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Fault Diagnosis with Multi-State Alarms in a Nuclear Power Control Simulator

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FAULT DIAGNOSIS WITH MULTI-STATE ALARMS IN A NUCLEAR POWER CONTROL SIMULATOR

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This research addresses how alarm systems can increase operator performance within nuclear power plant operations. The experiment examined the effect of two types of alarm systems (two-state and three-state alarms) on alarm compliance and diagnosis for two types of faults differing in complexity. We hypothesized three-state alarms would improve performance in alarm recognition and fault diagnoses over that of two-state alarms. We used sensitivity and criterion based on Signal Detection Theory to measure performance. We further hypothesized that operator trust would be highest when using three-state alarms. The findings from this research showed participants performed better and had more trust in three-state alarms compared to two-state alarms. Furthermore, these findings have significant theoretical implications and practical applications as they apply to improving the efficiency and effectiveness of nuclear power plant operations.

INTRODUCTION

Operator Roles

Given that nuclear power plant operators perform complex tasks, it is important to incorporate decision support tools that increase the safety and efficiency of plant operations. Currently, nuclear power plant control panels are designed to display plant status information; these panels are sophisticated and contain several indicators. Consequently, the complexities of operations increase when critical events arise (Vicente, 2007). During these events, operators must quickly extract and interpret task-critical information by monitoring numerous indicators. Therefore, it is desirable to incorporate alarms that assist operators in allocating attention to task-critical information (Woods, 1995) and provide additional diagnostic information where vast amounts of data may flood operators beyond their attention and processing capacitates. The purpose of this research is to investigate the differential effects of two types of alarms (two-state and three-state alarms) on alarm recognition, fault diagnosis, and trust as a function of fault type (simple and complex faults).

Alarms

Nuclear power plants typically use two-state alarms that are based on non-diagnostic set-point indicators. This type of alarm emits either one of two advisories based on a single sensor continuum (i.e., ‘OK’ or ‘Alarm’). Because these alarm thresholds are set to trigger on any change along the sensor continuum, they emit a high rate of false alarms. Furthermore, monitoring tasks can become burdensome when nuisance alarms flood operators and distract them from task critical information (Vicente, 2007). One solution for reducing high false alarm rates is by setting the threshold to be more conservative in triggering alarms; however, this reduces critical event detection (Bustamante, Bliss, & Anderson, 2007). While this may be effective in some domains, it is not ideal in nuclear power plant operations due to the critical nature of events. Bustamante (2007) proposed the use of likelihood alarms (three-state alarms) as a way to decrease the negative effects of false alarm prone systems without compromising the system’s high hit rate.

Three-state alarms provide operators with more diagnostic information by providing multiple alarm advisories based on the probability of events (i.e., ‘OK’, ‘Warning’, ‘Alarm’). Three-state alarms are designed with multiple predetermined thresholds, wherein advisories are emitted according to the respective probability the alarm is actually true. Furthermore, they are based on two automated alarm design principles: probability matching and urgency mapping. Probability matching is the tendency for operators to match their response frequency to the perceived reliability of the alarm (Bliss, Gilson, & Deaton, 1995). Urgency mapping is an operator’s tendency to respond more often to alarms that have a greater perceived urgency (Edworthy & Loxely, 1991).

An additional benefit of three-state alarms is the enhanced diagnostic information it provides operators who are diagnosing faults that have masked indicators. These types of events ensue when multiple faults occur, wherein the effects of one fault (i.e., the masking fault) make indicators for diagnosing a second fault (i.e., the contingent fault) misleading (U.S. Nuclear Regulatory Commission, 2009). In these cases, operators may use the urgency mapped onto the alarm to assist in diagnosing the event when indicators for that event are misleading.

Goals of This Study

This purpose of this study is to examine the differential effects of multiple alarm types on decision-making sensitivity and decision-making criterion. Using the complex scenario fro, the U.S. Nuclear Regulator Commission’s (2009) study as a framework, participants monitored and diagnosed two possible faults throughout the study, wherein there was a masking fault and a contingent fault. The contingent fault was more difficult to diagnose because its indicators were misleading at times. Combinations of two-state and three-state alarms were examined within the two fault conditions. Performance in alarm recognition and fault diagnosis provided the framework for measuring sensitivity and criterion, which framework closely resembles Bustamante's (2008) Two-Stage Signal Detection Theory Model. Moreover, alarm recognition is defined as an operator's ability to appropriately respond or not respond to alarm advisories, whereas fault diagnosis is defined as an operator's ability to correctly diagnose faults. Moreover, non-parametric measures were used for sensitivity and criterion. We calculated *A′* for sensitivity (Smith, 1995) and refer to it as 'sensitivity'. Meanwhile, we calculated *B*' for criterion (Wayne, 1992) and refer to it as 'bias'.

