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Original Article

The effect of communication quality on team performance in digital main control room operations

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ABSTRACT

A team of operators is required for nuclear power plant operation, and communication between the operators is an important aspect of the team's ability to successfully carry out tasks. It has been difficult to evaluate the quality of this communication though, and as the relationship between communication quality and team performance has yet to be clarified, it has not been applied to most human reliability analysis (HRA) methodologies. This study investigates the relationship between the quality of communication and team performance using data from a full-scope training simulator of a digital main control room (MCR). Two important characteristics of communication were considered to determine quality: each operator's ability to self-confirm the status of a given task in a digital MCR, and the type of communication, as divided into 1-way, 2-way, and 3-way between operators. To measure team performance, the concept of an unsafe act was employed, which is defined as a human error that has the potential to negatively affect plant safety. Analysis results showed that the communication quality and team performance were related to each other. With this more clearly defined relationship, the results of this study can be applied to related performance shaping factors to improve HRA.

1. Introduction

Probabilistic safety assessment (PSA) is commonly used to determine the level of safety of nuclear power plants (NPPs), with PSA-based risk information employed in regulation, operation, and management. Through PSA, NPPs must satisfy a quantitative safety value for core damage frequency, and one of the dominant contributors to this critical factor is human error. To quantitatively and qualitatively evaluate human error, human reliability analysis (HRA) has been adopted, which assesses the performance of operators as part of PSA [1]. There are various HRA methods to analyze human error, including THERP, HEART, and CREAM [2–4]. According to the particular method, human error probability (HEP) is obtained through various performance shaping factors (PSFs), which are related to the various conditions in the environment in which operators perform their tasks. As PSFs affect the tasks of the operators, and therefore HEP, they are the subject of ongoing research [5].

Reducing human error often derives from supporting an individual's ability to improve their performance. However, NPPs are too complex to be managed by one such individual, and as a result, operation is controlled by a team composed of various members. The performance of this operation team is influenced by various factors, one of which is the communication between the operators. Especially in an emergency situation, smooth communication among operators is an essential factor for proper accident management [6,7]. Beyond the nuclear industry, communication research has been conducted in a variety of fields. For example, more than 70% of the 28,000 reports submitted to the NASA Aviation Safety Reporting System over five years from 1976 to 1981 involved communication problems between pilots and air traffic controllers [8]; likewise, in the rail industry, most accidents involving rail repair and maintenance resulted from communication problems [9]. One study analyzed the relationship between communication and team performance for air defense teams [10]. As indicated by these studies, the impact of communication quality on team performance should be better explored with the goal to reduce human error.

Despite the importance of communication, as shown in Table 1,

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Table 1
Summary of PSFs according to HRA method [13].

CREAM	STAHR	HRMS	INTENT
Adequacy of organization	Quality of information:	Time	HMI[b]
Working conditions	−Design	Quality of information/interface	Stress
Adequacy of MMI[a] and operational support	−Meaningfulness of procedures	Training/Expertise/Experience/Competence	
Availability of procedures/plans	Organization:	Procedures	Experience
Number of simultaneous goals	−Role of operations	Task organization	Safety culture
Available time	−Teams	Task complexity	Training
Time of day	Personal:		Motivation
Adequacy of training and preparation	−Stress		Workload
	−Morale/motivation		Supervision
	−Competence		Communication
			Procedures
SLIM	**ATHEANA**	**INCORECT**	**Taylor-Adams'**
Quality of design	Plant conditions	Time availability	Alarms
Meaningfulness of procedures	Procedures	Plan availability and accessibility	Communication
Role of operations	Training	Information availability and accessibility	Ergonomic design
Teams	Communication	Simultaneous tasks	HMI[b] ambiguous
Stress	Supervision	Decision-making criteria	HMI[b] feedback
Morale/Motivator	Staffing	Response dynamics and system coupling	Labels
Competence	Human−system interface	Supervision	Lack of supervision/checks
PLG-SLIM	Organizational factors	Capability degrading factors	Procedures
Plant interface and indications of conditions	Stress	Teamwork and social factors	Refresher training
Significant preceding and concurrent actions	Environmental conditions	Organizational factors	Stress
Task complexity			Task complexity
Procedural guidance			Task criticality
Training and experience			Task novelty
Adequacy of time to accomplish action			Time pressure
Stress			Training
Other			Workload

