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An integrated alarm display design in digital nuclear power plants

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HIGHLIGHTS

- The effect of integrating system information into alarm displays in ACR was explored.
- A bar-based integrated alarm display design was validated through a lab experiment.
- The bar-based integrated design was preferred in detecting parameter trends.
- The bar-based integrated design helped better understanding of the current scenario.

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ABSTRACT

In main control rooms of nuclear power plants (NPPs), operators often have to frequently switch their attention between alarm displays and system information displays to incorporate information from different screens. In this study, we proposed the idea of integrating system information into alarm displays. A bar-based integrated design of alarm display was proposed, and it was compared against a tile-based integrated design, and a traditional separate design through a lab experiment. To verify the idea of integration, forty-eight participants were randomly assigned to the three integration conditions to perform basic alarm response tasks, and their situation awareness levels and subjective evaluations were collected. The results indicated that the participants preferred the idea of integrating system information into alarm displays. Besides, the bar-based integrated display supported higher correct rate of answers to situation awareness questions related to the developing scenario than the tile-based integrated design. The idea of integrating system information into alarm displays merits further research and may be applicable to other safety–critical industries.

1. Introduction

Alarm systems are designed to provide cues to make operators aware of an operational problem, so that mitigation action can be taken (Berg et al., 2011; Easter and Lot, 1992; Mumaw et al., 2000). The large number of alarms in nuclear power plants (NPPs) might cause alarm floods during plant transients, mode changes or component failures, thus leading to information overload, and imposing great challenges for operators (Woods, 1995). The design of alarm systems is a critical contributor to overall system safety (O'Hara et al., 2000). When an emergency occurs, operators need to respond to the alarm information, compare the alarm status described in the alarm display against that in the system information display, and assess the current situation. They have to observe, remember, and incorporate system changes continually in order to update their assessment of the plant state (Chen et al., Under review).

Most alarm systems currently in use are designed in a bottom-up manner, starting from each detailed system (Bye et al., 1999), with the alerting and informing functions separated. When an alarm occurs, operators need to access two types of displays: alarms are shown in alarm tiles or alarm lists on alarm displays, while system information is usually presented on other computer screens using process mimic displays (O'Hara et al., 1995). From an ergonomic point of view, this separate display approach poses several cognitive challenges for operators. First, the operator has to frequently switch his attention between the alarm display and system information displays to search the complete information and fully assess the current situation. The actions of display switching, visual scanning, and other secondary tasks (e.g., pointing, clicking, scrolling) require extra effort and time (Chen et al., Under review). Frequent and repetitive navigation among displays might make the operators "getting lost", which would negatively affect their performance

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(O'Hara and Brown, 2002). Second, it takes mental effort to recall and incorporate alarm information with process information from different displays. To search and compare the related system information, the operator needs to keep the alarm information in his working memory. Thus, it relies on the operator's cognitive ability to monitor system variables and recall acceptable ranges which change frequently during operation (Carvalho et al., 2008). In addition, the frequent attention switching and interface management tasks in the separate design approach may introduce negative effects on developing and maintaining adequate situation awareness (SA) of the system and the process. Such awareness is important for operators to understand the current plant status, to anticipate future states, and to establish proper operation plans (O'Hara et al., 2000; Sarter and Woods, 1991).

To mitigate this problem, there is a trend of designing alarm systems in a top-down manner as integrated systems in advanced control rooms (ACRs) (Bransby, 2001; Brown et al., 2000; Bye et al., 1999), integrating alarm displays and system information displays. Thus the distinction between "alarm systems" and "plant display systems" might become blurred (Brown et al., 2000). According to the proximity compatibility principle (O'Hara et al., 2000; Wickens and Carswell, 1995; Wickens et al., 2012), tasks that involve mental information integration, where attention must be divided between multiple elements but both are mapped onto a single task, such as those involved in alarm monitoring and identification, will benefit from high-proximity displays. The integration of alarm displays and system information displays can support operators' cognitive processing of information, i.e., enhancing parallel processing, lowering mental workload, aiding better understanding of the relationships between display elements, and helping develop a more rapid and accurate situation awareness (O'Hara et al., 1995).

