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# Haven't a Cue? Mapping the CUE Space as an Aid to HRA Modeling

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# Haven't a Cue? Mapping the CUE Space as an Aid to HRA Modeling

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**Abstract:** Advances in automation present a new modeling environment for the human reliability analysis (HRA) practitioner. Many, if not most, current day HRA methods have their origin in characterizing and quantifying human performance in analog environments where mode awareness and system status indications are potentially less comprehensive, but simpler to comprehend at a glance when compared to advanced presentation systems. The introduction of highly complex automation has the potential to lead to: decreased levels of situation awareness caused by the need for increased monitoring; confusion regarding the often non-obvious causes of automation failures, and emergent system dependencies that formerly may have been uncharacterized. Understanding the relation of incoming cues available to operators during plant upset conditions, in conjunction with operating procedures, yields insight into understanding the nature of the expected operator response in this control room environment. Static systems methods such as fault trees do not contain the appropriate temporal information or necessarily specify the relationship among cues leading to operator response. In this paper, we do not attempt to replace standard performance shaping factors commonly used in HRA nor offer a new HRA method, existing methods may suffice. In this paper we strive to enhance current understanding of the basis for operator response through a technique that can be used during the qualitative portion of the HRA analysis process. The CUE map is a means to visualize the relationship among salient cues in the control room that help influence operator response, show how the cognitive map of the operator changes as information is gained or lost, and is applicable to existing as well as advanced hybrid plants and small modular reactor designs. A brief application involving loss of condensate is presented and advantages and limitations of the modeling approach and use of the CUE map are discussed.

**KEY WORDS:** HRA, CUE map, advanced HSI, nuclear power plant control rooms, operator performance, situation awareness

## Introduction

In many process control applications, the human controller, i.e., operator, updates his/her model of the state process based upon procedures, i.e., a static external aid that presents information and functions to cue operator response; dynamic external cues such as alarms and changes in process state, and internalized crew experience that is triggered by cues which may be visual, auditory, cognitive or psychomotor. The operator's cues in predominantly analog control rooms are well known, have been well studied, and there is a vast world-wide operating experience. When it comes to HRA, even when cues are recognized as being dynamic in nature, the patterning and pathways and influences of these cues is only implicitly addressed. Even with review of digital systems performance in industries outside of nuclear, there is much that is unknown regarding cue structure, cue processing, or the use of cue relationships. We believe that the application of CUE MAP technology to represent the "cue space" for analog and digital domains will be equally advantageous. Below we highlight some interesting issues associated with control room performance.

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**Team cognition and cues.** The notion that team interaction is important and may involve different processes than individual cognition is not new. (Fiore and Salas 2004) There seems to be a blending of social processes and cognition. Approaches to team cognition consider influences such as team size, locus of decision making, and differences among teamwork and task work factors (Cannon-Bowers et al 1993, Kiekel and Cooke 2004, Stout et al. 1996). Additionally, the response to control room cues may influence overall team success. In the absence of empirical information on team cognition we would do well to ask how the operators, and by extension crews, are able to detect and formulate courses of action (COAs) which are responsive to changes in plant conditions. To a significant extent, crews orientate to changes in plant status via a number of cues including analog and digital visual displays of plant parameters, digital equipment status indications such as position lights and auditory alarms, procedures, and face-to-face interactions. Crews at plants are intensively trained on a suite of transient equipment failures, and conditions so that they are conditioned to expect certain responses such as patterns of alarm tiles that can help them quickly and accurately identify the type of problem, its severity, and expected path. Mapping the environmental cues that help to alert and orient operators can be a significant aid to analyst understanding of human performance. This characterization has the benefit that it supports the performance shaping factors analysis portion of risk analysis process. We begin with a simple representation of the operator-plant interface (See figure 1) and then create an abstract representation of the cognitive workspace that presents key information and cue relationships. We model the cue space in terms of sensory inputs. Cognition is also recognized, but at a task or subtask level. There are a number approaches to models of human memory and cognition that consider cognition in terms of short term versus long term memory, architectures, and or modality. (see Gardner, 1985).

