EXPERIMENTAL STUDY ON TEAM COORDINATION OF NPP PLANT OPERATORS BASED ON THE SIMULTANEOUS NIRS MEASUREMENTS

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ABSTRACT

One of the key features when dealing with severe situations far beyond the previous experiences and expectations is the coordination capability among operators with different roles. In this study, the feasibility of estimating coordination capability of nuclear plant operators has been examined based on the correlation analysis of brain activities among operators. The cognitive experiments have been performed in the full scope NPP simulator at BWR Operator Training Center Cooperation. Four experienced instructors participated in the experiments. They played different roles such as shift supervisor, turbine operator, reactor operator and auxiliary operator and were instructed to go through four training scenarios shown below with NIRS devices attached. The brain activity of each operator has been measured along with the progress of anomaly events and the correlation of brain activities for every pair of operators have been calculated. The correlations of brain activities have also analyzed focusing on the specific events along with the progress in the anomaly scenarios. It has been shown in the results that the higher correlation among all operators were observed when the global events occurred and the higher correlation among specific pair of operators related to the specific event were partially observed.
Key Words: NPP operator, coordination capability, severe accident, simulator, brain activities

1 INTRODUCTION

The nuclear accident at the Fukushima Daiichi nuclear power station (1F) on March 11, 2011 was caused by the Great East Japan Earthquake. Although the integrity of the power station had been maintained immediately after the earthquake owing to the designed safety features, the tsunami that followed the earthquake caused a station blackout, resulting in the lack of cooling. This was a type of an "unexpected event" for the operators who were at the site. Despite the enormous effort to recover the cooling function, the plants deteriorated and a large amount of radiation was released into the atmosphere, causing the evacuation of the people living near the site. After this disaster, all nuclear power stations in Japan were

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shut down, and to realize a higher level of safety against the largescale disaster, a new regulation standard for a nuclear power safety plan has been established. The new regulation requires nuclear power plants to manage a wider range of natural events such as a tornado, volcanic eruption, an earthquake, and a tsunami [1]. This new regulation focuses not only on the revision of the hardware safety system against these events but also refers to the required ability of the operator to handle a wider range of events. Although the plants approved by the new regulation will certainly become much safer against expected events, the possibility of events occurring beyond our expectation always remains. We believe that the role of the human operator with an adaptive capability is the key to dealing with such situations [2].

One of the key features when dealing with severe situations far beyond the previous experiences and expectations is the coordination capability among operators with different roles. The enhancement of this coordination capability is one of the target of operator training at the operator training center. However, it is rather difficult to evaluate the coordination performance based merely on the superficial observation during the training runs. Although subjective measures based on questionnaire and discussions are utilized to indirectly evaluate the state of coordination in the current training programs, they may be insufficient to evaluate the essential coordination at the human cognition level. Therefore, the objective and quantitative method for the evaluation of coordination of cognitively-demanding tasks is required in order to improve the effectiveness of coordination among operators facing severe situations.

Along with the significant advances in brain measurement technology and evaluation methods, it has become feasible to evaluate human cognitive activities based on the methodology of human brain mapping [3,4,5,6]. In the present study, the technique of functional NIRS (Near Infrared Spectroscopy) has been adopted to the evaluation of cognitive states of plant operators. As the NIRS device utilized in the present study is ultra-small and light one, the burden on the subjects and the limitations concerning the measurement are quite small. Furthermore, the simultaneous measurement of multi-subject is possible using the NIRS devices, which enables us to perform the analysis of correlation of brain activities among subjects. In our previous study, it has been confirmed that the level of correlation of brain activities among subjects can be the indication of some kind of coordination. In this study, the feasibility of estimating coordination capability of nuclear plant operators has been examined based on the correlation analysis of brain activities among operators.

2 METHOD

2.1 Measurement of Brain Activity

The ultra-small portable NIRS devices have been utilized, by which the distance correlation of brain activities between two subjects communicating has been calculated. Fig.1 shows the ultra-small single channel wireless NIRS device (HOT05) developed in the joint project of Tohoku University and HITACHI Ltd. funded by JST. The specific feature of this NIRS device is its two photo-diodes (2PD) measurement method, which enables to reduce the effect of skin blood flow. Two different wave lengths (695T 20nm and 830T 20nm) are used by the system, and its frequency is modulated for wavelengths and channels to prevent crosstalk. Reflected light (not absorbed) leaving the tissue is received by the photodetectors and transmitted into a set of lock-in amplifiers, which are limited to the particular frequencies of interest. Both wavelengths are used for estimating changes in oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) based on the measurements. In this study, the NIRS was set at the center of the forehead, where activity from the medial aspect of the prefrontal cortex can be measured.

