Empirical Study on Shared Situation Awareness among Operators in case of using an Active Group-view Display in Digitalized Control Room of Nuclear Power Plants

Sa Kil Kim*, Joo Hyun Sim, Tong Il Jang, Hyun Chul Lee
I&C and Human Factors Division, Korea Atomic Research Institute, Daejeon, Korea
**Corresponding author: sakilkim@kaeri.re.kr*

1. Introduction

In nuclear industry, human errors have been recently highlighted again after the recognition of the importance of the personal aspect as well as the system aspect in Fukushima accident [1]. The system side of the human errors still reveals the rooms to improve further not only the working environment, but also the management such as policy, personnel organization, reward and punishment, and education and training system, etc. The personal aspect of human errors has been mainly overcome by virtue of the education and training. However, in the system aspect, the education and training system needs to be reconsidered for more effective reduction of human errors affected from various systems hazards. Traditionally the education and training systems are mainly not focused on team skills such as communication, situational awareness, and coordination, etc. but individual knowledge, skill, and attitude. However, the team factor is one of the crucial issues to reduce the human errors in most industries [2].

In this study, we identify the emerging types of team errors, especially, in digitalized control room of nuclear power plants such as the APR-1400 main control room of Korea. Most works in nuclear industry are to be performed by a team of more than two persons. Even though the individual errors can be detected and recovered by the qualified others and/or the well trained team, it is rather seldom that the errors by team could be easily detected and properly recovered by the team itself. Note that the team is defined as two or more people who are appropriately interacting with each other, and the team is a dependent aggregate, which accomplishes a valuable goal [3]. Team error is one of the typical organizational errors that may occur during performing operations in nuclear power plants. In other words, team error is defined as human error made in team process [3]. Organizational errors sometimes increase the likelihood of operator errors through the active failure pathway and, at the same time, enhance the possibility of adverse outcomes through defensive weaknesses [4].

We incorporate the crew resource management as a representative approach to deal with the team factors of the human errors. We suggest a set of crew resource management training procedures under the unsafe environments where human errors can have devastating effects. Additionally, contingency guides and supporting tools are proposed for recovering the team errors in control room of nuclear power plants.

In general, there are three perspectives for human errors; individual, team, and organizational perspectives. According to the each human error perspective, different countermeasures are needed for reducing human errors because different factors accordance with those perspectives affect human errors as Fig. 1 [5]. So that the team errors should be considered with team perspective such as team decision-making, leadership & followership, shared situational awareness, shared mental model, team communication, team coordination, team spirit, etc.

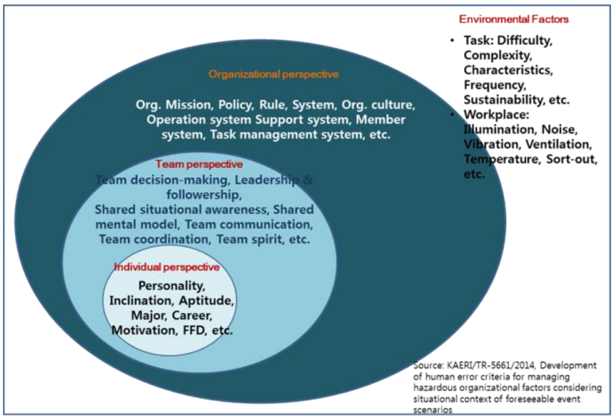


Fig. 1. Three perspectives for human errors

In the team perspective, team performance and effectiveness are the main topics to improve productivity and safety. However, team error has been dealt with one of the causes or performance shaping factors. Team error is recognized as a typical type of human errors also. Team performance is influenced by factors occurring not only at the team level but also at levels above and below such as culture, climate, individual performance, which can make it difficult to determine the root cause of a team failure [6]. Also, errors within teams can originate and manifest at both the individual and collective levels of analysis [7]. Bell and Kozlowski studied about the moderating influence of task interdependence on the relationship between individual and team error.

