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An Experimental Analysis on Relationship between PSFs and Operator Performances in Digitalized Main Control Room

조선대학교 대학원
원자력공학과
박주영

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- 디지털 주제어실 수행도형성인자와 운전원 수행도 간의 상관관계 실험적 분석 -

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수행도형성인자(Performance Shaping Factor, PSF)는 인간신뢰도분석(Human Reliability Analysis, HRA)에서 운전원 수행도에 영향을 주는 인자이다. HRA에서는 인적오류확률을 정량화하기 위해 다양한 PSF들을 고려해왔고, 절차서, 훈련, 경험, 스트레스 등이 대표적인 PSF들을 나타낸다. 그러나, PSF들은 HRA에 적용됨에 있어서 몇 가지 문제점을 갖는다. 첫째로, 대부분의 HRA방법론에서는 PSF들의 영향을 반영하여 인적오류확률을 추정하고 있으나, 과연 이러한 PSF들이 실제로 운전원 수행도에 영향을 주는지에 대한 부분이다. 특히, 디지털 주제어실의 경우 데이터 부족, 기술적 근거의 부족으로 HRA의 불확실성이 기존 아날로그 주제어실에 비하여 높아질 것으로 예상 됨에도 불구하고, 디지털 주제어실에서의 PSF들이 과연 운전원의 수행도에 영향을 주는 지에 대한 연구가 거의 수행된 바 없다. 둘째로, 인간공학 및 심리학 등 여러 분야에서 수행된 연구에 따르면 PSF들 사이에 상관관계가 충분히 확인되고 있음에도 불구하고, 현재 대부분의 HRA방법론들은 PSF들의 영향을 각각 독립적으로 가정하여 인적오류확률을 추정하고 있다. PSF들 사이의 상관관계를 고려하지 않고 오류확률을 추정하게 되면, 인적오류확률이 높거나 낮게 추정되어 불확실성이 더욱 높아질 가능성이 있다. 따라서, HRA 불확실성 감소 및 정확한 인적오류확률 평가를 위해 PSF의 영향에 대한 실험적

연구가 필요하다.

본 연구는 1) 디지털 주제어실에서의 PSF들과 운전원 수행도 사이의 상관관계와, 2) PSF 사이의 상관관계에 대하여 실험적으로 분석하는 것을 목적으로 하고 있다. 첫 번째 연구에서는 HRA에서 대표적으로 사용되는 총 3개의 PSF와 6개의 운전원 수행도를 대상으로, Randomized Factorial Experiment 기법을 적용하여 PSF가 운전원의 수행도에 미치는 영향을 조사하였다. 실험의 경우 실제 디지털 주제어실과 유사한 환경을 갖추기 위해 APR1400 디지털 주제어실 시뮬레이터와 실제 운전원들을 대상으로 수행하였다. 이 후, 실험 데이터를 바탕으로 적절한 통계적 기법을 통해, 선정한 PSF들과 운전원 수행도 사이의 상관관계를 확인하였다. 두 번째 연구에서는 앞서 수행한 실험 결과를 바탕으로 Correlation Analysis 및 Factor Analysis 방법을 적용하여 총 6개의 PSF 사이의 상관관계를 분석하였다. 이 후, Factor Analysis를 수행한 결과로서 얻은 2개의 PSF 그룹들이, 인적오류확률을 계산할 때 새로운 인자로 고려될 수 있는지를 분석하였다.

I. Introduction

Performance shaping factors (PSFs) are factors that influence human performance in human reliability analysis (HRA) [1,2]. Most currently applicable HRA methods for nuclear power plants (NPPs) use PSFs to highlight human error contributors as well as to adjust basic human error probabilities (HEPs) that assume nominal conditions of NPPs [2,3,4]. Typical examples of PSFs include experience, adequacy of procedure, stress, and task complexity.

Application of digital technology is a recent trend in the design of an Main Control Room (MCR). Features distinguishing digital control rooms from conventional rooms and analog rooms in NPPs include advanced alarm systems, graphic information display systems, computerized procedure systems, and soft control. These features could cause changes in operator tasks by changing the task characteristics or creating new tasks. Additionally, although this new technology has the potential to improve human performance, it also holds the potential to negatively influence the performance and create precursors to human error [5,6].

The features of digital control rooms are already implemented in new or upgraded NPPs. However, these features cannot be attributed to HRAs due to HRA issues related to digital MCR wherein there is a paucity of data on the influence of technology on human performance and on adjusting HEPs with respect to PSFs. A few previous studies were conducted on the influence of new design features on operator performances, such as advanced alarm systems [7,8,9,10], graphic display [11,12,13,14], computerized procedure systems [12,15,16,17], and soft control [18,19,20,21]. However, very few studies examined the effect of PSFs on operator performances with respect to digital MCR.

One of the other challenges for current HRAs to estimate HEPs based on the PSFs is related to inter-relationship between PSFs. There is sufficient evidence in the fields of psychology and human factors to indicate that there exist inter-relationships between PSFs. For instance, Park and Jung showed that the task complexity of emergency operating procedures has a relationship with the operator’s subjective workload in NPPs [22]. Task complexity, procedure, and workload are popular factors that many HRA methods consider as PSFs. In addition, the relationship between experience and workload has been reported in various areas: for example, in driving [23], aviation [24], and NPPs [25]. If an HRA ignores the inter-dependency of PSFs, it is possible that HEPs may be over- or under-estimated. When a complex task imposes a high workload on operators, separate consideration of the task complexity and workload may double-count the effect of complexity and lead to the overestimation of HEPs or vice versa. However, most HRA methods treat PSFs independently and generally do not consider this combined effect of PSFs on human performance in the estimation of HEPs.

This study aims to experimentally investigate 1) the effect of PSFs on operator performances and 2) the inter-relationship between PSFs by using an NPP simulator with a high fidelity. In the first study, a randomized factorial experiment was designed to examine whether PSFs affect operator performances. This study selected three PSFs, namely, operator experience, time urgency, and task complexity, which are representative PSFs in the HRA as well as controllable in the experiment. Six operator performances, such as time to enter the cooldown of the reactor coolant system, average completion time per instruction, number of secondary tasks, error rate, workload, and situation awareness, are measured and analyzed. An APR1400 simulator equipped with a fully digitalized human-system interface was used and six crews of operators participated in the experiment. A statistical analysis was also performed to show the relationship between the PSFs and operator performances. In the second study, correlation and factor analyses are performed to investigate the inter-relationship between PSFs and suggest a context-based approach based on the experiment’s results. This study selected six PSFs that were controllable and measurable, and sets of PSFs are different from those in the first study. A few groups of PSFs were identified from the factor analysis. Thereafter, the feasibility of the groups of PSFs identified from the factor analysis being treated as a new factor to estimate HEPs was examined using the experimental data.

II. Evaluation of PSFs in Digital Control Rooms

A. Digital Main Control Rooms in Nuclear Power Plants

Rapid progress of digital and computer technology has led to the incorporation of advanced technology by NPPs in the design of MCRs. Newly constructed NPPs around the world, such as APR1400 in Korea [26,27], AP1000 in USA [28], and EPR-1600 in France [29], adopt fully digitalized and computerized control rooms.

There are three major trends in the evolution of digital MCRs, namely 1) increased automation, 2) use of computer-based human-system interface (HSI), and 3) intelligent operator aids [30]. Computer-based HSIs and operator aids include features such as advanced alarm systems, graphic display systems, computerized procedure systems and soft controls. Advanced alarm systems provide processed alarms by eliminating nuisance and/or redundant alarms and prioritizing, filtering, and suppressing alarms [9]. Graphic display systems contain a variety of display types including graphic process displays that provide plant parameter information organized around plant system mimics and predefined as well as operator defined trend displays of plant parameters. The graphic display system can be accessed from any of the operator workstations. Computerized procedure systems provide different levels of functionality including systems that simply display a replica of paper-based procedures on a computer screen, systems that automatically retrieve relevant process data to form a procedure step and process the step logic as an aid to the operator, and systems that include procedure-based automation [31]. Soft controls use the input interface connected with control and display systems that are mediated by software instead of direct physical connections in analog MCRs [32]. Fig. 1 shows the primary tasks of NPP operators and the potential supportiveness of new features in digital MCRs [33].

These features may lead to changes in operator tasks by changing task characteristics or creating new tasks. The computerized HSI may influence the functioning of operators as a crew [3]. For example, computerized procedure and graphic display systems can provide a shift supervisor with plant parameter data required to work through the procedures. This may have two direct effects, namely reducing the need for low-level communication between the shift operators and the board operators and reducing cognitive workloads of board operators [34]. Furthermore, this new technology may introduce a new task that did not previously exist in the analog MCR. An example of this is the secondary task, which is also called an interface management task. Secondary tasks are performed to access information from workstations including configuring, navigating, arranging, interrogating, and automating. Interface management effects have the potential to increase the likelihood of human errors when the interface is poorly designed [35].

