

Is the higher level of automation the better? This paper gives you the answer.

Effects of Automation for Emergency Operating Procedures on Human Performance in a Nuclear Power Plant

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Abstract: The digitization of the control systems in the main control room of a nuclear power plant has changed the operators' role in coping with accidents and has thus brought about new human factor problems. This article focuses on the procedures that are used for guiding the emergency operating procedures in a nuclear power plant, and experimentally investigates the effects of the digitization of procedures on operators' mental workload and situation awareness. In these experiments, the procedures at three different levels of automation, namely, paper-based procedures (PBPs), electronic procedures (EPs), and computer-based procedures (CBPs), are used as the independent variables. According to the experimental results, using these procedures at a high level of automation enables the operator to exhibit favorable operational performance with a decreased mental workload; however, the operator's situation awareness (SA) is decreased. The research results presented here can provide a reference level for optimally setting the level of automation of the emergency operating procedures in a nuclear power plant and provide support

for the optimization of a corresponding HRA (Human Reliability Analysis) model. *Health Phys.* 121(3):261–270; 2021

Key words: operational topics; exposure, radiation; health effects; nuclear power plant

INTRODUCTION

Nuclear power plants generally use emergency operating procedures to guide the operators to properly handle accidents (Chiuhsiang et al. 2016). Seasoned operators can execute the necessary tasks even without the guidance of procedures (Chang et al. 1999); however, for complex tasks such as the normal startup and shutdown of the reactor, most operators experience a high cognitive workload (Peng and Zhi 2014). Therefore, under emergency situations, the operators should follow the guidance of emergency operating procedures. The procedures can be classified into two major types according to the medium such as paper-based

procedures (PBPs) and computerized procedures (CPs) (EPRI 2009).

Excessive reliance on automation can lead to mistakes due to complacency, operator inattentiveness, and lack of familiarity with the actual operations of a reactor plant. Automation-related automation bias and complacency have typically been considered separately and independently. Generally speaking, automation complacency happens under conditions of multiple-task load, while manual tasks compete with the automated task for the operators' attention. Automation complacency can be found in naive as well as expert participants and cannot be overcome with simple practice. Automation bias results in making both omission and commission errors when decision aids are deficient. Automation bias cannot be avoided by instructions or training, and it can affect decision making in individuals and teams. If automation bias is viewed as a special case of decision bias, our studies suggest that it depends on attentional processes that are the same as those involved in automation-related complacency. Complacency and automation bias show distinct manifestations of overlapping automation-induced phenomena, with attention working as an essential component. A model

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of complacency and automation bias demonstrates that they result from the dynamic interaction of personal, situational, and automation-related characteristics (Parasuraman and Manzey 2010).

The use of automation technology is becoming increasingly popular in complex systems, e.g., aviation, autopilot, nuclear power, health care, and driverless cars, and these technologies become more readily available. However, the extent to which automated aids will actually improve performance is difficult to predict, given that these aids are unlikely to be 100% reliable and, as such, operators may not trust them (Poornima et al. 2016).

Automation does not mean that humans are replaced; quite the opposite. Increasingly, humans are asked to interact with automation in large-scale and complex systems, including aircraft and air traffic control, nuclear power, manufacturing plants, military systems, homes, and hospitals. This is not an easy or error-free task for either the system designer or the human operator/automation supervisor, especially as computer technology becomes ever more sophisticated (Sheridan and Parasuraman 2005).

When operators trust an automation that is more reliable than manual performance, they are more likely to rely on the automation than on their own experience. Similarly, when operators distrust an automation that is less reliable than manual performance, they are more likely to ignore the automation and rely on themselves to control a situation. In both cases, appropriate reliance occurs. However, over-reliance or misuse can occur when an operator over trusts an automation aid that is less reliable than unaided performance. Likewise, when operators under trust an automation that is more reliable than manual performance, under-reliance or disuse of automation can occur.

In traditional analog control systems, paper-based procedures

are usually used for emergency operating procedures. Unfortunately, it has been found that PBPs are associated with various factors that can lead to human errors, which are described in detail as follows:

1. The operators must manually switch among different procedures, which increases the workload (Fink et al. 2009). In particular, when multiple accidents overlap, many operators feel confused (Converse 1995);
2. During the implementation of the procedures, the operators have to monitor the variation of the relevant parameters on different media (Niwa et al. 1996);
3. The displayed information is static and sometimes does not reflect the real-time status of the power plant (Fink et al. 2009); and
4. It is difficult to update and upgrade the procedures (Niwa et al. 1996).