2.2 Estimation of Empathy between Specific Operators

Another specific feature of this NIRS devices is its simultaneous and synchronized measurements of up to twenty subjects, which enables evaluation of similarity of the brain activation patterns among subjects. In our previous study, it has been confirmed that the level of correlation of brain activation patterns between two subjects has positive relationship with the quality of communication [7,8,9]. In the present study, brain activities of four plant operators, they are shift supervisor(SS), reactor operator(RO), turbine operator(TO) and auxiliary system operator(AO), has been measured using HOT05 and the correlations of every pair of operators have been evaluated considering the expected relationship on specific time in a scenario. The following aspects of operator behaviors are expected to be clarified based on the correlation analysis of brain activities;

(1) Communication between SS and other operators(RO,TO,AO)
SS is expected to make important decisions based on the information provided by RO,TO,AO. The quality of communication between SS and other operators(RO,TO,AO) should be evaluated as the overall indicator of team performance.

(2) Excessive concentration on a same event
An overlooking of important event may be possible when all operators concentrate too much on same specific event. The level of correlation among operators may be indication of this kind of narrow-mindedness.

(3) Excessive isolation
In our previous work, it has been shown that a correlation of one subject cognitively isolated from other subjects reduced significantly, which can be an indication of level of isolation from other people. An operator too much isolated from other operators may not contribute to the team coordination.

Authors believe that a correlation among operators may be an indication of a quality of communication among operators and also related to the onset of undesirable situations shown above. The definition of quality of communication should be clarified here. The existence of verbal interaction does not necessarily mean an existence of communication. Thus, a quantity of verbal utterance is not considered as direct indication of communication. Instead, quality of communication here is defined as the level of synchronized cognitive pattern among two subjects. Although NIRS measurement cannot reveal what they are actually thinking in detail, the increased correlation of brain activities may imply possibility of shared intension to achieve common goals.

2.3 Subjects and Malfunctions Utilized in the Test Scenarios

The cognitive experiments have been performed in the full scope NPP simulator at BWR Operator Training Center Cooperation. The detail of the experiment is described in the following.

Figure 1 Ultra-small single channel wireless NIRS device (HOT05)

2.3.1 Subjects

Four experienced instructors participated in the experiments. They played different roles, SS,RO,TO,AO, with NIRS device on for each scenario. One example scene of cognitive experiment is shown in Fig.2. As the utilized NIRS device has no wire for transmitting data, they were free to move around the control panels. The physical burden of wearing the NIRS device on subjects was much smaller compared with the conventional NIRS device.

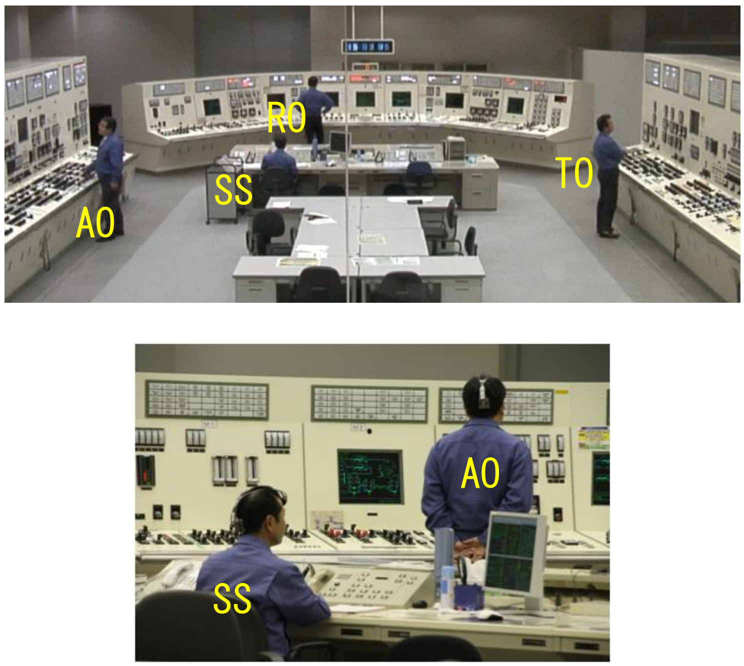

Figure 2 Example scene of cognitive experiment

2.3.2 Malfunctions utilized in the test scenarios

The following four malfunction scenarios have been adopted in the present study.

