Ecological Interface Design: The Aspect of Situation Awareness in an Advanced Control Room

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ABSTRACT

The purpose of this study is to validate whether an ecological interface design (EID) improves operators' situation awareness in an advanced control room of a nuclear power plant (NPP). EID is defined as an approach to interface design that was introduced specifically for complex socio-technical, real-time, and dynamic systems. The EID technology has not yet been adapted to the nuclear power industry due to lack of empirical studies. Especially in a situational awareness aspect, many researchers have predicted that the EID will support operators to detect unanticipated events. Just a few studies, however, unveiled the positive effect of the EID display on human performance using a full scoped simulator.

In this study, to investigate whether an EID improves operators' situational awareness, we developed an EID prototype for nuclear power operations and a partial scoped dynamic mockup to validate the effectiveness of the EID prototype. Three experienced operators were involved as subjects in our study and they were fully well trained for using the EID prototype. We compared two types of situations in terms of situation awareness. One is mimic based information display and the other is a mimic plus EID based information display. The result of our study revealed that a mimic plus EID based information display is more effective than a mimic based information display in terms of situation awareness. This study is significant in that the EID as an emerging technology is adoptable to a digitalized control room in an aspect of improving operators' situation awareness.

Keywords: *Ecological Interface Design, Situational Awareness, Human Performance, Information Display*

1. Introduction

Since the Ecological Interface Design (EID) framework introduced by Rasmussen and Vicente in 1989, a great many of studies based on the EID framework have been published. The EID is a theoretical framework for designing human-computer interfaces for complex socio-technical systems (Vicente, 2002). Most of the studies have dealt with functionality and effectiveness of the EID in medical, petrochemical, computer network, electricity distribution, transportation, and nuclear power industry (Burns et al., 2003; Burns et al., 2008; Drivalou & Marmaras, 2009; Itoh et al., 1995; Jansson et al., 2006; Jamieson & Vicente, 2001; Jamieson et al., 2007; Jungk et al., 1999; Lau et al., 2008; Lau & Jamieson, 2008; Li et al., 2006; Morineau et al., 2009; Naito et al., 1995; Upton & Doherty, 2008; Westrenen, 2011). For example, Jungk et al. (1999) evaluated a patient monitoring display based on ecological interface. They found that anesthetists failed to achieve the task in 37% using a trend display, in 19% using a profilogram display, and in 13% using an ecological interface display. Burns et al. (2003) designed an ecological interface display for monitoring network management and they validated that the ecological interface display is significantly more effective than the network node managing display in terms of detection time, diagnosis time, and diagnosis accuracy.

Particularly, there is a nuclear industrial case which designs interfaces for monitoring energy balance and mass balance in the boiling water reactor in Japan (Itoh et al., 1995; Naito et al., 1995). The effect of the ecological interfaces using analytical evaluations based on the use of qualitative model of man-machine interaction was validated. The interfaces were too crowded with information and to easily understand the plant situation was found. However, they pointed out it takes time for operators to become accustomed to the ecological interface display due to the lack of operator's mental compatibility with the natural environment. Recently Lau & Jamieson (2008) conducted an empirical study of ecological displays for the secondary subsystems of a boiling water reactor plant simulator, the Halden Man-machine laboratory boiling water reactor (HAMBO) was chosen, as the experimental platform for the study. They compared three display types – traditional, advanced, and ecological display – depending on a knowledge-based and procedure-based scenario. Ecological displays could provide a marked advantage for monitoring unanticipated events over the conventional displays in a setting representative of a nuclear power plant control room with professional operators was found. However, the scope of the ecological interfaces being limited to the secondary side was recognized and the overview display in the ecological display condition was the same as the traditional one. As a similar study with the empirical research by Lau & Jamieson (2008), Burns and his colleagues found that EID can support situation awareness during the monitoring of an unanticipated event for a process control task using the HAMBO (Burns et al., 2008).

2. Procedure for EID

EID is an approach that assists monitoring activity for system change and designing interface to decrease cognitive burden by visualizing socio-technical, complicated dynamic appearance and to form a system for information on the basis of abstraction hierarchy and skills-rules-knowledge framework. That is, as showing the condition of a plant in the form of balance from various levels, it is the interface design for decreasing cognitive burden of an operating organization and understanding unpredictable accidents by monitoring.