With the rapid development of computer technology and the progress of achievable levels of automation, the emergency operating procedures have been gradually digitized and computerized. The application of computerized procedures has become one of the defining characteristics in advanced main-control rooms around the world (Niwa et al. 2001). Computerized procedures represent the integration of paper-based procedures and advanced human-system interfaces. With the aid of the corresponding digital control systems, these computerized procedures can provide the operators with the following abilities (Li et al. 2011; Liu et al. 2007):

1. The operators can switch among different programs by simply clicking navigation links, which greatly reduces the workload under emergency situations;
2. The operators can monitor the relevant parameters to dynamically track the status of the entire plant;

3. The parameters that are required to be monitored by operators during the procedures are displayed together to reduce the difficulty in searching for information; and
4. The computerized procedures can be easily updated and upgraded.

It has been reported that the advanced features of computerized procedures can remarkably reduce the operators' workload and improve performance during the execution of procedures (Chiuhsiang et al. 2016). However, these computerized procedures change the operators' roles and their working conditions. The ability of automating some of the necessary routines becomes possible, but the computerized procedures may also bring about some new factors that can degrade a human's performance. For example, the overlapping of the digital display interfaces can easily cause an operator to lose situation awareness of the plant's condition, and thus reduce the operating team's understanding of the overall status of the plant (Kawai et al. 1999).

Kaber and Endsley (2020) improved the previous work on two methods to human-centered automation: intermediate levels of automation (abbreviated for LOAs) for keeping operator involvement in complex systems control and facilitating situation awareness; and adaptive automation (AA) for handling operator workload based on dynamic control allocations between the human and machines with time. The experiments were conducted to evaluate the LOA and AA approach independently, with the objective of detailing a theory of human-centered automation (Kaber and Endsley 2020).

A digital automation control system software test strategy based on real nuclear power plant platform was proposed. This proposed strategy analyzed the system function and software logic path

Table 1. Examples of functionality provided by different categories of computerized procedures (EPRI 2009).

Functionality	PBP	CPs		
		EPs	CBPs	CBPs with PBA
Medium for presentation of procedure	Paper			
Ability to select and display procedure on computer screen		Yes	Yes	Yes
Navigation links to aid in moving between procedures		Possibly	Yes	Yes
Automatic display of process information relevant to a procedure step			Yes	Yes
Automatic processing of procedure step logic and display of results			Possibly	Yes
Integrated soft controls providing capability to send control commands to equipment			Possibly	Yes
Ability for machine to carry out multiple steps on command from operator				Yes

characteristics and discovered the system state by the method of threshold boundary analyzing and designed a test approach based on the random combination of logical combination paths and parameter value intervals and, finally, created a real platform test environment. In particular, the functions of pressurized water reactor protection system were tested and the empirical results demonstrate that the test strategy has significantly improved the coverage of paths and parameters (Xi et al. 2020). The design of the automated human-machine interface in the power plant’s main control room should mainly aim to improve human performance (including mental load, situation awareness, etc.) and to optimize human factor engineering designs, analyses, and verifications in accordance with the tasks performed by the operators. In this study, the effects of the levels of automation on human mental load and situation awareness are investigated through experiments to provide a reference for the automated design of emergency operating procedures in nuclear power plants.

The organization of the work is given as follows. First, the levels of automation of the computerized procedure of a standard nuclear plant are introduced. Then, the experimental setup, the critical variables in the experiment, and the experimental procedures are

explained. Outcomes are analyzed, followed by the conclusion.

LEVELS OF AUTOMATION

Automation can be applied at four different stages in which the operator processes information: (1) monitoring, (2) status assessment, (3) planning of response, and (4) implementation of response (Parasuraman et al. 2000). The level of automation required at each of these cognitive stages is application dependent. Usually, automation at the lowest level simply integrates the information in order to facilitate status monitoring, while automation at a high level needs almost no human intervention.

Generally speaking, a lower level of automation means the operators’ operational load is higher, thereby leading to a decline in performance; using a higher level of automation can reduce the operational load to a certain degree;

however, the operators may rely too much on the automatic control system and relax, leading to a reduction of situation awareness and a decline in performance (Huey Wickens 1993; Kaber and Endsley 2000). Thus, automation reduces some aspects of the workload, but also introduces new issues. A higher level of automation may cause a decline in the operators’ situation awareness due to the following aspects: (1) reduction of alertness, (2) excessive trust in automation, (3) the automated systems are more complex, (4) unfavorable human-machine interface design, and (5) lack of trust in automation (Endsley 1997).