In some studies, alarm information is extracted and embedded into system information displays (Baker et al., 1985a,b; Braseth and Øritsland, 2013; Kaarstad and Nihlwing, 2007; Karlsson et al., 2002; O'Hara et al., 2000). A component failure can be shown by a change in color or flashing of the component icon. Although such integration reduces information access cost, and is commented by real operators as useful and helps to understand the relationships between alarms and the underlying disturbance, task performance was not significantly improved (O'Hara et al., 2000). Such integration also risks setting the alarm information apart, with some alarm information not being accessible from the high-level system information displays (e.g., overview displays). As operators need to go into lower level interfaces for more detailed alarm information, the key-hole effect is likely to occur (Woods et al., 1990), which is adverse to the safe operation of NPPs.

An alternative approach of integration, which has been explored less so far, is to integrate system information into alarm displays. Compared with the former approach, this approach of integration requires more engineering effort, and a deeper integration of the two systems. However, it may provide operators with a better overview of the plant, together with the information they need to check the current triggered alarm, thus improving operators' situation awareness by compelling them to keep an eye on the related system information adjacent to the triggered alarm. In addition, the features of the spatially dedicated, continuously visible (SDCV) alarm tiles could be preserved, allowing operators to recognize frequent faults or accidents from graphical patterns of triggered alarms, thus helping them develop a more rapid awareness of the situation (Brown et al., 2000).

To elaborate this integration approach, designers need to choose the proper presentation format. The most widely used alarm presentation formats in ACRs are alarm tiles and alarm lists (Brown et al., 2000). Although alarm lists can provide detailed information and support different methods of sorting, they are time consuming to read under alarm floods, difficult to identify the most important alarms, introduces increased memory load, and fails to provide spatially organized information that facilitates information processing (Brown et al., 2000; O'Hara et al., 2000). Alarm tiles can help operators maintain an overview of the process, which is very important as operators rely on alarm displays to obtain an overview of plant status (Bransby, 2001; Carvalho et al., 2008; Dos Santos et al., 2008). Besides, they can help operators interpret alarms at a glance, and diagnose faults through pattern recognition (Woods, 1995). However, they do not provide detailed information to help understand a disturbance (O'Hara et al., 2000). It should be pointed out that the alarm information shown in both alarm lists and alarm tiles are more like logic variables, i.e., it is either in alarm state or not. The operators cannot vividly capture the developing process of system state, and mitigate the potential problem in advance.

To address this issue, we proposed a bar-based integrated design of alarm display, which integrated system information into the alarm display, and used alarm bars to vividly show both the alarm and system information. To examine whether the bar-based integrated design would benefit operator performance as expected, we compared this design with a traditional separate design, and against a tile-based integrated design through a laboratory experiment. Forty-eight participants, randomly assigned to three groups, were asked to complete six scenarios using one of the three designs. The alarm frequency of scenarios was manipulated within groups. Situation awareness and subjective evaluations were collected. In the following section, we introduced the three alarm display designs in detail.

2. Alarm display designs

Six major subsystems of a simplified two-loop pressurized water reactor were included in the alarm interface design: the reactor, the reactor coolant system (RCS), two steam generators (SGs), the pressurizer, the auxiliary safety system, and the containment. A total of 55 system status related indicators and key operating parameters were identified. The alarms were classified into three levels (Cheon et al., 1993), with the Level-1 alarms being plant-wide, severe accident related signals (e.g., suspension of power generation or radiation leakage), the Level-2 alarms being subsystem-wide malfunctions (e.g., main pump failure of RCS), and the Level-3 alarms being subsystem abnormalities (e.g., pressure, temperature, liquid level too high/low). The difference in integration levels lay mainly in the presentation of the parameter-driven Level-3 alarms.

2.1. Separate design

Fig. 1 shows the two displays used in the separate design condition. Both the system information display and the alarm tile display were adapted from previous projects in our laboratory (Wu et al., 2012, 2016). It should be pointed out that in real ACRs, system information are shown on multiple process mimic displays, which would require more attention switching to obtain the current value related to a triggered alarm than in our separate design.

The three Level-1 alarms were arranged together in a group box indicating "Level 1" in the top area of the right display. The Level-2 and Level-3 alarms were grouped by subsystems. Within each subsystem, the Level-2 alarms were framed with a dotted line separating them from the Level-3 alarms. Under normal operation, all alarm tiles were grey. Once an alarm was triggered, it flashed until acknowledged by the participant, and stayed lit with the color corresponding to its alarm level (Level-1: red, Level-2: magenta, Level-3: yellow). The time of triggering was shown below the