In nuclear industry, team error is a challengeable topic because most of human errors have been dealt as an individual failure or organizational failure. Recently as digitalized techniques are adopted in control room of nuclear power plants, new digital interfaces make new concerns relevance with team communication, shared situational awareness, etc. The new team error issues related with digital control room are following:

- Shared situational awareness among team members - Individual situational awareness could be better. However, shared situational awareness could be worse;
- Sensitive team stability - Fluctuating change in a team could make problems such as poor leadership, declined team learning;
- Shared mental model - Different mental models could be coexisting in a team due to multi-generations;
- Team communication - Low frequent communication among team members owing to difficult of the 'Face to Face' communication and change of operational concept;
- Shared task procedures - Team members could perceive different task procedure each other in case of using computer-based procedures;
- Leader's mental workload - Leader should obtain much more information in his or her workstation in order to confirm the plant situations, which are reported by team members.

To cope with the current issues, we determined the following strategic countermeasures through experts' brain storming;

- Shared situational awareness among team members: A group-view display is determined as a vital coping tool. One of the strategic countermeasures is to provide common cues in a group-view display to share the situational awareness among operators. For example, providing a temporal pop-up in the group-view display whenever someone controls a component or system or providing a temporal mark-up function to leader in the group-view display using such as air writing technology or laser pointing marking technology are the representative countermeasures.
- Sensitive team stability: A crew resource management (CRM) training program is determined as a vital coping tool. Providing a CRM training program is to enhance adaptation ability against team instability such as a team error management program, team-customized training program, or leadership paired followership training program.
- Shared mental model: A crew resource management (CRM) training program is determined as a vital coping tool. Providing a CRM training program is to enhance shared mental model and shared understanding such as making a shared space through team seminar and dialogue and role playing. Also, providing a joint CRM training program is to enhance each understanding.
- Team communication: A computer-based procedure system is determined as a vital coping tool. Providing communication steps in the computer-based procedure system is to facilitate team members' communication via essential steps to communicate with each other or confirming function into the communication steps. Also, providing a supervision display to team leader using web-camera is to make more complete communication among team members.
- Shared task procedures: A computer-based procedure system is determined as a vital coping tool. Providing confirmed or be active information in a computer-based procedure system is one of the countermeasures.
- Leader's mental workload: To reduce the leader's mental workload in the digital control room, a new staffing is necessary. Providing vice-leader to share the leader's mental workload is a vital resolution. A new vice-leader as a safety technical assistant is one of the countermeasures. Also, providing a supporting system to help critical decision-makings is one of the other resolutions.

As mentioned above, the digital-based control rooms of nuclear power plant have adapted to not only Korea nuclear industry but also other countries' it. This is because that digital information and configurations provide many well-known advantages to the operators in the control room. In the control room, advanced interface technologies such as large group-view display, soft-controller, computerized procedures, etc. were induced to realize more compact and safer control room. However, these new technologies were not proven in terms of human errors in nuclear industry yet so that many researchers have concerned about the unanticipated human errors in condition of using new digital interfaces. Especially, team errors in digitalized control room are emerging recently such as team communication, team decision making, team situation awareness, etc. A group-view display and computer-based procedure system have deep relationships with team errors because these interfaces are designed for not individual but team. This study aims to propose alternative human-machine interfaces (HMIs) in terms of team errors in the digitalized control room of nuclear power plants. So we proposed alternative HMIs to improve shared situation awareness using a group-view display in this study.

To develop alternative HMIs we found team error hazards in digitalized control room based on team error model; proposed countermeasures against team error hazards in terms of HMI; reviewed the derived countermeasures with operational experts; determined alternative HMIs according to review criteria for selecting new and advanced interfaces; finally, validated each interfaces in terms of shared situation awareness. To validate an improvement of shared situation awareness of the proposed HMIs, we measured true similarity of situation awareness among operators using the SACRI (Situation Awareness Control Room Inventory). For the comparative study, we prepared two types of group-view displays: one is active and the other is passive display. Operation experts of nuclear power plants are involved in the experiment.

2. Methods and Results

The active group-view display prototype was developed in order to cope with the team error expected in the nuclear control room where digital technology was applied. The prototype development process is shown in Fig. 2.

