Eye Tracking Studies based on Attentional-Resource Effectiveness

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ABSTRACT

In the majority of cases, the primary means of information input to operators in nuclear power plants (NPPs) control rooms is through the visual channel. In this study, eye movement patterns of NPP operators are analyzed with eye tracking data obtained from simulator-based experimental studies. Two eye tracking measures of attentional-resource effectiveness in monitoring and detection tasks in NPPs which had been developed by the authors are introduced and several applications with the two eye tracking measures are discussed for the use of the measures. The underlying principle of the measures is that information sources should be selectively attended according to their importance. One of the two measures is the fixation to importance ratio (FIR), which represents attentional resource (eye fixations) spent on an information source compared to the importance of the information source. The other measure is selective attention effectiveness (SAE), which incorporates the FIRs of all information sources. The FIR represents the effectiveness on an information source, whereas the SAE represents the overall effectiveness on all information sources. Frequency and the duration of eye fixations of an operator on information sources are used as attentional resource. Finally feasible future applications with eye tracking data were discussed in terms of plant systems automation and operator training.

Key Words: eye tracking, monitoring, information searching, situation awareness, diagnosis

1 INTRODUCTION

As the design of Instrumentation and Control (I&C) systems for various plant systems including Nuclear Power Plants (NPPs) is rapidly moving toward fully digitalized I&C [1, 2], the role of the operators in advanced NPPs shifts from that of a manual controller to that of a supervisor or a decision-maker [3] and operator tasks are becoming more cognitive. In the majority of cases, the primary means of information input to operators in NPP control rooms is through the visual channel. Operators in NPPs are required to monitor a lot of information sources such as indicators, alarms, controllers, and mimic displays provided in ACRs but they have limited capacities of attention and memory. Hence NPP operators pay selective attention to relevant and important information sources to effectively understand the current status [4].

In this study, eye movement patterns of NPP operators are analyzed with eye tracking data obtained from simulator-based experimental studies. Two eye tracking measures of attentional-resource effectiveness in monitoring and detection tasks in NPPs which had been developed by the authors are introduced and several applications with the two eye tracking measures are discussed for the use of the measures in human factors. Finally discussed are feasible future applications with eye tracking data.

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2 ATTENTIONAL-RESOURCE EFFECTIVENESS (ARE)

Operators in NPPs continuously monitor the status of the plant system during normal operation. When they detect symptomatic events representing abnormal situations, they actively search for relevant information to correctly understand the situation. Stages of information processing depend on mental or cognitive resources, a sort of pool of attention or mental effort that is of limited availability and can be allocated to processes as required [5]. With regard to attentional resources, there are two aspects of attention: selecting information sources for further information processing and dividing attention between tasks. Attention is typically driven by four factors: salience, expectancy, value, and effort [6]. Salience refers to stimulus in the environment such as alarms, alerts, or some remarkable indication representing deviation from the normal situation. Expectancy shifts attention to specific sources which are most likely to provide information. Frequency of looking at or attending to an information source is modified by how valuable it is to look at. Attention may be inhibited if it is effortful compared to its value. Perception or understanding is accomplished by three simultaneous processes: bottom-up processing, top-down processing, and unitization (or matching) of the two processes. Bottom-up processing is derived by stimulus or salient information sources through sensing mechanisms. After detecting a stimulus, the information is matched to a mental model that is established based on knowledge and experience. Expectancy derived from the mental model leads to effective selection of information sources, which is top-down processing. The series of bottom-up processing, top-down processing, and unitization is the process of perception or understanding.