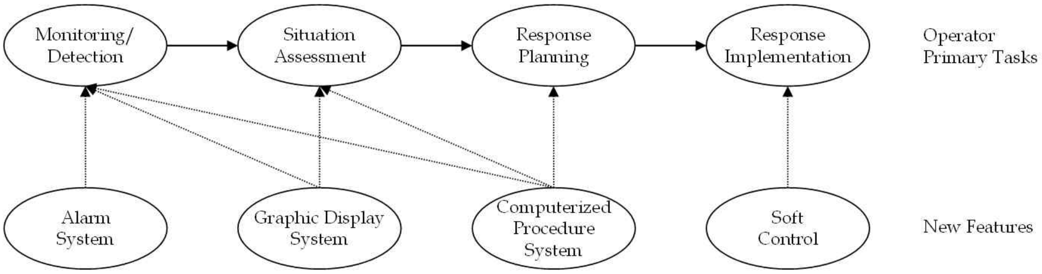


Fig. 1. The potential supportiveness of new features in digital MCRs [33]

B. Performance Shaping Factors in Digital MCRs

A PSF is defined as any factor that influences human performance [1,2]. In the ATHEANA Method [3], PSFs represent a set of influences on the performance of an operating crew that result from human-related characteristics of the plant, the crew, and the individual operators. The most commonly used HRA methods in the nuclear industry employ PSFs to adjust HEPs in different conditions. PSFs are also known by different terms based on the method. These terms include performance influence factors (PIFs), influencing factors (IFs), performance affecting factors (PAFs), error producing conditions (EPCs), and common performance conditions (CPCs) [36]. HRA methods generally provide analysis and guidelines with respect to PSFs to assess the state of a PSF through direct measurement or extrapolation. As shown in Table 1, Kim et al. [37] summarized PSFs and assessment approaches suggested by HRA methods. Most HRA methods rely on expert judgment and literature survey to identify PSFs and evaluate their effects.

Only a few studies reported the use of PSFs in digital MCRs. Lee et al. [38] suggested a systematic approach for qualitatively evaluating PSFs in a digital MCR through a literature review. This study considered the context changes that occurred in the use of computerized procedure systems, graphic information displays, and soft controls. Previous studies empirically investigated the effect of training and task complexity in the use of computerized procedure systems [39]. However, more studies that use experimental conditions of high fidelity to actual NPPs need to be performed to obtain insights on the effect of PSFs on operator performances in digital MCRs.

Table 1. The summary of PSFs and assessment for HRA methods [37]

HRA methods	Suggested PSFs	Underlying theory
A technique for human error rate prediction (THERP) [2]	Physiological stressors, psychological stressors, Task and equipment characteristics, Organization factors, Situational characteristics, Job and task characteristics	A general descriptive model of human performance in an NPP
Human error assessment and reduction technique (HEART) [40]	A channel capacity overload, a need for absolute judgments that are beyond the capabilities or experience of an operator, operator inexperience, a shortage of available time, lack of clear, direct, and timely confirmation corresponding to an intended actions, etc.	Error producing conditions (EPC) identified by the author's experience
Cognitive reliability and error analysis method (CREAM) [41]	Adequacy of HSI and operational support, working conditions, adequacy of organization, adequacy of training and experience, available time, crew collaboration quality, number of simultaneous goals, time of day, and availability of procedures/plans	Common performance conditions (CPCs) identified through the salient or dominant features of performances, as links in the space of man-technology-organization (MTO)
Human reliability management system (HRMS) [42]	Time, task complexity, task organization, procedures, training/expertise/experience/competence, and quality of information/interface	A large number of techniques and applications surveyed.
Standardized plant analysis risk HRA (SPAR-H) [43]	Available time, complexity, procedures, fitness for duty, stress/stressors, experience/training, ergonomics/HSI, and work processes	Human behavior model and PSF comparisons between HRA methods performed.
A technique for human error analysis (ATHEANA) [3]	Applicability and suitability of training/experience, available staffing/resources, suitability of relevant procedures and administrative controls, ergonomic quality of the HSI, operator action tendencies and informal rules, environment, etc.	The context developing process to identify the PSFs and plant conditions that are most relevant to the human action addressed.

III. The Effect of PSFs on Operator Performances with respect to Digital MCR

A. Experiment Design

As shown in Table 2, a randomized factorial experiment was designed to investigate the effects of PSFs on operator performance in the digital MCR. The details of the experimental design include the following.

Table 2. Experimental design – a randomized factorial experiment design

Time urgency	Task complexity	Operator experience		Scenario No
		More experienced crew	Less experienced crew	
More Urgent	DBA	Performances	Performances	1
	DBA + Masking	Performances	Performances	2
	BDBA	Performances	Performances	3
Less Urgent	DBA	Performances	Performances	4
	DBA + Masking	Performances	Performances	5
	BDBA	Performances	Performances	6

1. Performance shaping factors – controlled variables

Three PSFs are selected as controlled variables in the experiment, namely, operator experience, time urgency, and task complexity. The PSFs correspond to those that are commonly accounted for by many HRA methods as shown in Table 1.

a. Operator experience

Subjects are divided into two groups consisting of more experienced and less experienced crews. The more experienced crew group is composed of operators with operating licenses for a reactor that is of the same type as the simulator. The less experienced crew group is composed of operators possessing operating licenses for reactors that are different from the simulator.

b. Time urgency

Time urgency represents whether a scenario includes any task that should be performed quickly. The urgent group scenarios require operators to perform a task within 30 min of the reactor trip or the failure of component. The urgent tasks are identified from the assumptions of the deterministic safety analysis as well as from operator time windows of probabilistic safety assessment [44].

c. Task complexity

In this experiment, the task complexity refers to the complexity of the diagnosis and execution tasks in the scenario. The scenarios are divided into three groups along with the task complexity, namely 1) design basis accident (DBA), 2) DBA + masking of information, and 3) beyond DBA (BDBA). In the DBA scenario, operators follow an optimal recovery procedure (ORP), i.e., an event-based procedure that is well-established for a dedicated accident. The scenario of DBA + masking of information involves an additional failure of the radiation monitoring system (i.e., N16 radiation indicators) to DBAs, and this makes the diagnosis task more difficult. The BDBAs include the accidents that are normally assumed to occur very rarely in the NPP. In this scenario, it is necessary for operators to perform functional recovery procedures (FRPs), i.e., symptom-based procedures focused on the recovery of safety functions. It is widely known that the FRPs are more difficult to perform than the ORPs.

2. Scenarios

Six scenarios are developed to reflect the different conditions of two PSFs, i.e., urgency and task complexity. The scenarios are summarized in Table 3. Scenarios 1, 2, and 3 include an action that should be performed within 30 min of the initiation of failure or reactor trip. In Scenarios 2 and 4, the failure of N16 indicators, i.e., the radiation indicator of the steam line, is expected to make the diagnosis of SGTR and ESDE difficult since the detection of radiation in the steam line is a critical cue in determining these accidents. The SGTR with the failure of N16 indicators is also used as a difficult scenario in the human factors engineering validation for NPPs [45].

Table 3. The summary of scenarios

Scenario No.	Failures	Urgent Action	Task complexity
Scenario 1	Inadvertent opening of an ADV + Loss of offside power (LOOP)	Restoration of opened valve	DBA
Scenario 2	Steam generator tube rupture (SGTR) + Failure of N16 indicators (Masking of information)	Isolation of damaged SG	DBA + Masking of information
Scenario 3	Loss of coolant accident (LOCA) + Failure of safety injection system	Aggressive cooldown using ADV	BDBA
Scenario 4	Small break LOCA	None	DBA
Scenario 5	Excessive stem demand event (ESDE) + Failure of N16 indicators (Masking of information)	None	DBA + Masking of information
Scenario 6	Loss of all feedwater (LOAF)	None	BDBA

3. Operator performance measurements

The experiment measures six operator performances, namely average completion time per instruction, time to enter the cooldown of the reactor coolant system (RCS), error rate, the number of secondary tasks, workload, and situation awareness.

a. Average completion time per instruction

This refers to the average time to complete a procedure instruction. A procedure consists of steps and a step in turn consists of instructions. An instruction generally includes an operator action in the APR1400 procedure.

b. Time to enter the cooldown of the reactor coolant system

This time measures the period from the reactor trip to the start of the RCS heat removal through ADVs, steam bypass control system, or feed and bleed operation. In the APR1400 reactor, the RCS heat removal is a critical safety function that ensures the stability of NPP such that ORPs and FRPs request operators to maintain the RCS heat removal in an accident. All the scenarios also ended when the operators successfully enter the procedural step to perform the RCS heat removal.