1 Station blackout
2 ATWS (Anticipated Transient Without Scram)
3 Turbine first stage failure
4 Reactor water level unknown

These scenarios have been taken from the training scenarios of BTC. Considering the skill level of the subjects, relatively severe and difficult scenarios have been selected. The brain activity of each operator has been measured along with the progress of anomaly events and the correlation of brain activities for every pair of operators have been calculated. Role of each subject changed for Scenario1,2 and Scenario 3,4. Subjects performed same scenarios twice with different role assignment.

2.3.3 Evaluation criteria

The correlations of each pair of operators have been evaluated according to the progress of anomaly events. Each scenario has been divided into different sections based on important events during the course of event developments. The following is an example of the event definition in the scenario of "Station Blackout";

Event No.
1 Reactor scram initiated by external power failure
2 Emergency diesel generator (A) failed to initiate
3 MSIV closed automatically as the water level decreased
4 Emergency diesel generator (H) failed to initiate
5 Emergency diesel generator (B) failed to initiate, which resulted in station blackout
6 Attempted a manual initiation of diesel generator (H) and failed
7 Requested onsite surveillance of emergency diesel generators
8 Full insertion of control rod confirmed
9 Cause of malfunction of diesel generator(A) was reported from the site
10 Automatic initiation of RCIC at low water level was reported
11 Attempted to maintain water level by RCIC as the restoration of power was unlikely
12 Diesel generator (A) became ready to initiate and initiated
13 Rebooted cooling function
14 Sub-criticality was confirmed and continued monitoring

It has been assumed that the expected interaction between specific operators can be defined for each event considering the plant behaviors and required actions. When an event related to specific device in the plant system occurs, the brain activity of the operator in charge of this device is expected to increase.

3 RESULTS

3.1 Overall behavior of blood flow

Figure 3 shows the cerebral blood flow of each subject in the Station blackout scenario, which corresponds to the level of brain activity, around the time of onset of failure for two trials with different role assignment. Red line in the middle indicates the time of onset of failure. Until the onset of failure, the subjects performed continuous monitoring of the plant state walking in front of the control panel related to their assigned roles. The brain activities show stable behavior during this phase of the scenario. On the contrary, when the scram occurs and many alarms start to sound and flash, the brain activities show abrupt change and show large fluctuation, reflecting the change of the cognitive situations. Some of the fluctuation in the cerebral blood flow may be attributed to the increased body movement according to the required operation. However, the changes of cognitive state have been reflected in this change of measured cerebral blood flow as the NIRS device utilized in the present study adopted the correction algorithm excluding superficial blood flow, which is dominantly influenced by the head movements.

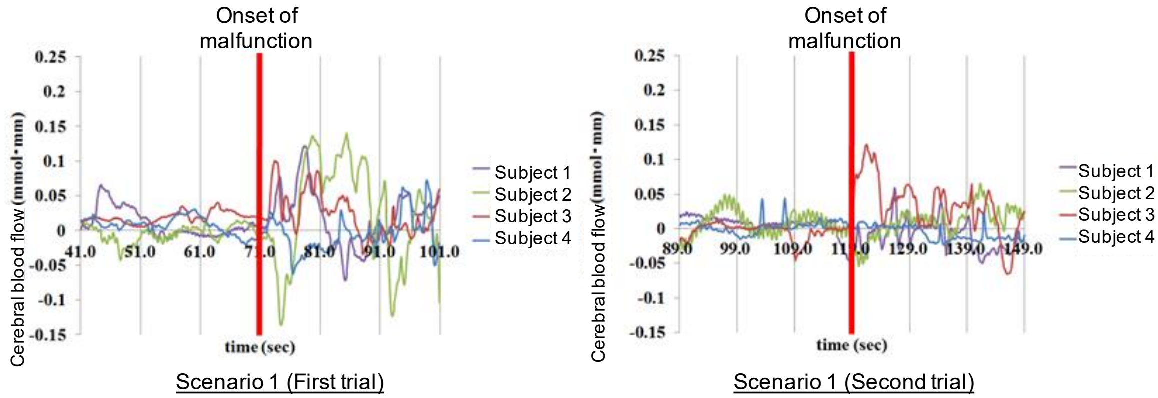

Figure 3 Overall behavior of cerebral blood flow of each subject

3.2 Empathy between Specific Operators

The distance correlations of every pair of subject have been calculated for every 10 seconds and the specific event with higher level of correlation (more than 0.8) have been identified. Time window to calculate distance correlation has been determined considering the brain response to the external stimuli and the threshold value to judge higher correlation has been determined based on our preliminary study on the quality of communication.