For completing the design concept of the EID, the procedure is as follows; 1) Target definition and organization 2) Work domain analysis 3) Making information into variables 4) Visualizing information and 5) Design review and evaluation. The composition of this procedure describes goal, guideline, results and examples as follows by targeting each detailed design activity.

- Goal: It describes the goal in carrying out detailed design activities.
- Guideline: As following procedure carrying out detailed design activities, it describes requirements and advices. Requirements are described as 'should~' and advices are described as 'it is possible~' or 'it is recommended~'
- Results: It describes the form and using methods used of final results induced by detailed design activities.
- Example: It describes carried out and detailed design activities for understanding of users.

3. Prototype of EID Displays

Abstraction-Hierarchy Model (A-H Model) adopted from analyzing operating areas describes features of an object system as 3 functional classes, which are abstract function, generalized function and physical function. In other words, high level function, middle level function and low level function, which are expressed in the graph. On the other hand, a user-oriented graphic is designed by using theories such as proximity principle, visual momentum, population stereotypes, and emerging local consistency rules for decreasing cognitive burden in the process monitoring system.

4. Method for the Validation

The EID effectiveness test aims to validate the EID technology after testing whether the EID information display supports situation awareness of operators or not. Therefore, an experiment comparing a mimic information display (MIC type) proved by a common information display technology with a mimic information display adding EID display (EID type) was conducted. In the experiment we evaluated the cognitive performance time, the cognition accuracy and the difference of situational awareness.

Additionally, because the experiment is the evaluation of situation awareness of the subjects, secondary tasks such as administration works and communication as well as primary tasks are set considering real operating conditions. It's because in normal condition operators can't focus only on monitoring tasks. Generally, 'dotting red dots' is used for expressing additional tasks in VDU-based test. The 'dotting red dots' task is the work dotting red dots if subject finds random red dots in their screen.

4.1 Participants

Three subjects of this test, who have more than 3 years experiences as operators in main control room in nuclear power plant, were selected. Their average age is 43.25(±3.06) and experience in plant is 21.46(±53.66) years and work experience as the operator is 20.74(±5.96) years, which meets subject requirements.

4.2 Test Scenarios

After developing the scenario, which is suitable to goal and range of the test on the basis of operation-based test limited to EID information display technology, this test uses it. Test scenarios consider following scenario requirements for measuring the degree of situational awareness on VDU-based monitoring information.

4.3 Test Design

As applying to random cause design, this test decides test order. The number of test is total 48 (the number of scenarios (8) × the number of subjects (3) × information display types (2)) and in each test, it takes average 30 minutes.

4.4 Measures

4.4.1 Cognitive Performance Time

Cognitive performance time is measured by the situation awareness evaluation system, self-developed for this test and it is divided into situation perception time and situation judgment time. Situation perception time means the time, taken by deciding unusual condition of plant through alarm and information of plant. Situation judgment time means the time, taken by selecting scenario lists explaining unusual condition well.

4.4.2 Cognitive Accuracy

Cognitive accuracy is measured automatically by the situation awareness evaluation system, self-developed for this test and it is calculated by the rate of subject's accurate checking scenario lists inputted in signal generator in all scenarios. That is, frequency checking it of 24 all unit tests decides cognitive accuracy. Plant conditions inputted in each unit test (scenario number), selected by subjects (scenario number) and accordance between them are judged.

4.4.3 Situation Awareness

Situation awareness of this test measures the degree of objective situation awareness using SACRI and subjective situation awareness using SART. Situation awareness measured by using SACRI adopts sensitivity (d') and response criterion (β) on the basis of SDT (Signal Detection Theory) through following variables. If sensitivity of operator is high, it is positive of situation awareness and if bias of judgment standard of operator is low, it is also positive.