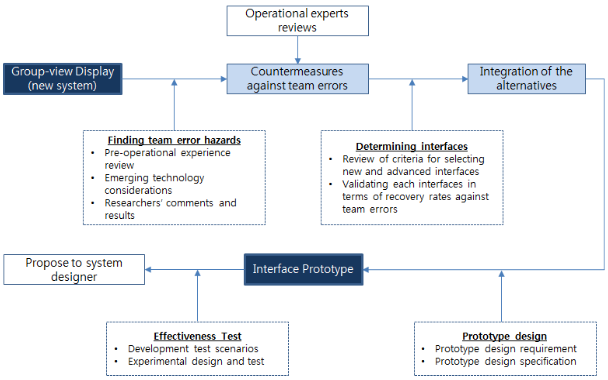


Fig. 2. Development process of active group-view display prototype

Firstly team error hazardous factors were derived based on the team error process. The team error process is based on the team error model introduced by Sasou and Reason (1999) (see Fig. 3). In order to eliminate or minimize the hazardous factors of team errors, we derived the countermeasures and confirmed whether the new features of the prototype are effective to reduce team errors or not.

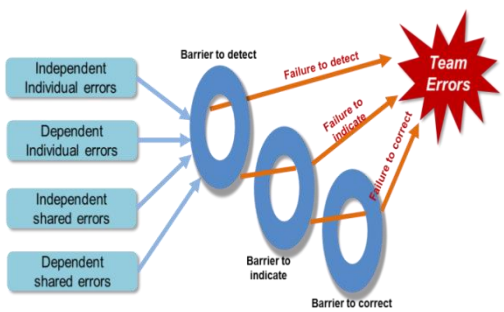


Fig. 3. Team error process model by Sasou & Reason

The developed unsafe scenarios were used for analyzing team error hazards and barriers for confirming the appropriateness of the new interface features. The new interfaces as barriers against team errors in a group-view display are following:

- Pointing and marking: On the group-view display, team leader can point an object and mark a line, circle, or text using a developed pointing and marking tool. Fig. 4 shows how to point and mark on a group-view display.
- Numeric directions: In case of a numeric value has a direction such as left, right, up, down, or right circulation, etc., the interface has a dynamic direction.
- Control state pop-up: Whenever someone controls a component or system, the control state will be displayed on the group-view display.
- Control history pop-up: In case someone wants to know what controls were performed, he or she can see the control history by pop-up display on the group-view display.

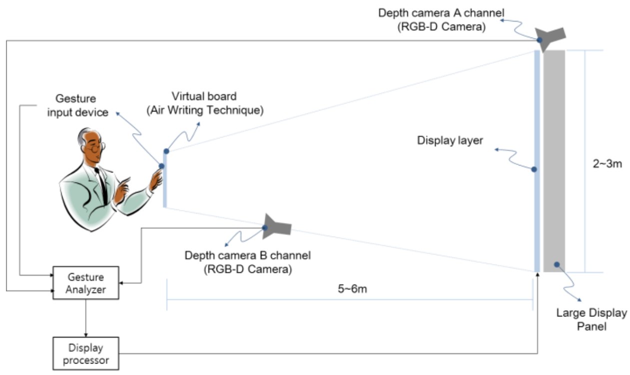


Fig. 4. Pointing and marking function on a group-view display

Lastly we performed an effectiveness test of the prototype in terms of communication and decision making failure as hazardous team error factors. This study focuses on the team situational awareness among nuclear power plant's operators because the team situation awareness aspect is important for communication and decision making. Team situational awareness is the degree of common awareness of situations that affect team members' effective goals.

We measured the degree of shared situation awareness among the subjects in terms of the difference between a passive and an active group-view display. The passive display is applied to the overview display existing commercial nuclear power plants. The active display adds pointing and marking interfaces to existing passive display so that operators can communicate with the active display and the additional information is actively provided on the screen. Therefore, we tried to verify the effectiveness of coping with the team error of the prototype developed through this study by comparing the passive type with the active type (see Fig. 5).

