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Original Article

Measuring Situation Awareness of Operating Team in Different Main Control Room Environments of Nuclear Power Plants

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ABSTRACT

Environments in nuclear power plants (NPPs) are changing as the design of instrumentation and control systems for NPPs is rapidly moving toward fully digital instrumentation and control, and modern computer techniques are gradually introduced into main control rooms (MCRs). Within the context of these environmental changes, the level of performance of operators in a digital MCR is a major concern. Situation awareness (SA), which is used within human factors research to explain to what extent operators of safety-critical systems know what is transpiring in the system and the environment, is considered a prerequisite factor to guarantee the safe operation of NPPs. However, the safe operation of NPPs can be guaranteed through a team effort. In this regard, the operating team's SA in a conventional and digital MCR should be measured in order to assess whether the new design features implemented in a digital MCR affect this parameter. This paper explains the team SA measurement method used in this study and the results of applying this measurement method to operating teams in different MCR environments. The paper also discusses several empirical lessons learned from the results.

1. Introduction

As digital technology develops, main control rooms (MCRs) of new nuclear power plants (NPPs) are planning to adopt computer-based human–system interfaces (HSIs). New MCRs have sit-down workstations from which operating personnel monitor the plant through computerized displays. Operators control the plant's equipment using soft controls that are accessed through computer workstations, and use computer-based procedures (CBPs) that offer the potential to undertake

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control actions directly from the procedure display, including semiautomated control measures where the operator authorizes the procedure to perform a series of actions [1]. An operator can also approach all the information and operating procedures using a computerized procedure system, which allows them to share the same information with the senior reactor operator.

While the introduction of advanced HSIs is generally considered to enhance operator performance, there is also the potential to negatively impact human performance, spawn new types of human errors, and reduce human reliability [2]. Moreover, it becomes possible for the performance of the team to be degraded when they engage in more personal tasks [3]. Thus, addressing human performance issues with new HSIs in NPPs is critical for the successful introduction of new HSIs [4,5].

To shed light on these issues, various studies have been carried out. For example, numerous studies regarding human factors in the nuclear industry have been conducted in relation to the Halden Reactor Project [6–8]. Moreover, prototypes of different design concepts of advanced HSIs have been implemented in the experimental control room facility of the Halden Reactor Project, and the effects on the operator performance have been evaluated through performance-based tests [9]. Furthermore, various factors that can affect human performance in an advanced MCR were derived as part of an effort to develop a human reliability method for an advanced MCR [10]. Along with these efforts, many researchers are working to develop appropriate performance measures to evaluate the effects of these advanced HSIs [11–15]. Among the suggested performance measures, situation awareness (SA), which is used within human factors research, to explain to what extent operators of safety-critical systems know what is transpiring in the system and the environment, is considered an important human performance measure, as SA dictates the ability to initiate correct actions given a particular situation and to respond properly to system feedback. In this light, SA continues to receive a considerable amount of attention from the ergonomics community, as insight can be gained into human information processing during interactions with dynamic and complex environments [16,17].

To date, measurement and assessment technologies for team performance are insufficient compared to those for individual performance [18]. Specifically for SA, much effort has been devoted to developing a measurement method and evaluating individual SA.

Although individual SA is important, most work is not done in isolation, but rather takes place in groups or in a team environment. Hence, much attention has been given to measuring the operating team's SA as the team is recognized as a key factor in safety-critical systems. Especially in the nuclear domain, team SA has received growing attention in light of the finding that MCR operators perform diagnostic tasks as a team unit so that NPPs can be safe. To resolve issues pertaining to human performance, specifically “team SA,” this study aims to measure the SA of an operating team, as it operates an MCR with new HSIs implemented, and to compare the results with those from a conventional MCR. First, this paper briefly explains the method used to measure the operating team's SA, as developed in a previous study [19]. Second, this paper shows the result of an additional case study to confirm the applicability of the method. Finally, the results of the operating team's SA in different MCR environments are shown, and several empirical lessons learned from this study are discussed.

2. Method for measuring an operating team's SA

2.1. *Brief description of the method*

As shown in Fig. 1, the concept of team SA in this method is mainly based on the concept derived by Endsley [20], who defines SA as “*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future*.” For a brief description of the SA concept, it has three generic aspects that are related to cognition: perception, comprehension, and projection. Level 1 SA, which implies perception, includes the outcome of all top-down and bottom-up perceptual processes. Thus, Level 1 SA addresses the extent to which elements are detected. Level 2 SA, which implies comprehension, includes the outcome of higher cognitive processes. Level 2 SA refers to an understanding of the meaning of the attended information. Level 3 SA, which implies projection, describes an operator with the highest understanding of a situation, in that the operator can forecast how the situation will develop. Endsley [20] refers to these as the three levels of SA, and forms a three-level hierarchy with Level 1 as the lowest, basic level and Level 3 as the highest level. This method conceptualizes team SA based on the concept of individual SA, as team SA also involves the team's assessment (perception, comprehension, and projection) of the current situation, including the surrounding environment, the task, and the team itself. Similar to Endsley's [20] concept, this method considers that team SA has three levels of SA, forming a three-level hierarchy with Level 1 as the lowest, basic level and Level 3 as the highest level.

The proposed method starts with the conceptualization of team SA. There is some debate over the concept of team SA, and there remains no universally accepted definition. However, this method considers team SA as the sum of individual SA instances, independent of any overlap in SA requirements among operators based on research results, suggesting that “team SA can be the sum of the SA for each individual” [21]. Although the process of conceptualizing total team SA needs to be more sophisticated with a consideration of the complex relationships or hierarchies of individual operators, the proposed method focuses on measuring team SA, treating it as the final product of a complex process, rather than on modeling team SA.