2.1 Development of ARE Measures

The attentional resources of operators in NPPs should be allocated to valuable sources of information in order to effectively monitor, detect, correctly understand, and diagnose the state of a system, since the operators receive too much information and they have limited attentional resources. Two measures of attentional resource effectiveness have been developed by the authors for monitoring tasks in NPPs [7]. The measures are based on the underlying principle that attentional resources should be paid selectively to information sources according to their informational importance. In the SGTR example, the pressurizer pressure, temperature, and level are definitely important information sources and selective attention should be paid to these sources proportionally to their importance. A measure of attentional resource effectiveness for an individual information source is defined as the relative attentional resources consumed on the information source divided by the relative importance of the information source. This ratio, AIR (Attentional resource to Importance of information source Ratio), is given by:

$$AIR(i) = \frac{\text{relative attentional-resources on information-}i}{\text{relative importance of information-}i} \tag{1}$$

Both the relative attentional resource and the relative importance of each information source should be normalized to range from zero to unity because they are relative measures. Information is provided to operators in NPP control rooms primarily through the visual channel. Hence the AIR is converted into a measure in terms of visual resources, Fixation to Importance Ratio (FIR), as:

$$FIR^{N}(i) = \frac{\dfrac{N_i}{\sum_{i=1}^{k} N_i}}{\dfrac{\omega_i}{\sum_{i=1}^{k} \omega_i}} \tag{2}$$

$$FIR^{D}(i) = \frac{\dfrac{D_i}{\sum_{i=1}^{k} D_i}}{\dfrac{\omega_i}{\sum_{i=1}^{k} \omega_i}} \quad (3)$$

$$FIR(i) = \frac{FIR^{N}(i) + FIR^{D}(i)}{2} \quad (4)$$

where, $FIR^{N}(i)$ = FIR with respect to number of fixations

$FIR^{D}(i)$ = FIR with respect to duration of fixations

N_i = the number of eye fixation on information source - i

D_i = the duration of eye fixation on information source - i

k = total number of information sources

ω_i = importance of information source - i

A lot of studies on information searching or visual sampling behaviors have employed fixation frequency or/and fixation dwell time. Fixation frequency, dwell time, or an integrated measure such as the average value of both could be used as visual resources. In this study, the average value is employed for the FIR calculation using Eq. (4). The relative attentional resources consumed on an information source should be equal to the relative importance of the information source in order to maximize the effectiveness of the attentional resource. Consequently, all FIR (i) should approach unity for the best effectiveness. The FIR is the ratio of relative attentional resources consumed on an information source to the relative importance of the information source. The FIR represents the attentional-resource effectiveness in terms of each information source. The Selective Attention Effectiveness (SAE) incorporates the FIRs for all information sources as:

$$SAE = \frac{\sum_{i=1}^{k} \left| FIR(i) - 1 \right|}{k} \quad (5)$$

Hence, the SAE represents the overall attentional-resource effectiveness based on all information sources. The SAE should approach zero to maximize the overall attentional resource effectiveness, because all FIR (i) should approach unity for the best effectiveness. An eye tracking system (FaceLAB 3.0) was used to obtain the eye fixation data (e.g., number and duration). The analytical hierarchy process (AHP) is applied to quantify the importance of information sources based on system behaviors [8].