[a] MMI: man−machine interface.
[b] HMI: human−machine interface.

while the INTENT [11], ATHEANA [12], and Taylor-Adams' HRA methods used in NPPs include communication as a PSF, communication is not considered in the more commonly used methods THERP, HEART, and CREAM [13]. Through the current study, the relationship between communication quality and team performance is investigated. Applying the results to PSFs may provide more reliable HEP to improve HRA accuracy.

2. Definition of communication methods

In Korean NPPs, the operation team consists of five members who work to achieve safe operation from the main control room (MCR). They are the shift supervisor (SS), reactor operator (RO), turbine operator (TO), electrical operator (EO), and shift technical advisor (STA). The RO, TO, and EO are also referred to as board operators (BOs). In an emergency situation, the operators follow a procedure called the emergency operation procedure (EOP) to mitigate the accident consequences and prevent the leakage of radioactive materials. The EOP, provided in the form of a series of steps, describes guidelines for the equipment and systems that require operation to restore safety-critical functions [14]. During emergency operation, the SS looks at the procedure and asks the related BO for the current plant status. Also, the SS instructs the BO to carry out the required action. As such, communication led by the SS is critical. Especially in emergency situations, the steps of the EOP are performed in sequence with the decisions required by all steps depending on the SS. Further, the beginning of most team communication is initiated by the SS, and the BOs accordingly respond to the direction and needs of the SS. Such communication occurs between the operators in order to complete the tasks of the procedural steps to stabilize the NPP.

The specific types of communication in the MCR can be divided into 8 main categories—*Call, Inquiry, Command, Suggestion, Observation, Judgment, Announcement,* and *Acknowledgement*—and 18 subcategories [15], all of which are arranged in Table 2.

The situation of the plant is recognized and shared among operators mainly through the *Observation*, *Suggestion*, *Judgment*, and *Announcement* communication types. Specific actions are considered and decided upon among operators by the *Inquiry* and *Reply* types, and performance of the procedural tasks is conducted via the *Inquiry* and *Command* types. In this study, communication is analyzed based on the performance of a procedure; as all procedural steps are performed using *Command* and *Inquiry*, other communication types such as *Observation*, *Suggestion*, and *Judgment* apply to the performance of additional tasks. As a result, the communication types of *Inquiry* and *Command* are the main focus of the present analysis.

Different forms of communication are involved with all communication types. Fig. 1 shows three forms between the MCR operators; here,1-way communication refers to a single statement by the SS with no reply from the BO, 2-way refers to a BO reply to the initial SS statement, and 3-way refers to further acknowledgement and confirmation of the BO's reply by the SS. In an emergency situation, 3-way communication is recommended to decrease human error. In this manner, this work defines communication quality depending on its form, with 3-way considered high-quality communication as compared with 1- and 2-way.

As also pictured in Fig. 1, there is a new characteristic of digital MCRs as compared to conventional analog MCRs, which is the ability of the SS to individually verify the status of the plant through such digital equipment as the computerized procedure system (CPS), large display panel (LDP), and the information flat-panel display. This verification is called "self-confirmation" and allows the SS to perform procedural tasks by observing the variables alone, thus affecting MCR communication.

Table 2
Communication type and definition [15].