- Detecting suitable information to situation (Hit Signal; Hit)
- Detecting false information, not suitable to situation (Correct Rejection; CR)
- Non-detecting suitable information to situation (Miss Signal; Miss)
- Non-detecting false information, not suitable to situation (False Alarm; FA)
- Subjective situation awareness measures following variables through the Likert 7 point scale.
- Demand for resources: instability of the situation, complexity of the situation, variability of the situation, arousal
- Supply of resources: focusing of attention, concentration of attention, spare mental capacity
- Understanding: information quality, information quantity, familiarity of the situation

5. Results

5.1 Objective Situation Awareness

At first, in the case of questionnaire of SACRI on mimic based environment, like the Fig. 1, 102 questionnaires in total 130 questionnaires are right situation explanations, which show signal probability (P(S)) of 78.46% and non-signal (noise) probability (P(N)) of 21.54%. As results of evaluation, the rate detecting the signal (P(Hit)) is 67.65% and mistaking non-signal to signal (P(FA)) is 25.00%. Therefore, in EID-based environment, like the formula 1, sensitivity of subjects (d') is calculated by 1.13. In this situation, sensitivity is supposing regulated value on the basis of the equal-variance model. Moreover, like the formula 2, formula of Macmillan & Creelman(1991), response criterion (β) of subjects is calculated by 0.105. In mimic based environment, sensitivity and response criterion are displayed in diagram, Fig. 2.

		Responses	
		Yes	No
Signal Types	Signal N=102 P(S)=78.46%	*Hit Alarm* N=69 P(Hit)=67.65%	*Miss Alarm* N=33 P(Miss)=32.35%
	Noise N=28 P(N)=21.54%	*False Alarm* N=7 P(FA)=25.00%	*Correct Rejection* N=21 P(CR)=75.00%

Fig. 1. Results of SACRI (MIC Type)

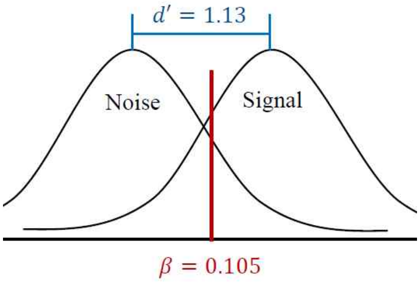

Fig. 1. Sensitivity and Decision Criteria (MIC Type)

$$d' = Z(P(Hit)) - Z(P(PFA)) = Z(0.6765) - Z(0.2500) = 0.46 - (-0.67) = 1.13$$

(Formula 1)

$$\beta = -\frac{Z(P(FA)) + Z(P(Hit))}{2} = -\frac{Z(0.2500) + Z(0.6765)}{2} = -\frac{-0.67 + 0.46}{2} = 0.105$$

(Formula 2)

On the other hand, in the case of SACRI questionnaire on the environment adding EID to mimic, like the Fig. 3, 98 explanations in 127 questionnaires are right situation explanation, which show signal probability (P(S)) of 77.17% and non-signal probability (P(N)) of 22.83%. As results of evaluation, the rate detecting the signal (P(Hit)) is 71.43% and mistaking non-signal to signal (P(FA)) is 31.03%. Therefore, in the environment adding EID to mimic, like the formula 3, sensitivity of subjects (d') is calculated by 1.06. In this situation, sensitivity is supposing regulated value on the basis of Equal-variance model. Moreover, like the formula 4, formula of Macmillan & Creelman(1991), response criterion (β) of subjects is calculated by -0.04. In the environment adding EID to mimic, sensitivity and response criterion are displayed in diagram, Fig. 4.

		Response	
		Yes	No
Signal Type	Signal N=98 P(S)=77.17%	*Hit Alarm* N=70 P(Hit)=71.43%	*Miss Alarm* N=28 P(Miss)=28.57%
	Noise N=29 P(N)=22.83%	*False Alarm* N=9 P(FA)=31.03%	*Correct Rejection* N=20 P(CR)=68.97%

Fig. 3. Results of SACRI (EID Type)

$$d' = Z(P(Hit)) - Z(P(PFA)) = Z(0.7143) - Z(0.3103) = 0.57 - (-0.49) = 1.06$$

(Formula 3)

$$\beta = -\frac{Z(P(FA)) + Z(P(Hit))}{2} = -\frac{Z(0.3103) + Z(0.7143)}{2} = -\frac{-0.49 + 0.57}{2} = -0.04$$