In terms of functionality, the computerized procedures exhibit different levels of automation. As listed in Table 1, three levels of automation in computerized procedures are defined by the Electric Power Research Institute (EPRI) (EPRI 2009):

Electronic procedures (EPs), i.e., to display the images and text on a computer screen. EPs basically reproduce the paper-based procedures on a computer screen and provide the most basic support such as the links for switching among relevant procedures;

Computer-based procedures (CBPs), which provide support in the following aspects: automatic retrieval and display of the specific information required to complete the current procedure; direct display of relevant information on the procedure interface or other interfaces;

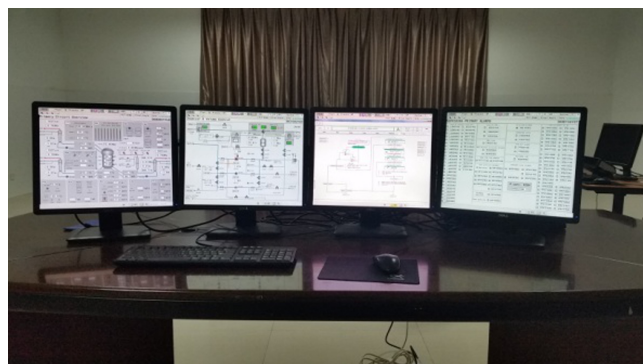


FIG. 1. Simulation platform in the experiments presented here.

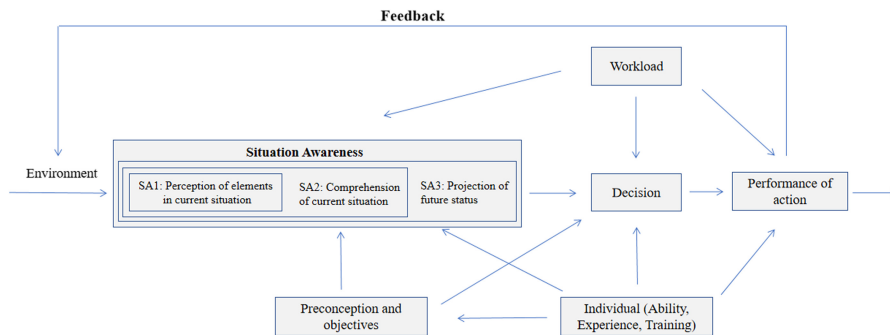


FIG. 2. SA Model.

monitoring the plant’s status and tracking the trends in important parameters; providing suggestions regarding the priority of processing for the emergency operations (which will be ultimately decided by the operators); and CBP with procedure-based automation (CBP with PBA), i.e., the operators can authorize a series of procedural steps such that the system can automatically implement the related decisions and operations according to the procedures.

Reliability of automation is an optimum balance between operator fatigue and operator complacency. Reliability of automation is known to impact operator reliance on automation. The influence of reliability and the effects of operator fatigue might interact. The present study conducted by Wohleber et al. (2016) investigated the impact of automation reliability on accuracy and reliance and how this impact changes with the level of fatigue during simulated multiple unmanned aerial vehicle operation. Participants completed a two-hour simulated multiple unmanned aerial vehicle mission assisted by an automated decision making aid of either high or low reliability. A decrease in subjective task engagement and performance over time marked the induction of passive fatigue by the mission. Participants were more trusting in the high reliability condition than in the low reliability condition. Lastly, reliance decreased with time at any reliability;

however, a significant interaction between reliability and time on task demonstrates that the decrease is of smaller magnitude as the automation was reliable.

EXPERIMENTAL DESIGN

A simulated steam generator tube rupture (SGTR) is designed as the accident in a nuclear plant which needs operators to intervene at different levels of automation. The experimental setup is stated as follows.

Subjects in the experiments

The subjects in the experiments presented here are all senior undergraduate and graduate students on campus in nuclear engineering and its relevant majors. The subjects include 14 males and 6 females whose ages range from 20 to 27 y, all of whom are familiar with computer operations but have no operations experience with the control systems in nuclear power plants.

Devices used in the experiments

A simulation platform of the control system in a nuclear power plant (as shown in Fig. 1), which was independently developed by the Hunan Institute of Technology, is used in the experiments presented here. This platform completely models the operators’ control platform and human-machine interface in the main control room of a nuclear power plant, and the actual state-oriented procedures of a nuclear power plant are used in the present study. The hardware for the simulation platform consists of four 19-inch color liquid crystal displays, which are numbered as No. 1 Screen to No. 4 Screen from left to right. The procedures in the experiments are divided according to different levels of automation, and all of the relevant operations are implemented on this digital platform.

The SGTR accident is selected as the experimental scenario. SGTR accidents have repeatedly occurred in the history of nuclear power, and the operators’ timely and accurate interventions are quite important. The necessary operational procedures include many steps, which make SGTR accidents a good representative test case. If the operators cannot give the correct response in time and according to the procedures, the primary coolant may be directly discharged into the environment through the pressure relief valve on the secondary side of the safety valve; more seriously, the broken vapor generator may be full and thus overflow, which would greatly

Table 2. LSD multi-comparison results of SA1 scores.