c. Error rate

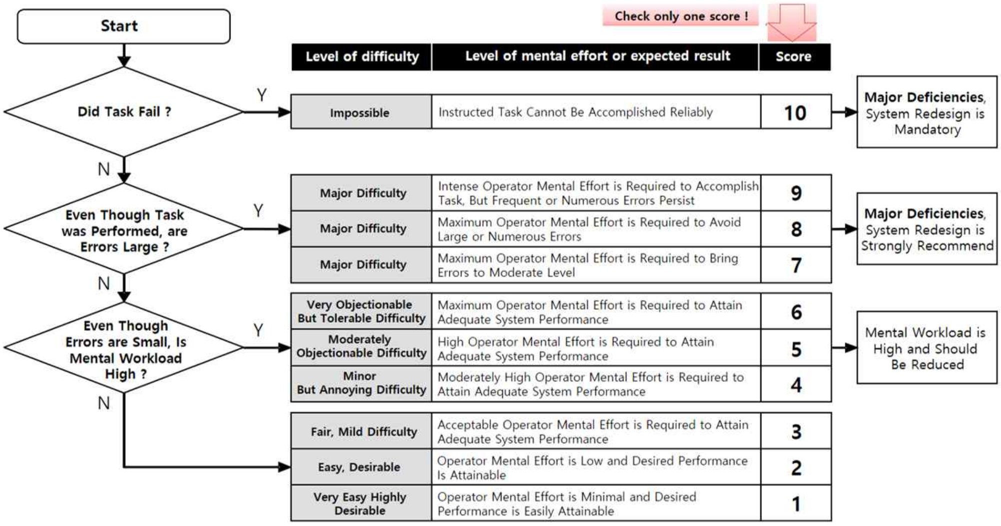
The error rate measures the deviation of operator task performances from the procedure. The number of errors including errors of omission and commission are counted and divided by the total number of tasks in each scenario.

d. Number of secondary tasks

Secondary tasks are also called interface management tasks. They refer to the tasks required to access information in a computerized MCR such as configuring, navigating, arranging, interrogating and automating the interface. These involve additional tasks as well as potential human factor issues in the computerized MCR [35,45,46]. The number of secondary tasks is also counted in the experiment.

e. Workload

This experiment considers the workload as an operator performance in contrast with many HRA methods that also regard the workload as a PSF. This study uses the modified Cooper-Harper rating scale (MCH) originally developed by the aviation industry to estimate the psychological and physical workloads of the operator. Fig. 2 shows the MCH questionnaire [47]. The operators answer the questionnaire after finishing each scenario.

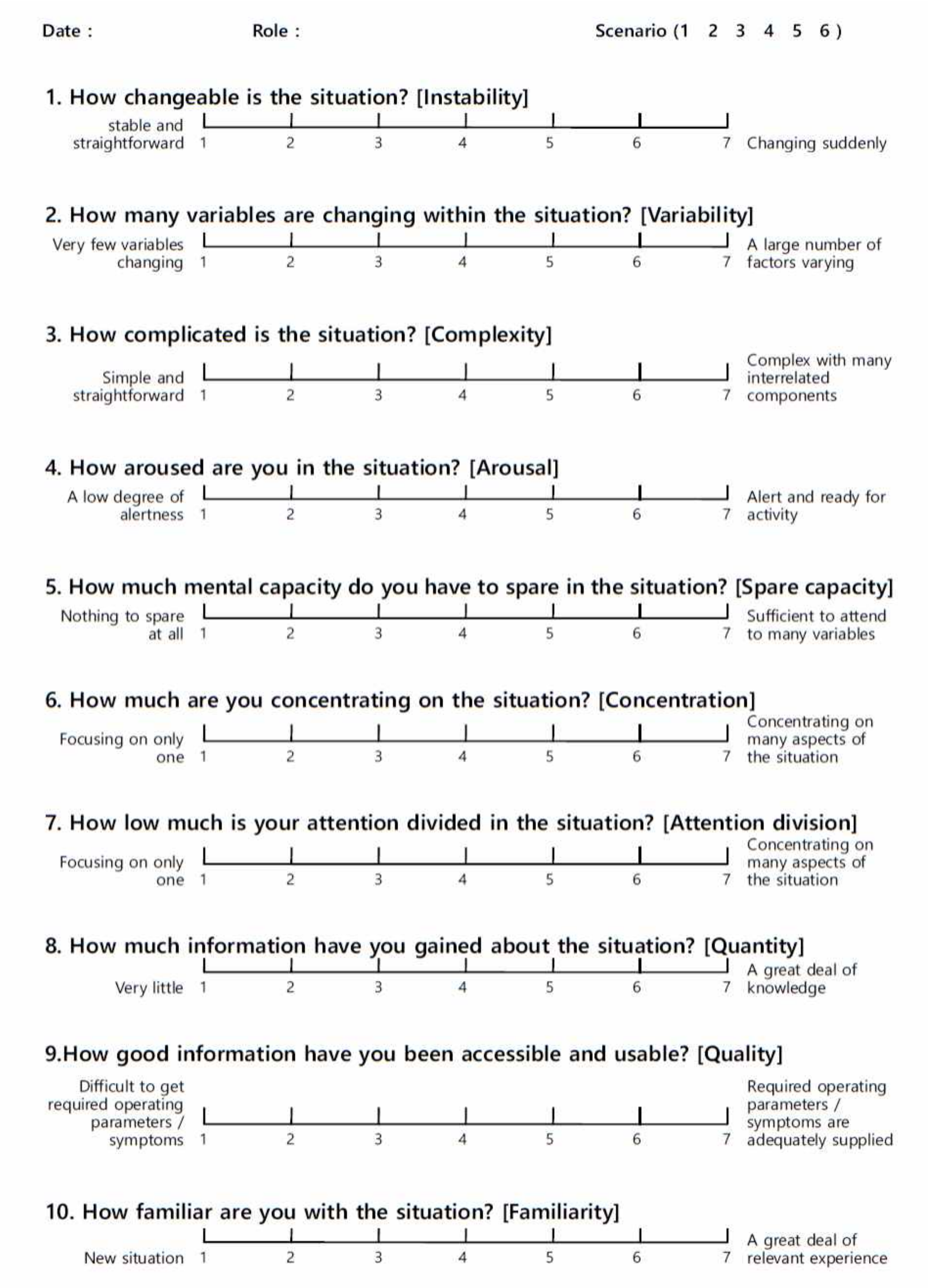


Level of difficulty	Level of mental effort or expected result	Score
Impossible	Instructed Task Cannot Be Accomplished Reliably	10
Major Difficulty	Intense Operator Mental Effort is Required to Accomplish Task, But Frequent or Numerous Errors Persist	9
Major Difficulty	Maximum Operator Mental Effort is Required to Avoid Large or Numerous Errors	8
Major Difficulty	Maximum Operator Mental Effort is Required to Bring Errors to Moderate Level	7
Very Objectionable But Tolerable Difficulty	Maximum Operator Mental Effort is Required to Attain Adequate System Performance	6
Moderately Objectionable Difficulty	High Operator Mental Effort is Required to Attain Adequate System Performance	5
Minor But Annoying Difficulty	Moderately High Operator Mental Effort is Required to Attain Adequate System Performance	4
Fair, Mild Difficulty	Acceptable Operator Mental Effort is Required to Attain Adequate System Performance	3
Easy, Desirable	Operator Mental Effort is Low and Desired Performance Is Attainable	2
Very Easy Highly Desirable	Operator Mental Effort is Minimal and Desired Performance is Easily Attainable	1

Fig. 2. Questionnaire of modified Cooper-Harper rating scale (MCH) [47]

f. Situation awareness

Situation awareness refers to the perception of elements in the environment within a volume of time and space and the comprehension of the meaning and the projection of the status of the elements in the near future [48]. Situation awareness is also measured in terms of operator performance in human factors engineering for NPPs [45]. Situation awareness rating technique (SART) is used to measure the operator’s situation awareness in the scenario. Fig. 3 shows the SART questionnaire [49]. The operators answer the SART questionnaire after finishing each scenario.



Date : Role : Scenario (1 2 3 4 5 6)

1. How changeable is the situation? [Instability]

stable and straightforward 1 2 3 4 5 6 7 Changing suddenly

2. How many variables are changing within the situation? [Variability]

Very few variables changing 1 2 3 4 5 6 7 A large number of factors varying

3. How complicated is the situation? [Complexity]

Simple and straightforward 1 2 3 4 5 6 7 Complex with many interrelated components

4. How aroused are you in the situation? [Arousal]

A low degree of alertness 1 2 3 4 5 6 7 Alert and ready for activity

5. How much mental capacity do you have to spare in the situation? [Spare capacity]

Nothing to spare at all 1 2 3 4 5 6 7 Sufficient to attend to many variables

6. How much are you concentrating on the situation? [Concentration]

Focusing on only one 1 2 3 4 5 6 7 Concentrating on many aspects of the situation

7. How low much is your attention divided in the situation? [Attention division]

Focusing on only one 1 2 3 4 5 6 7 Concentrating on many aspects of the situation

8. How much information have you gained about the situation? [Quantity]

Very little 1 2 3 4 5 6 7 A great deal of knowledge

9.How good information have you been accessible and usable? [Quality]

Difficult to get required operating parameters / symptoms 1 2 3 4 5 6 7 Required operating parameters / symptoms are adequately supplied

10. How familiar are you with the situation? [Familiarity]

New situation 1 2 3 4 5 6 7 A great deal of relevant experience

Fig. 3. Questionnaire of situation awareness rating technique (SART) [49]

4. Subjects

The experiment involves six crews (18 operators). Each crew consists of three operators, namely a shift supervisor (SS), a reactor operator (RO), and a turbine operator (TO). All the operators in the three crews have operating licenses for the APR1400 reactor which is a pressurized water reactor (PWR), and thus, they are assigned to the more experienced group. All the operators in the other three crews did not have the operating licenses for the APR1400 reactor but have licenses for other types of PWRs. Therefore, they are assigned to the less experienced group. The average age of all the participants is approximately 44 y, and the average experience of the plant operation is approximately 13 y, as shown in Table 4.