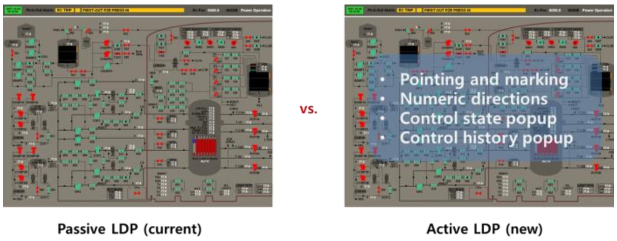


Figure 5. Passive and active group-view display

2.1 Participants

2.1.1 Subjects

The subject requirement of this test was limited to those who had at least 3 years of working experience in the nuclear power plant. In this test, a total of 3 subjects were composed of 3 persons and 1 subject, and a total of 9 subjects participated.

2.1.2 Test Simulator Instructors

The test simulator operator of this test was responsible for starting and stopping the test simulator, proceeding the test scenario, and solving the problem of the operation of the test simulator. The test simulator operator consisted of one test simulator expert who has more than 10 year-experiences in developing and operating the test simulator and two auxiliary operators who have experience in developing the test simulator for more than one year.

2.2 Apparatus

In this test, a CNS (Compact Nuclear Simulator) simulating Kori 2 was utilized. The CNS has the structure shown in Fig. 6.

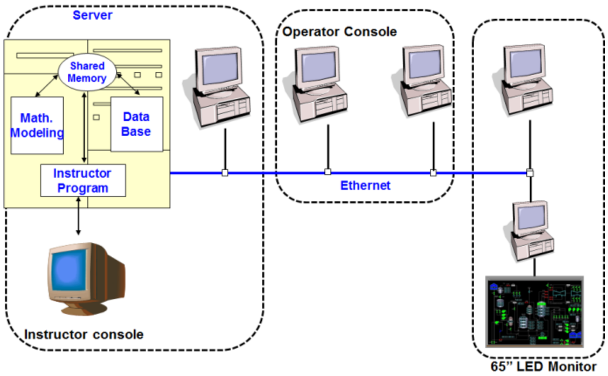


Fig. 6. Test signal simulation simulator structure

The instruction console has a text-based input function to simulate the test signal so that the scenario selected for this test can be set and stored and iteratively executed. In addition, the information display of the CNS simulate the control environment of the digital-based control room by providing digital-based information displays in the form of mimic information as shown in Fig. 7 and Fig 8.

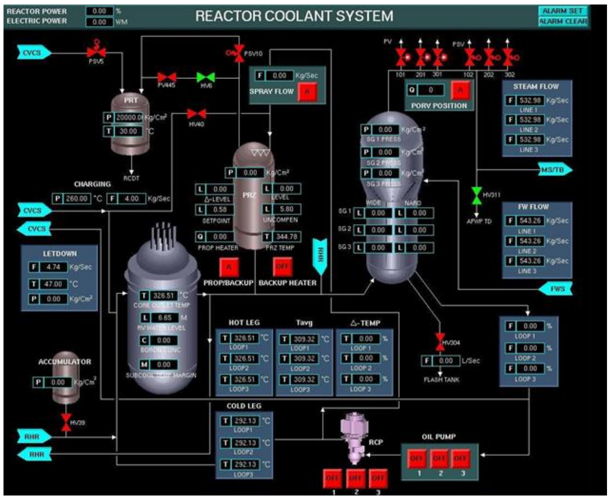


Fig. 7. Example of the Information Display

Fig. 8. Digital-based control room environment of test facility

2.3 Measurements and Tools

In this test, we tried to measure the situation awareness of the operator to evaluate the effectiveness of the human error coping effect. Especially, we tried to measure the team situation awareness - the degree of shared situation awareness among operators - in order to confirm the coping effect of team error.

The SACRI was used to evaluate situational awareness using questionnaires. The SACRI is a method that combines the SDT (Signal Detection Theory) to apply the SAGAT (Situation Awareness Global Assessment Technique, Endsley 1990) widely used in the aviation industry to the nuclear industry. The SACRI method applied in the original HRP (Handen Reactor Project) group is a method for objectively measuring the situation awareness of each operator only in the main control room of nuclear power plants. However, in this evaluation, only the similarity of the responses to the same evaluation items was measured for each pair of operators to measure the degree of sharing of the situation awareness among the operators. However, according to the SDT theory, 'False Alarm' or 'Miss' is neglected from the similarity analysis between the operators because it negatively affects the team situation awareness as a response that does not help each operator to recognize the correct situation. Sensitivity and response bias, which are essentially analyzed according to SDT theory, are not analyzed in terms of similarity of responses. This can be used to analyze the level of individual perception, but there is a limit to analyzing team situation awareness.