Category	Subcategory	Definition	Example
CALL	Call	Call to a specific person for communication	"RO"
	Response	Respond to the Call.	"This is the RO speaking"
	Call-Identification	Caller responds to the receiver's self-identification	"This is the EO"
	Call-Id-Acknowledgement	Receiver responds to the caller's self-identification	"OK"
INQUIRY	Inquiry	State a question	"Is the vacuum valve open?"
	Reply	Answer the question	"Yes, the vacuum valve is open."
	Reply-Ack	State that the reply was received	"OK"
COMMAND	Command	Specifically order an action to manipulate an object	"Close valve V202″
	Command-Ack	State that the command was received	"OK. I'll close valve V202″
	Command-Confirm	Confirm that the command was successfully received	"OK"
SUGGESTION	Suggestion	State a recommendation for a specific action or an introduction of an idea for consideration	"Should we try to start the charging pump?"
OBSERVATION	Observation	State a description of plant or equipment status	"The water level of the steam generator is increasing."
	Observation-Ack	State that the observation was received	"OK"
JUDGMENT	Judgment	Express a judgment of the situation	"Trouble is occurring because of low pressure of the vacuum pump."
	Judgment-Ack	State that the judgment was received	"OK"
ANNOUNCEMENT	Announcement	State information about something that happened or that will happen to the plant workers	"Attention please. EDG B will be started due to a scheduled maintenance. Three, two, one, go"
	Announcement-Ack	State that the announcement was received	"OK"
ACKNOWLEDGEMENT	Acknowledgement	State that any message was received	"OK"

3. Data collection and analysis

3.1. Scenario and data collection

The emergency situation chosen for analysis was a steam generator tube rupture (SGTR) accident. In the event of SGTR, there is a risk of radiation leakage due to the fracture of a steam generator, and the core, as the most important part of the NPP, can be damaged. Operators follow the relevant EOP to minimize any leakage of radioactive material from the steam generator(s) and also to cool the core using a cooling system [16].

To collect data, there are three major HRA data sources. The first is various types of accident reports reflecting actual operating experience, the second is experimental data using a full-scope or compact scope training simulator, and the third is crew or expert interviews [17].

The current study was performed using data from a full-scope training simulator of the Advanced Power Reactor 1400 MWe (APR1400), which is a Korean-type pressurized water reactor. The MCR of this NPP is equipped with digital technology. Digitalized MCRs are typically designed to incorporate LDPs, soft controls (SCs), computer displays, touchscreens, and computerized operator support systems like an advanced alarm system and a CPS [18]. The MCR environment of the APR1400 therefore differs from conventional MCRs, and various studies are currently underway to analyze the effects of the digital features [19].

During emergency situation training, the behavior and communication quality of the operators were analyzed using microphones and video recordings. Communication quality and team performance were analyzed using the accident simulation data from a total of nine different operator teams. Among the various PSFs (Table 1), this study considered the following common factors: operating experience of the SS, average operating experience of the team, digital MCR familiarity of the SS, average digital MCR familiarity of the team, stress, training experience, MMI quality, and procedure quality. The latter four were similar among all teams: the accident training scenario is an emergency situation such that each team had a high level of stress, all teams had prior training experience in the SGTR scenario, and the same MMI and CPS were used. The other four PSFs varied between teams, as shown in Table 3.

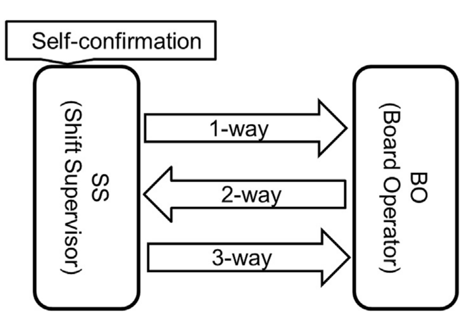

Fig. 1. Communication forms in digital MCRs.

3.2. Analysis method

In order to evaluate team performance, it is necessary to analyze all human errors that occur during the performance of the task. First, the concept of human error should be established. In some cases, the operator intentionally does not perform the task as required by the procedure; such intentional procedural non-compliance was observed in the simulation data of this study. In this case, it was difficult to conclude whether or not the action should be regarded as human error, because some non-compliances resulted in a safer plant condition. Experienced operators often tend to modify procedures, such as attempting to omit repetitive tasks or changing the order of tasks presented in the

Table 3
PSF level information for each team.