Alarm recognition. We expected the three-state alarm would improve alarm recognition above that of the two-state alarm for both faults. Furthermore, we predicted participants would tend to acknowledge the two-state alarm's false alarms, thereby significantly decreasing sensitivity and increasing bias within the two-state condition.

Fault diagnosis. We expected the three-state alarm would improve fault diagnosis above that of the two-state alarm for both faults. Furthermore, we predicted participants would have higher sensitivity and lower bias when using three-state alarms. We also predicted that participants would have higher sensitivity and lower bias for the contingent fault when using the three-state alarm during conditions where the indicators for diagnosing the contingent fault were potentially misleading.

METHOD

Experimental Design

We used a 2 x 2 x 2 mixed design with the following factors: alarm type (two-state or three-state) for the masking fault, alarm type for the contingent fault, and state of the masking fault (i.e., did it occur or not). We manipulated both alarm type factors between groups; consequently, participants were randomly assigned to on of four groups, each of which received a particular configuration of alarm types for the two faults: 1) both faults had a three-state alarm, 2) both faults had a two-state alarm, 3) the masking fault had a two-state alarm while the contingent fault had three-state alarm, and 4) the masking fault had a three-state alarm while the contingent fault had a two-state alarm. The state of the masking fault was manipulated within groups; consequently, there were two states of the masking event: 1) the masking event occurred, wherein the indicators for the contingent fault were potentially masked, and 2) the masking fault did not occur, wherein the indicators for the contingent fault where accurate. We recorded measures of sensitivity and bias for alarm recondition and fault diagnosis for the masking and contingent faults.

Participants

Sixty university students (26 female, 34 male) participated in this experiment. Participants ranged from 18 to 41 (*M = 21.86*, *SD* = 4.01). All participants reported having normal or corrected-to-normal vision and hearing. As an incentive, participants were compensated with two research credits. Researchers treated participants according to the American Psychological Association Ethical Guidelines.

Material and Apparatus

This experiment used four computer workstations, each equipped with two 19-inch monitors, a standard QWERTY keyboard, a pair of sound-attenuated headphones, and an optical mouse. Given that the average ambient noise level was 55 dB(A), an auditory signal of 65 dB(A) was emitted with each visual alarm stimuli. Participants performed the process control task on a monitor placed directly in front of them. On the other hand, participants performed the alarm monitoring and fault diagnosis tasks on a monitor just left of the center monitor, and turned at a 45-degree angel. This setup was to replicate the structural interference nuclear plant operators experience when monitoring control room panels.

Process Control Task

The process control task required participants to operate DURESS (Vicente & Pawlak, 1994), a simplified simulator that engages participants in process control tasks within an environment controlled by physical laws and functional relationships that govern the system states and control options. In DURESS, participants monitored and maintained an optimal water level, flow, and temperature by manipulating various valves and heaters as seen in Figure 1.

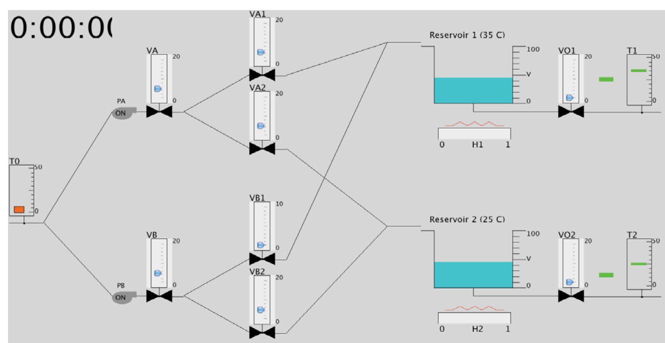

Figure 1. DURESS.

Alarm Monitoring Task

In concurrence with the process control task, participants executed a secondary task, in which they performed fault diagnosis by monitoring alarms and indicators. Participants performed this task through a simulated nuclear power plant alarm system and control panel called 'NPC' (Lew, 2011). NPC creates an environment where participants monitor and interact with alarm systems for two faults, wherein alarms are emitted at separate times but in the same temporal order. The first fault represented a major steam line break and was labeled 'MSB', while the second fault represented a major steam generator tube rupture and was labeled 'SGTR'. The MSB and SGTR faults were used in this study as illustrative purposes and do not represent the actual frequency that nuclear power plant operators encounter them, which is extremely rare.

This task's design is consistent with prior research (Clark, Ingebritsen, & Bustamante, 2010). Participants first monitored alarm advisories for the masking fault, wherein participants decided to ignore or acknowledge the advisory (see Figure 2).