(I) Level of Automation	(J) Level of Automation	Mean difference (I-J)	Standard error	Statistical significance	95% confidence level	
					Lower limit	Upper limit
PBP	EP	.093750 ^a	.042130	.030	.00939	.17811
	CBP	.187500 ^a	.042130	.000	.10314	.27186
EP	PBP	-.093750 ^a	.042130	.030	-.17811	-.00939
	CBP	.093750 ^a	.042130	.030	.00939	.17811
CBP	PBP	-.187500 ^a	.042130	.000	-.27186	-.10314
	EP	-.093750 ^a	.042130	.030	-.17811	-.00939

^aThe significance level of the mean difference is 0.05.

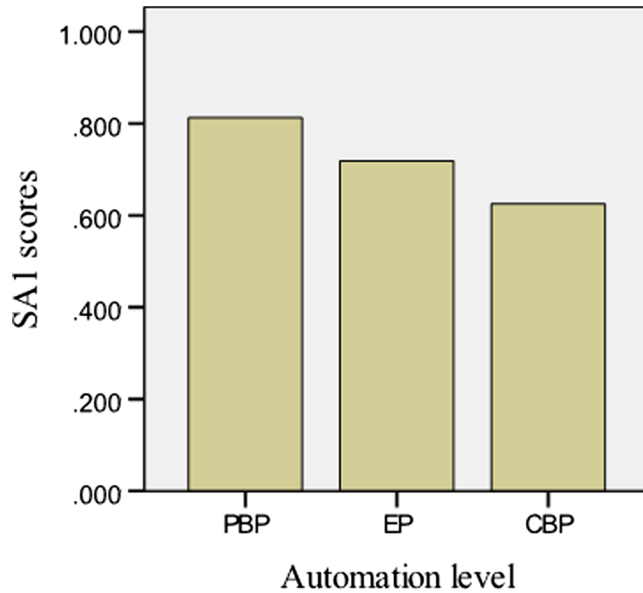


FIG. 3. SAI scores using the procedures at the different levels of automation.

aggravate the accident’s radiological consequences.

Variables in the experiments

The independent variables in the experiments presented here are the most common emergency operating procedures at three different levels of automation: PBPs, EPs and CBPs. Each subject is required to complete the experiments using the procedures at all three different levels. The descriptions of the procedures at the three different levels of automation in these experiments are:

1. PBPs: the required operation procedures in the experiments are displayed on paper, completely independent of a computer;
2. EPs: the PBPs are displayed on the computer screen in the form of images, and the links among the associated procedures and those between the procedures and the operation interfaces are provided; and
3. CBPs: in addition to the support provided by the EPs, parameters and systems that should be monitored and operated are automatically displayed according to the procedural steps being performed.

The dependent variables include the multi-level situation

awareness score, the human mental load. The detailed measurement methods are described below.

Multi-level situation awareness score. From the perspective of information architecture, Endsley classified the situation awareness (SA) into three levels as is depicted in Fig. 2 (Endsley 1995): the first level (SA1) is the human’s perception of the key environmental factors; the second level (SA2) is the human’s comprehension of the key factors, i.e., the human can understand the underlying meanings of the factors through further analysis and integration of the factors perceived at the first level of situation awareness; the third level (SA3) is the projection of the system’s future status, i.e., the human can predict the system’s future development tendency based on the integration

of the situation awareness from the first and second levels, and thus make appropriate decisions.

The situation awareness global assessment technique (SAGAT) is used to estimate the multi-level situation awareness scores of the subjects (Endsley 1988). The SAGAT freezes the experiment at a randomly selected time, and the subject must answer questions that correspond to different levels of situation awareness. The number and rate of correct answers are used as the evaluation criterion.

Mental load. In the present study, the task-load-index questionnaire proposed by the National Aeronautics and Space Administration (NASA) (also referred to as the NASA-TLX questionnaire is used to assess the subject’s mental load (Hart and Staveland 1988). The NASA-TLX questionnaire is a subjective assessment method that includes six representative indexes: mental demand, physical demand, time demand, performance, effort, and frustration level. After each experiment, the subject scores each index according to his/her subjective experience and determines the weight of each index through pairwise comparison.

Experimental procedures

Before the experiments, each subject received an experiment manual and a 3-h training course. The training included the following materials: the objective of the present study, the main system knowledge of a nuclear power

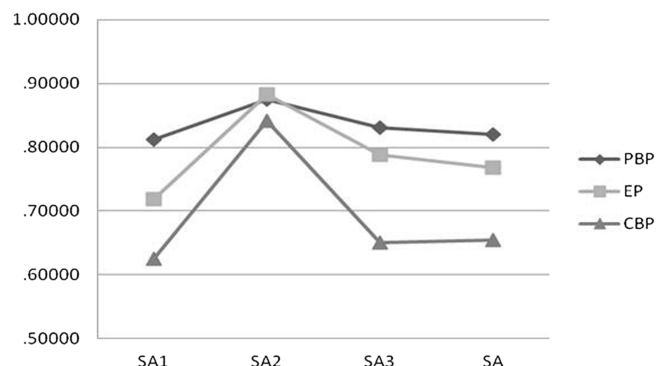


FIG. 4. SA2 scores using the procedures at the different levels of automation.

