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# Human Performance Improvement Tools and Situation Awareness in Nuclear Power Plant Outage Work

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Several human performance improvement tools (HPIs) are available to support the safe execution of work in scheduled maintenance outages in nuclear power plants (NPPs). Many can be conceived as "situation awareness tools" as they are intended to help outage workers form an accurate understanding of their task and surroundings and be sensitive to the presence of hazards and performance risks. Yet only a small selection of HPI tools have been explicitly linked to situation awareness. Furthermore, how these HPI tools improve situation awareness and, in turn, the safe execution of outage work, has not been thoroughly elaborated. In the present paper we address these limitations by conceptualizing how a broader range of HPI tools used in outages could prevent "situation awareness errors" in perceiving, comprehending, and projecting how a situation could develop. In doing so, we generate knowledge that can help NPP outage organizations and workers to make better decisions about the selection and use of HPI tools and direct future research on HPI tool usage and effectiveness.

*Keywords*: Human performance improvement tools, situation awareness, nuclear power, maintenance, scheduled outages.

## 1. Introduction

Regularly scheduled maintenance outages are needed to ensure the safe operation of NPPs. Yet, safely executing NPP outage work has its challenges. For one, this work involves large numbers of contract workers and newer, less experienced staff (IAEA 2005). Many outage workers may have insufficient knowledge to perceive and comprehend safety hazards in their work environment, or to anticipate the safety implications of their actions. Furthermore, outage work is characterized by coordination challenges, uncertainty, time-pressure, physical demands, and high workload (Hinze 2005; Reiersen and Gibson 1995; Hollnagel and Gauthereau 2001; Bourrier 1996; IAEA 2005; Haber, Barriere, and Roberts 1992). These characteristics decrease outage workers' ability to maintain an overview of and attend to safety-relevant information in their environment. Taken together, the challenges present in outage work increase the probability of human errors that lead to unwanted safety events, "situation awareness errors" in particular (Solberg, Nystad, and McDonald 2023).

Several HPI tools are available to help outage workers and teams anticipate, prevent, or catch errors before they cause harm, thereby supporting the safe execution of outage work. Many can be characterized as "situation awareness tools" (Wachter and Yorio 2013). This is because they intend to help workers form an accurate understanding of the work and equipment situation, detect the presence of unsafe work conditions, and be sensitive to the presence of hazards and the consequences of making a mistake (U.S. Department of Energy 2009). Yet only a small selection of HPI tools have been explicitly linked to situation awareness. Furthermore, how these tools improve situation awareness and, in turn, the safe execution of work, has not been clearly explained.

To address these limitations, in this paper we elaborate how a broader selection of the HPI tools could be important for situation awareness in NPP outage work. We do this by conceptualizing how 12 different HPI tools regularly used in outages could prevent different situation awareness errors that result in the failure to perceive, comprehend, or correctly project the future status of a situation. We build on Endsley's (1995a) taxonomy of situation awareness errors for this purpose.

In undertaking this work, we expand current knowledge about the importance of HPI tools for situation awareness. We also contribute to a better conceptual understanding of the relationship between HPI tools, situation awareness, and safe work execution. This information could help NPP outage organizations and workers make better decisions about the selection and use of HPI tools in practice. It can also be used to advance research on HPI tool usage and effectiveness.

Our paper starts with a review of different HPI tools used in NPP outage work and of the situation awareness errors identified to negatively influence performance. We then conceptualize how different HPI tools could help to prevent these situation awareness errors. The paper concludes with a discussion of findings and implications for practice and research.

## 2. HPI Tools

Despite having "tool" in the name, HPI tools are not physical instruments or apparatus. As described by the U.S. Department of Energy (U.S. DOE; 2009, 1), a HPI tool is "a set of discrete behaviors that help individuals and work teams anticipate, prevent, or catch errors before they cause harm to people, the facility, or the environment." Several HPI tools are used in NPP outage work. In this section, we describe the main behaviors comprised in the 12 HPI tools that we consider in this paper (highlighted in bold italics).