Table 4. Comparison of two groups with respect to operator experience

Groups	Average age	Work experience of plant operation	License
More Experienced	43 years	14 years	APR1400 and other types of PWRs such as OPR1000, WH1000, and WH600
Less Experienced	45 years	12 years	No APR1400, but other types of PWRs such as WH600, Framatom, OPR1000, and WH1000

5. Facility and data acquisition

As shown in Fig. 4, an NPP simulator with a high fidelity is used as the experiment facility. It contains an APR1400 plant model, which is an advanced PWR with 1400 MWe power generation. The APR1400 has many specific features such as passive safety facilities, digital instrumentation and control (I&C), and digital MCR [27]. The advanced control room design incorporates extensive computerization and automation of facilities to enhance operator decision-making and to reduce operator workload. The simulator consists of a large display panel and an operator console that can accommodate three operators. Each operator has three computer screens for the operation.

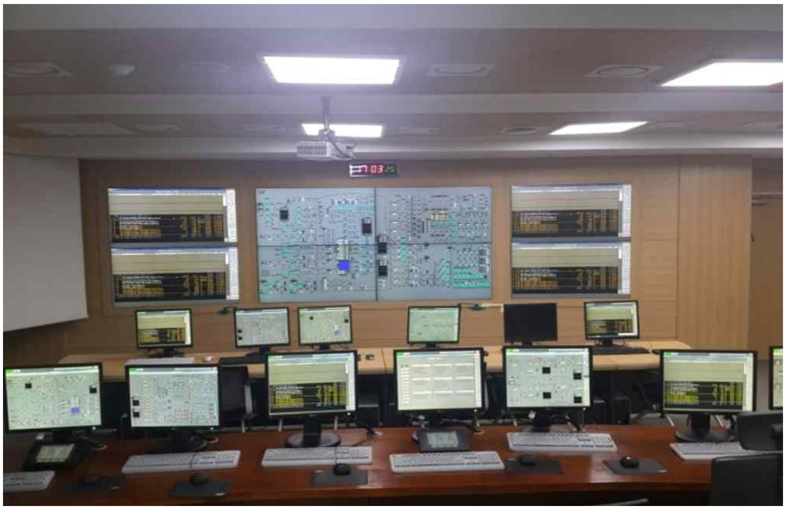


Fig. 4. APR1400 Simulator

Operator performance data, such as time, error rate, and secondary tasks, are collected through observation, audio/video recording, and simulator log data. Three or four HRA experts observe the operator task performances to collect operator error data in the scenario. As shown in Fig. 5, audio/video recording is also used to analyze time performances and errors. Operator log data in the simulator are stored to analyze the time and the secondary tasks as shown in Fig. 6.

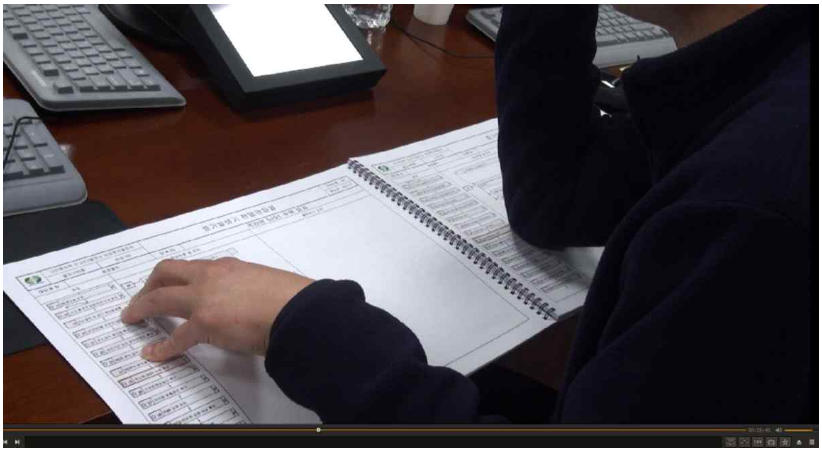
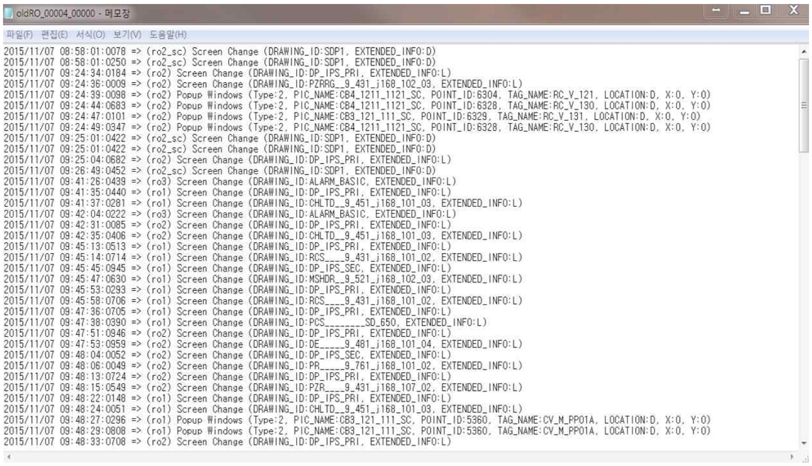