2.2 Evaluation of Importance of Information Sources

Operator's information searching behaviors (ISBs) should be analyzed to develop a method to evaluate importance of the information source in NPPs. The first studies on information searching (or visual sampling) behavior have been done for flight maneuver tasks by Jones, Milton, and Fitts [9-11]. They suggested that dwell time was a function of the difficulty of reading an instrument and of interpreting the data from it. The difference in the relative fixation frequencies was more than ten to one, and it was concluded that this was due to their relative importance [11]. The first theoretical model of the visual sampling was made by Senders [12]. Senders focused on the optimum sampling of dynamic instruments as a function of the bandwidth (change rate) of signals, employing optimal sampling theory. Senders's original scanning model was subsequently elaborated by others [13-17] to account for value in addition to the bandwidth. Wickens et al. have developed two models such as a descriptive model and an optimal prescriptive model which extend previous models [18]. The descriptive model identifies the role of event salience, effort, expectancy, and value in influencing where and when people look at different channels to sample information in dynamic environments. The optimal prescriptive model accounts for the role of expectancy and value, as these characterize the properties of channels necessary to serve tasks that may differ in their importance. While previous models have defined properties of each AOI (area of interest) or channel, purely in terms of the bandwidth and value of events along that channel, the optimal prescriptive model includes another factor "task significance". This model defines task significance and importance of AOIs for each task. The bandwidth obviously plays an important role in the monitoring behavior in NPPs. It permits operators not only to expect the location of valuable information sources (expectancy) but also to diagnose the state in more detail. As an example, if a loss of coolant accident (LOCA) occurs, after monitoring and detecting a set of symptoms such as the decreases of pressurizer pressure, temperature, and level and the increase of containment radiation the operator is supposed to assess the abnormal situation as a LOCA. The operator may want to know further into the LOCA such as the location of the leakage, the leakage amount (or diameter of leakage breach), and so on, which can be assessed with a set of change rates of the indicators. The expectancy played the most significant role in the basis of the models for situation assessment based on Bayesian inference [19, 20]. The two models were all based on the behavioral rules of a NPP in either a probabilistic or a deterministic form. The mental model in which the rules are established generates expectancy, when a deviation (or some deviations) from a normal state is (are) observed. Ha and Seong reviewed studies on ISBs in various industries and addressed implications for human factors studies in NPP MCRs [21]. Usually there is a set of symptoms given an accident or a transient in NPPs (i.e, situation-events relations). Symptoms generally have diagnostic attributes. It should be noted that there can be two kinds of symptom: a symptom representing changed part (e.g., onset of alarm or deviation in a process variable) and a symptom of stationary part (e.g., a process variable in normal state). In the LOCA example, if pressurizer pressure, temperature, and level decrease, then a LOCA and a steam generator tube rupture (SGTR) can be competing hypotheses. If the containment radiation has no change, it will be a SGTR not a LOCA. In this case, the containment radiation is a stationary symptom which has the ability to be diagnostic between a LOCA and a SGTR. Selective attention should be paid to stationary symptoms in order for operators to understand the situation correctly in NPPs, even though they are not changed. Hence, a set of symptomatic information sources including both changed and unchanged symptoms and the bandwidth should be considered as determining factors governing the visual sampling behavior in NPPs. Considering the above-mentioned factors, measures of attentional-resource effectiveness such as FIR (fixation to importance ratio) and SAE (selective attention effectiveness) have been proposed by the authors, which quantitatively describe operator's information searching behavior in NPPs [22]. There are two other important factors that also influence the visual sampling behavior such as effort and salience. Effort and salience may exert a greater or lesser influence on scanning to the extent that designers have adhered to good human factors practice in display layout, by correlating effort and salience with expectancy and value. Hence, effort and salience are matters to be considered during designing a HMI. Informational importance of a process variable should be a function of its ability to discriminate among competing hypotheses (abnormal states) of the cause of a plant symptom. Hence, a set of the informational importance for an abnormal state is evaluated by considering a symptom set which has the ability to be diagnostic across a set of competing hypotheses. Considering existing studies on the monitoring behavior, the attribute representing "the frequent change of the source (bandwidth)" is referred to as "informative value (IV)" and the attribute representing "the likelihood of the change (a set of symptoms)" as "informative expectancy (IE)". Finally, the AHP hierarchy structure was established with IE, IV, and area of interests (AOIs), as shown in Fig. 1.

Many of studies on the monitoring behavior in aviation paid more attention to the data-driven monitoring which is affected by display attributes of the information sources (i.e., salience or bandwidth (change rate)). Bandwidth has been treated as a property representing expectancy, because changing AOIs guide operators (or pilots) to important information sources in aviation (cf., some of researchers considered bandwidth as an attribute of value). Band width is also a determining factor in operator's monitoring behavior in NPPs. For the human factors studies including the development of a sound model of the information searching behavior in NPPs, both the data-driven monitoring and the knowledge-driven monitoring should be considered and balanced in a systematic way. If there is no correlation between instruments only data-driven monitoring can be considered. However, as correlation between instruments becomes close, the knowledge-driven monitoring should be considered according to the extent of the correlation. In the AHP hierarchy, the IE part is related to the knowledge-driven monitoring whereas the IV part is concerned with the data-driven monitoring. Equal importance (weight) is assumed between the two parts in this study.