Based on the concept of team SA, the proposed method makes logical connections between team communication and team SA. From the results of a literature review from various domains, the method is based on the assumption that team communication is closely linked to team SA in that team communication supports the knowledge-building and information-processing activities that lead to the construction

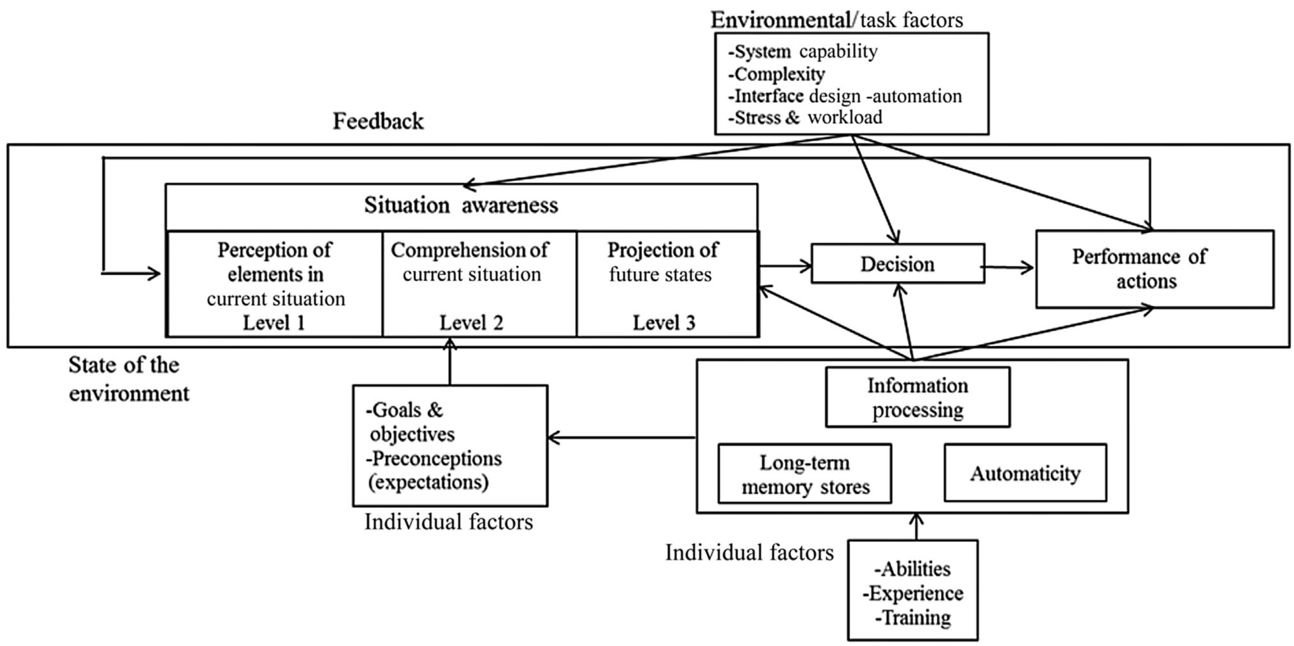

Fig. 1 – Endsley's three-level SA model. SA, situation awareness.

of team SA. Moreover, it highlights the importance of communication as a teamwork process.

The proposed method develops a logical connection between team communication and team SA using a decision ladder model developed to identify the decision-making process of experienced workers at thermal power plants. A decision ladder, as shown in Fig. 2, explains the information-processing steps; it consists of boxes that correspond to information-processing activities and circles that correspond to the state of knowledge. The method adopts insights from this model, which implies that the information-processing activities, considered as cognitive activities, can be observed from team communication. Consequently, the method selects the following cognitive activities from the decision ladder model: activate, observe, identify, predict, evaluate options, define, formulate, and execute.

Second, this method uses a mapping process between the selected cognitive activities and each level of team SA, using insights grained from research on railway systems, which attempted to understand how all the elements in the driver's

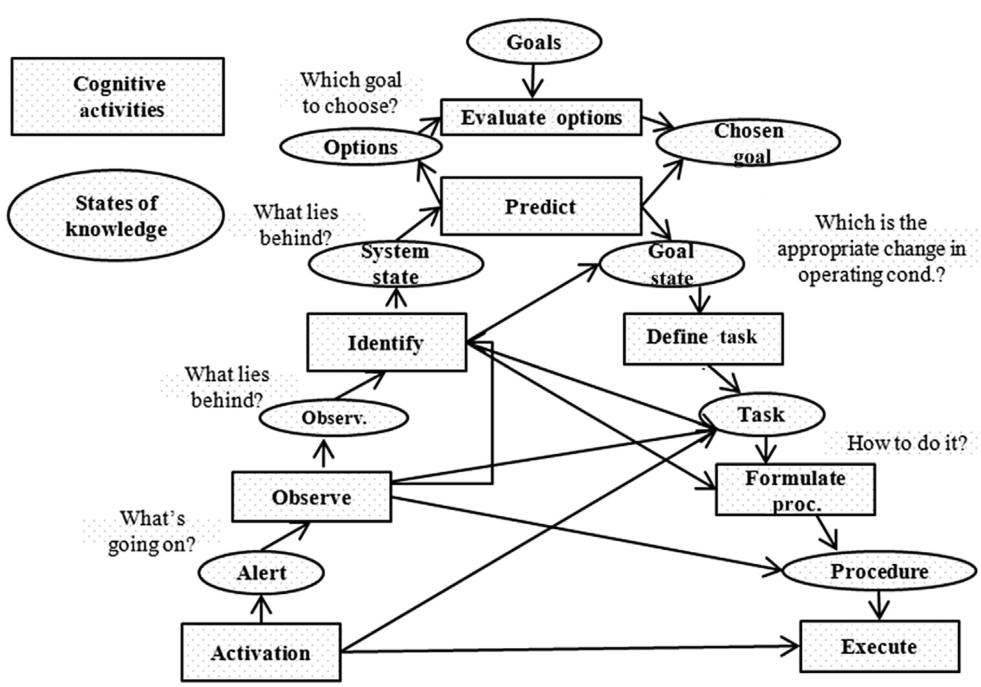

Fig. 2 – Decision ladder model. cond., condition; Observ., observation; proc., procedure.