Fig. 5. Audio / Video recording



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2015/11/07 08:58:01:0078 => (ro2_sc) Screen Change (DRAWING_ID:SDP1, EXTENDED_INFO:D)
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2015/11/07 09:24:34:0184 => (ro2) Screen Change (DRAWING_ID:DP_IPS_PRI, EXTENDED_INFO:L)
2015/11/07 09:24:36:0009 => (ro2) Screen Change (DRAWING_ID:PZRRG__9_431_j168_102_03, EXTENDED_INFO:L)
2015/11/07 09:24:39:0098 => (ro2) Popup Windows (Type:2, PIC_NAME:CB4_1211_1121_SC, POINT_ID:6304, TAG_NAME:RC_V_121, LOCATION:D, X:0, Y:0)
2015/11/07 09:24:44:0683 => (ro2) Popup Windows (Type:2, PIC_NAME:CB4_1211_1121_SC, POINT_ID:6328, TAG_NAME:RC_V_130, LOCATION:D, X:0, Y:0)
2015/11/07 09:24:47:0101 => (ro2) Popup Windows (Type:2, PIC_NAME:CB3_121_111_SC, POINT_ID:6329, TAG_NAME:RC_V_131, LOCATION:D, X:0, Y:0)
2015/11/07 09:24:49:0347 => (ro2) Popup Windows (Type:2, PIC_NAME:CB4_1211_1121_SC, POINT_ID:6328, TAG_NAME:RC_V_130, LOCATION:D, X:0, Y:0)
2015/11/07 09:25:01:0422 => (ro2_sc) Screen Change (DRAWING_ID:SDP1, EXTENDED_INFO:D)
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2015/11/07 09:25:04:0682 => (ro2) Screen Change (DRAWING_ID:DP_IPS_PRI, EXTENDED_INFO:L)
2015/11/07 09:26:49:0452 => (ro2_sc) Screen Change (DRAWING_ID:SDP1, EXTENDED_INFO:D)
2015/11/07 09:41:26:0439 => (ro3) Screen Change (DRAWING_ID:ALARM_BASIC, EXTENDED_INFO:L)
2015/11/07 09:41:35:0440 => (ro1) Screen Change (DRAWING_ID:DP_IPS_PRI, EXTENDED_INFO:L)
2015/11/07 09:41:37:0281 => (ro1) Screen Change (DRAWING_ID:CHLTD__9_451_j168_101_03, EXTENDED_INFO:L)
2015/11/07 09:42:04:0222 => (ro3) Screen Change (DRAWING_ID:ALARM_BASIC, EXTENDED_INFO:L)
2015/11/07 09:42:31:0085 => (ro2) Screen Change (DRAWING_ID:DP_IPS_PRI, EXTENDED_INFO:L)
2015/11/07 09:42:35:0406 => (ro2) Screen Change (DRAWING_ID:CHLTD__9_451_j168_101_03, EXTENDED_INFO:L)
2015/11/07 09:45:13:0513 => (ro1) Screen Change (DRAWING_ID:DP_IPS_PRI, EXTENDED_INFO:L)
2015/11/07 09:45:14:0714 => (ro1) Screen Change (DRAWING_ID:RCS____9_431_j168_101_02, EXTENDED_INFO:L)
2015/11/07 09:45:45:0945 => (ro1) Screen Change (DRAWING_ID:DP_IPS_SEC, EXTENDED_INFO:L)
2015/11/07 09:45:47:0630 => (ro1) Screen Change (DRAWING_ID:MSHDR__9_521_j168_102_03, EXTENDED_INFO:L)
2015/11/07 09:45:53:0293 => (ro1) Screen Change (DRAWING_ID:DP_IPS_PRI, EXTENDED_INFO:L)
2015/11/07 09:45:58:0706 => (ro1) Screen Change (DRAWING_ID:RCS____9_431_j168_101_02, EXTENDED_INFO:L)
2015/11/07 09:47:36:0705 => (ro1) Screen Change (DRAWING_ID:DP_IPS_PRI, EXTENDED_INFO:L)
2015/11/07 09:47:38:0390 => (ro1) Screen Change (DRAWING_ID:PCS________SD_650, EXTENDED_INFO:L)
2015/11/07 09:47:51:0946 => (ro2) Screen Change (DRAWING_ID:DP_IPS_PRI, EXTENDED_INFO:L)
2015/11/07 09:47:53:0959 => (ro2) Screen Change (DRAWING_ID:DE_____9_481_j168_101_04, EXTENDED_INFO:L)
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2015/11/07 09:48:06:0049 => (ro2) Screen Change (DRAWING_ID:PR_____9_761_j168_101_02, EXTENDED_INFO:L)
2015/11/07 09:48:13:0724 => (ro2) Screen Change (DRAWING_ID:DP_IPS_PRI, EXTENDED_INFO:L)
2015/11/07 09:48:15:0549 => (ro2) Screen Change (DRAWING_ID:PZR____9_431_j168_107_02, EXTENDED_INFO:L)
2015/11/07 09:48:22:0148 => (ro1) Screen Change (DRAWING_ID:DP_IPS_PRI, EXTENDED_INFO:L)
2015/11/07 09:48:24:0051 => (ro1) Screen Change (DRAWING_ID:CHLTD__9_451_j168_101_03, EXTENDED_INFO:L)
2015/11/07 09:48:27:0296 => (ro1) Popup Windows (Type:2, PIC_NAME:CB3_121_111_SC, POINT_ID:5360, TAG_NAME:CV_M_PP01A, LOCATION:D, X:0, Y:0)
2015/11/07 09:48:29:0808 => (ro1) Popup Windows (Type:2, PIC_NAME:CB3_121_111_SC, POINT_ID:5360, TAG_NAME:CV_M_PP01A, LOCATION:D, X:0, Y:0)
2015/11/07 09:48:33:0708 => (ro2) Screen Change (DRAWING_ID:DP_IPS_PRI, EXTENDED_INFO:L)
```

Fig. 6. Simulator log data

6. Experiment procedure

Each crew conducts six scenarios and a total of 36 scenarios of performance data are collected. Each crew takes approximately 6 h to perform six scenarios. Prior to conducting the scenarios, an introductory session is held to provide an overview of the experiment as well as information on the tasks that should be performed within 30 min.

An additional 1 day of training session is conducted for the less experienced group to familiarize the group with the digital MCR. A test scenario confirmed that the group showed a consistent performance prior to entering the scenarios.

B. The Result of Statistical Analysis

This study conducts an ANOVA test for the experiment data to analyze the effect of PSFs on the operator's performance. Table 5 presents a summary of results from the ANOVA test. The details of the results are discussed below.

Table 5. A summary of results from the ANOVA test on the effect of the PSF on the operator performance

PSFs	Operator performances					
	Average completion time per instruction	Time to enter the RCS cooldown	Error rate	The number of secondary tasks	Workload	Situation Awareness
Operator experience	★★	★★	★	•	★★	•
Time urgency	•	•	•	•	•	•
Task complexity	•	•	•	★★	•	★

Note: ★★ denotes that the performance shows a statistical difference with respect to the PSF with α=0.01.

★ denotes that the performance shows a statistical difference with respect to the PSF with α=0.05.

• denotes that the performance shows no statistical difference with respect to the factor.

1. Average completion time per instruction

The average completion time per instruction indicates a significant difference only for the operator experiences (α=0.01). On an average, the more experienced group spent less time to complete an instruction when compared with that of the less experienced group. Time urgency and task complexity did not lead to any statistical differences in the average completion time per instruction. Fig. 7 shows the comparison of the experimental data with respect to the average completion time per instruction.

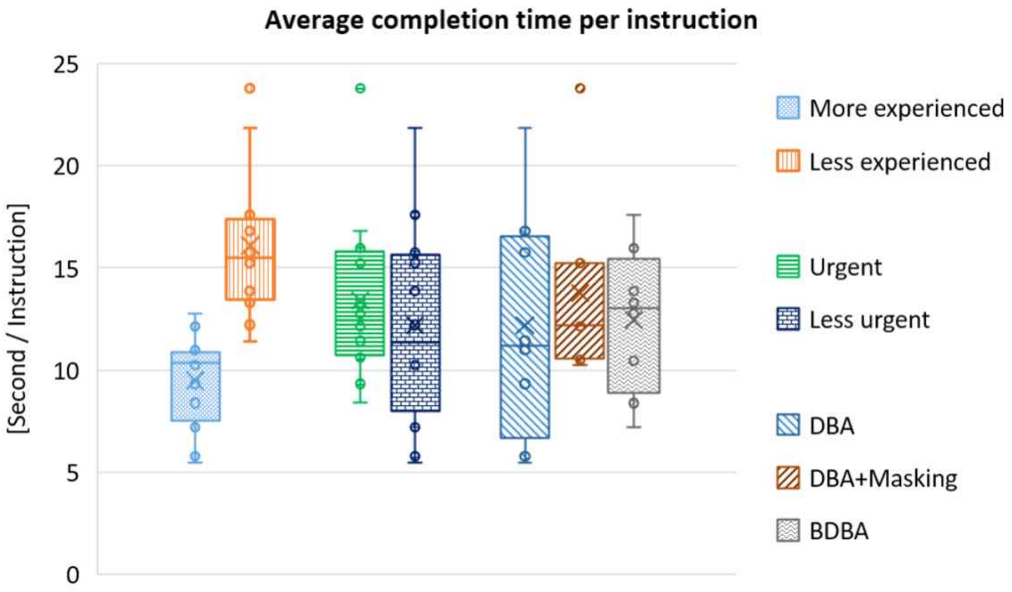


Fig. 7. Comparison of average completion time per instruction for the PSFs

2. Time to enter the cooldown of the reactor coolant system

Similarly, the time to enter the RCS cooldown only shows a statistical difference with respect to the operator experience (α=0.01). The more experienced group entered the RCS cooldown operation of RCS more quickly than the less experienced group. Fig. 8 shows the comparison of experimental data for the time to enter the RCS cooldown.

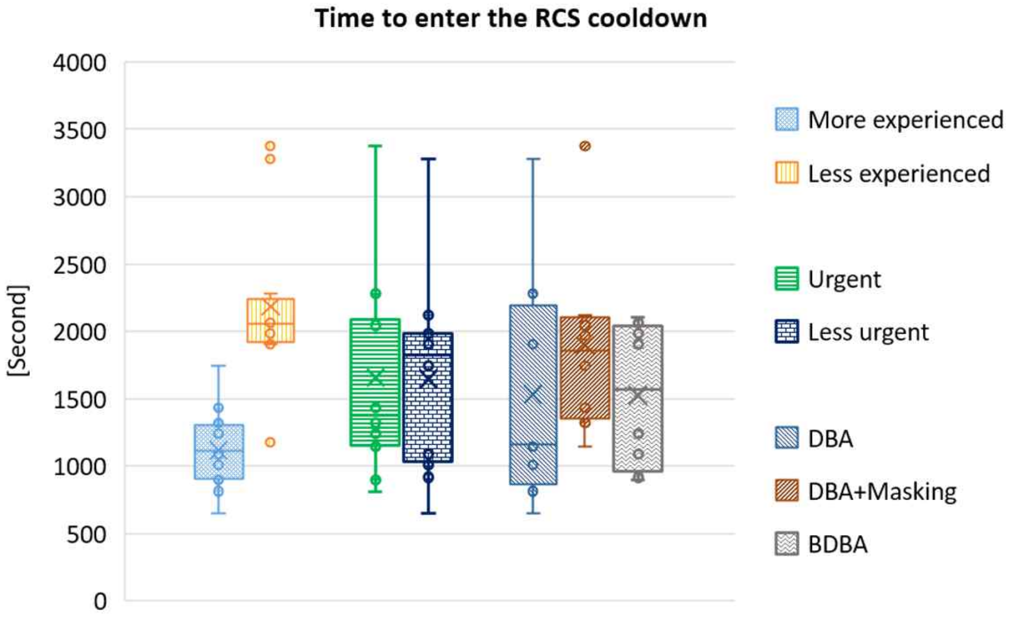


Fig. 8. Comparison of time to enter the RCS cooldown for the PSFs

3. Error rate

The result indicated that the error rate is also statistically different based on the level of operator experiences (α=0.05). The error rate of the more experienced group is lower than that of the less experienced group. However, there are no statistical differences with respect to time urgency and task complexity. Fig. 9 shows the comparison of error rates between the different levels of PSFs.