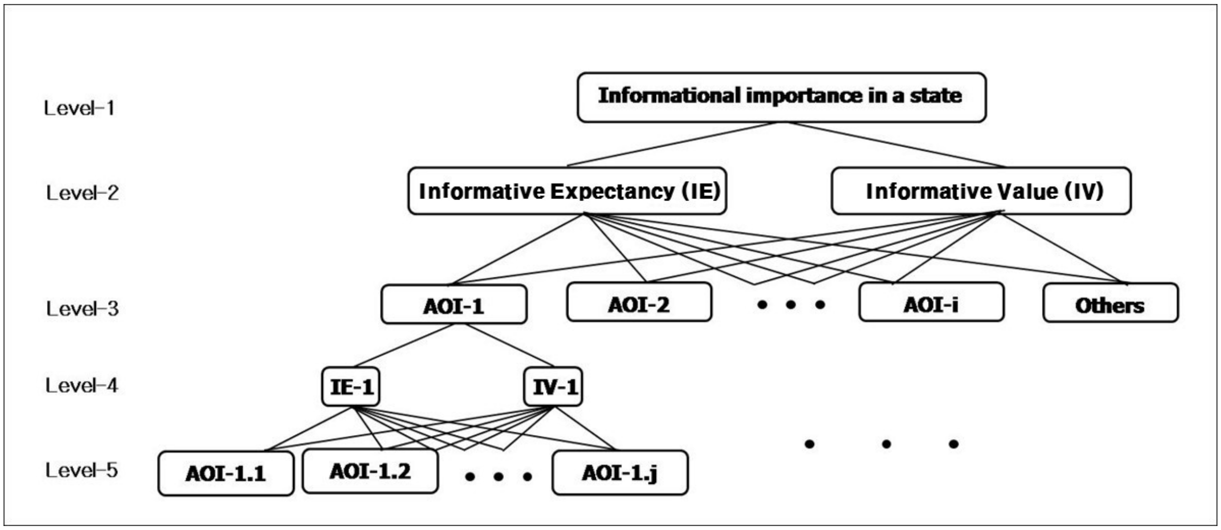

Figure 1. Setting up the AHP hierarchy

3 APPLICATIONS OF ATTENTIONAL-RESOURCE EFFECTIVENESS

3.1 Basic Analysis of Eye Tracking Data on Important Information Sources

The eye tracking data obtained in experiments with runs of FISA2 NPP simulator [23] are analyzed first in this study. FaceLAB™ 3.0 was employed to measure the number and the duration of eye fixations. As a lower bound of dwell times for the eye movement measurement, a figure of around 0.5 sec was suggested for real-life tasks, although shorter times might be observed in some laboratory experiments when static rather than dynamic patterns are used as displays [24]. In scene perception and reading tasks, fixation duration ranged from 0.15 to 0.6 sec [25]. The fixation dwell time was 0.2 to 0.5 sec in simple target tracing or detecting tasks [26-28]. In this study, AOIs were located at predefined areas and only values in the AOIs were changed dynamically. Consequently, a value lower than 0.5 sec (i.e. the lower bound reported) was deemed to be more appropriate in defining the fixation. From the investigation of eye fixation data in the pilot test, 0.25sec was empirically selected as a lower bound to operationally define a single fixation. A circular fixation area was employed in this study to define fixation. The fixation circle was larger than any indicator of the FISA2 simulator. If the fixation circle overlapped an indicator or an AOI for 0.25sec or more, it was counted as a single fixation. More eye fixations and durations on important information sources, which are enclosed in dotted circle lines in Fig. 2, were observed in these experiments.