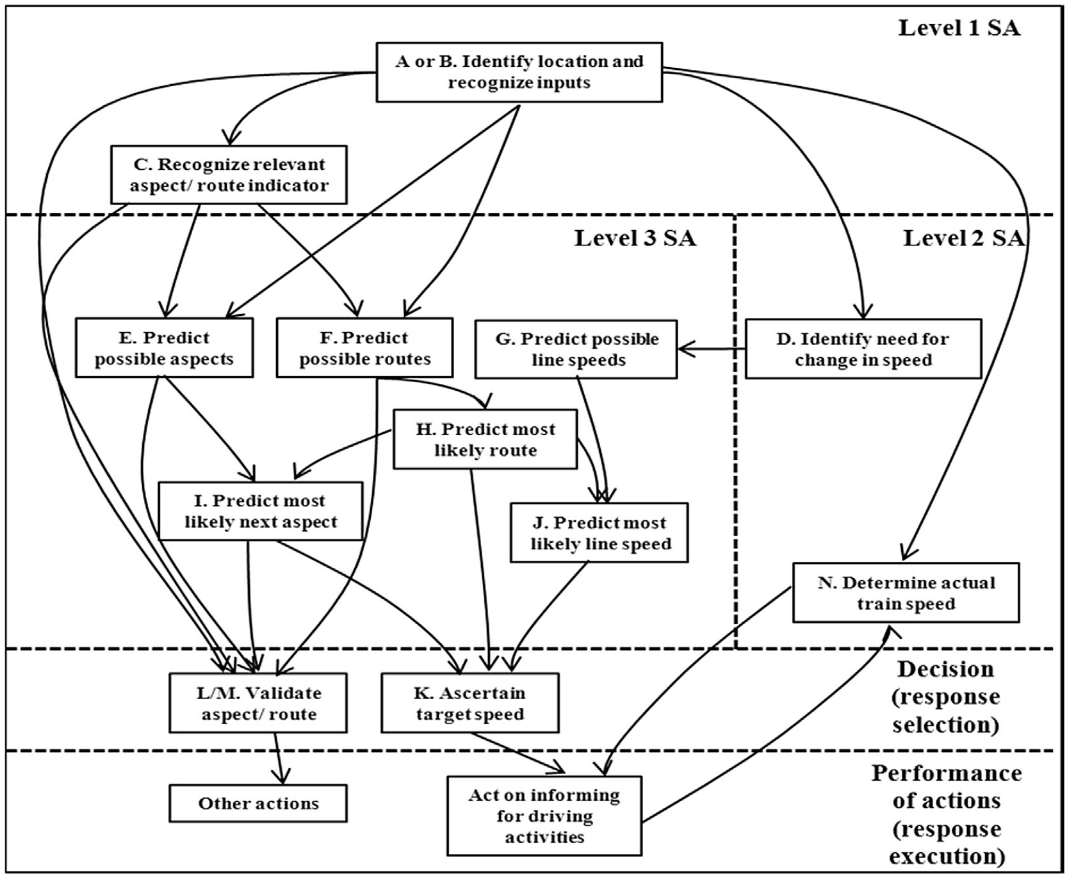

Fig. 3 – High-level of tasks of approaching and driving through junctions, and their task relationships to each other using the demarcations within Endsley's model of SA. SA, situation awareness.

environment interact and affect what is likely to happen next. As shown in Fig. 3, the railway system results, which show an SA model of the driver and describe each of the individual tasks in activity-flow diagrams, were adopted.

The proposed method uses insights suggesting that drivers of trains need to engage in the cognitive activities of "identification" and "recognition" to have Level 1 SA, "identification" and "determination" for Level 2 SA, and "prediction" for Level 3 SA. These results were considered during the development of a logical connection between the selected cognitive activities and each level of team SA, assuming that specific cognitive activities are required to achieve each level of team SA, as shown in Table 1.

After deriving the cognitive activities required for each level of team SA, the method implements a speech act coding scheme, which is used to summarize and interpret process tracing data and to capture the critical content in data and the frequencies and patterns in transcriptions. Among the various coding schemes suggested for the purpose of a verbal protocol analysis, the speech act coding scheme [22] developed by the Korea Atomic Energy Research Institute (KAERI) was adopted for this method, as shown in Table 2.

The method determines the relationships between the subcategories in a speech act coding scheme and the cognitive activities required for each level of team SA using the research results of Hollnagel et al [23], as shown in Fig. 4.

As Fig. 4 shows, the method considers that the subcategories of the speech act coding scheme can be mapped onto the cognitive activities required for each level of team SA. It was considered that the elements of "read," "see," and "look" are required for the cognitive activity of "observe." Given that "observe" is the cognitive activity required for Level 1 team SA, the method selects the subcategories of the speech act coding scheme for Level 1 team SA. The method uses the same process for Level 2 and Level 3 team SA. It should be noted that a speech act coding category such as "Announcement" is included in both Level 1 and Level 2 of team SA. This is because operators who liaise between operating teams can give specific information necessary for constructing Level 1 and Level 2 team SA, and play an important role in both of them.

These results are shown in Table 3. As shown in Fig. 5, the method was developed by logically connecting team SA

Table 1 – Cognitive activities required for each level of team SA.

Level of team SA	Cognitive activities for team SA
Level 1	Observe
Level 2	Identify
Level 3	Predict, evaluate, define

SA, situation awareness.

Table 2 – Speech act coding scheme adopted in this method.

Category	Subcategory	Definition	Example
Call	Call	A call for a specific person for communication	“RO?”
	Response	A response to the call	“This is RO speaking”
	Call-Identification	A caller's self-identification to the target person	“This is EO”
	Call-Id-Ack	A receiver's response to the caller's self-identification	“Yes”
Inquiry	Inquiry	A statement for asking	“Is the vacuum valve open?”
	Reply	An answer for the question	“Yes, the vacuum valve is open.”
	Reply-Ack	A statement representing that a reply was received	“Yes”
Command	Command	A specific order for responsibility by one to another to manipulate an object	“Close valve V202”
	Command-Ack	A statement representing that a command was received	“Yes, I'll close valve V202.”
	Command-Confirm	A confirm message that the command was sent successfully to receiver	“OK”
	Suggestion	A statement of recommendation for a specific action or an introduction of an idea for consideration	“Should we try to start the charging pump?”
Observation	Observation	A statement that describes the status of the plant or equipment	“The water level of steam generator is increasing.”
	Observation-Ack	A statement representing that an observation was received	“OK”
	Judgment	An expression that judges the situation	“The trouble is occurring because of low pressure of the vacuum pump.”
	Judgment-Ack	A statement representing that a judgment was received	“OK”
Announcement	Announcement	A statement to the public, which gives information about something that happened or that will happen	“Attention please. EDG B will be started, three, two, one, go.”
	Announcement-Ack	A statement representing that an announcement was received	“OK”
Acknowledgment	Acknowledgment	A statement representing that a message was received	“Yes, sir.”

and team communications, suggesting that each level of team SA can be measured using Table 3. In addition, the feasibility of the method was shown with verbal protocol data gathered from a full-scope simulator [19]. Each level of team SA was measured using Table 3, and the scores for the overall level of team SA were compared with the operating team's task performance scores, as measured by an operator performance assessment system (OPAS). OPAS was originally developed by the Halden Human-Machine Laboratory (HAMMLAB) of the organization of the economic co-operation and development (OECD) Halden Reactor Project, and it combines advantageous elements of a task-analytic modeling technique and subjective expert judgment.

