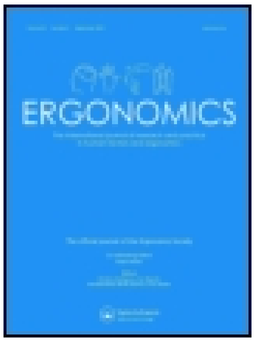

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Procedure and information displays in advanced nuclear control rooms: experimental evaluation of an integrated design

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ABSTRACT

In the main control rooms of nuclear power plants, operators frequently have to switch between procedure displays and system information displays. In this study, we proposed an operation-unit-based integrated design, which combines the two displays to facilitate the synthesis of information. We grouped actions that complete a single goal into operation units and showed these operation units on the displays of system states. In addition, we used different levels of visual salience to highlight the current unit and provided a list of execution history records. A laboratory experiment, with 42 students performing a simulated procedure to deal with unexpected high pressuriser level, was conducted to compare this design against an action-based integrated design and the existing separated-displays design. The results indicate that our operation-unit-based integrated design yields the best performance in terms of time and completion rate and helped more participants to detect unexpected system failures.

Practitioner Summary: In current nuclear control rooms, operators frequently have to switch between procedure and system information displays. We developed an integrated design that incorporates procedure information into system displays. A laboratory study showed that the proposed design significantly improved participants' performance and increased the probability of detecting unexpected system failures.

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Computerised procedures; information displays; integrated displays; advanced control rooms; situation awareness

1. Introduction

The sheer amount and high complexity of information impose great challenges for operators in main control rooms of nuclear power plants (NPPs). When an emergency occurs, operators need to follow a set of standard guides, i.e. emergency operating procedures (EOPs) to diagnose accidents and mitigate damages (O'Hara et al. 2002). To perform a procedure, the operator needs to understand the complex instructions, compare the system status described in the procedures against the real status and make operation decisions to recover the system (O'Hara, Higgins, and Kramer 2000). A major challenge for operators in this process is to resolve the competition for attention resources between two types of tasks: task planning and situation assessing. On the one hand, operators need to identify the appropriate system goals based on the current situation, select the appropriate procedure pathways and evaluate whether the goals have been achieved or not. On the other hand, the operators have to observe, remember and integrate system changes continually in order to update their assessment of the plant state and detect unexpected system events that do not fit their situation models.

Currently, operators need to access two types of displays in EOP tasks. While EOPs are described using text or flow charts on paper or computer displays, system information is usually presented on other computer displays using process mimic displays. From an ergonomic point of view, this approach with separate displays entails a number of cognitive challenges for operators. First, the operator has to switch among multiple displays to search the complete information to make a single decision. The actions of display switching, visual scanning and other secondary tasks (e.g. pointing, clicking, scrolling) require extra effort and time. Frequent and repetitive navigation among pages and displays can easily add to operators' disorientation (O'Hara, Brown, and Stubler 2002). In situations of time pressure, these secondary or interface management actions may cause more human errors, increase workload and undermine situation awareness (Reason 2000; Lee and Seong 2007). Second, it takes mental effort to recall and integrate related information from different displays. The operator

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needs to keep the procedure instructions – which often involves multiple acceptable ranges changing frequently – in his working memory so that he can search and compare the related system information. The efficiency and quality of operator performance in such tasks relies on their ability to manipulate information in working memory. In practice, some operators use handwritten sheets to help themselves in such cognitively demanding tasks (Mumaw et al. 2000; Carvalho et al. 2008).

In addition to the potential impact on performance and workload, the separate design approach creates inevitable context switching between verification and action (Jung, Shin, and Park 2000), which may impede operators from developing and maintaining adequate situation awareness of the system and the process. Empirical studies have found that operators strive to maintain good situation awareness even when their actions are largely dictated by EOPs (Roth, Mumaw, and Lewis 1994; Hollnagel, Edland, and Svenson 1996; O'Hara, Higgins, and Kramer 2000). Such awareness is important for operators to anticipate future states, to establish proper operation plans and to detect minor failures so that their potential influence does not accumulate over time (Sarter and Woods 1991; O'Hara, Higgins, and Kramer 2000; Lee and Seong 2009).

A possible approach to mitigate these problems is to integrate EOP displays and system information displays. According to the proximity compatibility principle (Wickens and Carswell 1995; O'Hara, Higgins, and Kramer 2000), tasks that require mental integration of information, such as those involved in an EOP, will benefit from high-proximity displays. In some studies exploring new design possibilities of computerised EOPs, system information is extracted and embedded into the EOP displays (Carvalho et al. 2008; Xu et al. 2008; Huang and Hwang 2009; Kim et al. 2012). Although such integration reduces information access cost and improves performance time as compared with paper-based procedures (Huang and Hwang 2009), it also brings about the possibility that an operator will monitor only the EOP display, which provides all the system information prescribed in the current EOP, and miss the global process and its continuous development. The safety operation is likely to become vulnerable to any unexpected system failures that are not prescribed in the current EOP.

An alternative approach, which has been explored less so far, is to integrate EOPs into information displays. Compared with the former approach, this approach requires more engineering effort and deeper integration of the monitoring system and the procedure system (e.g. each page of system displays related to the EOP at different steps must be modified; system information and control operations should be able to pass back and forth between the two systems at a speed fast enough to ensure the proper representation of the integrated display and the execution of the EOP procedures). But this approach may provide operators a better overview of the plant, together with particular information they need for the current procedure task. It may improve operators' situation awareness by compelling operators to keep watching the system information displays while executing EOPs.

This approach was first explored in the Halden Project (Strand et al. 2007), in which the mimic process displays were overlaid with the procedure step instruction and only one action was present at one time. While Strand et al. illustrated the idea with a prototype and received positive subjective feedback in a few user tests (Strand et al. 2007), the impact on operator behaviour and cognition of such integration has not been experimentally examined. In addition, Strand et al.'s study did not address an important issue for designers who want to elaborate this approach: at which level of granularity should the two displays be integrated? Complex EOPs in NPP may involve more than 30 logic steps and each step involves multiple actions, i.e. checks (comparing system parameters and status with corresponding ranges in the procedure) and operations (manipulating system controls to achieve a goal, e.g. close a valve). Some logic steps may involve more than 20 actions per step. On the one hand, integration with a too-fine division of EOPs (e.g. every single check and operation) may lead to a trail of minor actions of incomplete goals. It may fragment operators' understanding of logic steps and obscure the higher level goals they are intended to achieve. On the other hand, integration with chunks that are too large (all checks and operations in one step) may lead to too much information cluttered on the screen and a layout that is too complex for decisions but not hiding any important information.

To resolve these issues, the current study proposed a new design that integrates procedures onto system information displays based on not actions to be performed but goals to be achieved. We grouped actions that complete a single goal into operation units and showed these operation units on the displays of system states. In addition, we used different levels of visual salience to highlight the current unit and provided a list of execution history records. To evaluate the impact of this design on operator performance, mental workload and situation awareness, we conducted a laboratory experiment involving 42 participants to compare this design against an action-based integrated design and the existing separated-displays design.