Our approach to CUE mapping is directed toward supporting the HRA process. It is felt that this is sufficient to support the HRA process. In particular, for instances where the human factor representation is part of a typical PRA, we are looking at CUE mapping to identify the basis for operator decisions and actions and how multiple perceptual modalities – visual, auditory, and psychomotor are involved in cueing the operator and crew. We maintain that there are cognitive processes between stimulus and response that are influenced by dynamic cues in the environment and the operator's expectations and experiences. We acknowledge, in accordance with modern theory, that there is internal cognitive response based upon visual, auditory, psychomotor and semantic (cues). To simplify matters, we assume that long-term associations may be primarily on the basis of semantic aspects, and secondarily on the basis of visual and acoustic cues. The development of the CUE map therefore, focuses upon the "S" aspect of the Stimulus- Organism - Response paradigm as opposed to either the representation of knowledge (schemas, images, ideas) or any particular set of neurological structures.

*Auditory basics*. When auditory cues occur in the control room (CR), the operator's phonological loop stores a limited number of sounds for brief periods (Baddeley 1993). One component is the phonological store, which allows acoustically coded items to be stored for a brief period. The other component is the articulatory control system, which allows sub-vocal repetition of the items stored in the phonological store.

*Visual Basics*. The second type of cue present to operators are alarm tiles or screen displays which allow for visual patterning of alarms, their content, and color. The color and a flashing pattern have an immediate semantic component. The visuospatial sketch pad stores visual and spatial information. (*ibid*). For introduction to sensory memory , thought to be on the order of 250 msec, the reader is referred to the seminal work of Sperling (1960).

Generally speaking, the processing and storage limits of these two systems is thought to be independent. There are of course, additional cues presented to operators that can include the vibration associated with running of the HVAC in the control room (absence of which indicates a loss of power) or subtle background vibration associated with the stopping and starting of large equipment or systems.

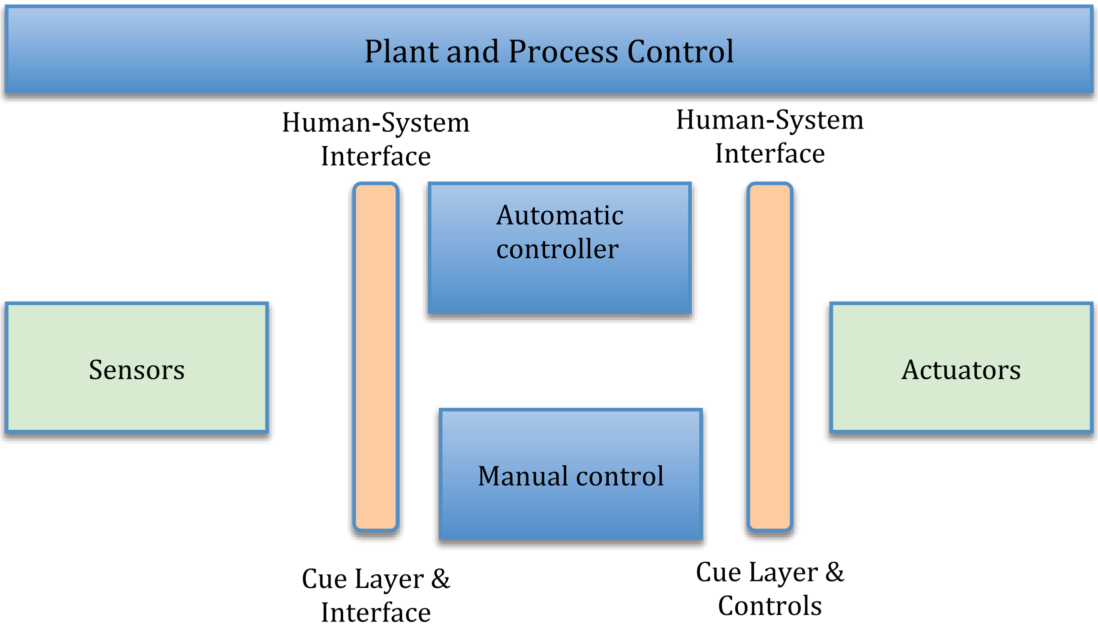


**Figure 1: Simple S-R Systems Interface Model**

## Method of Development

The use of software tools for concept mapping is not new. In this particular instance, the Institute for Human and Machine Cognition's (IHMC) CmapTools Version 5.04.01 software was used to draw the relations among different nodes. As with any concept map, graphical tools are used to organize and represent knowledge (Novak and Canas, 2008). The software we used differs slightly from other programs in that linking phrases (also called "propositions") are used between two concepts, making their relation apparent. This system is also useful in that merely reading the map develops propositional statements; general concepts are toward the top of the map, lower level detail is at the bottom. Although we use cognitive mapping to develop the model of cues available in control room settings, cognitive mapping has been used quite extensively as a learning aid. *(Ibid)*.