(Formula 4)

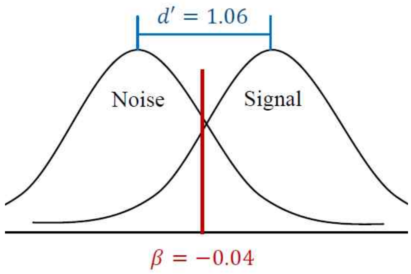

Fig. 4. Sensitivity and Decision Criteria (EID Type)

In respect of sensitivity, after detecting mimic based environment and the environment adding EID to mimic, because difference of sensitivity, 0.07 could be seen as the difference of the Z-value, standard normal deviate, it can be interpreted as the difference rate detecting signal, which could be maximum 2.79%. Rate detecting signal means detecting the signal (P(Hit)) or detecting false signal (P(CR)). But, because 2.79% rate detecting signal is in margin of error (±5%), there is no sensitivity difference comparing object environment (1.13≒1.06). Therefore, sensitivities of the operator in mimic based environment and the environment adding EID to mimic are equal.

Finally, in respect of response criterion, after comparing detection between mimic based environment and the environment adding EID to mimic, because 0.145 difference of response criterion could be seen as the difference of the Z-value, standard normal deviate, it can be interpreted as the difference of non-detecting signal rate, which could be maximum 4.55%. Non-detecting signal rate means non-detecting signal rate (P(Miss)) or the rate mistaking non-signal as the signal (P(FA)). But, because 4.55% non-detecting signal rate is in margin of error (±5%), there is no response criterion difference comparing object environment (0.105≒-0.04). Moreover, because it is possible to say response criterion of the operator is close to ‘0’, mimic-based environment and the environment adding EID to mimic are all have objective response criterion.

5.2 Subjective Situation Awareness

Comparing analysis is carried out by paired samples T-test. The subjective situation awareness in the environment adding EID to mimic (50.21±6.15) is better ($p=0.020<0.05$) than in mimic based environment (44.96±9.28). Therefore, operator judges monitoring display environment adding EID to mimic is better than mimic based environment.

6. Conclusion

As validating the difference on supporting situation awareness of operators in monitoring information display on the basis of mimic and adding EID to mimic, there is no difference in cognitive performance time, cognitive accuracy and objective situation awareness. Moreover, in respect of response criterion in objective situation awareness results, it is known that the operators understand situation with conservative response criterion. The conservative criterion means that the operators understand situation objectively in all environments (response criterion 0.105 in mimic based, -0.04 in adding EID to mimic). On the other hand, evaluation of subjective situation awareness in adding EID to mimic is better than in mimic based (95% confidence level, $p=0.020$).

Therefore, the level of supporting situation awareness in monitoring information display using EID displays added to mimic them is not less than the only mimic displays. Especially the level of subjective situation awareness in the EID displays is higher than mimic based displays. Conclusively, when the EID monitoring information technology is provided with mimic displays to operators, operators can understand plant situation more correctly.

This study has meaning in that the EID information display technology affects positive situation awareness of the operator especially in the case of unanticipated accident. Moreover, it has significant meaning in that it solves most of current problems suggested by NUREG/CR-6633 (O'Hara, 2000). That is, design procedure is developed for solving the shortage of EID design procedure and combining between EID and existing interface and problems relating with the amount of information are overcome by forming test environment. Moreover, operators in real site are selected as subjects, sufficient EID training is done to them and acceptance for EID is checked by them. Finally, because this positive research on primary side of nuclear power plant is discussed, which wasn't discussed in existing positive research, it is possible to support existing researches and solve some problems about shortage of operating experience.

Two major limitations of the study merit consideration. One is sufficient subject wasn't targeted for detecting. It's due to the requirement targeting operators in real site, which is very difficult. But, future and additional more operators in real site would be targeted for detecting the effect of EID. The other one is because this test focused on situation awareness, how to operator's activities were influenced by the EID displays. It's because developing scenarios for EID test has the limit too. Therefore, it is required to develop enough practical test scenarios to detect judgments or deciding operators' activities.

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