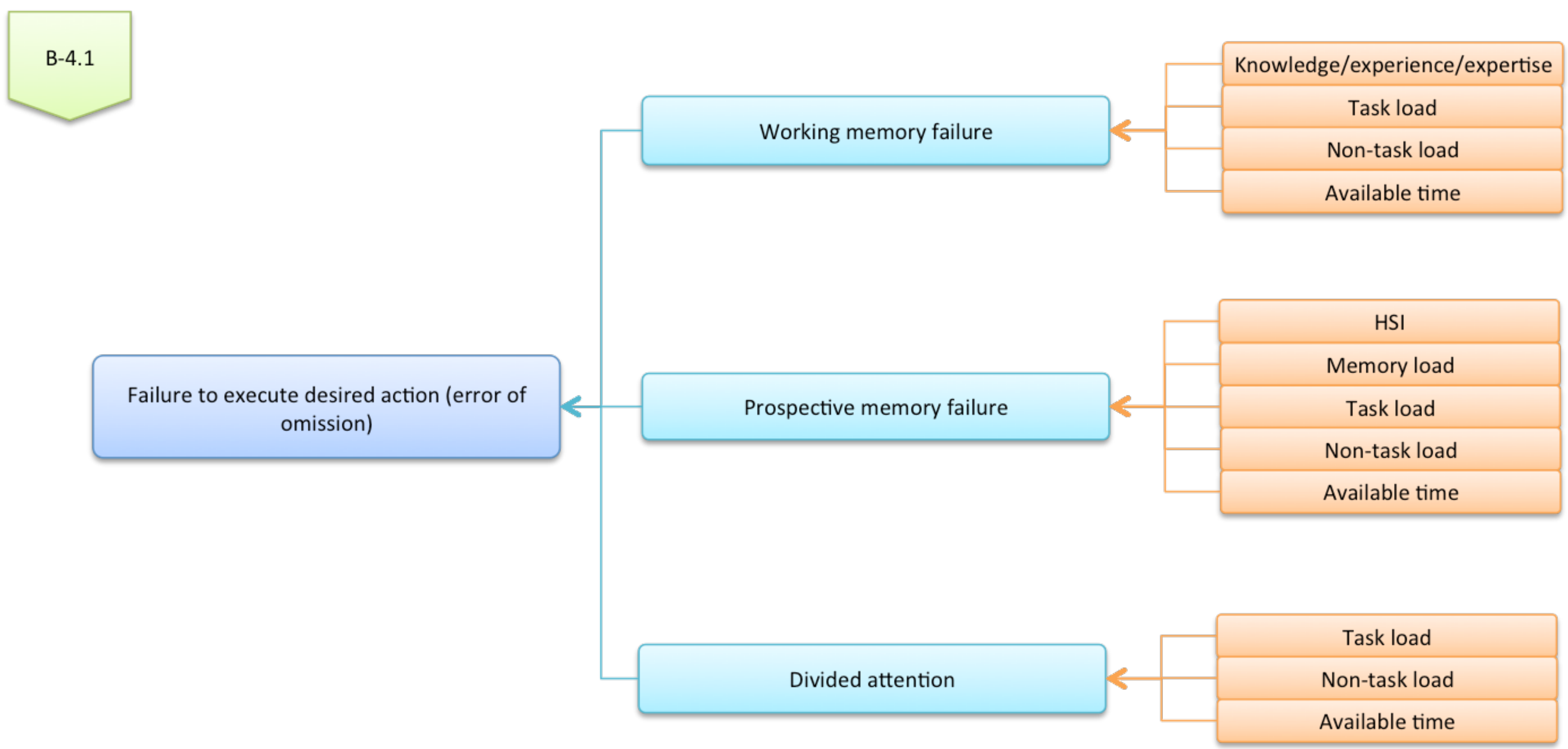
B-3.3 Incorrect Mental Simulation or Evaluation of Options



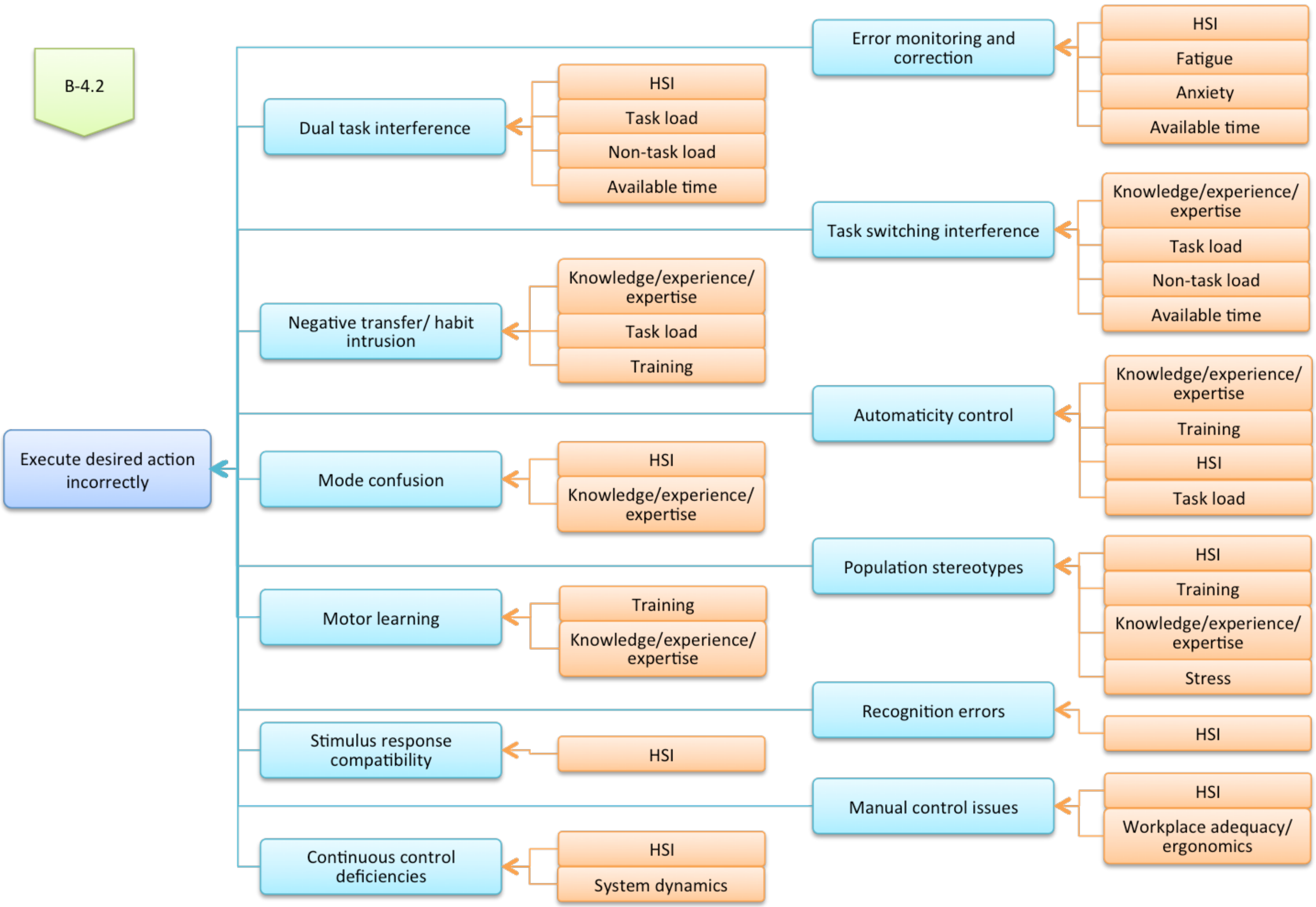
B-4. Action Framework



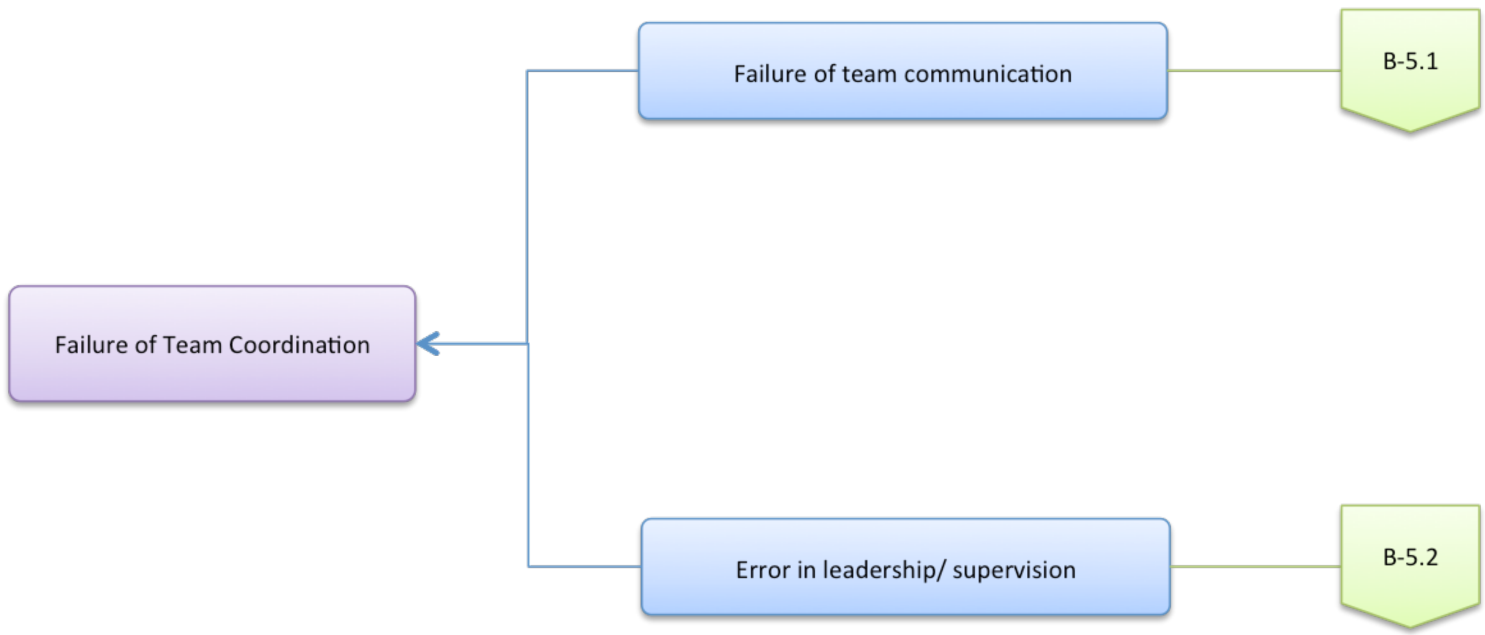
B-4.1 Failure to Execute Desired Action



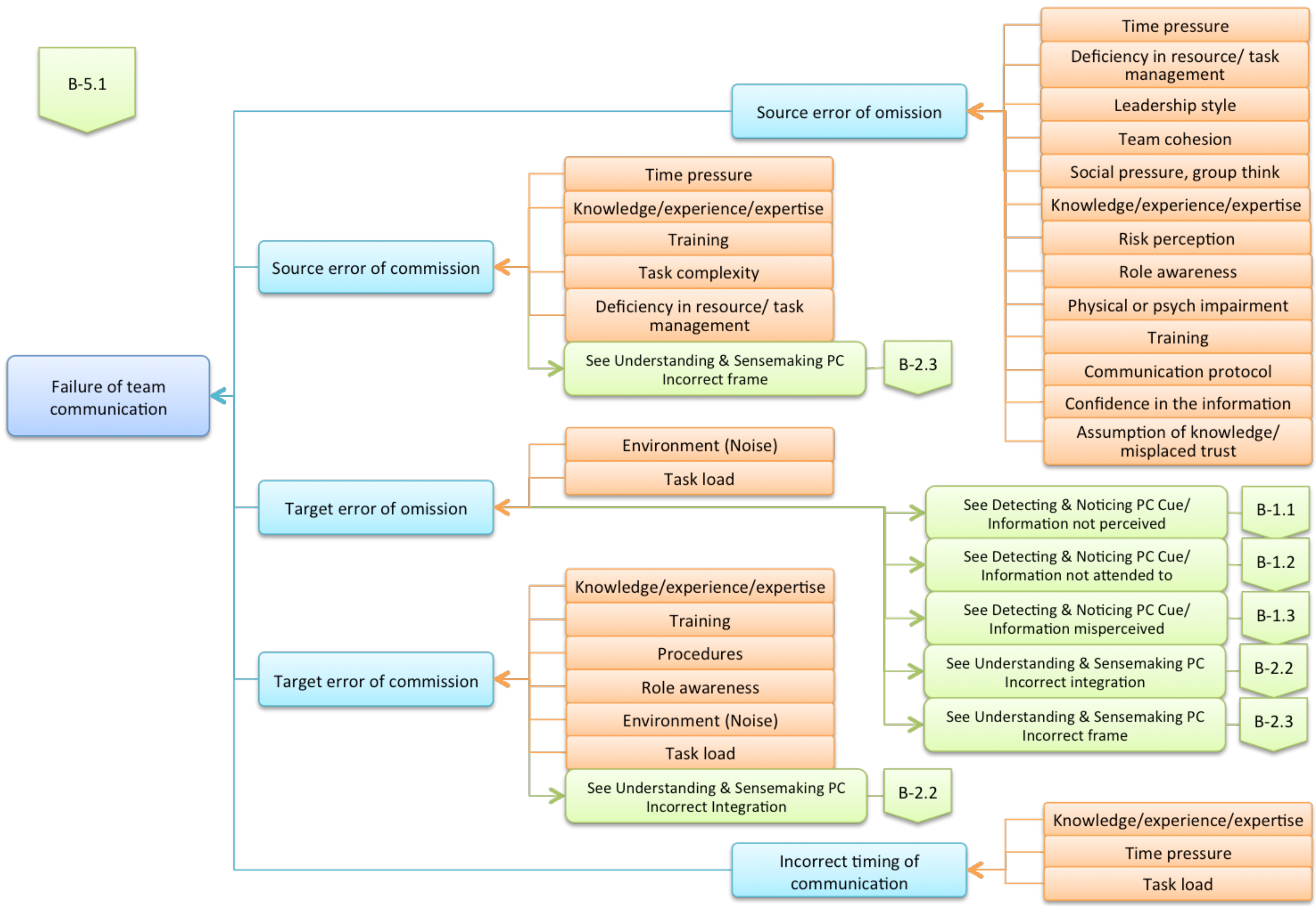
B-4.2 Execute Desired Action Incorrectly



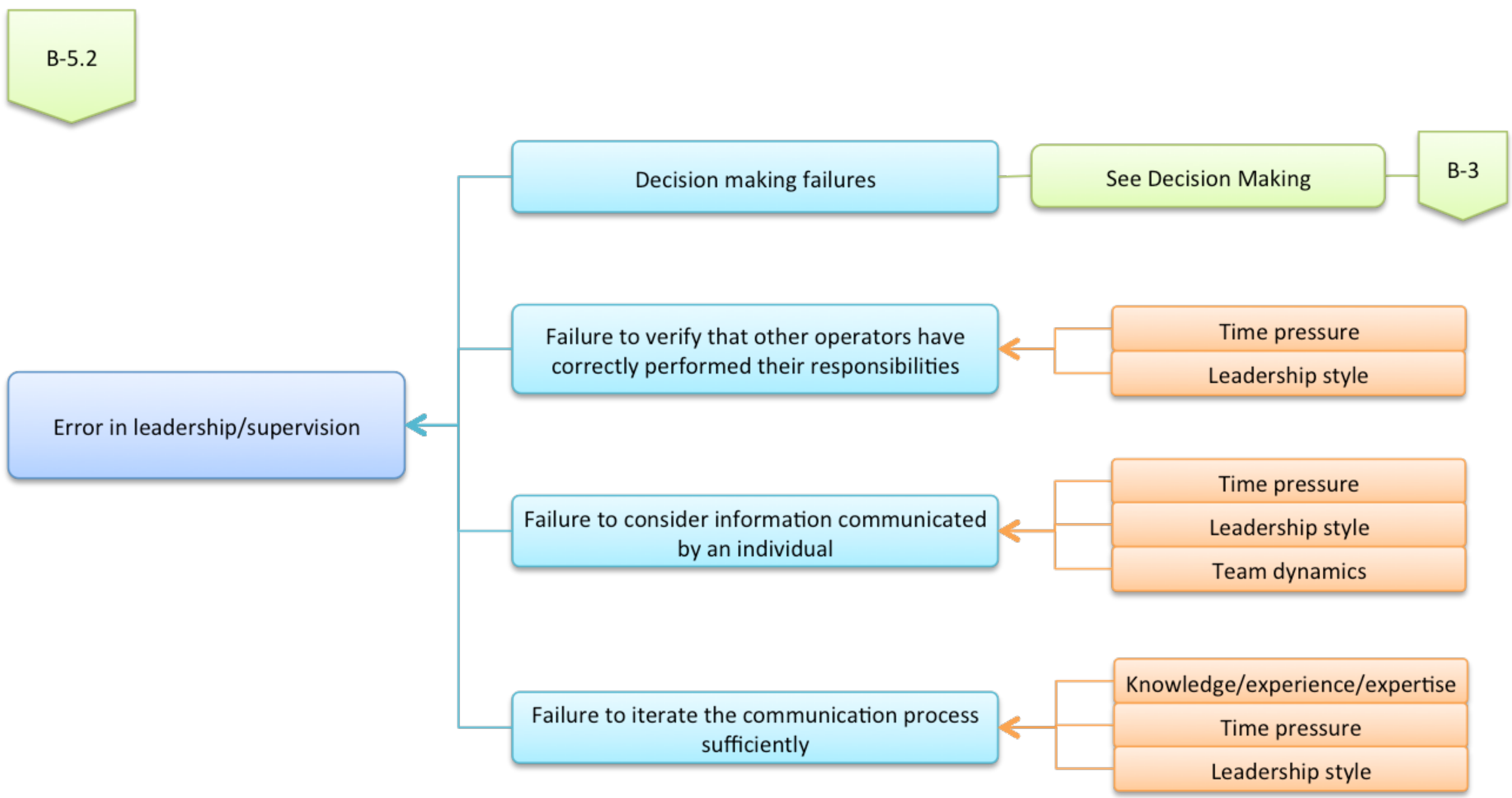
B-5. Teamwork Framework



B-5.1 Failure of Team Communication



B-5.2 Error in Leadership/Supervision



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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report documents the results of a literature review to synthesize human cognition research into a technical basis for human reliability analysis. The U.S. Nuclear Regulatory Commission (NRC) organized a team of researchers to review literature in psychology, cognition, behavioral science, and human factors and apply it to human performance in nuclear power plant operations. The project team synthesized the results into a cognitive framework that consists of five macrocognitive functions: (1) detecting and noticing, (2) understanding and sensemaking, (3) decisionmaking, (4) action, and (5) teamwork. For each macrocognitive function, the team identified proximate causes for why the cognitive function may fail, cognitive mechanisms underlying the failures, and factors that influence the cognitive mechanisms and may lead to human performance errors. Moreover, the project team used the information in the literature to infer causal relationships and links between different types of human failures and factors that influence human performance. This report provides a cognitive basis for human performance and a structured framework to assess how human performance may contribute to errors in the context of an evolving event scenario. The information can serve as the technical foundation for the NRC's human reliability analysis methods and human factors engineering guidance.

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