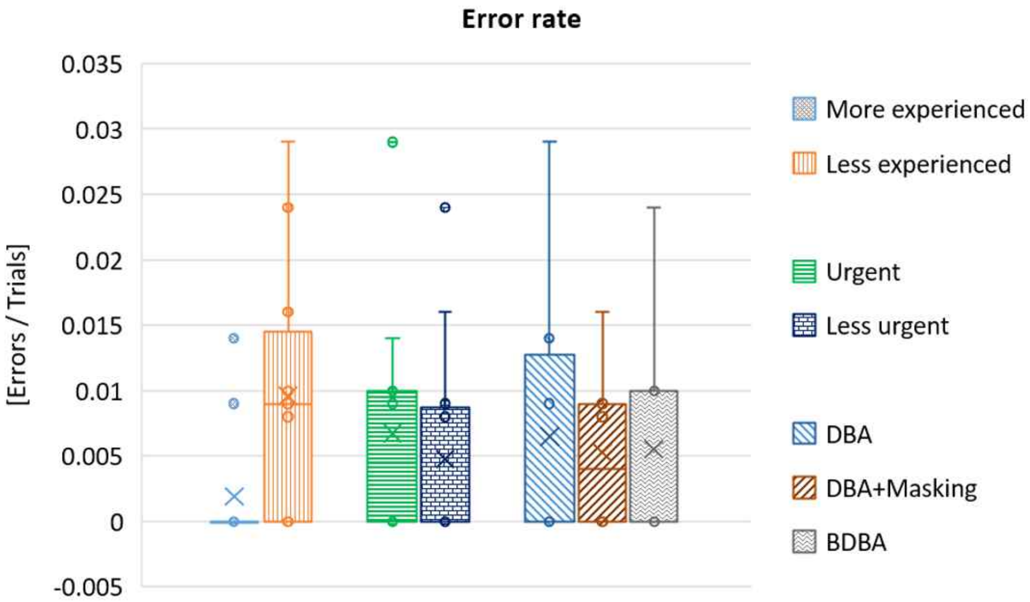


Fig. 9. Comparison of error rates for the PSFs

4. The number of secondary tasks

The number of secondary tasks shows significant differences only with respect to the task complexity (α=0.01). Fig. 10 presents the comparison of the number of secondary tasks to the PSFs. A Tukey test shows that the operators perform more secondary tasks in the scenarios of DBA + Masking of information when compared with those in the DBA and BDBA scenarios.

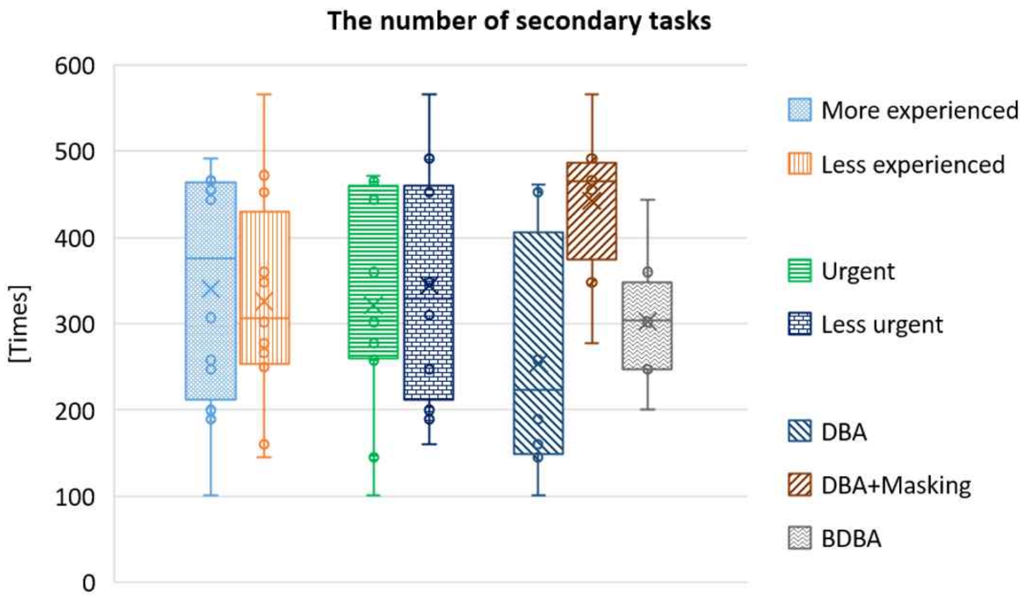


Fig. 10. Comparison of the number of secondary tasks to the PSFs

5. Workload

The results show that the less experienced group experience higher workloads in the experiment than the more experienced group (α=0.01). Time urgency and task complexity did not show any statistical differences with respect to the workload. Fig. 11 shows the comparison of workloads between the different levels of PSFs.

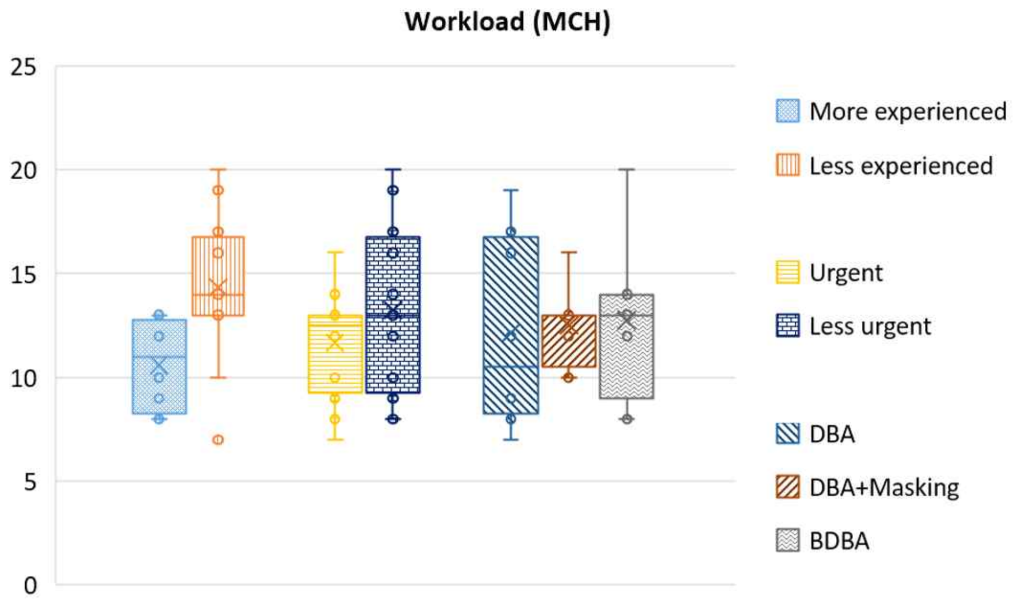


Fig. 11. Comparison of workloads for the PSFs

6. Situation awareness

The result indicates that the situation awareness shows a statistical difference with respect to the task complexity (α=0.05). Fig. 12 presents the comparison of situation awareness between the different levels of PSFs. A Tukey test indicates that the SART scale of the scenario of DBA + Masking of information is significantly higher than those of the DBA and BDBA scenarios. The operator experience and time urgency indicate no significant differences with respect to situation awareness.

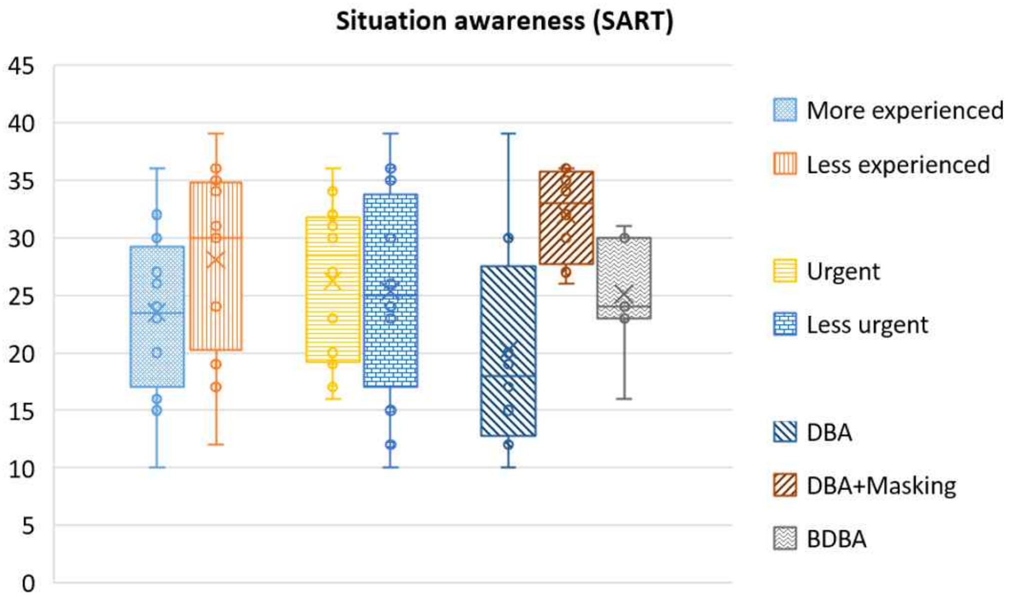


Fig. 12. Comparison of situation awareness for the PSFs

C. Discussion on the Result of Statistical Analysis

This study investigates the influence of three PSFs on six operator performances in the digital MCR. Among the six performances examined, three performances, i.e., average completion time per instruction, time to enter the RCS cooldown, and error rate, can be categorized into the performances of primary tasks, compared with the secondary task. Among the three PSFs, operator experience is most effective on the overall performances. The task complexity influences the secondary tasks and situation awareness, but did not indicate any statistical difference in the performance of primary tasks.

The result shows that the differences in operator experience affect the performances of primary tasks and workload. The difference between the two groups in the operator experience can be attributed to the possession of operating licenses for the APR1400 reactor which is the same type as the simulator. As shown in Table 4, the overall experience and knowledge of the two groups is very similar except with respect to the experience related to APR1400 reactor.

The time urgency did not show any differences relative to the operator performance. However, this result does not mean that time urgency has no influence on the operator performances. Instead, this experiment distinguishes the time urgency by specifying the requirement of 30 min. Therefore, the result indicates that the 30 min requirement does not make any significant difference in the operator performance.

It should be noted that 30 min is often used as a time criterion to discriminate the urgency of tasks in HRA methods [2,4,42,50]. Two different interpretations can be made based on the experiment results. The first interpretation is that the 30 min requirement does not impose additional burden on the operator irrespective of the MCR types, i.e., analog or digital control rooms. The other interpretation is that the features of digital MCRs may facilitate more rapid information gathering and control actions when compared with those of analog MCRs. The digital MCR holds the potential to help the operator obtain information and execute actions more quickly. For instance, all the operators can access any information related to the plant operation in the digital MCR. Conversely, in the analog MCR, the operator needs to communicate with other operators or physically move to the corresponding board to obtain information on the system that is the responsibility of the other operator. Furthermore, in the APR1400 MCR, the operators can share the same information through the large display panel located in front of the control room and can discuss the plant status in a convenient manner. However, in order to investigate the effect of time urgency in depth, further experiments that apply a wider span of time requirements, such as 10 min or 60 min, and compare the operator performances of analog and digital MCRs are required.

The result indicates that the task complexity can affect the performance of secondary tasks that are newly introduced in the digital MCR. On the other hand, time urgency and operator experience indicate no statistical difference with respect to the number of secondary tasks. A human factors issue relating to the secondary tasks involves the issue where the burden of secondary tasks may affect the performance of primary tasks. NUREG-6690 [35] pointed out that under high workload situations, the additional workload due to the secondary tasks may interfere with the operator’s ability to monitor and control the plant. Therefore, there is a possibility that the high task complexity may affect the performances of primary tasks in the digital control, although this relationship is not examined in the present study.

IV. Inter-relationship between PSFs based on an Experiment in a Simulator with a Digital Control Room

A. The Treatment of Inter-relationships between PSFs in HRA

Recent interest in the inter-relationships of PSFs has been increasing in the HRA field. A few approaches deal with the mutual dependency between PSFs in a systematic way, such as the Cognitive Reliability and Error Analysis Method (CREAM) [41], Standardized Plant Analysis Risk-HRA (SPAR-H) [43], and Information, Decision, and Action in Crew context (IDAC) [51]. CREAM describes how PSFs affect each other in a qualitative way, whereas IDAC tries to analytically describe the mutual dependencies among the states of PSFs and is a very complex application that requires a great deal of effort by the analyst. Boring [52] introduced a statistical correlation between PSFs and discussed the proper number of PSFs that should be considered by HRAs. Groth [53] performed correlation and factor analyses on PSF data and found four groupings to be the best fit for the data. De Ambroggi and Trucco [54] suggested a systematic approach for modelling and assessing dependent PSFs using the analytic network process, based on expert judgments. Although a few studies suggested a quantitative relationship between PSFs [52,53], they did not provide procedural guidance on using it to estimate HEP. In addition, a more objective guide needs to be developed so that analysts can handle inter-dependency between PSFs.