The SACRI questionnaire developed by HRP consists of the following three types of questionnaires regarding the current state, the present state relative to the normal state, and the near future state relative to the current state. However, in this evaluation, only the present state against to the near past state was evaluated based on the evaluation scenario due to the limitation of the evaluation facility.

- What is the current situation compared to the previous (   ) situation?
- Comparing the normal (   ) situation, what is the present condition?
- What is the status after the present (   ) situation?

On the other hand, situation awareness assessment using the SCARI should freeze the simulator and answer the question in a specific situation. However, there is a limit to perform the SACRI evaluation immediately after the point of using laser pen as a characteristic of the prototype which can affect the team error coping effectiveness of the active group-view display in this evaluation. This is because, in the context of the test scenario, the operator uses the laser pen to communicate with team members, make decisions, and determine the situation of the power plant. Therefore, even though the scenario was not completely terminated, the subject completed the scenario and performed the SACRI evaluation when it was judged that the subject fully understood the situation of the power plant.

Also, a video recorder was installed on the rear and left and right sides to record the test procedure and to maintain the reliability of the test procedure and to analyze the test results. The evaluation paper was coded using the MS Excel, and data analysis was performed using the SPSS 12.0 from SPSS Inc.

2.4 Test Scenarios

This test is a performance-based test limited to team performance among operators in the operation using a group-view display. It cannot satisfy the scenario requirements for human factors verification and validation of the NUREG-0711 regulatory guidelines. Therefore, scenarios suitable for the purpose and scope of the test were developed and used.

The scenarios used in this test considered the following scenario requirements to measure team situation awareness:

- The frequency of communication between team members shall be high.
- Gathering opinions from team members during decision making shall be included.
- Variation of variables shall be big.
- Multiple abnormal situations shall occur.
- Each scenario shall be performed within 10 ~ 20 minutes by operators.
- The number of scenarios shall be more than five.

The scenarios used in this test are as follows:

- S1: Leakages of reactor coolant into containment or into the secondary system, with areas up to 10% of the areas of a primary tube
- S2: Rupture of steam generator tubes
- S3: Main steamline break, nonisolable (inside)
- S4: Main steamline break, nonisolable (outside)
- S5: PRZ PORV stuck open

2.5 Test Design

This test was conducted in a total of 30 times (number of scenarios (5) × number of subjects (3 sets) × display types (2)) with randomized block design.

2.6 Analysis method

The team situation awareness was analyzed through team similarity analysis of responses to each question of the SACRI. The difference of team situation awareness through SACRI was verified by comparing the shared situational awareness through similarity of SACRI item response in the passive and active display. Here, True Shared SA (TSA) excludes 'False Alarm' and 'Miss' among the shared situation awareness among operators. The sharing of the misunderstood situation among the team members is the situation that the individual misunderstood in the subjective evaluation of the personal situation awareness so that the team has a negative point that can be measured positively. This is a reason that it recognizes the team situation and it is excluded because it can cause team error. In other words, sharing information among team members about misunderstood situations is a crucial factor that can cause team errors, so it must be controlled to evaluate the effectiveness of team error countermeasures.

A method of analyzing the degree of the shared situation awareness through the similarity of the responses to the same SACRI items between subject 1 and subject 2 by the TSA will be described as an example.