Prior to starting work, a ***task preview*** involves reviewing procedures and other related documents to familiarize oneself with the job to be executed, including its task sequences, critical steps, possible errors traps, and the likely consequences of errors. A task preview is meant to be done individually, before attending a ***pre-job briefing***, that involves holding a meeting with individual job performers and supervisors prior to starting work. In this meeting, tasks, critical steps, hazards, and safety precautions are discussed and task objectives, roles, and responsibilities, and resources are clarified. Furthermore, a ***job-site review*** (also referred to as a "2-minute review" or "take two") involves exploring the physical location in which a job will be carried out and its adjacent surroundings and comparing the conditions and hazards observed in the job site with information from the pre-job briefing. If deviations or unexpected conditions or hazards are identified, steps are taken to address them before starting work.

Used during work execution, ***procedure use and adherence*** involves following work procedures as written in the sequence specified by the procedure document. Complementing procedure use and adherence, ***place keeping*** involves physically marking steps in a procedure that have been completed so that steps are not omitted. ***Flagging*** can also help in ensuring error-free execution of work. It involves distinctly marking the component that is to be manipulated in a task using, for example, colored adhesive dots or tags. It can also involve marking components that should not be touched or manipulated.

***Phonetic alphabet*** and ***three-way communication*** are both aimed at improving oral communication during work execution. Phonetic alphabet involves using a common word in place of each letter of the alphabet (e.g., "Alpha" for A, "Bravo" for B). It is typically used when communicating the unique identifiers for specific components. Three-way communication involves a set of three actions carried out by a message sender and a message receiver to ensure that a message is correctly understood. First, the sender states the message. Second, the receiver repeats back a paraphrased version of the message. Third, the sender informs the receiver that the message is properly understood. If the receiver asks for clarification/repetition of the message or if their paraphrasing is incorrect in step two, the sender returns to step one and restates the message.

Applicable to both the work planning and work execution, a ***questioning attitude*** involves proactively searching for and calling attention to omissions, inconsistencies, and ambiguity or other information that challenges taken-for-granted assumptions about the work to be conducted. Another HPI tool that could foreseeably result from displaying a questioning attitude is ***stop when unsure*** (also called "pause when unsure"). This HPI tool involves stopping an activity when confused, uncertain, or in doubt or when conditions are believed to be unsafe. When an activity is stopped, the job performer is to notify their supervisor and seek help from more knowledgeable persons.

In the final cluster of HPI tools we consider, ***self-checking***, also referred to as ***STAR*** (Stop, Think, Act, Review), involves four steps. First, the job performer *stops* or slows down to focus on the intended action to be completed, the components involved, and the expected outcomes. Next, they *think* to identify the correct actions to be performed and what would happen if the correct/incorrect action was taken. Third, they *act*, performing the action that they determined to be correct. After the action is executed, they *review* the result of their performance to ensure that it was as anticipated. If not, they apply a contingency. Some applications of STAR include a fifth step in which the performance result is communicated. ***Peer checking*** is like self-checking but done in pairs. It describes when a job performer and a peer together check to confirm the planned action is the correct action to perform. The job performer carries out the agreed upon action. Then the peer reviews the result of the performance and confirms that the correct action was executed.

## 3. Situation Awareness Levels and Errors

Situation awareness can be described as a three-level information processing process that involves perceiving relevant information in the environment (level 1), comprehending the meaning and significance of this information (level 2), and projecting from this information how the situation may develop to anticipate possible consequences (level 3) (Endsley 1988, 1995b). When information processing across all three levels is successful, it results in a state of knowledge that enables better decision-making and safer performance. On the other hand, the failure to perceive, comprehend, or project the future status of a situation can result in poor decisions and the occurrence of safety incidents.