2. Operation unit-based integration of EOP displays and information displays

2.1. Define the granularity of integration – operation units

The two types of displays should be integrated at a proper level of granularity so that (1) each interface provides all the information (both procedural instructions and system status) for the operator to complete a single system goal, and (2) the interface complexity and information abundance should not overburden the operator's cognitive resources. For this purpose, we grouped those indivisible actions (single checks and operations) into *operation units*. We defined an operation unit as all checks and operations prescribed in the EOP for accomplishing a single goal. A goal is either accomplishing a system change or making a decision on (1) performing a system change or not, or (2) going to another step/procedure or not. For example, to decide whether to open the let-down loops or not, the operator needs to check whether any of the three automatic valves in the Automatic Depressurization System is open. The three checking actions are grouped into an operation unit because they together constitute a decision on performing a system change or not. To perform this change (i.e. open the let-down loops), the operator needs to open a number of let-down valves and pumps on the let-down path. For each pump and each valve, the operator first needs to check its status and then open it if it is closed. All of these checking and opening actions are grouped into another operation unit because together they accomplish one system change.

2.2. Integrating the two displays based on operation units

We integrated EOP instructions onto system information displays in such a way that at each time point, the screen shows all the information required for completing an operation unit. As shown in Figure 1, instructions for performing the current operation unit is shown in a yellow rectangle box on top of the system information display. The box is placed near to, but not on top of, the system information related to the current operating unit in order to minimise user effort for visual search and mental integration. System information related to an operation unit, as we specified, includes (1) parameters and devices to be checked or operated in the operation unit; (2) other information about the devices being checked or operated (not specifically checked in the operation unit, though); (3) the devices that are physically linked to the devices being checked/operated and their parameters. The purpose of including (2) and (3) is to enable operators to better understand the status of the device being checked and to anticipate possible changes over time.

There are three levels of salience on the system display: information related to the current operation unit is shown

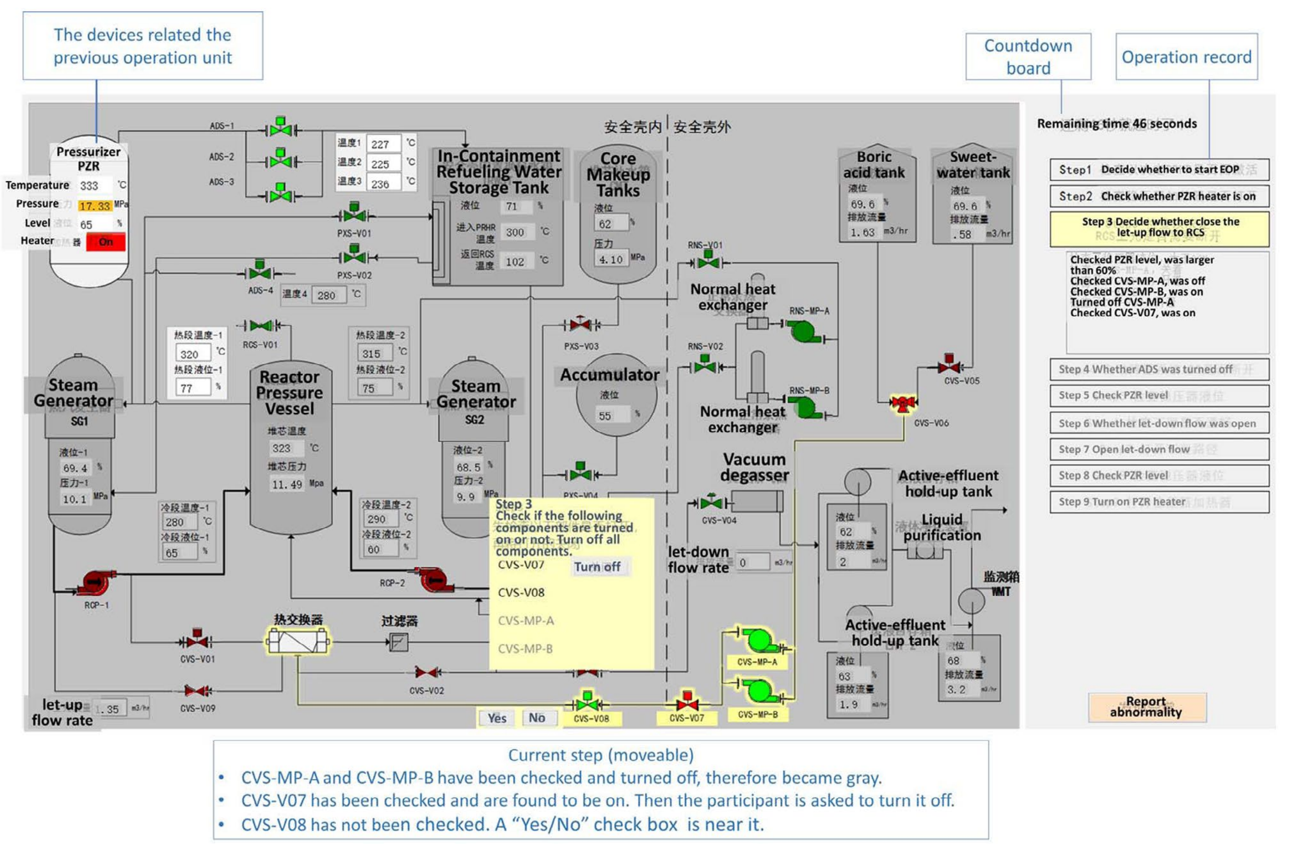

Figure 1. A screenshot of the operation-unit-based integrated display.
Notes: The current operation unit involved checking and closing CVS-V07, CVS-V08, CVS-MP-A and CVS-MP-B. System related to the current operation unit was shown in high salience. The immediate previous operation unit involved checking pressuriser level, and system information related to this operation unit was shown in moderate salience.

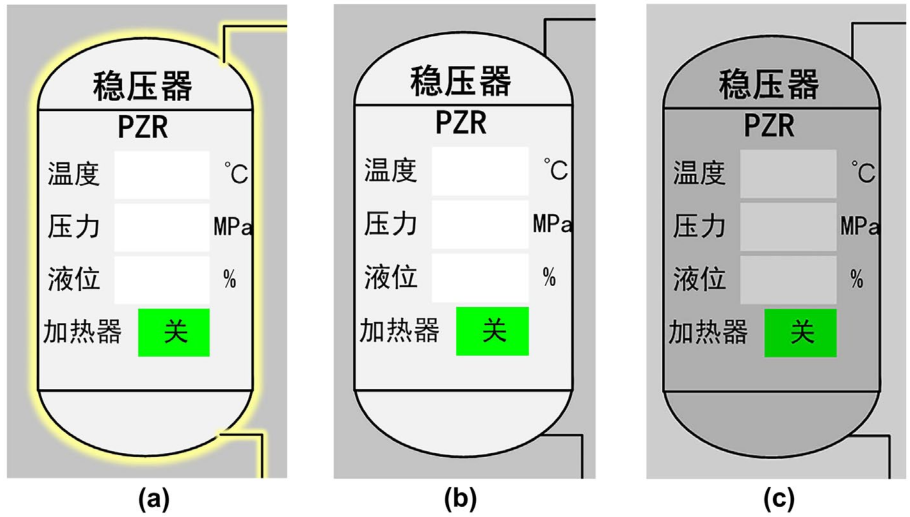

Figure 2. The salience of the device related to the current operation unit, the device related to the immediate previous operation unit, and other devices. (a) information related to the current operation unit is shown in highest salience, with a strong contrast and a glowing effect; (b) information related to the immediate previous unit is shown in moderate salience, with a strong contrast but no glowing effect; (c) other information is shown in low salience, with a low level of contrast between foreground and background.

in highest salience, with a strong contrast and a glowing effect (Figure 2(a)); information related to the immediate previous unit is shown in moderate salience, with a strong contrast but no glowing effect (Figure 2(b)); other information is shown in low salience, with a low level of contrast between foreground and background, as shown in Figure 2(c). The aim of highlighting information not only related to the current unit but also the immediately previous unit was to help operators keep track of execution history and to improve their understanding of the chronological development of the situation.