This study attempts to answer three questions regarding the treatment of inter-relationships between PSFs, based on the experiment introduced in the previous Section. One of the benefits of this experiment is that it is possible to control and measure the PSFs directly. Therefore, more flexibility is possible in the experiment for the study of inter-relationships between PSFs. The first question is, between which PSFs do inter-relationships exists and how strong are the relationships between them? To answer this question, this study includes a correlation analysis using the experimental data. The second question is, can PSFs that influence others or each other be categorized into groups? A factor analysis was used to identify a PSF group in which PSFs showed similar patterns. The answer to this question may also have an effect on reducing the number of PSFs considered in a HRA, because the excess of PSFs is a problem with existing HRA methods [52]. The third question is, how can a group of PSFs be applied to the quantification of HEPs? This study investigates the feasibility of the results of a factor analysis (i.e., PSF groups, factor loadings and eigenvalues) in the estimation of HEPs in the experiment.

B. Inter-relationship of PSFs: Correlation and Factor Analyses

In the experiment, a total of 36 scenarios were conducted. Six PSFs were selected for the analysis: operator experience, available time, task complexity, workload, situation awareness, and secondary task. Among them, Two PSFs were controlled by the experimental conditions: experience and task complexity. Three were measured in the experiment: workload, situation awareness, and number of secondary tasks. Available time was estimated by using a combination of controlled and measured variables. Table 6 shows the experimental conditions of the PSFs for the 36 scenarios and the quantitative values of the conditions used for the correlation analysis. The quantitative value is based on the multiplier of PSFs in the SPAR-H method.

Table 7 presents the results of a correlation analysis between PSFs. The correlation between experience and task complexity was not analyzed because both were controlled variables. The results indicate that the relationships of six pairs of PSFs were statistically significant. Fig. 13 shows the relationships between the PSFs with correlation coefficients and statistical significances. A strong correlation was found between workload and the number of secondary tasks (R=0.507). Workload and situation awareness showed a strong negative correlation (R=-0.551).

Two factor groups were identified through the factor analysis, on the basis of their eigenvalues being over 1.0, as shown in Table 8. In Factor Group 1, three PSFs—workload, situation awareness, and number of secondary tasks—showed a similar pattern. Workload and number of secondary tasks contributed positively to this group, while situation awareness contributed negatively. The second group included experience and available time. The pattern of this group is obvious because the less-experienced crews performed tasks slower than the experienced ones, and so the time required increased and the available time became less sufficient.

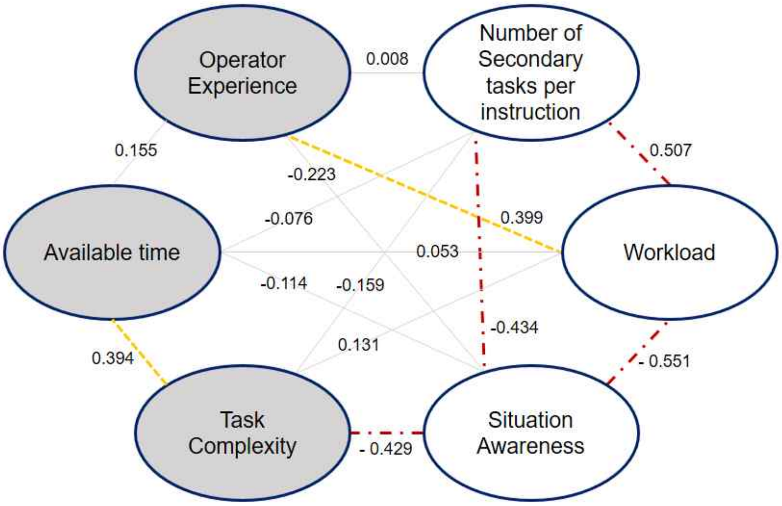
Table 6. Experimental conditions of PSFs

Crew	Scenario	Experience		Task Complexity		Available Time	
		Level	Quantity	Level	Quantity	Level	Quantity
1	1	High	0.5	Nominal	1	Sufficient	0.1
	2	High	0.5	Moderate	2	Nominal	1
	3	High	0.5	Complex	5	Nominal	1
	4	High	0.5	Moderate	2	Sufficient	0.1
	5	High	0.5	Nominal	1	Sufficient	0.1
	6	High	0.5	Complex	5	Nominal	1
2	1	High	0.5	Nominal	1	Sufficient	0.1
	2	High	0.5	Moderate	2	Nominal	1
	3	High	0.5	Complex	5	Nominal	1
	4	High	0.5	Moderate	2	Sufficient	0.1
	5	High	0.5	Nominal	1	Sufficient	0.1
	6	High	0.5	Complex	5	Sufficient	0.1
3	1	High	0.5	Nominal	1	Nominal	1
	2	High	0.5	Moderate	2	Nominal	1
	3	High	0.5	Complex	5	Nominal	1
	4	High	0.5	Moderate	2	Sufficient	0.1
	5	High	0.5	Nominal	1	Sufficient	0.1
	6	High	0.5	Complex	5	Nominal	1
4	1	Low	3	Nominal	1	Sufficient	0.1
	2	Low	3	Moderate	2	Nominal	1
	3	Low	3	Complex	5	Insufficient	10
	4	Low	3	Moderate	2	Sufficient	0.1
	5	Low	3	Nominal	1	Sufficient	0.1
	6	Low	3	Complex	5	Nominal	1
5	1	Low	3	Nominal	1	Sufficient	0.1
	2	Low	3	Moderate	2	Nominal	1
	3	Low	3	Complex	5	Nominal	1
	4	Low	3	Moderate	2	Sufficient	0.1
	5	Low	3	Nominal	1	Sufficient	0.1
	6	Low	3	Complex	5	Nominal	1
6	1	Low	3	Nominal	1	Sufficient	0.1
	2	Low	3	Moderate	2	Nominal	1
	3	Low	3	Complex	5	Nominal	1
	4	Low	3	Moderate	2	Sufficient	0.1

Table 7. Results of the correlation analysis for six PSFs from the experiment

	Experience	Available Time	Task Complexity	Number of Secondary Tasks	Workload	Situation Awareness
Experience	1					
Available Time	0.155	1				
Task Complexity	–	0.394*	1			
Number of Secondary Tasks	0.08	-0.076	-0.159	1		
Workload	0.399*	0.053	0.131	0.507**	1	
Situation Awareness	-0.223	-0.114	-0.429**	-0.434**	-0.551**	1

Note: ** = p<0.01, * = 0.01p<0.05



Value of Correlation Coefficient	Line Shape & Color		P-value
± 0.8 – ± 1.0	·	·	≤0.05
± 0.6 – ± 0.8	———	Red	≤0.05
± 0.4 – ± 0.6	— · — · ·	Red Brown	≤0.05
± 0.2 – ± 0.4	- - - - -	Orange	≤0.05
± 0.0 – ± 0.2	············	Gray	≤0.05
·	———	Light Gray	>0.05

Fig. 13. An illustration of the correlations between six PSFs from the experiment

Table 8. The results of the factor analysis from the experiment

PSFs	Factor 1	Factor 2
Operator experience		0.709
Available time		0.76
Task complexity		
Number of secondary tasks	0.808	
Workload	0.837	
Situation awareness	-0.774	
Eigenvalue	2.044	1.253

C. Feasibility of a Context-based Approach to Treating the Inter-dependency of PSFs

In a factor analysis, a factor is defined as a construct operationally defined by its factor loadings [55]. Furthermore, factor loadings are the correlations of a variable with a factor. In other words, a factor is a condensed statement on the relationship between a set of variables. Factor loadings represent a statistical correlation between a variable and a factor. The sum of squares of the factor loadings of each factor reflects the proportion of variance explained by each factor. An eigenvalue is the total amount of variance for the factor. The average of the squared loadings of a factor (i.e., eigenvalue/the number of variables in the factor) shows the percentage of variance explained by that factor. For instance, if a factor has an eigenvalue of 1.74 and four variables, then, 1.74/4=0.43; thus, the factor can explain 43 percent of the variance in the correlation matrix.