In this study, OPAS is used, and includes the results of task analysis and the derivation of ideal activities for the given tasks that were performed by KAERI. It was shown that the method generated a high correlation between the team SA scores and the task performance scores. Therefore, the proposed method can reasonably infer team SA.

Reasons for selecting this method can be given in a more detailed manner. Based on a review of these SA measurement techniques, it was found that most are beset with flaws, and there remains considerable debate over which of the available measures is most appropriate for assessing team SA (TSA). It can be claimed that four key requirements should be encompassed by the TSA measurement method. First, “continuity” should be considered. A TSA measurement method should not interrupt the performance of a participant's primary task, as such an interruption disturbs the actual measurement of TSA. Second, “objectivity” should be considered. A measurement should not be based on a participant's recall, as measuring TSA based on participant recall can be subjective. Third, “validity” should be considered. Constructs making up a method should actually measure participants' SA and not their memory. Furthermore, SA, as measured by a given method, should have a certain level of correlation with a participant's performance, as a high level of SA will likely correlate with a high level of performance. Fourth, “sensitivity” should be considered. As one of the reasons for the focus on SA is its practical use in improving interface design, a method should accurately detect changes in TSA caused by different types of technologies. The method chosen in this study can meet these requirements. First, it can be stated that this method can maintain “continuity” because no further interruption during the operation team's simulation is necessary. Second, the method can maintain “objectivity” because the data analysis is performed after the simulation and does not need to be based on participant recall. Third, this method can maintain “validity.” As will be explained in detail with the additional case study related to the proposed method in Section 2.2, a high level of correlation exists between the total TSA scores and the operation team's performance scores. This result infers that the proposed method is feasible to some extent, thus providing evidence of its “validity.” Finally, this method can maintain “sensitivity.” This will also be shown by the experimental studies in Section 3, the purpose of which was to measure an operation team's SA in different MCR environments. The method presented here can measure differences in TSA under different technical situations.

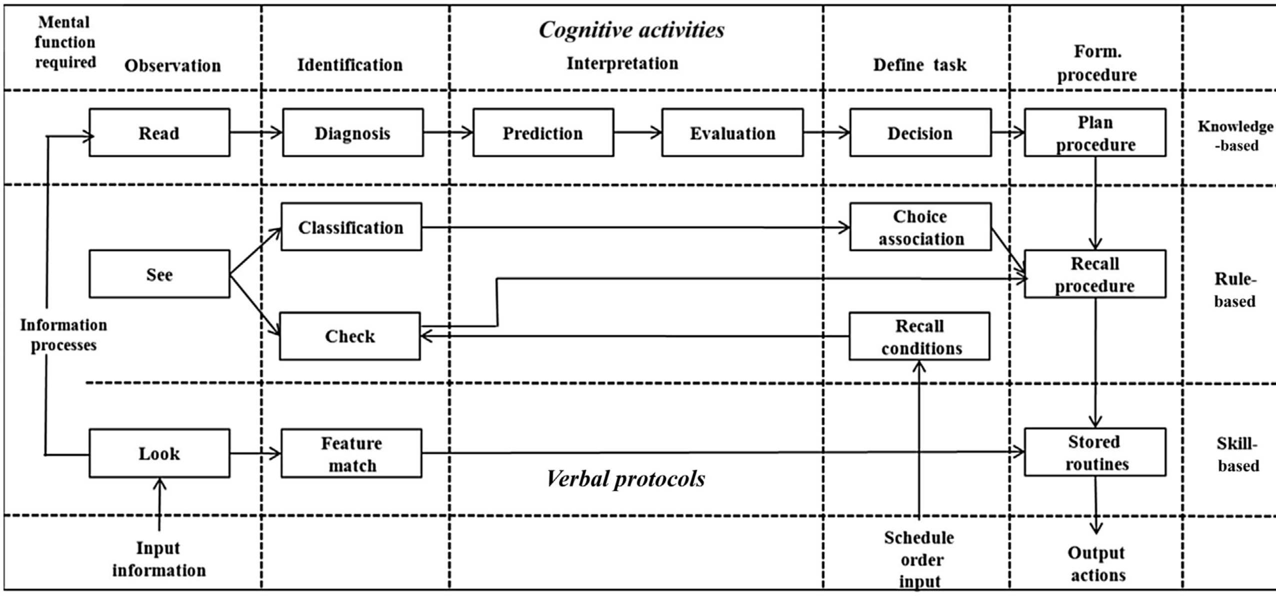

Fig. 4 – Schematic diagram of various internal data processing mechanisms that can be applied to the steps of a decision sequence.

2.2. *Additional case study related to the method*

Although the results from a preliminary study showed that the proposed method has a certain degree of feasibility, an additional case study was required to assess the feasibility of this method. First, we collected simulation data from nine operating teams working in NPPs. A simulation was performed on a full-scope simulator, which is a replica of the MCR of a conventional 1,000 MWe pressurized water reactor with traditional alarm tiles, indicators, trend recorders, and control devices installed. Moreover, an interfacing system loss of coolant accident (ISLOCA) scenario was used, as in the Nuclear Regulatory Guides/Control Room-6208 (NUREG/CR-6208) [24,25].

As this scenario requires the integration of multiple symptoms across different systems, it is cognitively demanding; thus, it is likely that the feasibility of the method could be clearly shown in this way. To assist with the comprehension of the scenario, a description of its main features follows.

The scenario is an ISLOCA from a high-pressure reactor coolant system (RCS) to a low-pressure residual heat removal (RHR) system. Fig. 6 provides a simple diagram of the systems involved in the scenario, and Fig. 7 briefly shows the sequence.