	SS operating experience (year)	Team average operating experience (year)	SS digital MCR experience (year)	Team average digital MCR experience (year)
Team 1	25	8.6	6	4.6
Team 2	29	12.8	5	4.5
Team 3	20	9.3	5	4.9
Team 4	32	10.8	7	5.6
Team 5	20	6.5	0	1.3
Team 6	25	10.2	2	2.4
Team 7	30	10.8	2	2.2
Team 8	30	9.1	2.8	4.5
Team 9	20	11.8	5	5.8

Table 4
Example of analysis method [24].

Step	Contents	Communication Quality	Unsafe Act
1-1(1)	Verify that the reactor power is decreasing	Self-confirmation	X
1-1(2)	Check whether the startup rate is negative	3-way	X
1-1(3)	Check that the control rods are fully inserted	2-way	O
1-1(3)-RNO	Boric acid is injected into the reactor coolant system (RCS) to ensure shutdown margin	–	–

procedure [20]. For example, when the SGTR occurred, one team immediately isolated the steam generator upon obtaining information about the rupture, regardless of the order of the procedure. Therefore, rather than using the procedural steps to determine team performance, this study focused on unsafe act (UAs), which are defined as human error that has the potential to negatively affect NPP safety [21–23]. Operator behavior in terms of UAs was thus observed and analyzed from the simulator data.

Table 4 shows an example of the analysis process. Operators perform a given task in the accident scenario step by step, and the communication quality during the task is monitored with UAs determined. As a first example, the conversation and behavior of operators in the 'Check whether the startup rate is negative' task (Step 1-1 (2)) were analyzed. The SS asked the RO: "RO, is the startup rate negative?" The RO replied to the SS: "Yes, it is negative." The SS then confirmed the answer: "OK. It is negative." In this case, the communication form was 3-way, and a UA did not occur because the startup rate was negative and the RO executed the proper action. As a second example, the conversation and behavior of operators to perform the 'Check that the control rod is fully inserted' task (Step 1-1 (3)) was analyzed as follows. The SS asked the RO: "Are the control rods fully inserted?" The RO replied to the SS: "Yes." The conversation finished at this point, but the actual situation reflected that three control rods were not fully inserted. Thus, the RO reported the wrong information to the SS, who did not confirm the task. As a result, operators were not able to conduct the 'Boric acid is injected into the reactor coolant system (RCS) to ensure shutdown margin' task that they had to perform. In this case, the communication quality was 2-way, and a UA occurred. All tasks were analyzed accordingly.

4. Communication quality effect analysis

This study analyzed team performance and communication quality in a digital MCR. Video was analyzed of the SGTR scenario using full-scope simulation data from nine teams comprising SS, RO, TO, EO, and STA members. The concept of UA was applied as an evaluation factor of team performance; that is, teams with high performance committed fewer UAs during the emergency situation. Team performance was evaluated by dividing the number of UAs by the number of procedural steps; it should be noted that as the number of procedural steps increase, the possibility of UAs increases. The communication forms were 1-way, 2-way, and -way, with the additional self-confirmation ability of the SS to check the steps in a digital MCR. High levels of communication quality were considered to include mostly 3-way communication.

In addition to communication quality, this study also analyzed other PSFs. Figs. 2 and 3 show the analysis results of team performance according to the operating experience of the SS and of the team, respectively. Since the SSs of all teams had more than 20 years of experience, SS operating experience did not affect team performance in this study; likewise, with no clear trend, team operating experience also had no effect on team performance.

Additionally, the digital MCR experience PSF was also analyzed. As shown in Figs. 4 and 5, there was no relationship between this PSF and team performance, and thus it can be said that digital MCR experience, like operating experience, did not affect team performance in this study. With these results, and the fact that the remaining PSFs, namely stress, training experience, and procedure quality, were the same for all teams as discussed previously, the analysis results focusing on communication quality are believed to be more meaningful.