This study identified two PSF groups from the experiment. Fig. 14 shows the two factor groups and the factor loadings of PSFs, which indicate the correlation between a PSF and the factor.

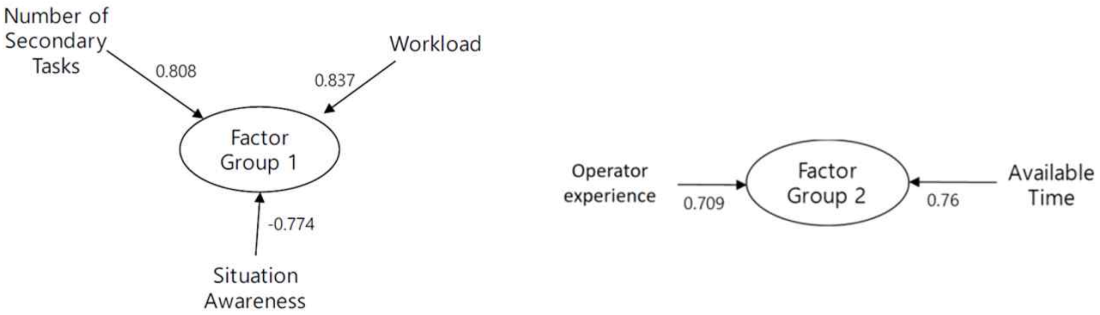


Fig. 14. Identified PSF groups from the experiment

This section discusses the feasibility of applying PSF groups to the estimation of HEPs. The experiment in the previous Section also measured operators' errors while following the instructions for the procedures. This section investigates how the results of the factor analysis could be used to estimate the HEP in the experiment. First, we defined a PSF group score. It evaluated the effect of a PSF group that contained PSFs. A PSF group score could be calculated by the sum of multiplications with factor loading of PSFs and a normalized score of an individual PSF. The normalized score of an individual PSF represented the result of a PSF evaluation in the HRA. For instance, if the scenario was evaluated as “extremely complex,” we assigned “1 (highest score)” to the normalized score of complexity. Thus, the PSF group value was calculated as follows:

$$PSF\,group\,score = \sum_{i}^{n} factor\,loading\,of\,PSF\,i \times normalized\,score\,of\,each\,PSF\,i \quad (1)$$

$$(n = the\,number\,of\,PSFs\,in\,the\,group)$$

Table 9 shows an example of the normalized scores of individual PSFs for Scenario 2 in the experiment. Workload, situation awareness, and number of secondary tasks in the scenario were evaluated as 0.30, 0.53, and 0.49, respectively. Then, the PSF group score of Group 1 for the scenario could be calculated using the factor loadings in Fig. 14, as below:

$$PSF\,group\,score\ \mathrm{for}\ Group\,1 = 0.837 \times 0.30 - 0.774 \times 0.53 + 0.808 \times 0.49 = 1.09$$

Then, the total PSF score was defined. The total PSF score was the weighted sum of the PSF group scores. The total PSF score evaluated the effect of total PSFs that were influential in a scenario. As a weighting factor, the score used the “eigenvalue of a factor/the number of variables in the factor,” which means the extent to which the factor could explain the variance in the correlation matrix, as mentioned above. The total PSF score could be calculated by using the following formula:

$$Total\ PSF\ Score = \sum_{j}^{m} \frac{Eigenvalue\ of\ Group\ j}{The\ number\ of\ PSFs\ in\ Group\ j} \times PSF\ group\ score\ \text{for}\ Group\ j \qquad (2)$$

$$(m = the\ number\ of\ PSF\ groups)$$

For the example in Table 9, the total PSF score for the scenario was calculated as follows:

$$Total\ PSF\ Score\ \text{for}\ Scenario\ 2\ = \frac{2.044}{3} \times 1.09 + \frac{1.253}{2} \times 0.076 = 0.79$$

Table 9. An example of calculating 1) PSF group scores and 2) total PSF scores

Scenario	Normalized Score of Individual PSFs for Group 1			Group Score of Group 1	Normalized Score of Individual PSFs for Group 2		Group Score of PSF Group 2	Total PSF Score	Error Rate
	Workload	Situation Awareness	Number of Secondary Tasks		Available Time	Operator Experience			
2	0.30	0.53	0.49	1.09	0.10	0	0.076	0.79	0.009

To investigate whether the PSF group score and total PSF score could explain error rates in the experiment, this study compared correlation coefficients for 1) PSF group score and error rate, 2) total PSF score and error rate, and 3) SPAR-H PSF score and error rate. The scores and correlation coefficients of the 36 scenarios in the experiment were calculated. For the SPAR-H PSF scores, the experimental conditions of PSFs in Table 6 were used. For instance, the multiplication of PSF quantities for Scenario 1 of Crew 1 could be calculated as follows:

$$\begin{aligned} SPAR-H\ Score\ &= \sum_{1}^{3} PSF\ Quantity\ i \\ &= 0.5(\mathrm{E}xperience) \times 1(Task\ Complexity) \times 0.1(Available\ Time) = 0.05 \end{aligned}$$

Table 10 presents the results of the correlation analysis. The results show that the correlations between the PSF group scores for Groups 1 and 2 and error rates were statistically significant, individually. In addition, the total PSF score showed a stronger correlation with the error rate than individual group values. However, the SPAR-H PSF score did not show any statistical correlation with the error rates. Therefore, the results indicate that among the four relationships, the total PSF score had the highest correlation with the error rates in the experiment.

Table 10. Correlation analysis for the PSF group values and error rates in the experiment

Relationship	Correlation Coefficient (p-value)
PSF group score of group 1 vs. error rate	0.458 (0.005)
PSF group score of group 2 vs. error rate	0.379 (0.023)
Total PSF score vs. error rate	0.539 (0.001)
SPAR-H PSF score vs. error rate	0.085 (0.623)

V. Conclusion

This study attempted to experimentally investigate 1) the effect of PSFs on operator performances and 2) the inter-relationship between PSFs by using an NPP simulator with a high fidelity.

The first study analyzed the relationship between PSFs and operator performance in a digital control room. Three PSFs and six operator performances were considered in the experiment. An experiment with a high fidelity was conducted with four groups of licensed operators. The experimental results statistically indicate that the PSF of operator experience affects most operator performances, such as average completion time per instruction, time to enter the RCS cooldown, error rate, and workload. The study also shows that the task complexity influences the number of secondary tasks and situation awareness. However, there is no difference in operator performances with respect to the time urgency. This study represents an on-going effort to experimentally collect data on the effects of the operator performances with respect to different PSFs. In the future, more experiments will be conducted, for example, by extending the time urgency requirements to 10 min and 60 min. It is expected that this study would contribute to a realistic estimation of human error probabilities with more data.

In the case of the second study, the inter-relationships between PSFs were investigated for HRAs of NPPs. Although it is obvious that PSFs have relationships with each other, current HRA methods do not treat the combined effect of PSFs on human errors sufficiently. Based on the experiment with a simulator—this study performed correlation and factor analyses. As a result, several PSF groups in which PSFs showed a similar pattern were identified. Finally, this study discussed the feasibility of using the identified PSF groups to estimate HEPs in the results of the experiment.

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