The identification of the cue types and nodes and patterns was based upon the literature on crew response in the presence of automation, and human factors and HRA experience among INL human factors and HRA practitioners. The assignment of nodes and their patterns can be verified in a full plant simulator, the effect of losing an individual node can also be assessed by having operators interat with the simulation with and without the presences of certain types of cues and observing the corresponding changes in human-systems performance.

## Concept mapping: The generic case

Figure 2 below presents a typical concept map that explains the rain cycle. In making such a construction the usual sequence of events is to analyze the scenario or problem space, list what is known, list possible actions, and analyze information collected.

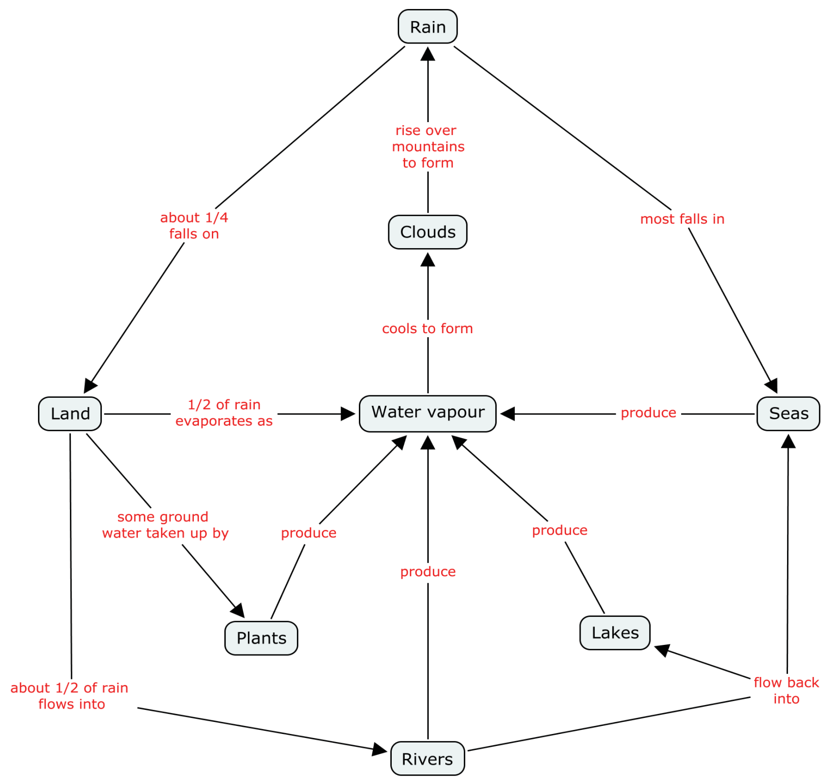


**Figure 2: Concept Map Example**

All maps will have an overall network structure, but not all have to be hierarchical; some may have a central hub. Our example of the CUE MAP in Figure 3 is a specialized example of a concept map.

## Transition to CUE mapping beyond procedures

Procedures have been described as a template, map, or cue set for operator performance, however, procedures are not the only instance of operator cues existing in the NPP CR environment. Annotating the CUE map for the arrival (or absence) of additional cues can reveal insights in predicting operator response, even though the map itself is static. Once this mapping has been performed, the potential exists to explore how the presence and absence of expected "mapped cues" could impact on plant performance.

For example, what if either or both the condensate pump or feedwater pump alarm trip status indications fail to be present? Are there backup indications? Are there procedural alternatives or work-arounds? If so what cues are associated with the work arounds.

The steps for building the CUE MAP are as follows:

1) Map the relevant cues, including alarms, from the physical environment.

2) Elicit operators conceptual cue space (What do they look for, expect and how are different cues related?)
3) Acknowledge differences among designers and operators in terms of cue representation and meaning and their potential impact. (This is not addressed in this paper).
4) Consider the operator's ability to integrate multiple cues for consistency, trending and importance.