2.3. *Show the procedure history record*

To further support the operator to track the execution of the EOP, we integrated an EOP history panel on the right of the display. As shown in Figure 3, the operator can click the title of previous steps to expand the records of what he performed for that step in detail. The current step is highlighted in yellow and kept expanded. Future steps that have not been performed are listed to remind the operator what needs to be done later, but the titles are greyed out and cannot be expanded (no execution history yet).

3. Methodology

3.1. *Hypothesis*

To examine whether the operation-unit-based design benefits operator performance as expected, we compared this design with the traditional separate displays design and against the action-based integrated design through a laboratory experiment.

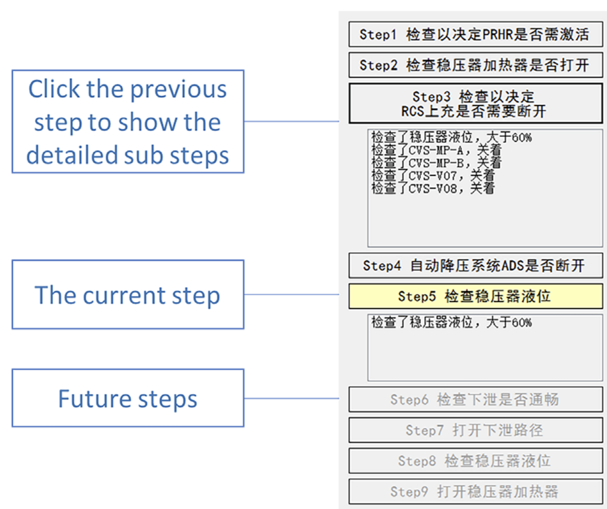

Figure 3. The list of the records of operation history.

Figure 4 shows the two displays used in the separate design condition. The system information display was adapted from the process mimic display developed and validated in a previous project in our laboratory (Ding et al. 2015). The desktop simulator was developed to represent response characteristics of Advanced Passive 1000 pressurised-water reactor. The following systems were modelled: reactor coolant system, passive core cooling system, chemical and volume control system, normal residual heat removal system and liquid radwaste system. We followed the convention of user interface design in the nuclear domain to indicate component states: closed valves and stopped pumps were in green, whereas opened valves and started pumps were in red. The EOP display was adapted

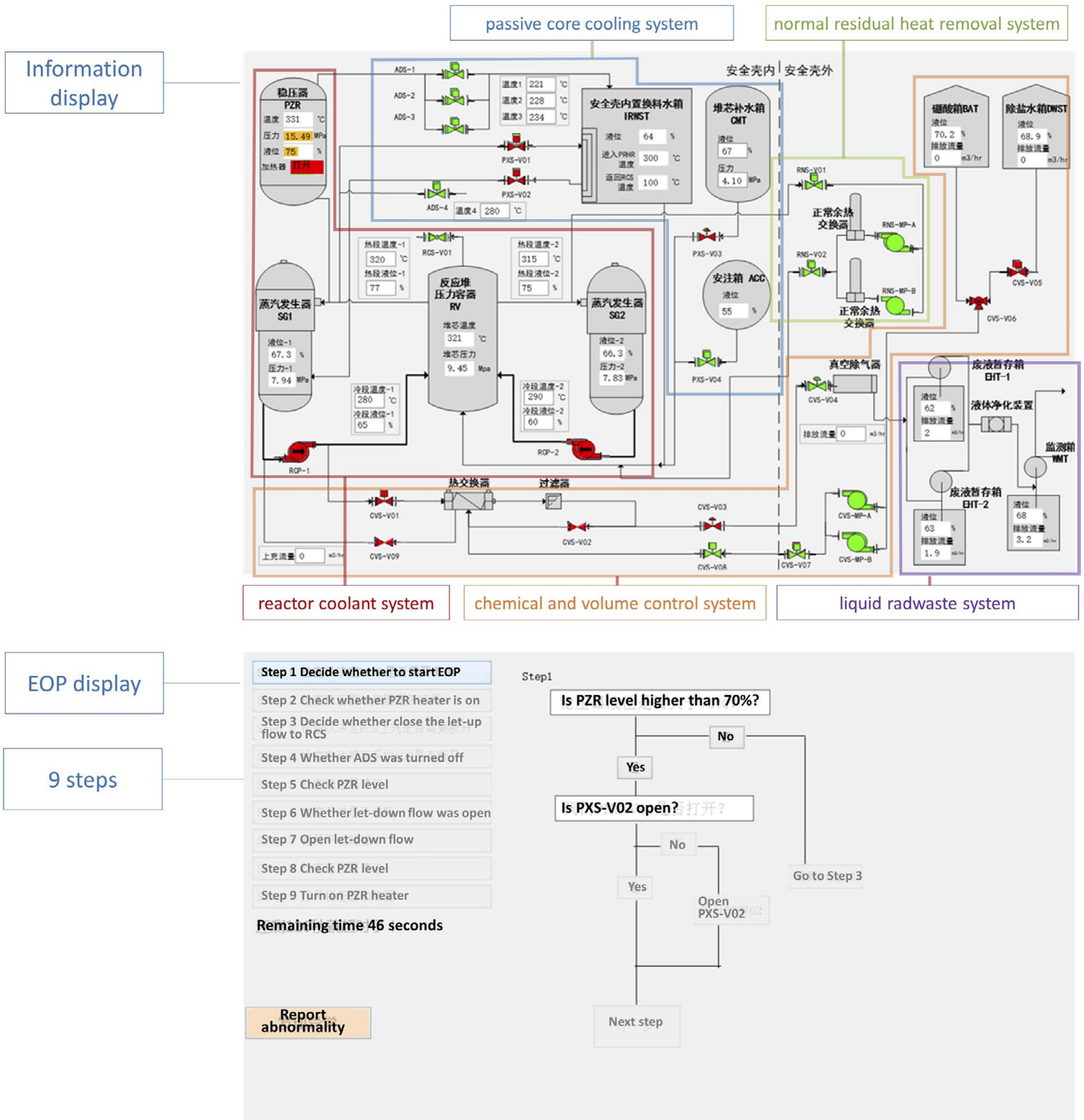

Figure 4. A screenshot of the separate displays.

from an EOP design in a study by Xu et al. (2008). On the left is a list of all steps in the current EOP. The detailed logical structure and required actions of the current step are shown on the right.

The same system display from the separated design condition was used in the two integrated conditions, but with EOP instructions overlaid and relevant system information highlighted. Figure 5 shows an action-based integrated design. EOP instructions were integrated into the system information display at the finest level of granularity. Only one single check or action was presented each time. Devices or parameters directly related to the current action were highlighted (i.e. the salience design was applied to action-based integrated design, as well as to operation-unit-based integrated design, to avoid possible confounding). The EOP history panel was provided in this condition so that the effect of integration granularity could be investigated with fewer confounding factors.