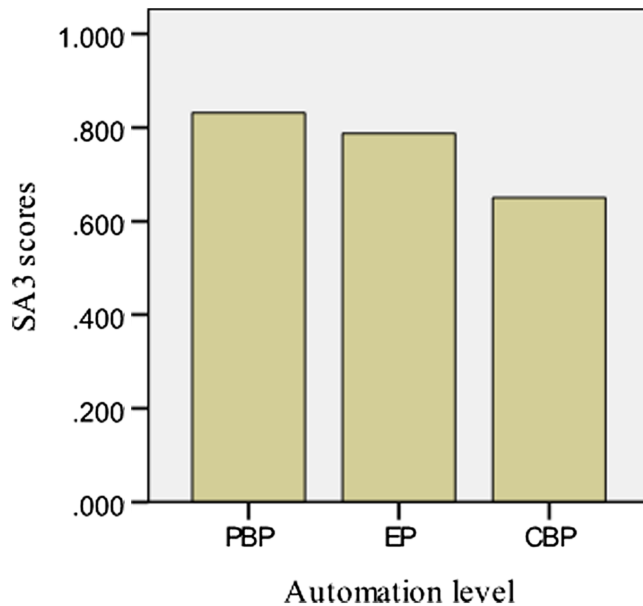


FIG. 5. SA3 scores using the procedures at the different levels of automation.

plant, the operation approach of the simulation platform, and the application method of the procedures. After the training was finished, each subject implemented the operations and exercises no less than three times. The procedure and interface during practice were the same as those during the formal experiment except that the operation was not terminated by operation error.

After a 15-min rest, the 20 subjects finished the execution of the procedures at the above-described three levels of automation in a randomly drawn order. During the process of coping with the SGTR accident, each subject needed to keep an eye on the power plant status information by using the status display interface. This information included the status of various devices and the variation tendencies of relevant parameters. The subjects should carry out the correct response in time according to the procedures. System status variables were simulated to change with time so a subject might have to select different routes and perform different controls from one repetition to another. During the experiments, the experimenter randomly froze the images once for three minutes, during which the experimenter

quickly asked the subject to answer the three-level situation awareness questionnaire. Once the questionnaire was finished, the operation prior to freezing the images was resumed. Then, after finishing each experimental operation, each subject filled out the NASA-TLX questionnaire according to his/her subjective feelings during the operation process according to the procedures at the corresponding level of automation. A rest period of 10 minutes was given after the questionnaire was filled out, and then the experiments using the procedures at the next level of automation were carried out.

RESULTS AND DISCUSSIONS

Using SPSS (version 19) as the statistical tool, the acquired experimental data were analyzed to

explore how the level of automation affects human performance.

Situation awareness

Effects of the levels of automation on the first level.

The first level scores of the operators using the procedures at the three different levels of automation are displayed in Fig. 3, and we can observe that the SA1 scores decrease gradually with increasing levels of automation.

Conducting a one-factor analysis of variance (ANOVA) for the first level scores using the procedures at the three different levels of automation shows that the independent variables significantly affect the operator's first level ($F = 9.903$ and $P = 0.000 < 0.05$). Table 2 shows the results of a least significant difference (LSD) multiple comparison on the first level scores using the procedures at the different automation levels. It is observed that significant differences in the first level exists at the different levels of automation; specifically, the first level when using PBPs is significantly higher than when using EPs and CBPs, and the first level when using EPs is significantly higher than that when using CBPs.

The most likely reason is that in the level of the CBP, subjects were based mainly on an interface and to monitor the remaining three interfaces, so reduced the detection of the equipment and parameters on other interfaces, which caused lower first level scores; while using EPs, the subjects need to search for relevant controls on

Table 3. LSD multi-comparison results of SA3 scores.

(I) Level of automation	(J) Level of automation	Mean difference (I-J)	Standard error	Statistical significance	95% confidence level	
					Lower limit	Upper limit
PBP	EP	.043750	.038456	.260	-.03326	.12076
	CBP	.181250 ^a	.038456	.000	.10424	.25826
EP	PBP	-.043750	.038456	.260	-.12076	.03326
	CBP	.137500 ^a	.038456	.001	.06049	.21451
CBP	PBP	-.181250 ^a	.038456	.000	-.25826	-.10424
	EP	-.137500 ^a	.038456	.001	-.21451	-.06049

^aThe significance level of the mean difference is 0.05.