Fig. 6 shows the ratios of 1-way, 2-way, and 3-way communication along with self-confirmation. The two largest proportions were 2-way and self-confirmation at 55% and 23%, respectively. In the emergency situation, the operators tried to deal with the accident by quickly going through the procedure, which was facilitated by 2-way communication and self-confirmation as faster

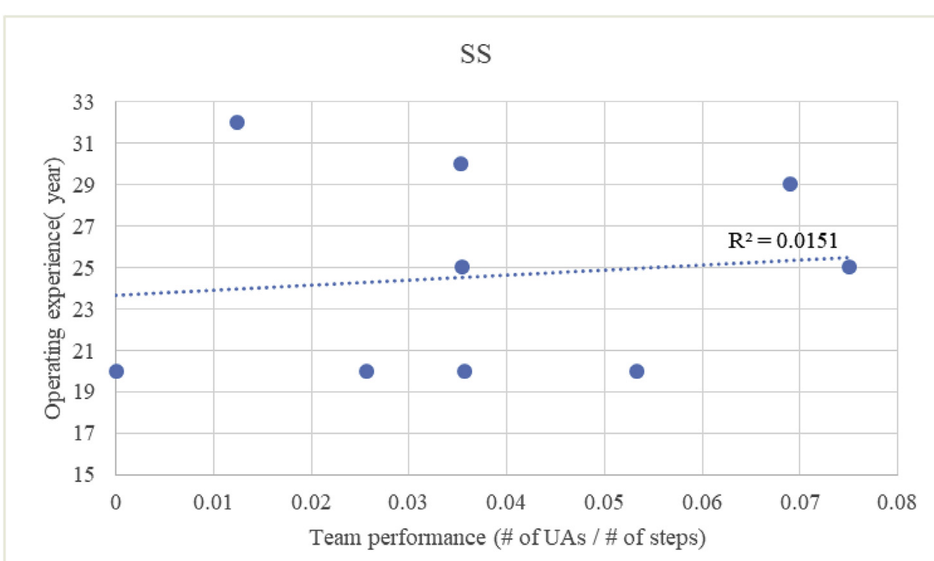

Fig. 2. Team performance by SS operating experience.

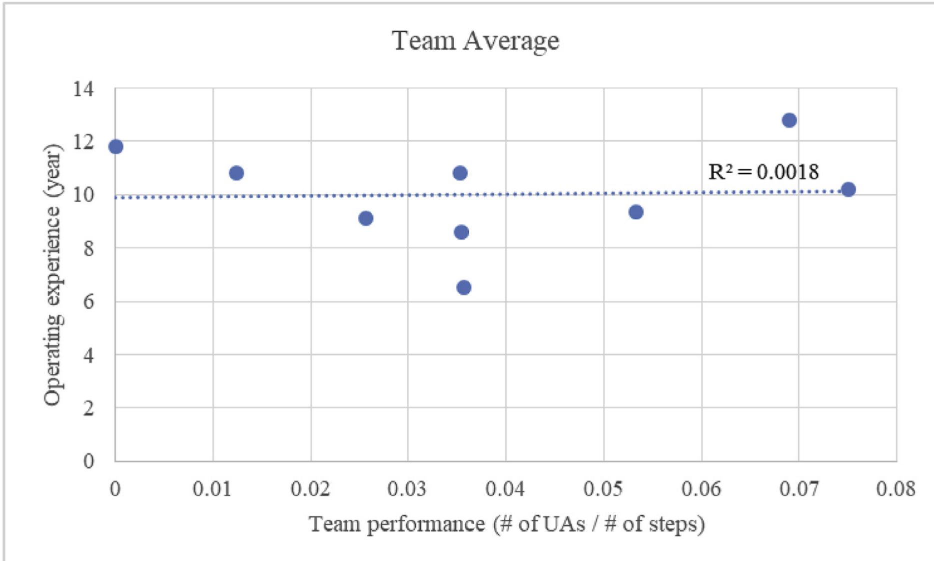

Fig. 3. Team performance by team average operating experience.

forms than 3-way communication. Thus, following the tendency of the teams for quick procedural execution, 3-way communication was observed less frequently, at 18%. The lowest proportion was 1-way communication, which at 4% was only observed during changes between procedures.