Several "situation awareness errors" are identified in the literature across the three levels of information processing, resulting in the failure to perceive, comprehend, or project the future status of a situation (Jones and Endsley 1996; Endsley 1995a). Starting at level 1, ***situation awareness errors in perception*** include not detecting relevant situational information, not observing or monitoring relevant situational information, incorrectly perceiving relevant situational information, or perceiving and then forgetting relevant situational information. Multiple factors can contribute to situation awareness errors in perception. For one, relevant information may not be available in the situation and thus imperceptible. This may be due to a lack of system indicators (e.g., failure warnings) or because the equipment or apparatus that would signal relevant information are located in a place where they cannot be observed (e.g., within a pipe) (Sneddon, Mearns, and Flin 2006). Less-than-adequate interpersonal communication can also result in relevant situational information not being available (Sandhåland, Oltedal, and Eid 2015; Jones and Endsley 1996). Alternatively, relevant situational information may be available, but difficult to detect or discriminate due to conditions such as poor visibility, obscured line of sight, or high noise levels (Sneddon, Mearns, and Flin 2006; Naderpour, Nazir, and Lu 2015; Sandhåland, Oltedal, and Eid 2015). Furthermore, distraction, high task load, and being too narrowly focused on a task can result in the failure to observe or monitor relevant and information that is readily perceptible in the situation (Endsley 1995a). Disorientation or communication distortion can result in relevant situational information being misperceived (Sneddon, Mearns, and Flin 2006). Finally, disruptions and distractions can result in relevant situational information being forgotten (Endsley 1995a).

At level 2, ***situation awareness errors in comprehension*** include the inability to integrate and make sense of the information perceived in the situation or incorrectly integrating and making sense of the information perceived in the situation. These errors are likely to occur when people lack a mental model of how something is and how it works, as this helps them to know what information to attend to in their environment and how to interpret it (Endsley 2000, 1995b). It can also occur because a person has a poor (incomplete) or incorrect mental model (Endsley 1995a). Just as people who lack a mental model, people who have a poor or incorrect mental model about the equipment they work with or the tasks they are engaged in are more likely to overlook the need to attend to certain elements in the environment because they do not understand that they are important. Having a poor or incorrect mental model also makes it difficult to interpret the situational information that is perceived.

At level 3, ***situation awareness errors in projection*** include being unable to predict how the situation could develop or incorrectly predicting how the situation could develop based on one's perception and understanding of the situation. Like situation awareness errors in comprehension, situation awareness errors in projection occur when the mental model needed to anticipate how the situation could develop is lacking or when a poor (incomplete) or incorrect model is applied for this purpose. The lack of, or use of a poor or incorrect mental model, leads to the inability to correctly project the safety consequences of a decision or action taken in the environment (Sneddon, Mearns, and Flin 2006; Sandhåland, Oltedal, and Eid 2015).

## 4. HPI Tools and Situation Awareness Errors Across Levels

We now turn our attention to analyzing how different HPI tools identified in section 2 could help to prevent the situation awareness errors identified in section 3.

### 4.1. *HPI tools and level 1 situation awareness errors*

As described in section 3, level 1 situation awareness is jeopardized when relevant situational information is not detected, not observed or monitored, incorrectly perceived, or perceived and then forgotten. We identify several HPIs that could help to prevent these situation awareness errors from occurring by helping outage workers to focus their attention on the task and task environment and detect, discriminate, and remember information important for safe performance.

First, the ***job site review*** is intended to help job performers identify the right equipment and components involved in a work activity and any conditions or hazards that may be present on-site that require their attention while carrying out the work (U.S. Department of Energy 2009). Accordingly, we identify job site review as a HPI tool applied prior to work execution that could help to prevent the situation awareness error of not detecting relevant situational information. Specifically, the job site review should help job performers to focus their attention on the task and task environment and detect relevant situational information that should be observed or monitored while executing their work, also information that may be difficult to detect or discriminate.

When executing work, ***procedure use and adherence*** is intended to help a job performer to remain attentive to information important for carrying out their work safely and efficiently (U.S. Department of Energy 2009). We therefore identify procedure use and adherence as a HPI tool that can help to prevent the situation awareness error of not monitoring or observing relevant situational information by focusing job performers' attention on information relevant for the safe execution of work (i.e., information that is specified in work procedures).

