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An Experimental Evaluation for an Effect of Operating Support Systems on Human Operators in NPPs

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1. Introduction

The operating environment of an advanced MCR has been changed from the conventional analog type to the digital type. The design of instrumentation and control (I&C) systems in nuclear power plants (NPPs) is also rapidly becoming fully digitalized I&C [1, 2]. Large display panels (LDP), soft-controls, computerized procedure systems, and advanced alarm systems were all applied to APR-1400(Advanced Power Reactor-1400) [3]. Thus, the role of the operator in advanced main control room (MCR) in NPPs shifted to suit more of a supervisor or a decision maker's role than that of a manual controller; hence the operator's tasks have become more cognitive oriented [4].

The digitalized advanced MCR leads operators to conduct highly cognitive works rather than physical works compared to the MCR in conventional NPPs, and various digital operating support systems such as navigation systems, computerized procedure systems, operation validation systems have been developed to reduce operator's mental workload and stress. The operator support systems aim to provide useful information to operators for reducing the workload of operators and convenient operation environment. However, they could cause not only positive effects but also negative effects on the system safety. Since operator support systems could directly affect the decisions of an operator, their effects should be evaluated carefully. The new systems could reduce the possibilities of some human errors, but new types of human errors could occur or possibilities of some human errors could increase [5]. Thus, the operating support systems in NPPs need to be evaluated to determine how much they assist human operators to reduce workload and improve performance. In order to evaluate the effect of operating support systems from the human operators' mental workload point of view, a physiological signal-based workload evaluation measure is developed in this study. Electroencephalogram (EEG) is one of physiological measures that evaluate the human operators' conditions objectively, and it is appropriate to evaluate the mental condition of human operators. In nuclear fields, NASA-TLX is the most widely used for evaluating mental workload, however, it is a subjective measure and it could not reflect the mental workload precisely. Thus, the EEG-based Workload Index (EWI) is suggested to evaluate the human operators' mental workload, and experiments were conducted to estimate the validity. The suggested EWI was estimated that it evaluates the human operators' workload like NASA-TLX, and it reflects workload better than NASA-TLX. The EWI was also estimated that it evaluate workload better than other EEG index.

The suggested EWI is expected to be useful for evaluating workload objectively, and the effects of operating support systems on human operators.

2. Development of an EEG-based mental workload evaluation method

Workload is invoked to account for various aspects of the interaction between a person and a task that cause task demands to exceed the person's capacity to deliver. Mental (Cognitive) workload is clearly an attribute of the information processing and control systems that mediate between stimuli, rules, and response [6, 7]. Mental workload of human operators can be measured by various methods including performance measures, questionnaire surveys, and physiological measures. In this study, physiological measures was selected for evaluating the mental workload of human operators.

2.1 Physiological measure

Physiological techniques measure the physiological change of autonomic or central nervous system associated with cognitive workload [8]. Electroencephalogram (EEG), Galvanic skin response (GSR), heart rate related measures, and eye movement related measures are representative tools for physiological cognitive workload evaluation. EEG is selected for physiological measure in this study. Various studies based on tasks such as in-flight refueling mission, air traffic control, and automobile driving reported that the EEG measures have proven sensitive to variations of mental workload in applied settings regarding arousal in vigilance situations [9-12]. There are also several advantages of physiological measure such as the EEG. Subjects can be measured quantitatively by an array of physiological sensors, some requiring contact with the subject's body through electrolyte sensors. Physiological measures permit a more objective workload assessment and can provide real-time evaluation, thus allowing the system designer to quickly and accurately identify usability problems as they occur. Possibility of detailed and various analysis of results [13].

2.2 EEG-based Workload Index (EWI)

There are two methods to get the power of EEG brainwaves

-Absolute (Abs.) band power: Total energy intensity of an electrode on a certain region at different frequency bands

-Relative (Rel.) band power: The relative power of a specific band to the total power

EEG power values differ from individual to individual. The relative band power that is the fractions of power in certain frequencies to the power of all frequencies of brainwaves should be used in order to accurately assess an individual's EEG power value rather than absolute band power. The EEG signals were divided into five parts (δ, θ, α, β, γ). The delta (0~4 Hz) band is removed in this study to eliminate noise such as pulses, neck movement, and eye blinking.