In this scenario, the RCS leak into the RHR eventually led to an RHR pipe rupture in the auxiliary building, causing the reactor coolant fluid to spill onto the floor of the auxiliary building.

This scenario was designed to be difficult in terms of situation assessment. The objective is to create a situation where the operating teams have to identify and isolate the leak into the RHR without explicit procedural guidance.

While the emergency operation procedures include procedures for identifying and isolating an ISLOCA, it is possible to create a situation where the operating teams could not reach the appropriate procedure within the emergency operation procedure network, as the plant symptoms generated early in the event are similar to the pattern of symptoms that would be produced by a loss of coolant accident (LOCA) inside the containment. By timing the dynamics of the event carefully, it is possible to create a situation where the emergency operation procedures direct the operators to the procedure for a LOCA inside the containment.

However, there is no explicit transition to the ISLOCA procedure. The crews eventually reach a step in the procedure that asks them to "try and identify and isolate the leakage." It is possible to observe the operating team's performance in a situation where the procedure explicitly requires the operating team to identify and isolate the leak without more detailed procedural guidance.

The operating team has to identify the ISLOCA into the RHR when attempting to isolate the leak. The first alarms indicate pressure, and the level decreases in the pressurizer. These are soon followed by alarms indicating radiation inside the containment. Radiation in the containment strongly indicates an RCS leak directly in the containment caused by a leak into the RHR. A relief valve in the RHR system vents to the pressurizer relief tank inside the containment. The pressurizer relief tank eventually ruptures, resulting in radiation in the containment. The operating team needs to recognize these physical system interconnections in order to link the symptoms in the containment with a potential problem in the RHR.

Table 3 – Table used for measuring each level of team SA.

Level of team SA	Cognitive activities for team SA	Speech act coding scheme
Level 1	Observe	Inquiry, announcement
Level 2	Identify	Judgment, announcement
Level 3	Predict, evaluate, define	Suggestion

SA, situation awareness.

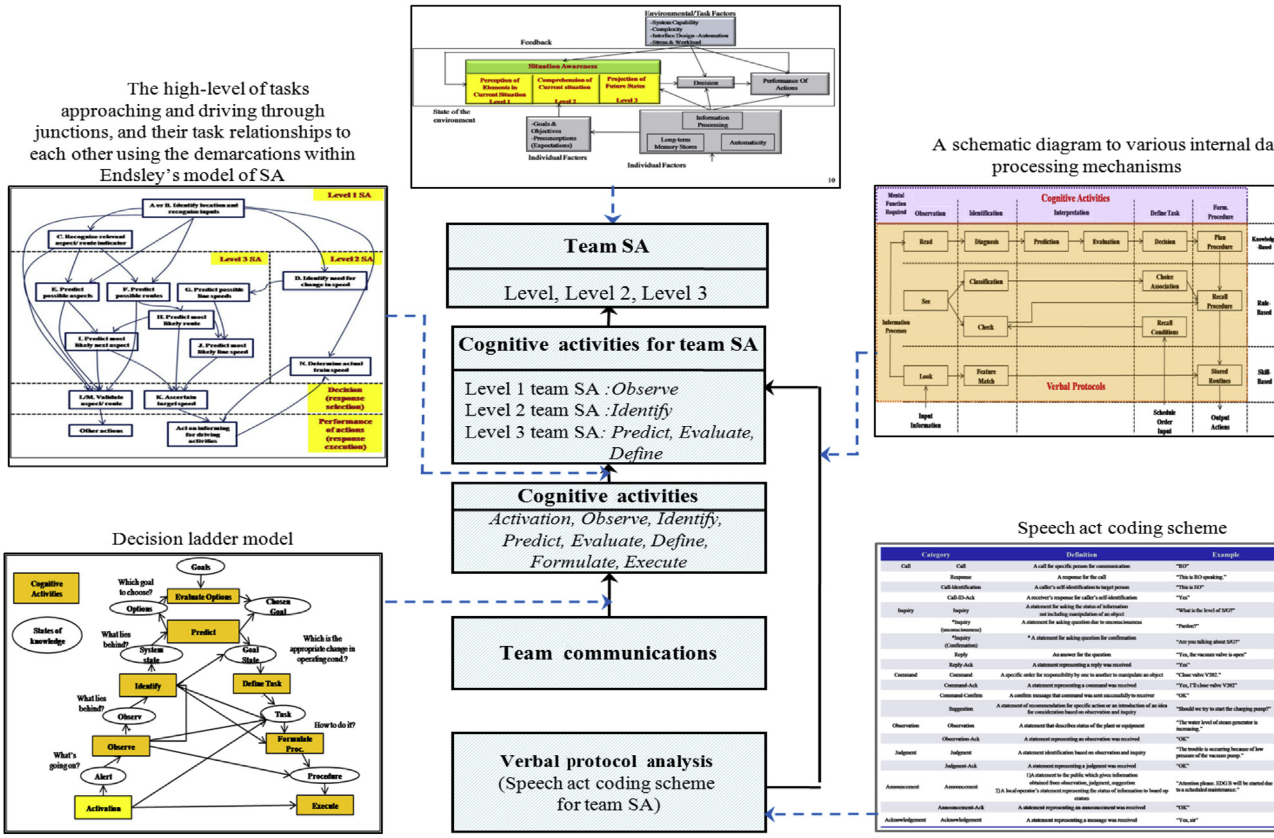

Fig. 5 – Overview of the development process for a team SA measurement method. SA, situation awareness.

Once the operating team identifies a leak into the RHR, they need to take action to attempt to isolate the leak. The appropriate action that needs to be taken depends on the postulated source of the leak. In the event, two hypotheses with regard to the source of the leak are equally plausible in that they can fully explain the available evidence. One is a failure of the two isolation valves between the hot leg loop of the RCS system and the RHR on the suction side of the RHR pump. This is the event postulated. Given this hypothesis, the actions required to isolate the leak are to call the auxiliary building to request that the valves be re-energized, to verify that they are closed, and to close them if they are not. The alternative hypothesis is that there is a leak back from the RCS through a series of failed check valves. Given this hypothesis, the leak could be isolated by closing an isolation valve on the discharge side of the RHR pump that is normally kept open.