Fig. 7 illustrates the relationship between communication quality and team performance. In this study, the higher the 3-way communication ratio, the higher the communication quality, which, as shown in Fig. 7, affected team performance. As team performance is based on the number of UAs per number of procedural steps, team performance was considered high when the number of UAs per steps was low. Taken together, higher communication quality led to higher team performance.

Fig. 8 depicts the ratio of communication forms in the tasks in which UAs occurred. Results of the analysis excluded the UA cases of procedural omissions and BO operational errors that were not related to communication. Here, the ratio of 3-way communication is the smallest. This supports the finding that active 3-way communication improves team performance.

5. Discussion and conclusion

Nuclear power plants are operated by teams rather than by individuals, and therefore communication between operators is essential. This study analyzed the impact of communication quality on team performance. Data recorded from an emergency training situation were utilized for a total of nine teams in a digital MCR. In an emergency situation, the SS directs the other operators using the relevant procedures to deal with the accident; this study classified three forms of communication between the team, with 3-way determined to indicate high-quality communication. Team performance was evaluated via the number of UAs.

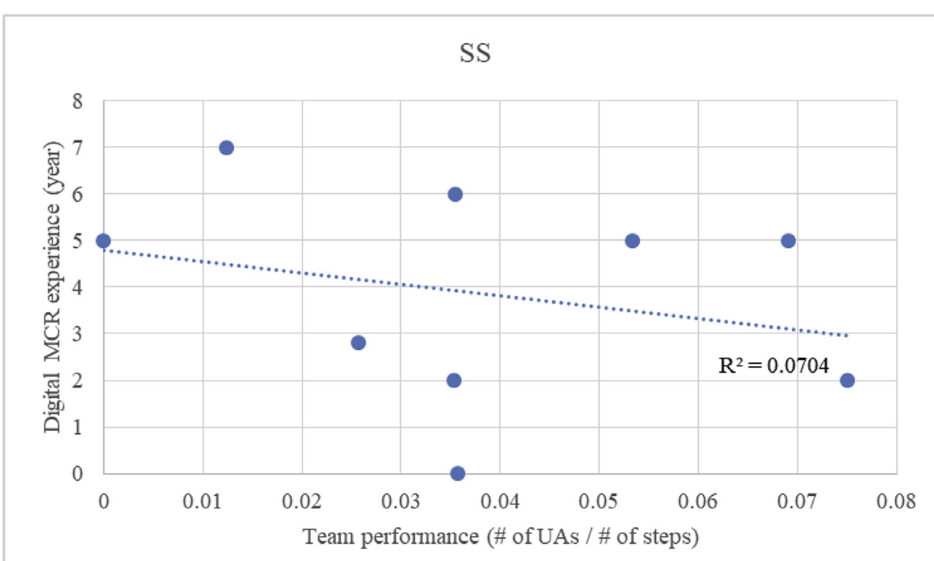

Fig. 4. Team performance by SS digital MCR experience.