Similarly, ***place keeping*** helps a job performer whose attention is constantly shifting from the procedure they are following to indicators and physical equipment, and to other people and elements of the environment that may distract or disrupt their work (U.S. Department of Energy 2009). We therefore also see place keeping as a HPI tool that can help to prevent situation awareness errors of not observing relevant information (i.e., steps in a procedure) or with forgetting relevant information (i.e., where one is in a procedure) if a disruption or other distraction should occur. Relatedly, ***flagging*** is intended to help a job performer identify the correct component on which to perform their work, or to continue work on after taking a break or being disrupted or distracted (U.S. Department of Energy 2009). This is particularly important when the component a person is working with is near other similar-looking components. Based on this information, we identify flagging as a tool that can help to prevent situation awareness errors related to misperceiving situational information based on the difficulty to detect or discriminate between similar looking components. Flagging could also help to prevent errors of forgetting relevant situational information (i.e., which component one is working with) if a disruption or other distraction should occur.

Furthermore, a ***questioning attitude*** is intended to help job performers remain alert to potential hazards, warning signs, critical activities, or other uncertainties or error precursors in the work environment, even in work tasks prescribed by work procedures (U.S. Department of Energy 2009). For this reason, we identify questioning attitude at the activity level as an important HPI tool for preventing situation awareness errors related to relevant situational information not being detected or observed and monitored. This is because displaying a questioning attitude should help the job performer to identify information in the situation that is important to observe or monitor, even information that may be missing or is difficult to detect or discriminate. However, it must be recognized that to display a questioning attitude a job performer must have some understanding of the task and task environment (as elaborated through HPI tools discussed in the next section), such that they comprehend of the meaning and significance that the omissions, inconsistencies, ambiguity, or other important situational information they detect have for the safe performance of work. This could distinguish having a questioning attitude from simply asking a lot of questions, some that may be irrelevant and become a distraction that hinders safe performance (Oedewald et al. 2015).

Finally, ***phonetic alphabet*** is intended to help clearly distinguish the unique identifiers used for specific components (U.S. Department of Energy 2009). It is held to be particularly useful when communicating over the telephone or other channels that could distort sound or when communicating in a stressful or noisy situation that could make letters difficult to discriminate by the receiver. Accordingly, we identify phonetic alphabet as a HPI tool that could help to prevent the situation awareness error of misperceiving relevant information, particularly misperception resulting from communication distortion.

### 4.2. *HPI tools and level 2 situation awareness errors*

As described in section 3, level 2 situation awareness errors include the inability to integrate and make sense of information perceived in a situation or incorrectly integrating and making sense of this information. Both are likely to result from issues with job performers' mental models.

We identify three HPI tools that could help to prevent situation awareness errors from occurring at level 2 by enabling the information elaboration necessary for job performers to develop a rich and accurate mental model of the task and task environment. Notably, the HPI tools ***task preview*** and ***pre-job briefing*** are both aimed at helping job performers to familiarize themselves with the work to be performed and to understand what is to be accomplished and the associated hazards (U.S. Department of Energy 2009). Accordingly, we identify both HPI tools as helping to elaborate the information necessary to develop a good mental model of the task, preventing, in turn, the likelihood of errors related to the inability to integrate and make sense of the information perceived in the situation. Maintaining a ***questioning attitude*** during the task preview and pre-job briefing is also important, however, for critically assessing the work plans and associated hazards in ways that help to develop a correct and complete understanding of the task (U.S. Department of Energy 2009). Because of this, we also identify questioning attitude as a HPI tool that should help to prevent level 2 situation awareness errors by enabling the information elaboration necessary to develop a richer and more accurate mental model of the task and task environment.

We also identify one HPI tool that could prevent situation awareness errors at level 2 by helping to ensure that job performers correctly comprehend the meaning or significance of information they receive. Notably, ***three-way communication*** is aimed at helping to prevent misunderstandings between an information sender and receiver in oral communications (U.S. Department of Energy 2009). Three-way communication is likely to help prevent level 1 situation awareness errors in misperceiving orally communicated information. However, its primary purpose is to ensure that the receiver understands (not only correctly hears) the information communicated. Therefore, we identify three-way communication as important for preventing situation awareness errors associated with incorrectly integrating and making sense of the information received from a message sender.