Using this cognitively demanding scenario, a feasibility study was performed. First, each level of team SA was measured using Table 3, and scores of the total level of team SA were compared with the operating team's task performance scores, as measured by an OPAS. A correlation analysis of operating teams' task performance scores and the scores of the total level of team SA was performed based on the fact that an operating team with a high level of team SA shows good performance.

As shown in Fig. 8, the result shows a certain level of correlation between performance scores and total team SA scores. From this result, we could assess the feasibility of this method.

3. Measuring an operating team's SA in different environments

3.1. *Description of the experiment*

As described above, this method is mainly based on analyzing verbal protocols from operators. For verbal protocol data from a conventional MCR, data from experiments conducted by KAERI were used [24]. With a full-scope simulator, which is a replica of the MCR of a conventional 1,000 MWe pressurized water reactor with traditional alarm tiles, indicators, trend recorders, and control devices installed, KAERI undertook experiments to observe the performance of an operating team under off-normal situations in NPPs. A total of 12 operating teams who are currently working in conventional control rooms at existing NPPs participated in this study. For the experiments, a LOCA scenario was used and all the communications from operators were recorded by audio–visual recording facilities in the simulator.

For the verbal protocol data from an advanced MCR, we collected 11 verbal protocol data from an advanced MCR simulator equipped with new HSIs. The major new HSIs of this

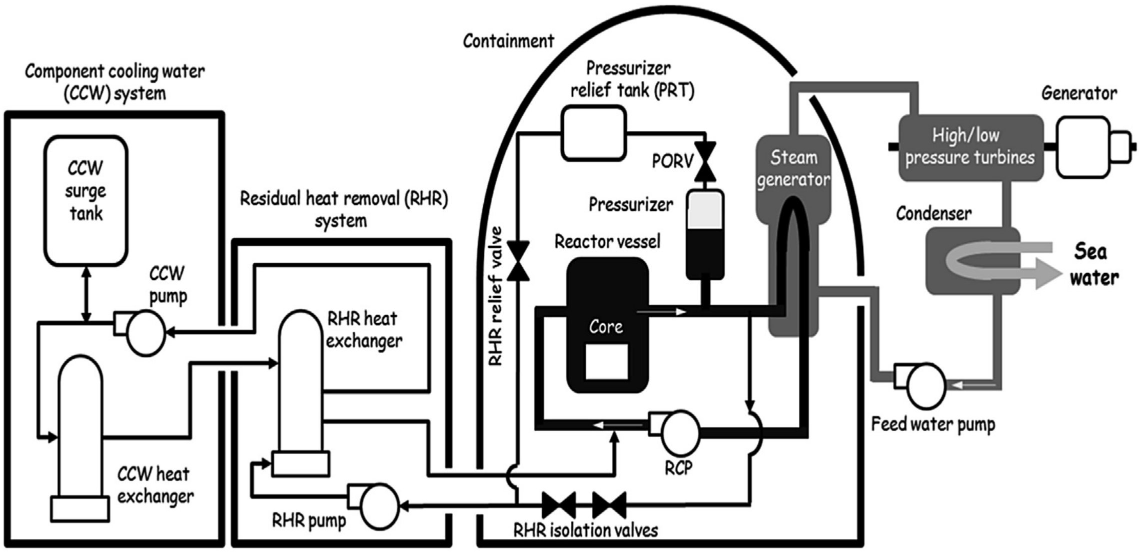

Fig. 6 – Simplified diagram of the target systems. CCW, component cooling water; PORV, pilot-operated relief valve; PRT, pressurizer relief tank; RCP, reactor coolant pump; RHR, residual heat removal.

MCR include a large display panel, a workstation-based information system, a CBP, a soft controller, and an advanced alarm system. For the experiments, a total of 11 operating teams who are currently working in conventional control rooms at existing NPPs participated. They had requisite training and education on the new HSIs before the experiments.

All the verbal protocol data from both MCRs were transcribed, including the contents and the speakers, and the speech act coding scheme developed by KAERI was encoded. Using Table 3, the scores of each level of team SA were measured and the total team SA scores were calculated by summating each level of team SA.

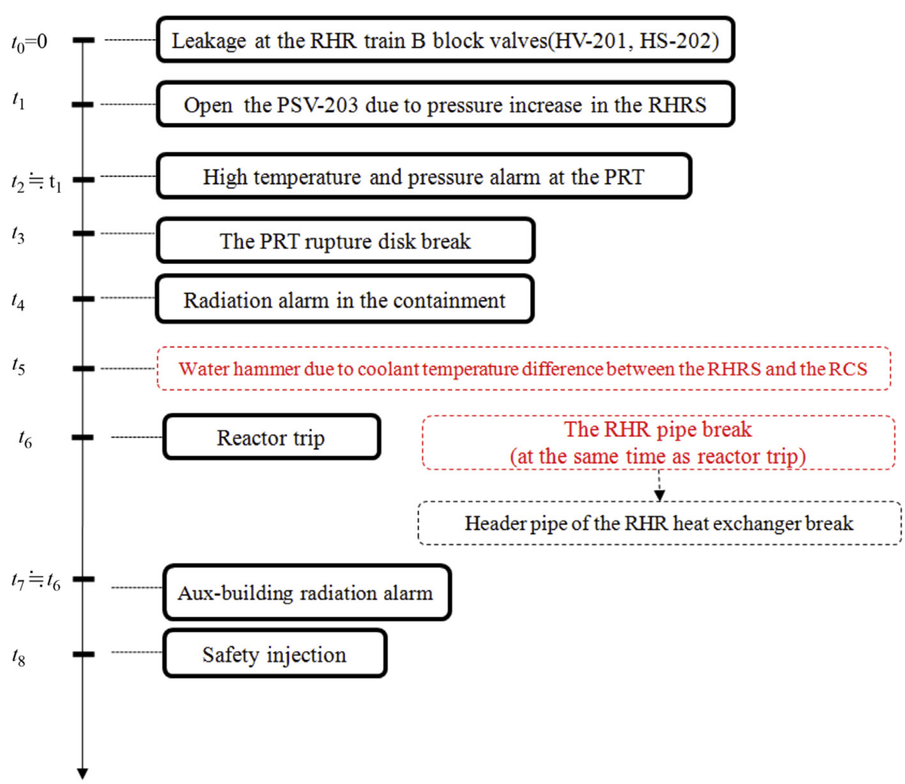

Fig. 7 – Sequence of the ISLOCA scenario. ISLOCA, interfacing system loss of coolant accident; PRT, pressurizer relief tank; RCS, reactor coolant system; RHR, residual heat removal; RHRS, residual heat removal system.