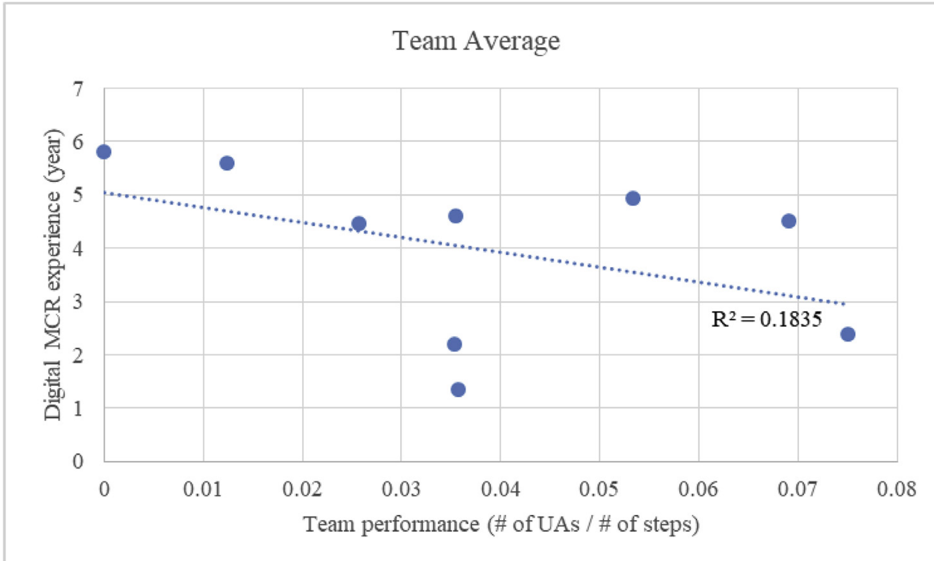

Fig. 5. Team performance by team average digital MCR experience.

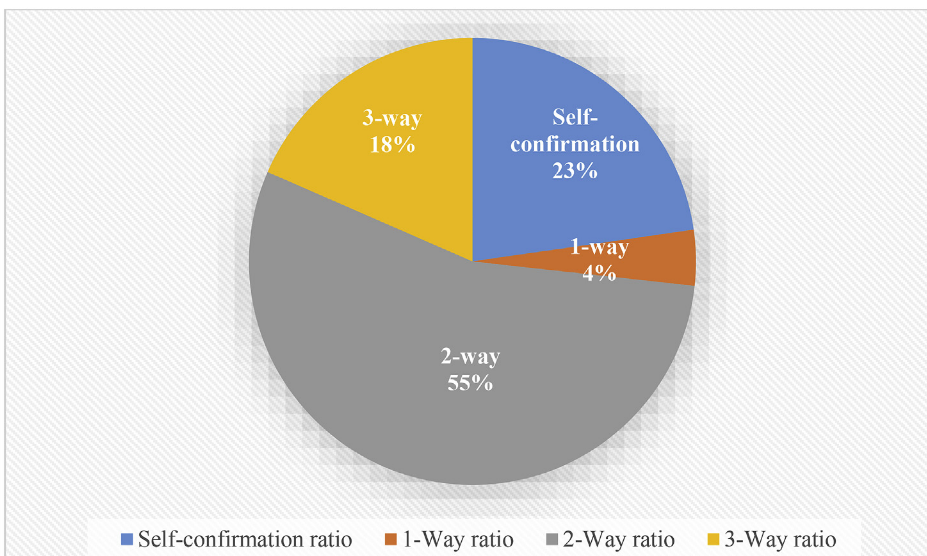

Fig. 6. Ratio of communication forms.

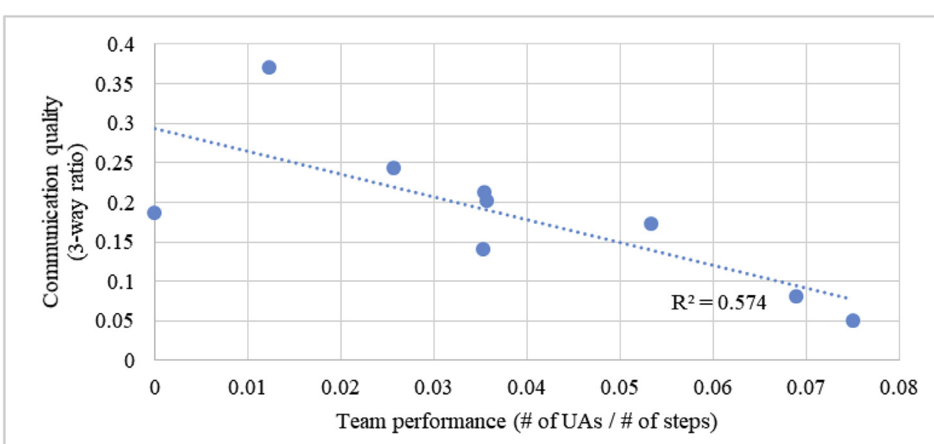

Fig. 7. Team performance by communication quality.