With the integrated designs, operators do not need to frequently switch between different screens. The effort required for searching and pointing to related information and for keeping procedure and system information in working memory is reduced. Thus, we expected that the operators using integrated displays would perform better with a lower level of mental workload.

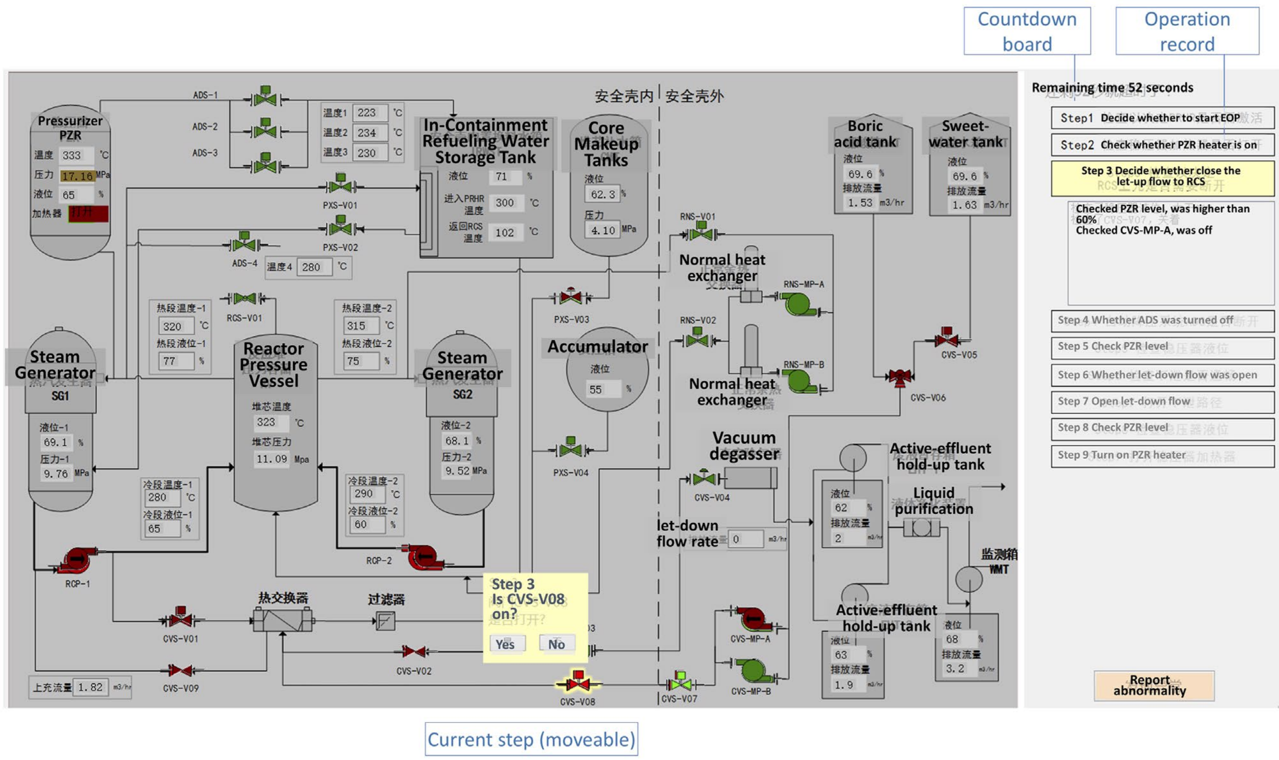

Figure 5. A screenshot of the action-based integrated display.

Hypothesis 1: The *operation time of the EOP task* under integrated display conditions (action-based and operation-unit-based) is shorter than that under the separate display condition.

Hypothesis 2: The *completion rate of EOP tasks* under integrated display conditions (action-based and operation-unit-based) is higher than that under the separate display condition.

Hypothesis 3: The *workload* under integrated display conditions (action-based and operation-unit-based) is lower than that under the separate display condition.

A major motivation for integrating EOP instructions into system information displays was to support situation awareness. We expected that the operation-unit-based integrated design would facilitate operators' situation awareness the most among the three design options for the following reasons: with the separate design, the effort for searching and integrating information from different screens costs cognitive resources. The cognitive resources for developing and maintaining situation awareness are reduced, and situation awareness failures are likely to take place (Endsley, Bolte, and Jones 2003). While action-based integrated design reduces the effort for searching and integrating information from different screens, presenting single actions with only incomplete goals makes it difficult for operators to be goal-oriented and aware of what is going on. Compared with these two designs, operation-unit-based integration balances the need to attend to the plant states and the need to keep track of the task procession. We expected that such a design would significantly improve situation awareness.

Hypothesis 4: The situation awareness under the operation-unit-based display condition is better than that under the other conditions.

We expected that the good situation awareness could help operators to detect unexpected system failures. Due to the large number of components and instruments, there are always components or subsystems that work imperfectly (Mumaw et al. 2000). Small failures may not influence the function of the system, but they change the way in which information should be interpreted. When an equipment failure occurs unexpectedly, operators with good situation awareness are more likely to detect and diagnose the failures based on their expectation of the process development. Therefore, we hypothesised that:

Hypothesis 5: Operators using the operation-unit-based integrated display are more likely to detect unexpected system failures than operators using two other displays.

3.2. Tasks

The experimental procedure was adapted from a real EOP dealing with an unexpected high pressuriser water level in the reactor coolant system (Ding et al. 2015). There were three stages in the original EOP: (1) cooling and reducing pressure (step 1, 2, and 5), cutting off injections to the Reactor Coolant System (step 3 and 6) and evaluating whether to go to other EOP (step 4), (2) flowing coolant out from Reactor Coolant System to CVS (step 7 and 8) and (3) setting the pressuriser to normal working state (step 9). All the major steps were retained in the adapted EOP. The logic and structure of the original EOP, as well as the necessary complexity of the physical subsystems involved in the EOP, were retained as much as possible. But the number of multiple checking/actions serving a same goal in the original EOP was reduced in the adapted version, for example, checking and closing two pumps, i.e. RCP-1 and RCP-2 in step 6, instead of four pumps in the original procedure.

The final EOP consisted of nine logic steps, and each step consisted of one to eight actions. Since different causes for high pressurised-water reactor pressure, corresponding system symptoms and diagnosis procedures are different. We simulated eight possible paths (six long paths and two short paths) in the experiment. All of the six long paths were comprised of nine steps, but the number of actions differed across different paths from 24 to 34 actions. The two short paths contained four steps and 11 actions. Figure 6 shows outlines of one long path and one short path.

Two unexpected system failures were simulated. One was easy to detect (low-difficulty) and the other one was relatively difficult to detect (high difficulty). The easy-to-detect failure occurred in one of the long paths. The participant was instructed to open the valves to the chemical and volume control system with the aim to reduce the pressuriser level. After the participant opened the valves, the let-down flow rate should be larger than 0, but in the failure case, the value was still 0 due to a valve malfunction. The next action involved checking pressuriser level (whether the pressuriser level decreases under 45%). If the valve works well, pressuriser level should be quickly reduced to the required level. But in the failure case, pressuriser level does not change. If the participant noticed this abnormal reading, it was easy for him to find out the reason: there was no let-down flow after the valve was opened. The participant was asked to press a reporting button on the screen to pause the system and report to the investigator when he noticed any unexpected system failure. If the participant did not notice the abnormal reading of pressuriser level and just followed the if–then relationship in the EOP to choose 'no', the detection task was judged as having failed – the participant failed to notice unexpected system failures that have changed the way in which EOP information should be interpreted. The system then paused automatically, and the investigator explained the failure to him. In both cases, the participant then clicked a 'fix and continue' button to continue the task, assuming the failure was fixed immediately.