Finally, we identify one HPI tool that could prevent situation awareness errors at level 2 by helping to stop work when a good/complete mental model of the task and task environment is not available. Specifically, ***stop when unsure*** is a HPI tool intended to stop job performers from carrying out an activity when they are confused or uncertain about what to do. In this way, it could prevent the likelihood of making situation awareness errors associated with the inability to integrate and make sense of a situation, by helping job performers to stop work and get help when needed. However, it is important to acknowledge that for this HPI tool to be used, job performers must have a sufficient mental model of the task and task environment (as elaborated, for example, through task preview and pre-job briefing) to recognize that they are encountering situations or conditions inconsistent with, or beyond the scope of, what was planned or expected.

### 4.3. *HPI tools and level 3 situation awareness errors*

Level 3 situation awareness errors include the inability to predict, or incorrectly predicting, how the situation could develop based on one's perception and understanding of situational information. Similar to situation awareness errors made at level 2, level 3 errors are likely to result from issues with job performers' mental models.

We identify two HPIs that could help to prevent situation awareness errors from occurring at level 3 by enabling the information elaboration necessary for helping job performers develop a good mental model of the safety consequences of a decision or action taken in the task environment. ***Self-checking*** or ***STAR*** seems particularly well-suited to address level 3 situation awareness errors. This HPI tool is intended to help a job performer reflect on an intended action and what will happen when it is taken, prior to proceeding (U.S. Department of Energy 2009). Therefore, we believe it could prevent level 3 situation awareness errors related to the inability to predict, or incorrectly predicting, how actions taken could cause the situation to develop, by prompting job performers to stop and elaborate this information. As ***peer-checking*** is similar to and often used to augment self-checking (U.S. Department of Energy 2009), we also identify this HPI tool as one that could help to prevent level 3 situation awareness errors in the same way. If job performers or peer checkers are unable to predict what would happen if the correct or incorrect action was taken, ***stop when unsure*** could also help to reduce situation awareness errors at this level by helping job performers to stop and ask for help when they are confused or uncertain about the correct course of action.

## 5. Discussion

In this paper, we conceptualize how different HPI tools could help to prevent situation awareness errors in perception, comprehension, and projection that can lead to unwanted safety events. A summary of the main propositions put forward is provided in Table 1.

Table 1. A summary of how HPI tools could prevent situation awareness errors across levels.

| |
|---|
| 1 - Perception |
| *Errors:* Not detecting, not observing or monitoring, incorrectly perceiving, or forgetting relevant situational information. |
| *HPI tools:* Job site review, procedural use and adherence, place keeping, flagging, questioning attitude (activity level), phonetic alphabet. |
| *Mechanisms:* Helps job performers focus their attention on the task and task environment and detect, discriminate, and remember information important for safe performance. |
| 2 - Comprehension |
| *Errors:* Being unable to integrate or interpret relevant situational information or incorrectly integrating and interpreting relevant situational information. |
| *HPI tools:* Task preview, pre-job briefing, questioning attitude (work planning and prep). |
| *Mechanisms:* Enables the information elaboration needed to develop an accurate/rich mental model of the task and task environment through which relevant situational information can be integrated and interpreted. |
| *HPI tools:* Three-way communication |
| *Mechanisms:* Helps to ensure that job performers use a correct mental model to integrate and interpret of communicated information. |
| *HPI tools:* Stop when unsure |
| *Mechanisms:* Helps job performers to stop work when a good/complete mental model of the task and task environment is not available. |
| 3 - Projection |
| *Errors:* Being unable to predict, or incorrectly predicting, how the situation could develop |
| *HPI tools:* Self-checking/STAR, peer checking |
| *Mechanisms:* Enables the information elaboration needed for job performers to anticipate the safety consequences of a decision or action taken in a particular task environment. |
| *HPI tools:* Stop when unsure |
| *Mechanisms:* Helps job performers to stop work when a good/complete mental model is not available to help anticipate the safety consequences of a decision or action. |

In conducting this work, we expand current knowledge about the extent to which HPI tools could be important for situation awareness. Currently, industry standards only identify task preview, job site review, questioning attitude, and stop when unsure as HPI tools important for situation awareness (U.S. Department of Energy 2009). Our analysis finds that a broader range of HPI tools could be important for situation awareness by preventing situation awareness errors across levels. Furthermore, by linking specific HPI tools to different situation awareness errors and identifying the mechanisms that could relate them, our work better explains how HPI tools influence situation awareness and, in turn, safe work performance than we have found in existing literature on the topic.