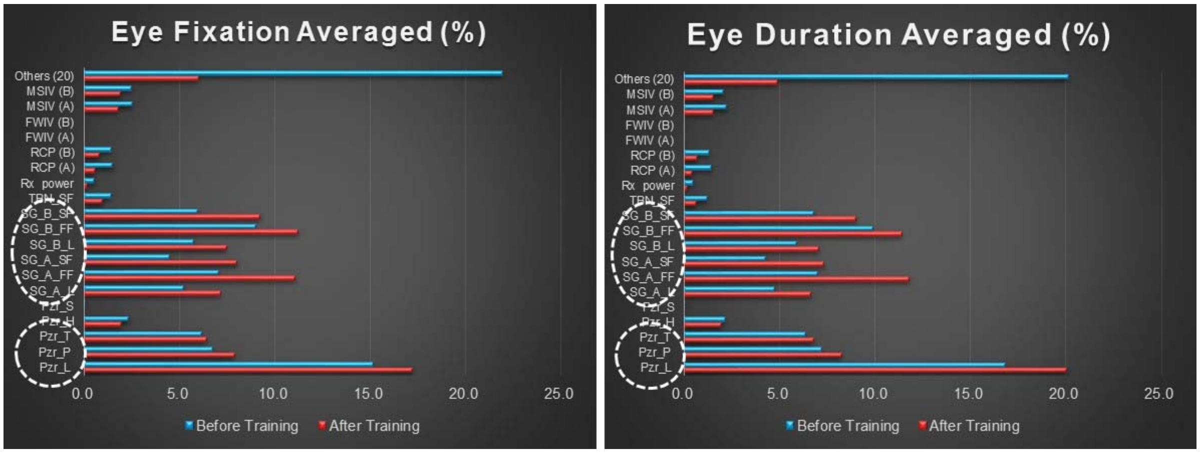

Figure 2. More eye fixations and durations on important information sources

3.2 Development of Eye Tracking Measures for Human Factors in NPPs

The HMI design in the advanced control rooms (ACRs) can be validated through performance-based tests to determine whether it acceptably supports safe operation of the plant. Plant performance, personnel task performance, situation awareness, workload, teamwork, and anthropometric/physiological factor were considered as factors for development of human performance evaluation support system (HUPESS) [29]. Eye tracking measures for level-1 and 2 situation awareness were developed and proposed in the HUPESS. This method was elaborated and two eye tracking measures of the FIR and the SAE were developed and validated in an experimental study [7]. The FIR and SAE were proposed as measures of perception and diagnosis in NPPs with theoretical, empirical, and experimental studies [30].

3.3 Development of an HMI Evaluation Method based on FIR & SAE

A model for information searching (monitoring & detection) in NPPs was developed based on the studies of operator's information searching behaviors, as shown on Fig. 3 [31]. This model and two ARE measures of the FIR and the SAE have been used as performance measures in a HMI (human–machine interface) evaluation method named "DEMIS (difficulty evaluation method in information searching) [32].

Operator competence and HMI design are modeled to be most significant factors to human performance in this model. Poor performance in information searching tasks is modeled to be coupled with difficulties caused by poor mental models of operators or/and poor HMI design. Human performance in information searching tasks is evaluated by analyzing the FIR and the SAE. Operator mental models are evaluated by a questionnaire-based method. Then difficulties caused by a poor HMI design are evaluated by a focused interview based on the FIR evaluation and then root causes leading to poor performance are identified in a systematic way, as shown in Fig 4.