The difficult-to-detect failure occurred in another long path, which was outlined in Figure 6. This path involved operations for decreasing the pressuriser level. To do this, the participant had to cut off the flow-in loops first, and then turn on the valves that enable the let-down loops. The unexpected failure occurred in one of the operations for cutting off the flow-in loops (the first action in Step 6): the participant checked the valve PXS-V03 between the core make-up tank and the reactor to ensure it was turned off. In normal status, the level of Core Makeup Tank (CMT) should stop declining if the valve was closed. In the failure case, however, the CMT level was still declining, though the indicator showed that the valve was closed, due to a valve failure. When the participant continued operations for decreasing the pressuriser level, i.e. monitoring pressuriser level while turning on the valves to the Chemical and Volume Control System in order to enable the let-down loops, he might detect this failure by observing the change of the CMT level and interpreting the trend over time. It was more difficult than checking the yes/no status of a value, as in the former case. He could press the reporting button on the screen to pause the system and report the failure to the investigator then. If the participant did not notice the failure, when proceeding to the 7th action in Step 7, he would be confronted with an obviously erroneous situation: the pressuriser level did not decrease, although he had cut off all the flow-in loops and turned on all the let-down loops. If the participant did not report the failure before this action, the detection task was judged as failed and the system then paused automatically. The investigator explained the failure to him. The participant then clicked a 'fix and continue' button to continue the task, assuming the failure was fixed immediately.

3.3. Dependent variables and measures

(1) Operation time of EOP tasks: The operation time of the last successful trial for each of the six long paths was averaged and used as the measure of EOP operation time for each participant.

(2) EOP completion rate: This was defined as the ratio of the number of trials that a participant took to complete the EOP task without errors or timeouts to the number of all trials. Participants might make errors in checking and evaluating the state of system (e.g. misreading a parameter, wrong interpretation of an indicator). In case of errors, the current trial would fail and be terminated. Note that, if the assessment of the situation was correct and the participant chose the correct option in the EOP instructions, the EOP system would provide only one

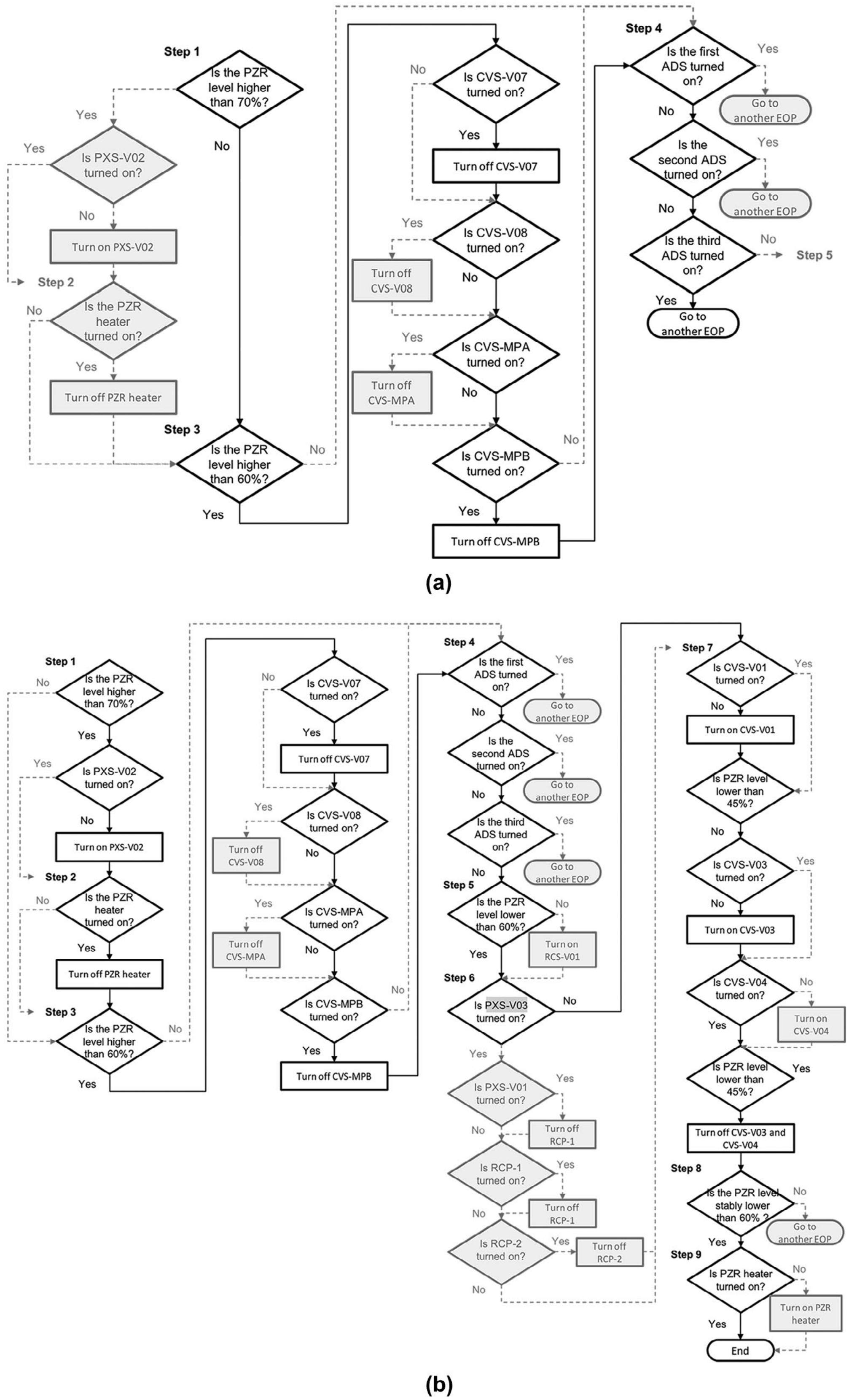

Figure 6. Outlines of example paths of the EOP task. (a) a short path containing 4 steps; (b) a long path containing 9 steps.

correct action based on the assessment and thus exclude possibilities of execution errors (e.g. making the right decision but turning off the wrong valves by mistake).

(3) Workload: Workload was measured by a Chinese version of the National Aeronautics and Space Administration task load index (NASA-TLX) (Gao et al. 2013), which consists of six dimensions: mental demand, physical demand, temporal demand, effort, performance and frustration level (Hart and Staveland 1988). All questions were rated from 1 to 10. We used the Raw NASA-TLX scores, which weights of the six dimensions were treated as equal to each other. Previous literature suggested that the unweighted NASA-TLX scores and weighted NASA-TLX scores are often highly correlated (Byers, Bittner, and Hill 1989; Moroney et al. 1992). Because our experimental task was rather difficult and tiring for the participants, we chose the Raw TLX version to reduce the time and effort for the participants to respond.