Figure 3 below presents a generic CUE MAP for control room operations. Operator decision-making is a combination of sensory and perceptual elements – visual, auditory and psychomotor (including psychomotor-tactile modalities), and operator cognition. Thus, we borrow from Wickens' simplified model that has proved useful to aerospace and transportation researchers (see for example, Yee et al, 2007 for a review of these components across some 68 in-vehicle tasks and subtasks.) We acknowledge that auditory cues could include face to face or loudspeaker messaging, equipment noises such as water hammer, and auditory alarms that usually accompany changes in control room alarm tile status. This overview is a basic template that can be modified (nodes and relations can be added or deleted) as a function of expected conditions. The analyst is to keep in mind the tasks to be performed as well as changes in conditions that appear during a scenario. Successful implementation requires the analyst to conduct a task analysis or interviews with experts to understand the operator role. Once information is gathered and used to construct the MAP it is to be discussed, reviewed and verified. The level of MAP detail is best described as necessary and sufficient to understand the extent of cues available and most probably to be acted upon.

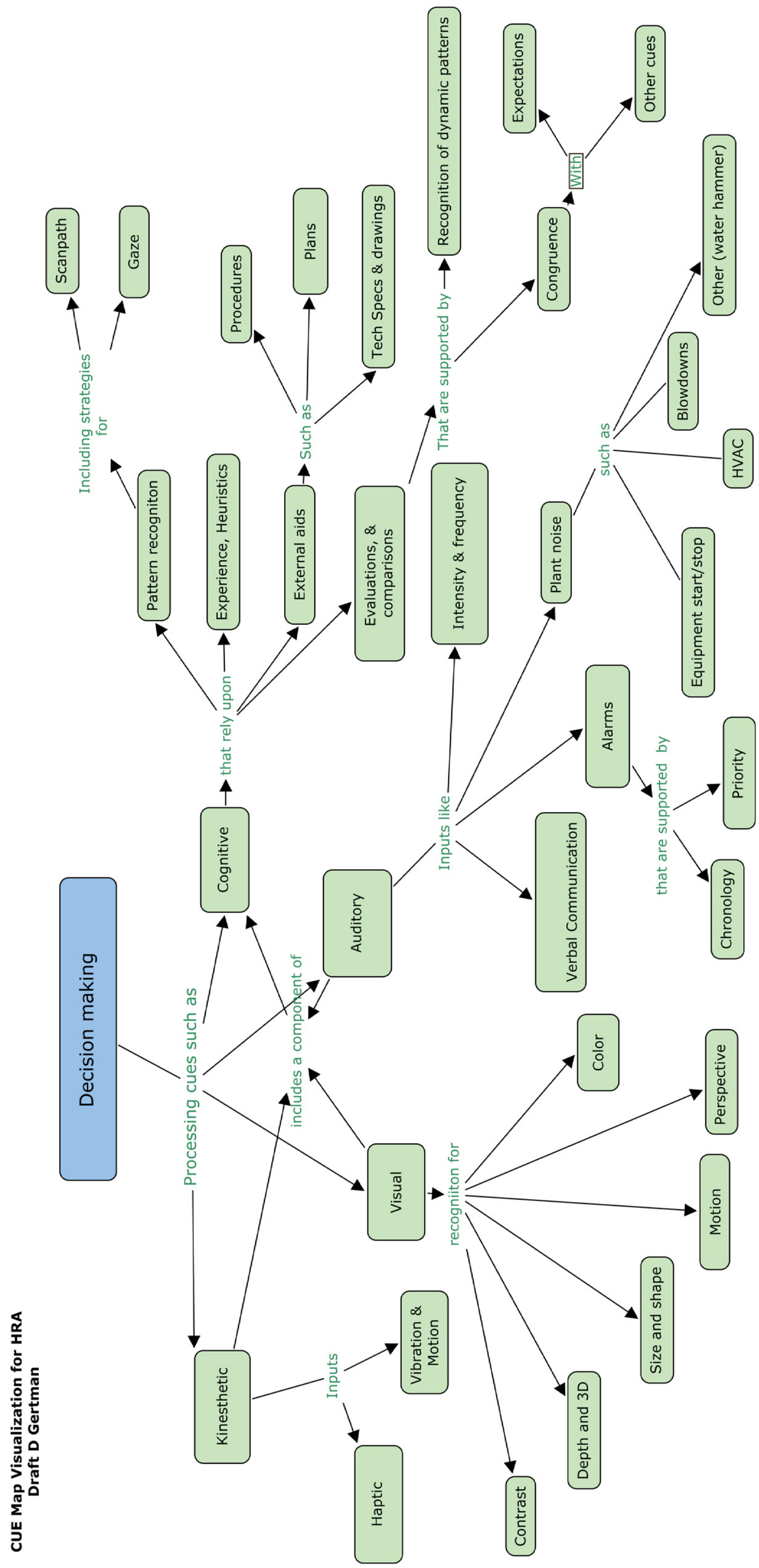


**Figure 3: Decision-making Concept Map**

**Application to Loss of Condensate**

The condensing of steam in a nuclear power plant (NPP) is a vital part of the nuclear power generation process and the condensate system is an active, non-safety grade system. After passing through the low-pressure turbine, the steam is routed to the main condenser. Cool water, flowing through the tubes in the condenser, removes latent heat from the steam, which allows the steam to condense. The water is then pumped back to the steam generator for reuse.

> "The condensed steam collects in the hotwell area of the main condenser. The condensate pumps take suction on the hotwell to increase the pressure of the water. The condensate then passes through a cleanup system to remove any impurities in the water. This is necessary because the steam generator acts as a concentrator. If the impurities are not removed, they will be left in the steam generator after the steam forming process, and this could reduce the heat transfer capability of the steam generator and/or damage the steam generator tubes. The condensate then passes through some low-pressure feedwater heaters. The temperature of the condensate is increased in the heaters by using steam from the low-pressure turbine (extraction steam). The condensate flow then enters the suction of the main feedwater pumps, which increases the pressure of the water high enough to enter the steam generator. The feedwater now passes through a set of high pressure feedwater heaters, which are heated by extraction steam from the high pressure turbine (heating the feedwater helps to increase the efficiency of the plant). The flow rate of the feedwater is controlled as it enters the steam generators."