The enhanced theta brainwaves (4-8 Hz) induces a relaxed state of wellbeing and alleviates pre-performance anxiety. In the words of one student, "It makes one's mind breathe". An enhanced theta brainwaves induces a relaxed state of wellbeing and alleviates pre-performance anxiety. Theta activity aid the retrieval of information from working memory.

The alpha wave frequency of brain waves ranges from 8 to 13 Hz. When a person is relaxed, the proportion of alpha waves in the brain increases. This means that alpha waves can be used to detect when a person is relaxed. Receiving too much beta frequency waves may lead us to experiencing excessive stress and/or anxiety. The high frequencies such as gamma waves are associated with high levels of arousal.

Based on the above discussion, EWI is defined as the following in this study.

EEG-based Workload Index (EWI): (Relative beta power+ Relative gamma power) / (Relative theta power+ Relative alpha power)

2.3 Experimental design for validation of the suggest index

The experiment was conducted to determine whether the suggested index for evaluating the mental workload is valid or not. To prove the validity of the suggested index, there are three hypothesis for this validation.

- The suggested index is appropriate for measuring mental workload if it has a meaningful relationship with NASA-TLX.

-The suggested index is preferable to other EEG-based index if it has better relationship with NASA-TLX.

-The suggested index is preferable to NASA-TLX for evaluating the mental workload if it has better relationship with performance.

31 students majoring in nuclear engineering participated in the experiment. Compact Nuclear Simulator (CNS) and Bluetooth EEG measurement equipment (LAXTHA) were used. Steam Generator Tube Rupture (SGTR) was selected as the malfunction of the simulator. In this scenario, subjects should follow steps of procedures (EOP). The procedure is composed of 22 steps including 37 sub-tasks. For example, subjects are required to control S/G pressure PORV controller from set-point to 79.1 kg/cm^2, or they should monitor RCP status and make RCP-1 and RCP-3 stop.

Measured data were 2 channel EEG data (pre-frontal lobe), NASA-TLX questionnaire which is a widely-used, subjective, multidimensional assessment tool that rates perceived workload in order to assess a task, system, or team's effectiveness or other aspects, and the number of human errors as performance measures. Human errors were counted by following criteria [14,15,16].

-Operation omission: An operator omits performing a sub task when performing a task.

-Wrong object: An operator selects a wrong device when performing a task.

-Wrong operation: An operator performs a wrong operation, such as pressing the 'OPEN' button instead of the 'CLOSE' button. (Pressing 'CLOSE' button is originally intended to perform.)

-Mode confusion: An operator performs a right operation in a wrong mode.

-Inadequate operation: An operation is executed insufficiently. All operations that are performed incompletely.

-Delayed operation: An operation is not performed at the right time.

3. The results of the experiments for validation of the EWI

3.1 Relation between EWI and NASA-TLX

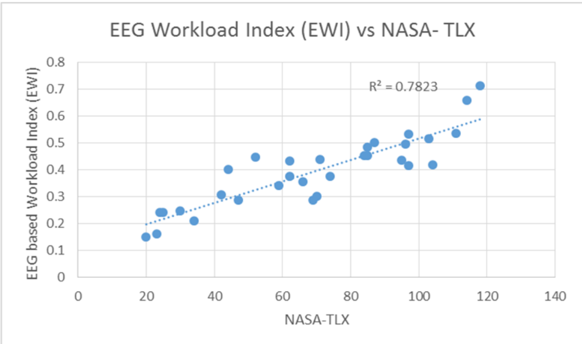

Fig 1. EEG-based Workload (EWI) vs NASA-TLX

The relationship between EWI and NASA-TLX was analyzed in order to validate the EWI is appropriate for evaluating the mental workload. By statistical analysis, the meaningful correlation with EWI and NASA-TLX was analyzed (Significant F-value 4.11E-11 < 0.05) as shown in Fig 1. The EWI can be considered as a tool for measurement of the mental workload.