(4) Situation awareness: Situation awareness was measured with an adapted version of Situation Awareness Global Assessment Technique (SAGAT) (Endsley 1988). The SAGAT questionnaire covered three levels of situation awareness, which were (1) perception of the elements in the environment (13 items, e.g. 'Is the pressurizer water level lower than, higher than, or in the normal range?'), (2) comprehension of the current situation (six items, e.g. 'Was the temperature of reactor core increasing, decreasing, or steady in the last few seconds?') and (3) projection of future status (one item, e.g. 'Will the pressurizer water level be >70%, 60% ~ 70%, or <60% after this action?') (Endsley, Bolte, and Jones 2003). At each frozen point, the full battery of 20 items was administrated to the participants. All questions were multiple choice. The questions were designed to elicit the participant's understanding of the global status of the system and the process**.** The correct rate of the questions in the questionnaire was calculated as the SAGAT score. During the experiment, the SAGAT questionnaire was administrated to each participant twice. The average of the two scores was used as the measure of situation awareness for the participant.

(5) Detection of unexpected system failures: The number of participants who completed the detection tasks in each condition was used to measure the performance in the unexpected failure detection task

3.4. Participants

Forty-two students from Tsinghua University were invited to participate in the experiment. Because the majority of operators in NPPs in China are male, we recruited only male students. The age of the participants ranged from 18 to 26 (M = 22.43, SD = 1.63). All the participants were students from science or engineering disciplines in Tsinghua University. They were familiar with computer operations but had little prior knowledge of NPP.

The participants were randomly assigned to one of the three conditions, with 14 participants in each condition. An analysis of background information showed no significant difference in age, major, computer experience, knowledge of NPPs and computerised control systems among the three groups. They were paid RMB 80 Yuan for their participation in the experiment.

3.5. Apparatus

The experiment system was developed using Microsoft Visual Studio 2012. The desktop simulator was developed to represent response characteristics of Advanced Passive 1000 pressurised-water reactor in a simplified way. The following systems were modelled: reactor coolant system, passive core cooling system, chemical and volume control system, normal residual heat removal system and liquid radwaste system. In the separated design condition, the system information display was shown on a 13.3-inch screen with a resolution of 1920 × 1080, whereas the EOP display was shown on a 15-inch screen with a resolution of 1024 × 768. In the integrated design conditions, the system information display and the EOP display were integrated and presented on the 13.3-inch screen with a resolution of 1920 × 1080.

3.6. Procedures

Each participant took part in the experiment individually in a quiet room. The participant first read and signed the informed consent and filled out the background questionnaire. Then, after being trained in the necessary knowledge about NPP systems for 10–15 min, the participants were demonstrated the experimental system and the tasks. The participant needed to practice the procedure to become familiar with the system. The practice session would not end until the participant completed at least 16 trials with three consecutive successes. It took about 30 min on average. No unexpected system failure occurred in the practice session. In the formal experiment, the participant was informed that their goal was to recover the system to steady-state operation and that unexpected system failures might occur, and that they need to detect and report them according to their own assessment of the situation instead of the EOP instructions. They were also informed that they might be prompted questions about their assessment of the system and process during the experiment. The participant needed to finish 16 trials (8 paths × 2 replications) and successfully complete each of the six long paths at least once. In two trials, the participant would confront with the two unexpected system failures (easy-to-detect and difficult-to-detect), respectively. The sequence of the appearance of different paths was randomised. To impose pressure on the participant, we set a time limit of 120 s for each trial and showed a countdown clock on the EOP display. The length of the time limit was determined according to the result from a pilot study. In the middle of two randomly chosen trials, the system was frozen and the SAGAT questionnaire was administrated to the participant. The participants could take as long as they need to answer the queries. The time they spent on SAGAT queries was recorded and subtracted from the operation time. After the formal test session, the participant completed the NASA-TLX questionnaires and was debriefed about his opinions and experience in the experiment. The entire experiment took about 80 min.

4. Results and discussion

For each dependent variable except for the completion rate of detection tasks (a categorical variable), we first examined the normality and homogeneity assumptions for parametric analysis. Given the assumptions satisfied, ANOVA was used to examine the effect of the independent variable (display design) and post hoc tests with Bonferroni correction were run in cases of significant ANOVA results. For data that violated these assumptions (i.e. operation time, EOP completion rate, and physical demand and Temporal demand in NASA-TLX), we conducted the Kruskal–Wallis rank sum test to test the effect of display design, and Mann–Whitney's U test with Bonferroni correction for post hoc tests. The completion rate of detection tasks was analysed with Fisher's exact.

4.1. Operation time

As shown in Table 1, the integration of displays had a significant effect on operation time ($\chi^2(2) = 23.19$, $p < 0.001$). The participants performed the fastest with the operation-unit-based integrated display ($M = 49.00$, SD = 10.15), second fastest with the action-based integrated display ($M = 55.68$, SD = 11.34) and the most slowly with the separate design ($M = 80.24$, SD = 15.80). The post hoc tests (see Table 2) showed that the difference between any two conditions was significant ($p < 0.05$).

Hypothesis 1 was supported. Both integrated designs led to a shorter operation time than the separate design. Furthermore, the operation-unit-based integration led to an even shorter operation time than the action-based integration. It may be attributed to the fact that the operator can combine tasks of the same type, and consequently, switch the focus of attention less frequently with the operation-unit-based design than with the action-based design. For example, cutting a path between two containers may require the operator to check the status of four valves and close them afterwards. With the action-based displays, the operator needs to check the status of a valve and close it if it is open, and then check the next valve. His focus of attention constantly switches between checking the system status (see if the valve is open or not), planning the operation (need to close or not) and performing the operation. Such switches cost operation time and increase error probabilities, as consistently found by cognitive psychologists (Rogers and Monsell 1995; Garavan 1998; Oberauer 2003; Oberauer and Bialkova 2009; Kiesel et al. 2010). With the operation-unit-based design, the operator can combine the same type of tasks together and process

Table 1. Summary of descriptive statistics and hypothesis testing for operation time, task completion rate, workload and situation awareness.

	Separate displays ($N = 14$)	Action-based display ($N = 14$)	Unit-based display ($N = 14$)			
	M (SD)	M (SD)	M (SD)	Statistics	Value	p
Time (s)	80.24 (15.80)	55.68 (11.34)	49.00 (10.15)	$\chi^2(2)$	23.19	<0.001*
Task completion rate	0.88 (0.07)	0.94 (0.05)	0.94 (0.06)	$\chi^2(2)$	7.03	0.03*
NASA-TLX	25.71 (5.59)	22.21 (6.41)	21.00 (6.52)	$F(2, 39)$	2.19	0.13
1. Mental demand	6.14 (1.75)	5.07 (1.94)	4.79 (2.16)	$F(2, 39)$	1.88	0.17
2. Physical demand	1.29 (1.27)	1.57 (1.22)	1.29 (1.14)	$\chi^2(2)$	0.51	0.77
3. Temporal demand	3.14 (2.25)	2.07 (1.82)	1.21 (1.31)	$\chi^2(2)$	6.08	0.048*
4. Effort	6 (1.8)	4.36 (2.1)	4.64 (1.39)	$F(2, 39)$	3.38	0.04*
5. Performance	4.14 (2.74)	5 (1.8)	5.29 (1.94)	$F(2, 39)$	1.02	0.37
6. Frustration level	2.29 (2.4)	3.14 (2.38)	3.36 (1.91)	$F(2, 39)$	0.90	0.30
SAGAT	0.72 (0.12)	0.77 (0.11)	0.78 (0.11)	$\chi^2(2)$	3.68	0.16
1. Perception	0.76 (0.15)	0.81 (0.14)	0.86 (0.11)	$\chi^2(2)$	3.68	0.16
2. Comprehension	0.67 (0.14)	0.70 (0.11)	0.65 (0.17)	$F(2, 39)$	0.32	0.73
3. Projection	0.43 (0.33)	0.57 (0.33)	0.50 (0.39)	$\chi^2(2)$	1.17	0.56

Table 2. Post hoc tests for operation time, task completion rate, and the score of the temporal demand dimension and effect dimension in NASA-TLX.