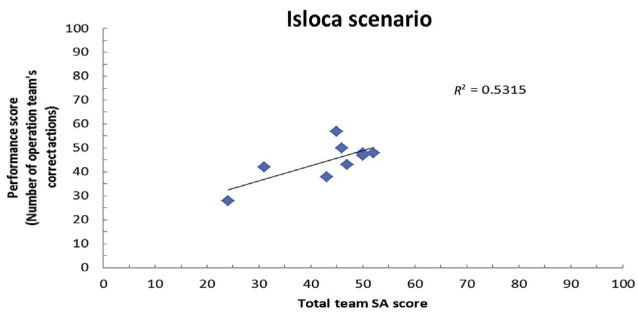

Fig. 8 – Overview of the development process for a team SA measurement method. ISLOCA, interfacing system loss of coolant accident; SA, situation awareness.

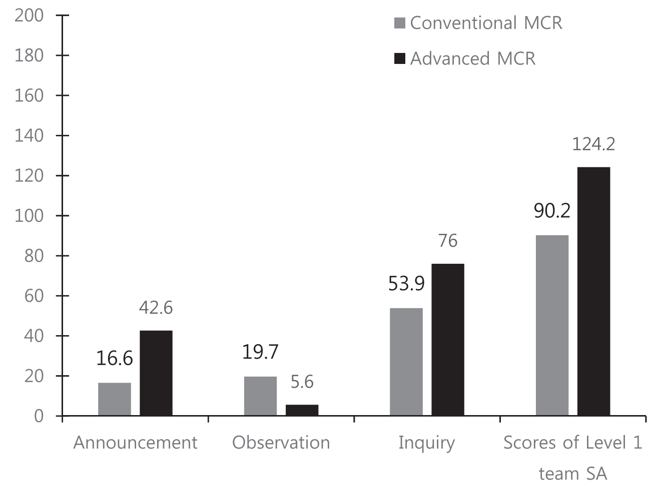

Fig. 10 – Comparison of the scores of the constituents of Level 1 team SA in a conventional and advanced MCR. MCR, main control room; SA, situation awareness.

3.2. *Results of the experiment*

Fig. 9 shows the average scores for each level and the total team SA for a conventional and advanced MCR. As shown in Fig. 9, the operating team in the MCR with new HSIs had higher scores by 56.16% for the total team SA compared to the operating team in the conventional MCR. For each level of team SA consisting of the total team SA, the operating team in the advanced MCR had higher average scores. Specifically, operating teams in the advanced MCR had higher scores by 37.54% for Level 1 team SA, by 149.45% for Level 2 team SA, and by 11.11% for Level 3 team SA relative to the conventional MCR case.

Fig. 10 shows the detailed results for Level 1 team SA. As stated above, the scores of Level 1 team SA could be measured using certain subcategories of the speech act coding scheme such as “announcement,” “observation,” and “inquiry.” Fig. 10 shows the average scores of these subcategories. As shown in Fig. 10, the average scores of the subcategories comprising Level 1 team SA were higher in the advanced MCR with the exception of “observation.” Examining the results in detail, the average score for “announcement” was 156.62% higher, while that for “inquiry” was 41% higher in the advanced MCR. However, it was shown that the average score for “observation” was 71.57% lower in the advanced MCR relative to the conventional MCR.

Fig. 11 shows the detailed results for Level 2 team SA. As stated above, the scores of Level 2 team SA could be measured using certain subcategories of the speech act coding scheme such as “announcement” and “judgment.” Fig. 8 shows the scores for these subcategories. As shown in Fig. 11, the average scores of the subcategories comprising Level 2 team SA were higher in the advanced MCR. Specifically, the average score was 156.62% higher for “announcement” and 75% higher for “judgment” in the advanced MCR.

Fig. 12 shows the detailed results of Level 3 team SA. As stated above, the scores for Level 3 team SA could be measured using a certain subcategory of speech act coding scheme such as “suggestion.” Fig. 12 shows the average scores of this subcategory. As shown in Fig. 12, the average score of the subcategory comprising Level 3 team SA was higher in the advanced MCR. When observing this result in detail, it was found that the average score was 11.11% higher than “suggestion.”

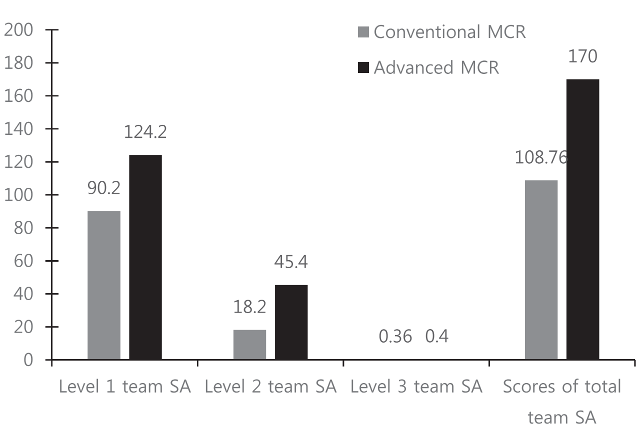

Fig. 9 – Comparison results of the operating team's SA in a conventional and advanced MCR. MCR, main control room; SA, situation awareness.

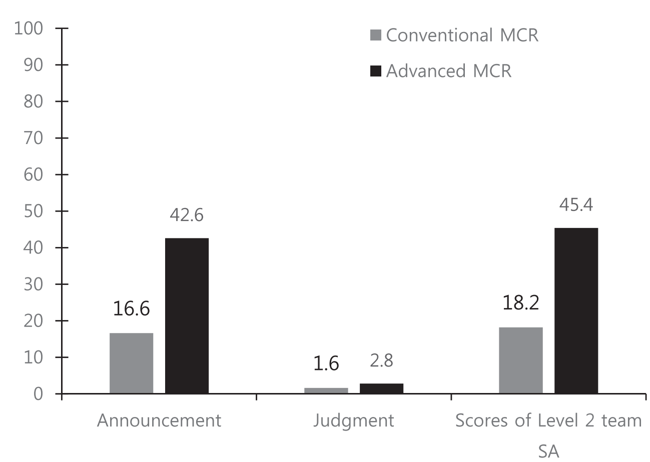

Fig. 11 – Comparison of the scores of the constituents of Level 2 team SA in a conventional and advanced MCR. MCR, main control room; SA, situation awareness.