>
> \- *US NRC Tech Training Manual 0603*

In response to a loss of condensate, operators need to determine that plant state indications are moving out of their normal ranges and then act appropriately as defined by operating procedures. This section presents a CUE map we generated that can be used to help the HRA analyst codify visual, auditory and psychomotor cues available to the crew in response to a loss of condensate scenario. The PWR plant described here is a generic PWR and was chosen for illustrative purposes only. Table 1 collapses the conceptual cue space for the scenario. The more salient cues are presented along with any competing cues present. Discussion with operators were used to determine the cues available and sought after to support cognitive elements. We do not model other cues that may hamper or otherwise interfere with operator response to the loss of condensate pump1, which is the subject of a future analysis. The information present in the cue map helps to provide a tractable basis for application of performance shaping factors that are used to adjust base failure rates in a method such as SPAR-H (Gertman et al 2005).

*Event flow*. The human actions and plant conditions are provided below in Table 1. The plant layout showing the condensate system and associated systems (condensate pumps, demineralization, condensate heater, main feedwater [FW] pumps, main feedwater regulating valves and steam generators [SGs]) is presented in Figure 4: Generic PWR Condensate System. Figure 5 presents the CUE map application to a loss of feedwater scenario.

**Table 1. Human activities and plant conditions**

| **Plant Status** | **Alarm tiles (V)* & (A**)** | **Turbine Op (V, A, P)** | **Rx Op (V, A, P)** |
|---|---|---|---|
| 1) CP 1 trips on low voltage | CP trips<br>FWP low PSR alarm | • Announce CP trip<br>• Announce CP auto start | • Select rod bank (VP)<br>• Prepare to insert control rod (VP) |

| | | | |
|---|---|---|---|
| | | • Try to start standby coolant pump | • Observe decreasing SG LVL on analog recorder |
| 2) Low FW pressure leads to FWP trip | FW pump trips<br><br>SG $H_2O$ LVL lo<br><br>SG VLV Pre-trip | • Announce FWP trip<br>• Observe SG LVL<br>• Announce alarms for SG LVL<br>• Watches turbine alarm and analog recorder<br>• Turbine trips<br>• Announces general trip | • Request SRO permission to drive rods<br>• Drive rods<br>• Watch for power decrease<br>• Observe SG levels approach low low<br>• Request SRO permission to trip RX (V)<br>• Obtain permission (V) Trips RX (V,P) |

| | | | |
|---|---|---|---|
| * | Visual | FW | Feedwater |
| ** | Auditory | FWP | Feedwater Pump |
| *** | Psychomotor | PSR | Pressure |
| CP | Cooling Water Pump | SG | Steam Generator |
| VLV | Valve | RX | Reactor |
| LVL | Level | SRO | Senior Reactor Operator |