Dependent variable	Alternative hypothesis	*U* value	Adjusted *p* value	*Z* value	Effect size $r = \frac{z}{\sqrt{N}}$
Operation time	Action-based ($N = 14$) < Separated ($N = 14$)	74	<0.001*	3.72	0.70
	Unit-based ($N = 14$) < Separated ($N = 14$)	82	<0.001*	4.09	0.77
	Unit-based ($N = 14$) < Action-based ($N = 14$)	41.5	0.04*	2.23	0.42
Completion rate	Action-based ($N = 14$) > Separated ($N = 14$)	−53.5	0.03*	−2.30	0.43
	Unit-based ($N = 14$) > Separated ($N = 14$)	−54.5	0.04*	−2.28	0.43
	Unit-based ($N = 14$) > Action-based ($N = 14$)	−13	1.00	−0.29	0.06
Temporal demand	Action-based ($N = 14$) > Separated ($N = 14$)	22	0.28	1.35	0.26
	Unit-based ($N = 14$) > Separated ($N = 14$)	43.5	0.03*	2.36	0.45
	Unit-based ($N = 14$) > Action-based ($N = 14$)	20	0.32	1.29	0.24
		t (26)	Adjusted *p* value		Cohen's d
Effort	Action-based ($N = 14$) > Separated ($N = 14$)	2.225	0.052		0.84
	Unit-based ($N = 14$) > Separated ($N = 14$)	2.233	0.052		0.84
	Unit-based ($N = 14$) > Action-based ($N = 14$)	−0.42	1.00		0.16

them in a batch. The number of switches of the focus of attention from one type of task to another is reduced. Furthermore, the operation-unit-based design involves fewer switches of task displays and may require less time for reading repetitive instructions than the action-based design.

4.2. EOP completion rate

Table 1 shows that the integration of displays significantly impacted the task completion rate ($\chi^2(2) = 7.03$, $p = 0.03$). The post hoc tests (see Table 2) show that the task completion rate with the separate design ($M = 0.88$, SD = 0.07) was significantly lower than the two integrated designs (operation-unit-based: $M = 0.94$, SD = 0.06; action-based: $M = 0.94$, SD = 0.05; both $p < 0.05$). No significant difference was found between the two integrated designs.

Hypothesis 2 was supported. Both integrated groups improved the completion rate more than the separated design. A detailed analysis of the data shows that the participants made more errors ($M = 0.10$, SD = 0.08) with the separate design than with the integrated designs (operation-unit-based: $M = 0.06$, SD = 0.06; action-based: $M = 0.07$, SD = 0.05). Furthermore, there were four occurrences of timeouts in the separate displays group, whereas no one reached the time limit in the integrated design groups. Together, the result of completion rate suggests that the integration of displays is effective in helping operators to complete EOP tasks by reducing the effort for searching and integrating information.

4.3. Workload

As expected, the overall workload rating was the lowest under the operation-unit-based integration condition ($M = 21.00$, SD = 6.52), slightly higher under the action-based integration condition ($M = 22.21$, SD = 6.41), and the highest under the separate displays group ($M = 25.71$, SD = 5.59). The difference, however, was not significant at the level of 0.05 ($F(2, 39) = 2.39$, $p = 0.13$). Post hoc analysis showed that the difference between the operation-unit-based integration and the separate displays group was marginally significant ($p = 0.076$).

Examination of the individual scales showed significant effects of display integration on required effort ($F(2, 39) = 3.38$, $p = 0.04$) and temporal demand ($\chi^2(2) = 6.08$, $p = 0.048$) as perceived by the participants (see Table 1). With post hoc analysis, as shown in Table 2, the effort score under the separate displays group ($M = 6$, SD = 1.8) was marginally significantly higher than under either integration condition ($M = 4.36$, SD = 2.1 for action-based, and $M = 4.64$, SD = 1.39 for operation-unit-based, both $p = 0.052$). In addition, the temporal demand score under the separated displays condition ($M = 3.14$, SD = 2.25) was significantly higher than that under the operation-unit-based integration condition ($M = 1.21$, SD = 1.31). This was consistent with the results of operation time: the operation-unit-based integration led to the shortest operation time, and the participants' perception of temporal demand significantly correlated with operation time (Pearson's correlation coefficient $r = 0.42$, $p = 0.005$, $N = 42$).

Overall, the results suggest that integration of an EOP display into the system information display reduces operator effort to accomplish the task as compared with the separate displays group. Furthermore, the operation-unit-based integration significantly relieves time pressure perceived by operators, which can be attributed to the elimination of low-level cognition and motor tasks.

4.4. Situation awareness

As shown in Table 1, no significant difference was found in the total score and the scores of three levels in SAGAT query among the three groups. There was a slight trend ($\chi^2(2) = 3.68$, $p = 0.16$) where the score of the perception level under the integration conditions, particularly under operation-unit-based integration condition (M = 0.86, SD = 0.11), was higher than that of the separate displays group (M = 0.76, SD = 0.15). No such trend was found for the comprehension level or the projection level.

We found that three limitations in our experimental design may influence the effectiveness of situation awareness measurement. First, our participants had very limited experience with the nuclear domain. Past research has found that the ability to build situation awareness develops with experience (Carretta, David, and Ree 2009). Compared with experts, novices have been found employing a more rigid visual search strategy, lacking memory structures that allow for effective chunking of interrelated information, and having difficulties in coping with the cognitive load while attending to the task (Randel, Pugh, and Reed 1996; Crundall and Underwood 1998; Underwood, Ngai, and Underwood 2013). All these limitations impede the development of comprehension and projection based on the current situation. In particular, the limited training may not allow the participants to develop an accurate and complete mental model of the system. A mental model is the operator's internal representation of the physical system and its operation, and has been found critical for NPP operators to make predictions – mental models provide the principles upon which predictions can be made (O'Hara, Higgins, and Kramer 2000). As a result, a floor effect occurred in all three groups at the projection level, indicated by the low mean values and the high dispersions. Second, in NPP systems, the inter-dependency of components and parameters is great, and the speed of process changes and control responses is often slow in comparison to other domains, such as aviation (Hogg et al. 1995; Lau, Jamieson, and Skraaning 2012). The short task time in our experiment may not be enough for developing a high-level comprehension and prediction for the scenario being tested. Finally, Endsley, Bolte, and Jones (2003) suggested that each SAGAT item should be administered 30–60 times for each experimental condition. In our experiment, each SAGAT item was administrated 28 times (14 participants × 2 times of administration) for condition, which was slightly lower than the recommended number. This may also influence the effectiveness of the following statistical analysis.