3.4 Inference of Operators' Thoughts from Eye Movement Data in NPPs

Sometimes we need to figure out somebody's thoughts from his or her behaviors such as eye movement, facial expression, gestures, and motions. Usually, inference of somebody's thoughts from his or her behaviors includes lots of uncertainty, because the same behaviors might have different meanings depending on their context. However, if a person is doing his or her job in a very specific situation, the uncertainty coupled with the inference of the person's thoughts from his or her behaviors can be reduced and the inference of thought could be utilized for some helpful applications. Operational tasks in control rooms of NPPs are one of the representative examples which have very specific job characteristics. Effective selective attention to important symptoms or information sources should correspond with correct understanding and eventually correct diagnosis during abnormal situations given that the operator have well-developed knowledge of the system behaviors. This kind of operator's thought (understanding or diagnosis of a current situation) can be inferred from his or her selective attention pattern which is analyzed with the SAE evaluation. The better an operator selectively attends to information sources according to their informational importance, the lower the SAE value is expected to be, because the SAE should approach zero to maximize the overall attentional resource effectiveness. If a diagnostic task with a specific accident simulation is given to an operator who has well-established knowledge of the system behaviors, the operator's selective attention is expected to be made well according to the importance of information sources for the specific accident. However, if the SAE evaluation is made with sets of informational importance other than the relevant accident, the SAE value would be higher than that with the sets of informational importance of the relevant accident. In an experimental study conducted by the authors, about 80% of the operator's thought can be correctly inferred from the proposed method [33]. Hence it was concluded that the inference method has a great potential for useful applications in NPPs such as development of an improved operator training program, a new type of operator support system, and human performance measures for the human factors validation.

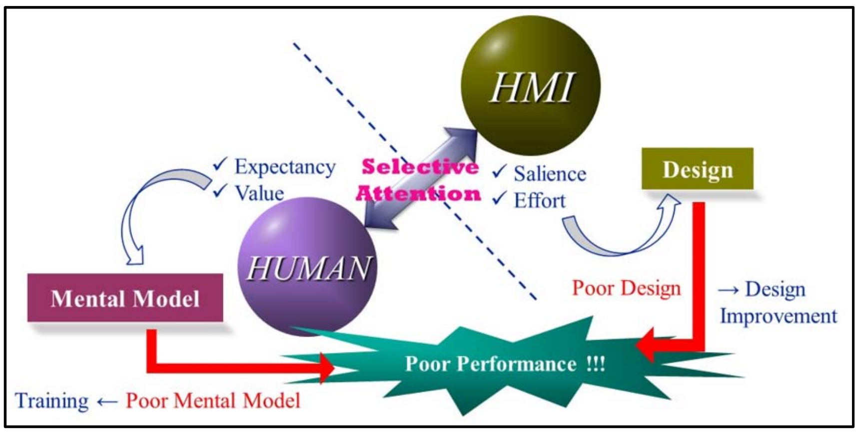

Figure 3. A model for information searching (monitoring & detection) in NPPs [31]

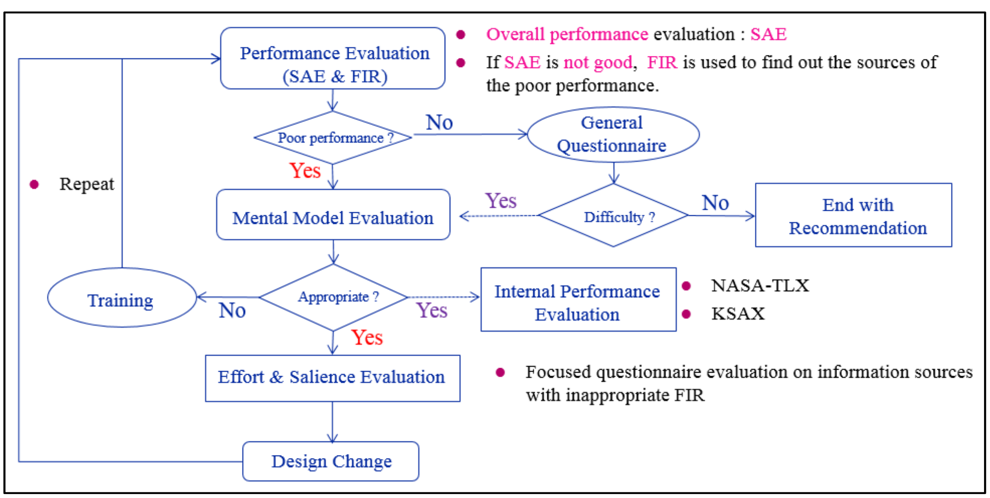

Figure 4. DEMIS: Difficulty Evaluation Method in Information Searching [32]