3.2 Comparison of EWI and other EEG-based index

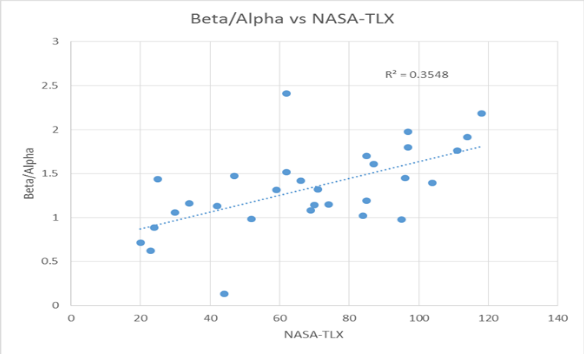

Fig 2. Beta/Alpha vs NASA-TLX

The "EWI vs NASA-TLX" has better relationship compared to "Beta/Alpha Index vs NASA-TLX" which is used in medical fields, as shown in Fig 1 and Fig 2 (Coefficient of determination of "EWI vs NASA-TLX" was 0.7823 and that of "Beta/Alpha index vs NASA-TLX" was 0.3548). Because of the characteristics of tasks in nuclear power plants demanding high cognitive works, it is desirable to consider theta and gamma waves as suggested. In nuclear fields, it is thought that the EWI is preferable to other EEG based index for evaluating the mental workload of human operators.

3.3 Comparison of EWI and NASA-TLX

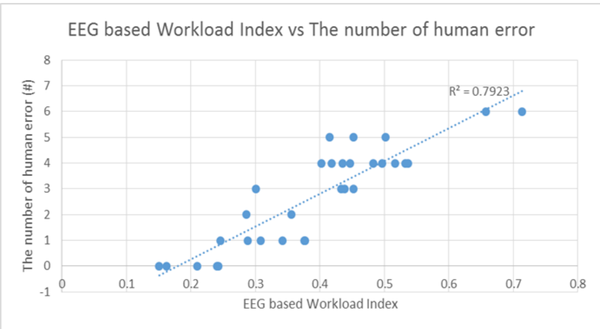

Fig 3. EWI vs the number of human errors

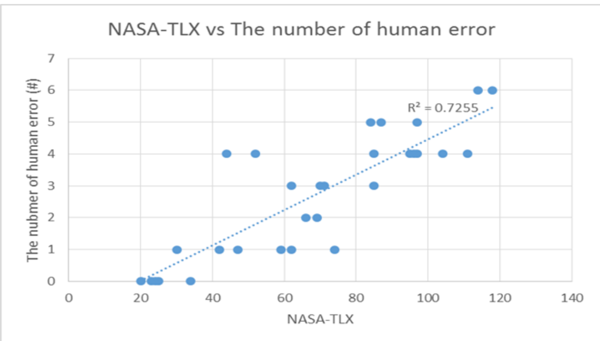

Fig 4. NASA-TLX vs the number of human errors

The "EWI vs the number of human errors" has better relationship compared to "NASA-TLX vs the number of human errors" (EWI: R^2=0.7923 > NASA-TLX: R^2=0.7255) as shown in Fig 3 and Fig 4. The EWI is not allowed to do the self-assessing the workload for subjects, and it reflects more accurate mental workload. The EWI is thought preferable to NASA-TLX to evaluate the mental workload and predict the human performance.

4. Conclusion

The EWI is suggested to measure the mental workload of human operators precisely and objectively. The EWI has a meaningful relationship with NASA-TLX by conducting the statistical analysis. It is shown that EWI is proper to measure the mental workload of human operators. By comparing the 'EWI vs NASA-TLX' to 'the other EEG based Index vs NASA-TLX', the EWI is preferable for measuring workload than the other index. By comparing the 'EWI vs human error' and 'NASA-TLX vs human error', the EWI is preferable to NASA-TLX to evaluate the mental workload and predict the human performance. It is expected that the suggested index (EWI) can be used for evaluating the effect of operating support systems on human performance in terms of operators' competence. In future works, the effect of the operating support system on operators will be investigated by using the EWI.

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