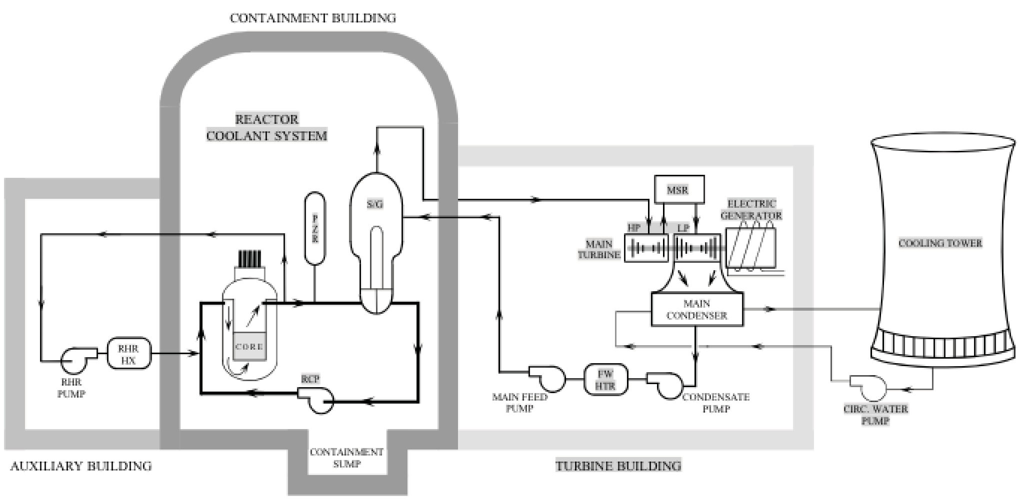


**Figure 4: Generic PWR Condensate System – NRC Technical Training Manual 0603**

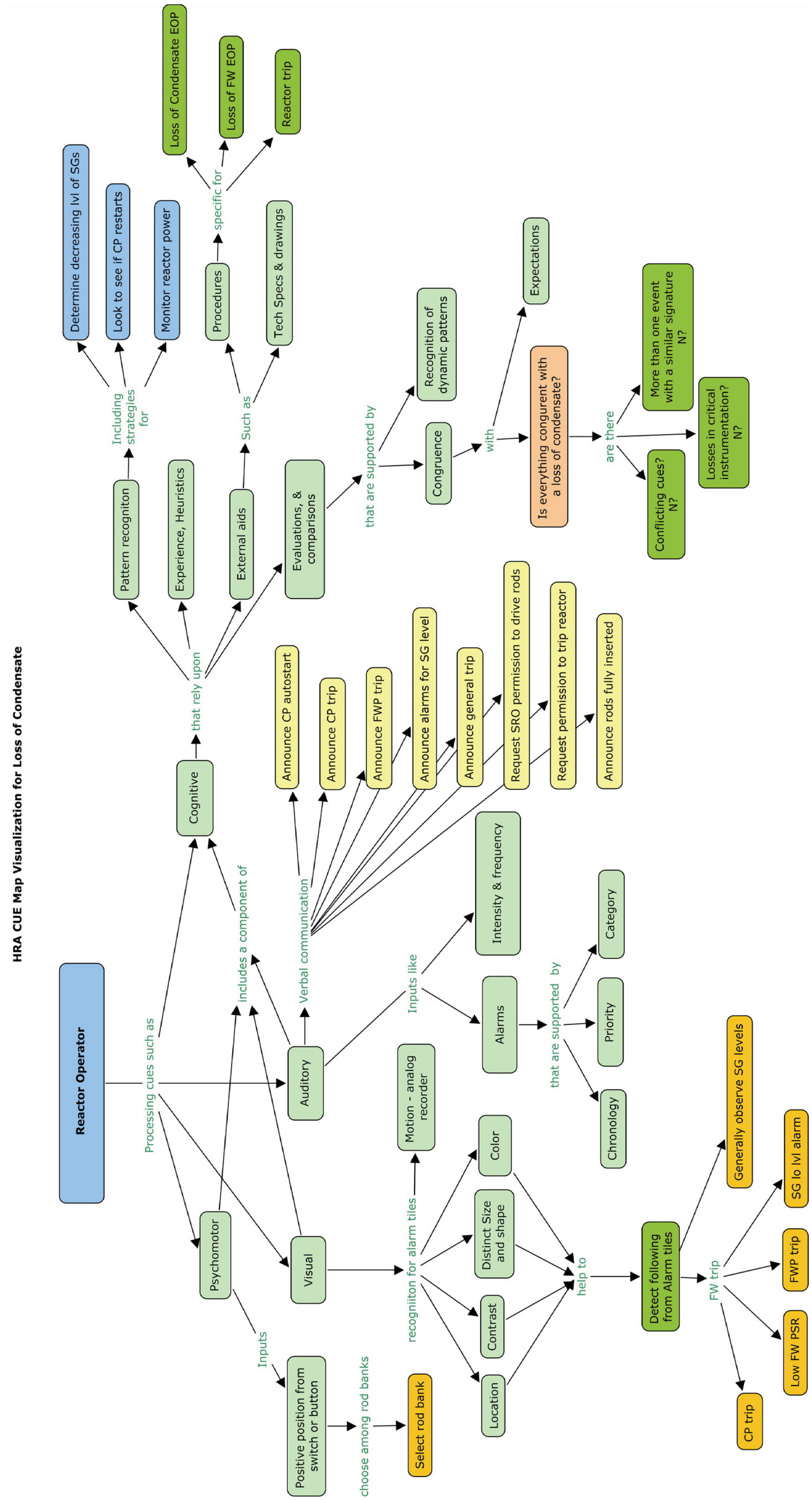


**Figure 5: HRA Cue Map**

(Key: Orange = visual cues, Yellow = auditory/verbal, Dark green = procedural cues, Blue = strategies)

## Discussion

When performed properly, HRA is a context-informed process that calls upon the skill of the analyst to conceptualize and verify a large number of potential performance shaping factors. There are many different ways in which the analyst builds a characterization of operator cognition and the contextual factors of the surrounding environment including task analysis, debrief, and analysis of procedures. In this paper, an approach is reviewed which provides a central place for characterizing and considering the salience, interaction, and relation of cues to plant and system status. The Maps in this report present the first application of the CUE space mapping process. The suggested map of the operator cue space depicts the relation among cues present to operators in advanced digital environments; in practical application, the salience of these cues can be represented in the ergonomics PSF as well as the complexity or stress PSFs in SPAR-H. Conceptually the map elements are compatible with dimensions contained in Wickens' (1988) VACP human performance framework and with PSF analysis in HRA methods

Other methods may also allow for the characterization or consideration of multiple operator cues. For example, HRA methods such as ATHEANA may afford opportunity for the analyst to consider the specific impact of misleading cues or cues, which are absent on operator performance. Older methods such as THERP contained alarm response models.

The map of the CUE space avoids the tendency to infer a temporal sequence that is a consequence of using a table or event tree to present information. It supports discussion with the operators regarding the timing, appearance, adequacy and redundancy of cues and their role in shaping operator response.