3.5 Discussions on Most Controversial Issues Coupled with ARE Measures

In most human factors studies or training in NPPs, operational scenarios are determined in advance. Hence, the operational situations are analyzed by evaluators (i.e., subject matter experts (SMEs) or human factors experts) in advance. Attention should be paid to the possibility that an operational strategy of operators might differ from the optimal strategy analyzed by evaluators. Sets of informational importance are obtained based on the optimal strategy. Hence, if operators adopt a different strategy, the informational importance should be modified accounting for the different strategy. Evaluators should carefully monitor operators' selective attention during scenarios and then analyze with operators after the scenarios. If a different strategy is identified as one adopted by operators, sets of informational importance should be modified accordingly. The FIR and the SAE should be reevaluated with the modified sets of informational importance. This kind of approach was applied in an evaluation of personnel task performance [34]. An optimal task solution was prepared in advance by evaluators. If deviations were identified during the simulation, these deviations were reflected in the modification of the optimal task solution.

4 WHAT CAN BE DONE MORE WITH EYE MOVEMENT DATA?

In safety-critical and complex systems such as NPPs, human errors have been considered as a serious cause of accidents, especially after the TMI accident. There have been two general approaches to cope with human errors in NPP control rooms. The first approach is to develop well-constructed training programs to which the inference method with operators' eye movement data can be effectively applied. The operator's understanding or diagnosis during a simulation training can be monitored in real time with the inference method. Advice and/or recommendation can be provided in a timely manner with the inference results. Also, operators' eye movement pattern can be evaluated and trained for the best performance. The second approach to reduce human errors in NPP control rooms is to design the NPP control room with improved interfaces and operator support systems (OSSs). OSSs refer to the systems which provide useful information to operators or automated systems for preventing human errors [35]. A new types of OSS can be developed based on the inference method proposed in this study. An NPP is operated by a shift consisting of several operators including a supervisor. When an abnormal situation occurs, the supervisor needs to check other operators' understanding of the current situation. The inference method can be applied to give real time information on other operators' understanding of the current situation to the supervisor. This kind of information could help the supervisor effectively make a diagnosis when his diagnosis result agrees with other operators' or monitor human errors which might be committed by other operators with incorrect understanding. This kind of human error associated with incorrect understanding has been considered as one of the most significant human errors in NPPs. Also, the methods with the ARE measures can be effectively applied to automation in NPPs. One of the key Issues in NPP automation is the lack of situation awareness due to the out-of-loop problem [36]. A well-developed mental model coupled with accurate situation awareness, enable the operator's performance to become more "open- loop" and thus, system control becomes more anticipatory and "smoother" through the use of prediction and expectancy to guide control responses [37]. However, being out of the loop can also make detection of system failures difficult. This problem becomes greater when the operator is largely removed from the control loop as is the case in highly automated systems [38]. This kind of out-of-loop problem can be resolved by evaluating the FIR and the SAE in real time (FIR (i) = 1 and SAE = 0), which means that operators continuously attend important information sources for obtaining and maintaining situation awareness.

5 CONCLUSIONS

Two eye tracking measures of the FIR and the SAE of attentional-resource effectiveness in monitoring and detection tasks in NPPs developed by the authors were introduced and applications with the two eye tracking measures were discussed for the use of the measures. The underlying principle of the measures is that information sources should be selectively attended according to their importance. The FIR represents the effectiveness on an information source, whereas the SAE represents the overall effectiveness on all information sources. Feasible future applications with eye tracking data were discussed in terms of plant systems automation and operator training. Even though sometimes it might not be easy to evaluate the importance of information sources in dynamic environments in large scale process control systems such as nuclear power plants, this problem can be overcome with the approach addressed in the discussion section. The two ARE measures of the FIR and the SAE are concluded to be noble approaches and more applications would be made in the near future.

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