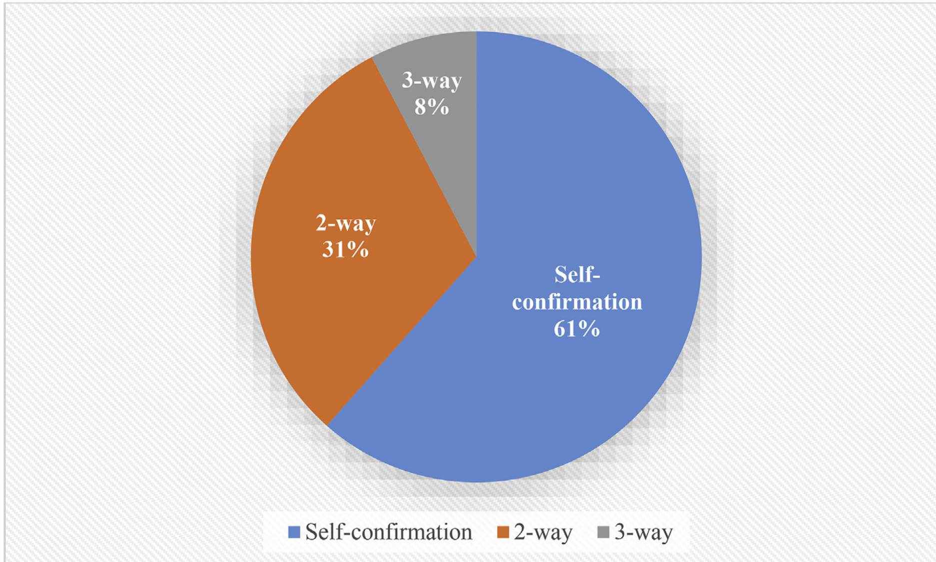

Fig. 8. Communication form observed during UA occurrence.

The following issues from this study should be addressed.

- ✓ Habitual responses, such as a simple acknowledgement without actual confirmation, are reflected in the analyzed 3-way communication cases. For example, although one SS checked the plant state via 3-way communication, a UA still occurred, possibly because the 3-way communication was a simple habitual response rather than an actual confirmation. Further analysis is needed to clarify such habitual 3-way communication.
- ✓ This study analyzed only the SGTR scenario; more scenarios and data analysis will lead to more reliable results.
- ✓ The digital MCR environment, in terms of information sharing and manipulation, differs from analog MCRs. As this study focused on the digital environment, comparative analyses with communication studies in analog MCRs are necessary, as numerous NPPs with analog MCRs are still in operation and thus could benefit from improved HRA.
- ✓ Operations teams recovered most of the UAs by repeating particular procedural steps or by operators recognizing the errors and recovering them. However, recovery was not considered in this study.

The communication quality results as found in this study are believed to be reliable, as the other PSFs considered here, such as operating experience, did not affect team performance. Notably, one factor though that seemed to affect communication quality was the speed of the team in conducting their tasks. To perform the procedure quickly, 2-way communication and self-confirmation occupied the largest proportion of communication. While it is important for the team to promptly perform procedures, accuracy is more important. Thus, operators need to increase the ratio of 3-way communication to improve team performance, as indicated by Fig. 8, which shows that UAs hardly occur with 3-way communication. In addition, this figure suggests the vulnerability of the self-confirmation characteristic, with its high percentage of UAs. Most HRA methodologies do not have a weighting factor based on communication quality when deriving HEP; through this study, it was found that communication quality affects team performance, thereby indicating that a weighting factor for communication quality is needed when deriving HEP to ultimately improve HRA.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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