*Limitations*

This is the first attempt to employ this CUE MAP approach and a number of limitations emerged. First, the map is not dynamic, and therefore does not specify the sequence and timing of cues, it serves to remind the HRA analyst what needs to be considered in support of PSF analysis for such PSFs as: teamwork, complexity, workload, and HMI – PSFs that tend to be part of any HRA method. Although the cue density may be determined from this mapping approach, the pacing of cues, and the time for operators to react are not part of the diagramming approach an in-depth interviews or simulation is needed to assess these factors. In the example, we also map the operator's initial strategies and this approach needs to be expanded upon and more deeply explored. For example, should this category be limited to heuristics or propositions, or perhaps to prioritized goals?

The CUE MAP can be used to help inform the HRA process. The most notable strength of the MAP is that it depicts the breadth and relation among cues including indirect influences in an easily manipulated graphic presentation mode. In the future, the map could be driven by a simulation engine that turns on and off cues in a real time run equivalent. Thus, dynamic factors including the temporal sequencing and persistence of cues could be reviewed.

Evaluation of human performance in dynamic control systems can be challenging. As an complementary tool for existing HRA methods and possibly human factors engineering, this approach to mapping the operator cue space holds promise, but application to additional scenarios is needed along with empirically determined estimates of inter-rater reliability and validity. Finally, extended analysis of the cue structure may support the assessment of cue-response capability in terms of operator strategy.

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