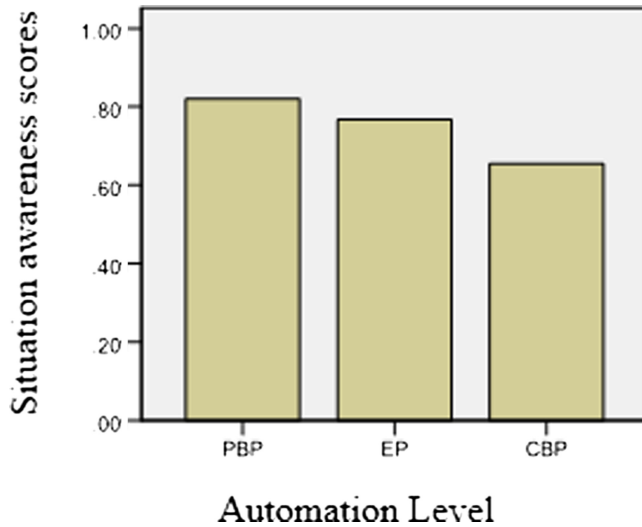


FIG. 6. SA scores using the procedures at the different levels of automation.

each interface, the detection of the equipment and parameters on other interfaces are strong, so the first level is relatively higher; PBP levels for the subjects are most familiar, subjects wouldn't be interfered by procedure interface in the process of operation and monitoring, therefore to the equipment, the detection of the equipment and parameters are strongest, so leading to a highest SA1 score.

Effects of the levels of automation on the second level.

Conducting a one-factor ANOVA for the SA2 scores using the procedures at the three different levels of automation shows that the operator's second level scores exhibit no significant difference from each other ($F = 0.486, P = 0.617 > 0.05$). The most likely reason is that all subjects have nuclear engineering background and accept training about systems and equipment of a nuclear power plant before the experiment; therefore, all have a better understanding of its main parameters and the understanding stored in long-term memory of the participants not affected by the levels of automation of the EOPs, therefore leading to a relatively higher second level score compared with other SA levels, as shown in Fig. 4.

Effects of the levels of automation on the third level.

The SA3 scores of the operators using the procedures at the three different levels of automation are displayed in Fig. 5. Similar to SA1, we can observe that the third level scores decrease gradually with increasing levels of automation.

Conducting a one-factor ANOVA again for the third level scores using the procedures at the three different levels of automation shows that the independent variables significantly affect the operator's third level ($F = 12.097$ and $P = 0.000 < 0.05$). The results of the LSD multiple comparison on the third level scores using the procedures at the different levels of automation are listed in Table 3. It is observed that the third level scores are significantly higher when using PBPs and EPs than those obtained when

using CBPs; the results between using PBPs and EPs exhibit no significant difference from each other.

The most likely reason is that using PBPs forces the operator to manually switch between the different procedures and pay more attention to searching the interfaces for parameters and devices, thereby leading to a higher mental load; while using EPs, the difficulties in the switching procedures and searching interfaces are reduced, but the attention needed for the interface management task still causes a high mental load.

Interviews with the subjects reveal that the higher degree of automation at the CBP level implies that the procedures performing becomes easier, hence the mental workload stays at the lower level, reducing the ability of analysis and prediction, and resulting in the relatively lower third level scores. On the other hand, the use of PBP and EP in the arousal level of mental workload results in the stronger ability of analysis and prediction; therefore, the third level score is higher.

Effects of the levels of automation on SA.

The overall SA scores of the operators using the procedures at the three different levels of automation are displayed in Fig. 6, and we can observe that the situation awareness scores decrease gradually with increasing levels of automation.

A one-factor analysis of variance for the acquired situation awareness scores shows that the independent variables have significant effects on

Table 4. LSD multiple comparison of SA scores.

(I) Level of automation	(J) Level of automation	Mean difference (I-J)	Standard error	Statistical significance	95% confidence level	
					Lower limit	Upper limit
PBP	EP	.05250	.03397	.128	-.0155	.1205
	CBP	.16500 ^a	.03397	.000	.0970	.2330
EP	PBP	-.05250	.03397	.128	-.1205	.0155
	CBP	.11250 ^a	.03397	.002	.0445	.1805
CBP	PBP	-.16500 ^a	.03397	.000	-.2330	-.0970
	EP	-.11250 ^a	.03397	.002	-.1805	-.0445

^aThe significance level of the mean difference is 0.05.