4.5. Detection of system errors

Six participants in the operation-unit-based group and three participants in the action-based group completed the low-difficulty detection task. No participant in the separated group completed the detection task. As shown in Table 3, Fisher's exact tests with Bonferroni correction showed a significant difference between the operation-unit-based integration condition and the separate displays condition (p = 0.024). No participant in any group completed the high-difficulty detection task.

Table 3. The Fisher's exact test for the score of the completion rate of the low-difficulty detection task.

Alternative hypothesis	Adjusted p value	Effect size (Phi-coefficient)
Action-based (N = 14) > Separated (N = 14)	0.33	0.35
Unit-based (N = 14) > Separated (N = 14)	0.02*	0.52
Unit-based (N = 14) > Action-based (N = 14)	0.63	0.23

The results indicate that, compared with the other two designs, the operation-unit-based integration supports the operator better in detecting obvious system abnormality that resulted from a previous operation. Highlighting system information related to the previous unit encourages the operator to keep an eye on the feedback of their previous operations. Though such feedback information is also available on the system display under the separate display condition, the operator is less likely to attend to information that is not directly related to his current operation. As found before, the integration of displays effectively reduces operator effort and perceived time pressure so that it is psychologically possible for the operator to check the effect of his previous actions. In addition, compared with action-based integration, operation-unit-based integration allows the operator to be more goal-oriented, i.e. to know clearly the desired outcome for an action rather than mechanically following task instructions. Such goal-directedness may improve the feeling of being in control, and encouraging the operator to more proactively observe what happens after his action and compare the outcome with the expectations.

No participant in any group completed the high-difficulty detection task. The participants found it difficult to monitor changing trends of parameters due to the absence of extra trend displays and the limited training and practice time.

5. Conclusion

This study explored the possibility of integrating EOPs into system information displays to support NPP operators' performance. Moving beyond the initial idea of simply overlaying EOP instructions on top of system displays (Strand et al. 2007), we proposed the operation-unit-based integrated design, which takes the impact of integration granularity into consideration along with the difficulties for operators to keep track of task processes. We compared this design with the action-based integrated design and the separate displays design through a laboratory experiment.

Our results indicate that integrating EOPs into system information displays, both action-based and operation-unit-based, improves operation time, EOP completion rate and perceived effort demand. Compared with the action-based integration, operation-unit-based integration shortens operation time and further reduces time pressure. Such a reduction of operation time and time pressure is important in an emergency – operators can save more time for other important issues, which requires their knowledge and analysis.

A major motivation for integrating EOPs into system information displays is that operators have the global system information in sight and can develop better situation awareness. Our results show a slight trend that the operation-unit-based integration improves the participants' situation awareness at the perception level. Furthermore, the number of participants who detected the unexpected system failure was significantly higher under the operation-unit-based condition than under the separate displays condition. Together, the results indicate that operation-unit-based integration can improve operators' perception of changes of relevant elements in the environment and help them to detect unexpected system failures – at least the obvious ones. These small failures, if not detected in time, will complicate the operators' ability to assess the situation and their ability to devise proper operations dealing with the situation.

Our operation-unit-based integrated design does not, however, improve the higher levels of situation awareness (comprehension and projection), or the detection of less obvious system failures. The fact that no participant in any group complete the task indicates a clear floor effect. This result is consistent with the result that the participants in our experiment can hardly develop projection of the future development of the system, which would in turn guide monitoring and interpreting activities. As discussed in Section 4.4, this can largely be attributed to the limited training and experiences of the participants. Another factor adding to the difficult to detect less obvious failures is that the design of the mimic system information display used in our experiment requires the participants to mentally track and combine low-level data to derive a higher level understanding of the system process. An easy and effective way to improve this problem is to provide additional displays, such as "minitrends," for tracking the changes of key parameters (Burns et al. 2008; Carvalho et al. 2008; Lau et al. 2008). A more advanced design of system information displays that are goal-means-oriented, such as ecological interface design (Vicente and Rasmussen 1992) and function-oriented displays (Andresen et al. 2005; Ding et al. 2015) may further improve the operators' understanding of the scenario (Burns et al. 2008; Ding et al. 2015). How to integrate EOPs into these novel designs of system information displays and determining the impact of such integration on performance would be an interesting and promising direction for future research.

There are a number of limitations we need to consider when further generalising our results. First, the participants were all college students. The advantage of having student participants instead of real operators in this study is that students are less biased towards the traditional design than operators often are (because of similarity). However, although the students' knowledge of and experience with the system were enough for solving the experimental tasks, they are still very different from real operators, particularly in their motivations and response styles. Second, the experiment was conducted in a simulated environment and the scope and complexity of the simulated NPP system was greatly reduced than real NPP systems. As a result, the participants were less likely to be stressed by the complexity/uncertainty of the system and the severity of possible accidents as real operators do. We imposed time pressure on the participants deliberately to create a stressful situation, but still the nature of such stress was different from what is experienced in real NPPs. Furthermore, this measure encouraged the participants to perform quickly if they could, whereas operators in real working conditions were less likely to be hurried by time. To further examine this concept for practical settings, implementation on full-scope simulators and verification with real operators is needed. Third, as the first study to investigate the behavioural effect of integrating EOPs into system information displays, we used a simplified scenario and did not consider the switches among different pages of the system information display. In practice, it is possible that the operator needs will be navigated through a number of pages of system information displays to complete an EOP. How to design a proper navigation mechanism and to provide useful navigation aids would be a critical issue and needs to be explored in future studies. Fourth, the unexpected system failures in our experiment were related to the current EOP being executed. It should not be overgeneralised that the operation-unit-based integration can help the operator to detect all small system failures during the execution of EOPs. Finally, the integrated designs in the current study differ from the traditional separated design in the design of not only information integration and also visual salience. Therefore, it is unclear which aspect contributes more to the positive effect of the operation-unit-based integrated design. To obtain further insight into this issue, a full factorial design should be considered in future studies.

Though the finding of the current study supports the beneficial impact of the operation-unit-based integrated design concept, we should note that such benefits come with a reduction of the size of the original information display, which may lead to visual clutters in some situations. A possible solution is to adopt wider screens for integrated displays. In addition, if the mental integration of system and task information is facilitated by the integrated design, separated displays should also be available and can be displayed on other screens in situations when the operator needs to focus on a specific aspect (system/task) – such tasks will benefit from the separated design concept (Goettl, Wickens, and Kramer 1991; Wickens and Carswell 1995). Furthermore, to make the comparison fair between different displays, we deliberately avoided changes to the information content on the integrated display from that on the separated displays, which were adopted from the existing and commonly used designs, as much as possible. To further benefit from the integration of the two systems, however, the integration of the human-system interface design should occur not just at the information display level but also at the information content and structure level. A possible approach is to integrate information requirements identified by both work domain-based and task-based work analysis methods, and to accommodating these requirements with more innovative design using more advanced design framework, such as EID, as demonstrated by Jamieson et al. (2007). This is a promising direction for future research on integrated interface design. Finally, this study concerned only individual operators' performance. In real practice, operators work in teams to conduct EOPs. A recent work (Gao et al. 2015) has found that a procedure display integrated with teamwork information helps operators keep aware of other team members' status with less communication efforts. Our future work direction is to extend the incorporate our operation-unit-based integrated design with necessary teamwork information, without developing a too complex display with overwhelming information.

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