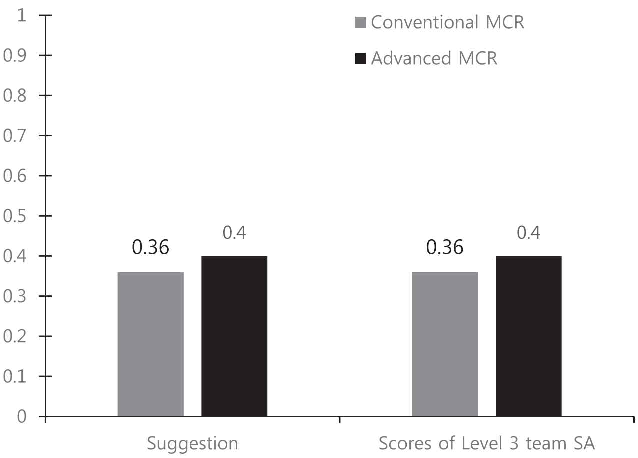

Fig. 12 – Comparison of the scores of the constituents of Level 3 team SA in a conventional and advanced MCR. MCR, main control room; SA, situation awareness.

4. Discussions and general conclusions

Generally, the average scores of the total team SA and each level of team SA in the advanced MCR were higher than those in the conventional MCR. This section discusses the results of increases or decreases of the constituent factors for each level of team SA, based on the observed operators' communications during the experiments.

For the increase in the number of communications regarding an "announcement" in an advanced MCR, it was observed that the senior reactor operator (SRO)'s communication, which tends to entail the reading of high-level step titles audibly so that other board operators can understand the goal, as well as to attempt to keep the crew synchronized by calling out important information for all board operators, contributed to an increased number of "announcements" in the advanced MCR. As operators in an advanced MCR can access information individually, the SRO was concerned with distracted attention with regard to the SRO's actions when performing the procedure. The SRO in the advanced MCR tried to draw other board operators' attention to the procedure to keep pace with the SRO's actions. This does not imply that the SRO in the conventional MCR did not have adequate communication regarding "announcement," but it appears that the difference in the number of communications was partly due to concerns raised over distraction of attention. The SRO in the advanced MCR exerted more efforts to keep other operators synchronized by communication regarding "announcement." In addition, it appears that the SRO attempted to announce the status of the plant to other operators more frequently, as the SRO in this case can gain access to the plant's information more easily than the SRO in the conventional MCR.

The capability of individual access to the information also contributed to the communication regarding "observation." As shown in the results, there were relatively few communications regarding "observation" in the advanced MCR. It was observed that communications to acquire new information were reduced, as the degree of accessibility to information by the operators has been changed. It was noted that the necessity to send new information to the SRO and to other board operators was reduced. Moreover, it appears that the atmosphere increased the SRO's concern over distractions.

Regarding "inquiry," the number of communications increased in the advanced MCR despite concerns that the SRO would not ask for information from other board operators. It was expected that the number of communications would decrease when the SRO is coping with an emergency situation using the CBP, because the CBP has functions that can directly provide information to the SRO. However, it was observed that the SRO in the advanced MCR still asked for information from the board operators to confirm what the SRO perceived from the CBP. This implies that the SRO had more opportunities to engage in communication regarding "inquiry" using other HSIs as alternative information sources to reassess the information. Moreover, checking all the substeps of the CBP so that the CBP can evaluate whether the higher-level steps are satisfied or violated contributed to an increase in the number of communications defined as "inquiry." It was observed that the SRO in the conventional MCR occasionally resolved and performed the substeps without communication with others when the SRO felt that the status of the plant was reasonable. However, the SRO in the advanced MCR had to check all the substeps with other board operators because the CBP requires all the substeps to be conducted.

For communications regarding "judgment," it is difficult to determine that it was higher in the advanced control room, because the average scores of the communication did not show a significant difference. This appears to be a result of the characteristics of the scenario used in this experiment. Although the emergency operating procedure requires the operator to diagnose the event, it does not require the operator's diagnostic process throughout the emergency operating procedure. It was expected that the results comparing the communication regarding "judgment" in these two MCRs would show more pronounced differences on the basis of scenarios describing abnormal situations. However, it was observed that the operating teams with the highest level of communication regarding "judgment" used multiple independent sources of information to support judgments of the situation.

A similar result was also obtained for the type of communication classified as "suggestion." As the scenario used in this experiment is relatively straightforward for the operators, the number of communications suggesting alternative actions or predicting the plant's status was not high. This implies that further experimental studies with abnormal situations need to be performed in order to assess the difference between the Level 2 and Level 3 team SA, which involves higher cognitive activity.

In conclusion, this study evaluated the effects of new HSIs that are implemented in advanced MCRs on human performance. To compare human performance, team SA is selected as a performance measure, as "SA" is frequently used in research on human factors to compare new design concepts, and insight can be gained with regard to human information processing during interactions with dynamic and complex environments. Moreover, the concept of "team" was considered, because a safe operation of the tasks at NPPs can be guaranteed through teamwork.

In general, team SA in an advanced MCR was relatively high, and the results from observations of the operator's communication during the experiment showed that an increase in the number of communications in the form of “announcement” contributed to the increased Level 1 team SA and Level 2 team SA in an advanced MCR. According to the definition of each level of team SA used in this study, an advanced MCR with new HSIs provides more information to operators and thus achieves greater Level 1 team SA. Based on this information, operators could achieve higher Level 2 team SA, which means that operating teams would have more situational knowledge for coping with emergency situations. As the event scenario used in this experiment does not place substantial demands on the operator's cognitive activities, a difference in Level 3 team SA, which requires the highest level of cognitive activity, was not clearly shown in this study.

Conflicts of interest

The authors have no conflicts of interest.

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