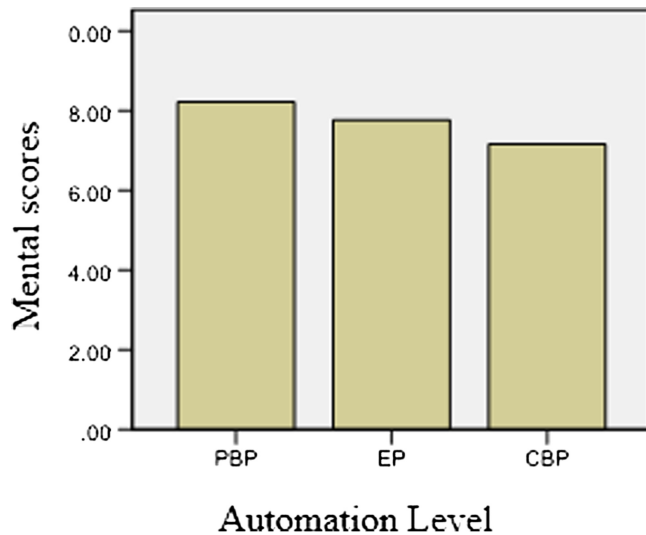


FIG. 7. Mental load scores using the procedures at the different levels of automation.

the situation awareness when using the procedures at the three levels of automation ($F = 12.314$ and $P = 0.000 < 0.05$). The results of a least significant difference (LSD) multiple comparison on the situation awareness scores using the procedures at the different levels of automation are listed in Table 4. It is observed that the situation awareness scores are significantly higher when using PBPs and EPs than those obtained when using CBPs; the results between using PBPs and EPs exhibit no significant difference from each other. One possible reason is that, by using CBPs, the information required in the execution of tasks is automatically displayed. This could cause an operator to become relaxed and inattentive due to a dependency on the automatic system. Additionally, because the collected information is mainly displayed on the procedure information interface, the operator's ability to perceive devices and parameters at other interfaces is weakened, i.e., the operator changes from actively searching for information when using PBPs and EPs to passively receiving information. Accordingly, the operator's alertness and analytical and prediction abilities for the system are all reduced.

Mental load

The mental load scores of the operators using the procedures at the three different levels of automation are displayed in Fig. 7, in which the operators' mental load level decreases with increasing levels of automation in the procedures.

One-factor ANOVA for the mental load scores using the procedures at these three different levels of automation shows that the independent variables significantly affect the operator's mental load level ($F = 24.083$ and $P = 0.000 < 0.05$). Table 5 shows the results of an LSD multiple comparison on the acquired mental load scores using the procedures at the different automation levels. It is observed that significant differences in the mental load exists at the different levels of automation; specifically, the mental load level using PBPs is significantly higher than that using EPs and CBPs,

and the mental load level using EPs is significantly higher than that using CBPs. The most likely reason is that using PBPs forces the operator to manually switch between the different procedures and pay more attention to searching the interfaces for parameters and devices, thereby leading to the higher mental load; while using EPs, the difficulties in the switching procedures and searching interfaces are reduced, but the attention needed for the interface management task still causes a high mental load. When separately conducting one-factor ANOVA for the six indexes in the NASA-TLX questionnaire using the procedures at the three levels of automation, only the physical demand exhibits significant differences ($F = 20.079$ and $P = 0.000 < 0.05$). This index gradually decreases as the level of automation of the procedures increases, as shown in Fig. 8. These results suggest that improvements in automation reduce the operator's physical exertion as expected, and thus the operator can pay more attention to the analyses of the system and its parameters.

Operational performance

The operational performance scores of the operators using the procedures at the different levels of automation are shown in Fig. 9. As the level of automation of the procedures increases, the operational performance also increases.

One-factor ANOVA for the operational performance of the operators using the procedures at the three levels of automation shows

Table 5. LSD multiple comparison of mental load scores.

(I) Level of automation	(J) Level of automation	Mean difference (I-J)	Standard error	Statistical significance	95% confidence level	
					Lower limit	Upper limit
PBP	EP	.44800 ^a	.15304	.005	.1415	.7545
	CBP	1.05800 ^a	.15304	.000	.7515	1.3645
EP	PBP	-.44800 ^a	.15304	.005	-.7545	-.1415
	CBP	.61000 ^a	.15304	.000	.3035	.9165
CBP	PBP	-1.05800 ^a	.15304	.000	-1.3645	-.7515
	EP	-.61000 ^a	.15304	.000	-.9165	-.3035

^aThe significance level of the mean difference is 0.05.