The existences of higher correlation for the specific time in the scenario have been evaluated for each time window and they have been compared with the specific events defined in advance. Table.1 shows that result of correlation analysis for the specific events in the scenario. The event numbers correspond to the events in the Scenario 1 (Station Blackout) described in 2.3.3. Symbols "O" means the higher correlation exists between the pair of subjects at the time of each event. The existence of higher correlation during specific events has been judged qualitatively. The hatched cell means that interaction should be existed between the pair considering the plant behavior and required actions. When the symbol "O" is shown in the hatched cell, it means that the estimated correlation among subjects is consistent with the expected behavior of operators.

The higher correlations are shown between most of the subject pairs in the event of 1 and 14, which are scram initiation and confirmation of sub-criticality. As all operators have been expected to be involved in these events and to performed the required action cooperatively, the existence of higher correlation among all subjects is consistent with the situation.

In this station blackout scenario, all of the emergency diesel generators failed to operate and the it was expected that the cognitive burden on TO may have been larger. The higher correlations among TO-RO, SS-TO, TO-AO have been observed in the events related to DG operation (Events 2,4,5,6,12), which is also consistent with the situation in this scenario.

Table.1 Result of Correlation Analysis for Specific Event in the Scenario 1 (Station Blackout)

	Event No. in Scenario 1 (Station Blackout)													
Pair of Subjects	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SS - TO	○	○				○		○		○		○		○
SS - RO	○		○			○			○			○		○
SS - AO	○											○		○
TO - RO	○	○	○	○	○	○	○	○	○	○		○		○
TO - AO	○						○	○		○				
RO - AO							○							○

Table.2 Result of Correlation Analysis for Specific Event in the Scenario 2 (ATWS)

	Event No. in Scenario 2 (ATWS)											
Pair of Subjects	1	2	3	4	5	6	7	8	9	10	11	12
SS - TO		○	○		○	○			○	○	○	
SS - RO			○		○	○	○	○	○	○		
SS - AO		○								○	○	
TO - RO	○	○	○							○	○	
TO - AO	○	○	○		○	○	○	○	○	○	○	
RO - AO		○	○						○	○	○	

Table.2 shows that result of correlation analysis of Scenario 2 (ATWS). The higher correlations of SS with other operators are significant, which may be because of the severity of this scenario. After the turbine trip, the control rods became inoperable and the operator attempted to perform manual insertion of control rods (Events 7,8,9). Higher correlation among SS-RO in these events may have reflected the required cooperative action.

Although the hatched cells without higher correlation and unhatched cells with higher correlations imply the inconsistent brain activation behaviors, authors believe that the proposed estimation methods of cooperative behavior of subjects can provide qualitative information on the team behavior of plant operators.

4 CONCLUSIONS

In this study, the feasibility of estimating coordination capability of nuclear plant operators has been examined based on the correlation analysis of brain activities among operators. The cognitive experiments have been performed in the full scope NPP simulator at BWR Operator Training Center Cooperation in which four experienced instructors participated. They played different roles such as shift supervisor, turbine operator, reactor operator and auxiliary operator and were instructed to go through four training scenarios with NIRS devices attached. The brain activity of each operator has been measured along with the progress of anomaly events and the correlation of brain activities for every pair of operators have been calculated.

Although the results of correlation among operators didn't show consistent behaviors enough to confirm the existence of clear empathy in the dynamic environments, authors believe that the basic validity of the correlational analysis of the simultaneous NIRS measurements for estimating coordination capability was partially confirmed.

Although further analyses are required in which the relationship between the level of coordination among operators and correlation estimated based on the brain activities is analyzed extensively, authors believe that the proposed method may contribute to the objective evaluation of the team coordination in the operator training.

5 ACKNOWLEDGMENTS

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