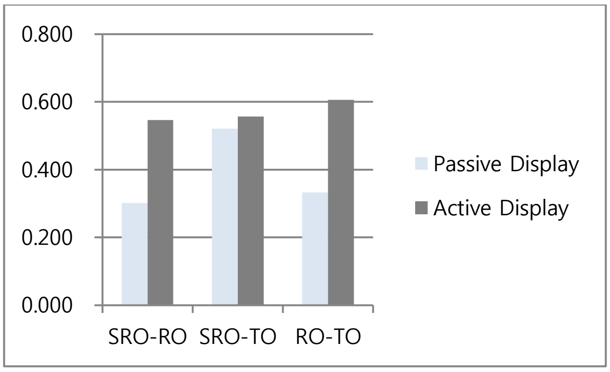
- Subject 1: S_1
- Subject 2: S_2
- SACRI question: Q_1 to Q_{10}
- SACRI response: R_1 to R_{10}

- Similarity of R1(S_1- S_2)= 1- absolute value of [(S_1 R_1- S_2 R_1) / (S_1 R_1+ S_1 R_1)]
- Mean of similarity = (Sum (Similarity of (S_1- S_2) from R_1 to R_{10})) / 10
- Inflated Shared SA = Mean of all items similarity scores
- True Shared SA = (Mean similarity) × (Shared Accuracy)
- Shared Accuracy = 1- Square Root of [(S_1R_n Deviation Proportion)^2 + (S_2R_n Deviation Proportion)^2]

2.7 Test Results

First, the difference between passive and active group-view display was analyzed as a pair of the participant in the test. Here, the operator pair means the configuration of SRO-RO, SRO-TO and RO-TO, and verified the difference in team situation awareness between passive and active for each operator pair.

Table 1 and Fig. 9 show the validation results according to each operator pair.



SRO: Senior Reactor Operator; RO: Reactor Operator; TO: Turbine Operator
Fig. 9. T-test results

As shown in Figure 9, the difference in team situation awareness between SRO-RO and RO-TO was statistically significant. However, the difference in team situation awareness between SRO-TO was not revealed. Therefore, it can be said that active group-view display positively affects the team situation awareness at least between SRO-RO and RO-TO.

3. Conclusions

In this study, we developed a prototype by adding pointing and marking interface to active group-view display. The prototype was developed through analysis of team hazardous factors and preventive measures against countermeasures according to the team error process. Also, the effectiveness test was performed to confirm the effect of the countermeasures against team errors on the developed prototype. The effectiveness test is aimed to confirm that the expected team error according to the team error mechanism is prevented according to the interface characteristics of the prototype. The team situation awareness was measured and the degree of shared situational awareness among the subjects participating in the test was validated by the difference between the active and the passive type. Team situation awareness was performed by analyzing the similarity of situation awareness among team members, and only team similarity in terms of team purpose was considered as team situation awareness. This is because, in terms of effect of countermeasures against team error, elements that do not match the team goals (e.g., 'False Alarm', 'Miss') can contaminate team performance.

As a result of the effectiveness test, it was analyzed that the team situation awareness between the main positions (SRO, RO, TO) of operators differs according to the characteristics of the information display interface of active and passive type. In other words, it was analyzed that the active group-view display positively influences the team situation awareness than the passive type. As a result, it is believed that the use of active group-view display is effective to prevent team error based on scenarios and based on the team error mechanism by improving the team situation awareness among operators relatively more than when using passive type. However, there was no statistically significant difference between the SRO and the TO according to the types of display. This result is related to the fact that the operation of the nuclear power plant is concentrated on the interface between the SRO and the RO. In particular, the reactor trip scenario only used in this test is one of the test scenarios. However, in the emergency situation, the interaction between the SRO and the RO is relatively higher than the interaction between the SRO and the TO.

This study is intended to suggest a tool to cope with human error through interface improvement using a group-view display as one of the countermeasures against the team error. However, human errors expected in the digital control room should be addressed through a systematic analysis of various interfaces such as a computer-based procedure, a digital alarm indicator, and a mimic-based information display as well as group-view displays.

Acknowledgements

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Table 1. T-test results of each pair

	Differences					t	Degree	P-Value
	Mean	Std. Deviation	Std. Error	95% Reliability				
				Lower	Upper			
Passive SRO_RO[1)] – Active SRO_RO	-.245217	.459665	.095847	-.443991	-.046443	-2.558	22	.018
Passive SRO_TO – Active SRO_TO	-.049043	.481051	.100306	-.257065	.158978	-.489	22	.630
Passive RO_TO – Active RO_TO	-.273304	.480163	.100121	-.480943	-.065666	-2.730	22	.012

[1)] SRO: Senior Reactor Operator; RO: Reactor Operator; TO: Turbine Operator