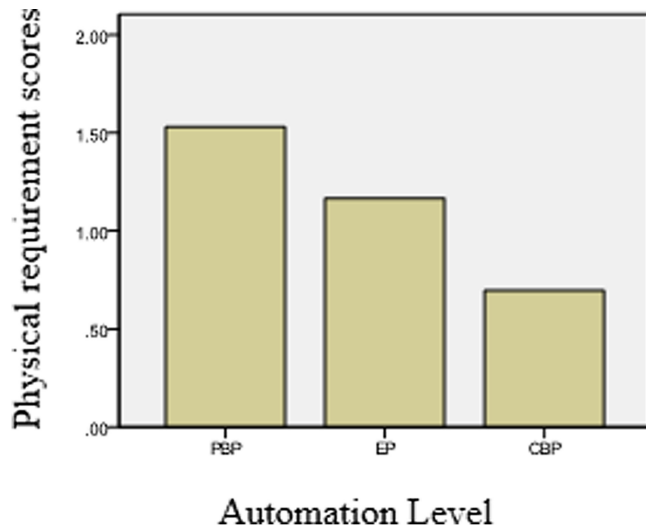


FIG. 8. Physical demand scores using the procedures at the different automation levels.

that the independent variables can impose significant effects ($F = 47.501$ and $P = 0.000 < 0.05$). The LSD multiple comparison results of the operational performance show that significant differences exist when using the procedures at the three levels of automation, as can be seen from Table 6. The operational performance when using CBPs are significantly higher than the results when using EPs and PBPs, while those when using EPs are significantly higher than when using PBPs. This is mainly due to the fact that variations in the automation level can result in a reassignment of tasks. By using CBPs, the tasks that are executed by the operators such as switching procedures and interface management in PBPs and EPs are assigned to the computer, which can thus enhance the operators' performance in executing the main task.

CONCLUSION

This work experimentally investigated how using emergency operating procedures at different levels of automation affects human mental load and situation awareness. Although the realization of automated procedures has increased the efficiency of executing operations, the experimental results and the related discussions show that increased levels of

automation can reduce the operator's situation awareness and thus severely affect the operator's evaluation of the system status and their ability to make appropriate decisions under accident conditions in nuclear power plants. Therefore, the design of automated procedures should fully account for various factors to enhance the operator's situation awareness, to maintain the operator's mental load at an appropriate level, and eventually to improve the overall reliability of nuclear power plants.

The conditions for a reduced operator mental workload making it possible for the operator to concentrate on more important

matters rather than wasting mental effort on mundane items includes: (1) an easy-to-use automation control system which provides a friendly interface and can be operated by operators without experiences; (2) the functions provided by the automation system should not be so complicated; and (3) the automation system should remind the operators to take a break after working for two hours.

The present research results are expected to provide a reference for the training of operators in nuclear power plants and the design of automated emergency operating procedures. It should be noted that the present study also has some limitations. In a real nuclear power plant, the accidents are generally handled by an operation team; however, the present study only focuses on a single operator's performance and often neglects the correlation among various performance factors. These will be considered and accounted for in the follow-up studies.

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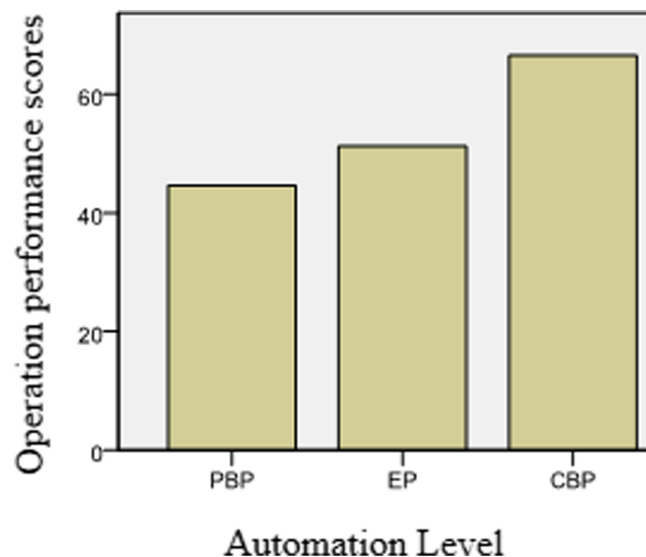


FIG. 9. Operational performance scores using the procedures at the different automation levels.

Table 6. LSD multi-comparison results of operational performance scores.

(I) Level of Automation	(J) Level of Automation	Mean difference (I-J)	Standard error	Statistical significance	95% confidence level	
					Lower limit	Upper limit
PBP	EP	-6.600 ^a	2.305	.006	-11.22	-1.98
	CBP	-21.900 ^a	2.305	.000	-26.52	-17.28
EP	PBP	6.600 ^a	2.305	.006	1.98	11.22
	CBP	-15.300 ^a	2.305	.000	-19.92	-10.68
CBP	PBP	21.900 ^a	2.305	.000	17.28	26.52
	EP	15.300 ^a	2.305	.000	10.68	19.92

^aThe significance level of the mean difference is 0.05.

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