### 5.1. *Practical implications*

Knowledge that a broader range of HPI tools could be important for situation awareness and a better understanding of the relationship between HPI tools, situation awareness errors across levels, and safe work execution could have important implications for practice. Notably, research shows that NPPs might only implement a selection of available HPI tools in maintenance work (Oedewald et al. 2015). Furthermore, our own discussions with NPP outage personnel uncover that different people may use and enforce an even more limited selection of HPI tools in practice. We believe that decisions about why and when to use different HPI tools could be better informed if knowledge about how these tools could prevent situation awareness errors at different levels was considered. For example, it could help in ensuring that the HPI tools selected for use are well-suited to prevent situation awareness errors across all three levels of information processing.

A better understanding of the relationship between HPI tools, situation awareness across levels, and safe work execution could also be important for addressing a dilemma in outage work: that procedural use and adherence (a primary HPI tool in this context) may not prevent errors that can lead to unwanted safety events if procedures are inaccurate or incomplete, which they sometimes are. Therefore, job performers must always display a questioning attitude when following procedures to detect hidden flaws (U.S. Department of Energy 2009). As discussed by Gotcheva et al. (2013), questioning attitude can be an unreliable barrier in this context, because it is tied to the individual understanding of the task and task environment. Our analysis supports this proposition. As presented in section 4.1., questioning attitude should help job performers to detect omissions, inconsistencies, ambiguity, or other flaws in work procedures. However, to display a questioning attitude successfully, a job performer must have some understanding of the task and task environment and what could happen if certain actions are taken/not taken. If not, they will not be able to comprehend of the meaning and significance that the information they detect has for safe work performance. We suggest that other HPI tools, aimed at preventing situation awareness errors at level 2 (comprehension) can help job performers gain the understanding needed to display questioning attitude more successfully at the activity level.

The discussion point above calls attention to the fact that using HPI tools to support situation awareness at one level may depend on a job performer's situation awareness at another level, for which other HPI tools can be relevant.

### 5.2. *Future research needs*

In this paper, we have attempted to better explain how HPI tools influence situation awareness and, in turn, safe work performance, by preventing situation awareness errors across levels. Future research is needed, however, to test the propositions we put forward.

As a first step, empirical research could test if outage workers' (or other job performers') implicit understanding of why and when to use different HPI tools corresponds to our conceptualization of how different HPI tools are important for preventing situation awareness errors at different levels. This could help to validate the usefulness of the conceptual model put forward in this paper. It could also help to identify possible misconceptions and mistakes using HPI tools.

Furthermore, empirical research could test the mechanisms proposed between specific HPI tools, situation awareness, and safe work execution. For example, in section 4.2, we suggest that pre-job briefing enables greater information elaboration about the task(s) to be accomplished and their associated hazards. This should contribute to a more accurate and richer mental model of the task and task environment, which in turn facilitates safer work execution. This proposition could be tested in empirical research by determining if pre-job briefing results in a "cognitive cause map" with more constructs and causal links, and if this explains variation in outcomes between work teams (c.f., Ellis and Davidi 2005). We encourage future research to consider this, and other relationships discussed in our paper. Doing so could help to advance research on HPI tool effectiveness.

## 6. Conclusion

In this paper, we have conceptualized how a range of HPI tools used in NPP outage work could prevent situation awareness errors in perceiving, comprehending, and projecting how a situation could develop. In doing so, we expand current knowledge about which HPI tools could be important for situation awareness and why. This knowledge can help NPP outage organizations and workers make better decisions about the selection and use of HPI tools. It can also direct research on HPI tool usage and effectiveness.

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