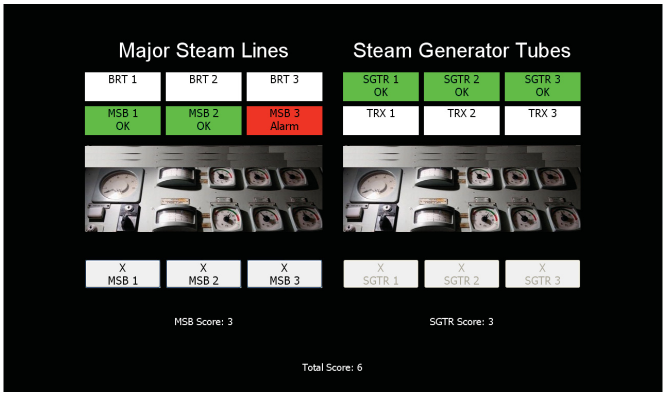

Figure 2. NPC.

If participants decided to acknowledge alarm advisories, they clicked the corresponding button for the alarm in question. At this point, the indicators for the fault appeared on the screen for participants to diagnose the fault. The key indicator was red when the fault occurred, and green when the fault did not occur. Once participants completed this process for the masking fault, the same sequence occurred for the contingent fault, the caveat being that the indicators for this fault were misleading when both the masking and contingent faults occurred within the same sequence. This cycle continued 40 times so that participants received 40 alarm advisories for each masking and contingent fault. The four fault scenarios were counterbalanced, wherein 1) both faults occurred, 2) both faults did not occur, 3) the masking fault occurred and the contingent fault did not occur, and 4) the masking fault did not occur and the contingent fault occurred. All transpired 10 times each throughout the experimental trial. Depending on the experimental condition, participants were aided with one of four alarm system configurations.

Alarm Type

Alarm type was manipulated in a similar method as Bustamante (2008). However, within this study the reliability of both alarms was set to .5. The two-state alarms emitted two types of advisories, wherein 'Alarm' advisories had a 50% hit rate and 50% false alarm rate, while 'OK' advisories had a 100% correct rejection rate.

In addition to the two-state alarm advisories, three-state alarms emitted a third state advisory with the signal words 'Warning'. This advisory indicates a low probability that the fault occurred, whereby the 'Alarm' advisory indicates a high probability that the fault occurred. Moreover, 'Alarm' advisories had a 90% hit rate and 10% false alarm rate, while 'Warning' advisories had a 10% hit rate and a 90% false alarm rate. The 'OK' advisories had a 100% correct rejection rate.

Procedure

When participants arrived to the laboratory, they first read and signed the informed consent form. At this point, researchers explained the nature of the experiment and presented participants with a PowerPoint presentation instructing them on how to perform both tasks. Participants then practiced both tasks individually and concurrently. The experiment consisted of two 30-minute trials with a 5-10 minute break in between. Participants completed two sessions to allow their performance to plateau at a reliable level. Furthermore, sensitivity and bias were examined in the second trail only.

RESULTS & DISCUSSION

When reviewing these results it is important to know the interpretation of the measures used. Sensitivity ranges between 0-1, wherein 0 represents complete inability to distinguish the signal, .5 represents distinguishing the signal at chance levels, and 1 represents perfectly distinguishing the signal. On the other hand, measures for bias range from -1 to 1, whereby negative scores indicate liberal bias, 0 indicates neutral bias, and positive scores indicate conservative bias. Based on the probabilities of signal and noise distributions, optimal bias for both alarm detection and fault diagnosis is 0.

Alarm Detection

Masking fault. Sensitivity and bias were submitted to separate 2 x 2 between-groups ANOVAs with alarm type for the masking fault and the contingent fault being the two independent variables (two-state, three-state).

Results for sensitivity supported our hypothesis and showed a statistically significant main effect $F(1, 56) = 329.13$, $p < .05$, partial $\eta^2 = .86$, observed power 1. On average, participants had greater sensitivity when using three-state alarms ($M = .92$, $SE = .01$) compared to the two-state alarms ($M = .47$, $SE = .02$).

Results for bias also supported our hypothesis and showed a main effect $F(1, 56) = 43.26$, $p < .05$, partial $\eta^2 = .44$, observed power 1.00. On average, participants had less bias in making affirmative diagnoses in the three-state alarm condition ($M = -.17$, $SE = .06$) compared to the two-state alarm condition ($M = -.82$, $SE = .08$).

Contingent fault. Sensitivity and bias were submitted to separate 2 x 2 x 2 MANOVAs with alarm type for the masking and contingent faults (two-state, three-state), and the state of the masking fault (occurred, did not occur) being the three independent variables.

Results for sensitivity supported our hypothesis that sensitivity would be higher when participants used three-state alarms. However, we also found an unexpected three-way interaction $F(1, 56) = 12.34$, $p < .05$, partial $\eta^2 = .10$, observed power .43, wherein sensitivity dropped to chance levels when the masking fault had two-state alarms, the contingent fault had three-state alarms, and the masking fault did not occur. On the other hand, sensitivity decreased below chance levels when the masking fault and the contingent fault had two-state alarms and the masking fault occurred (see Figure 3).

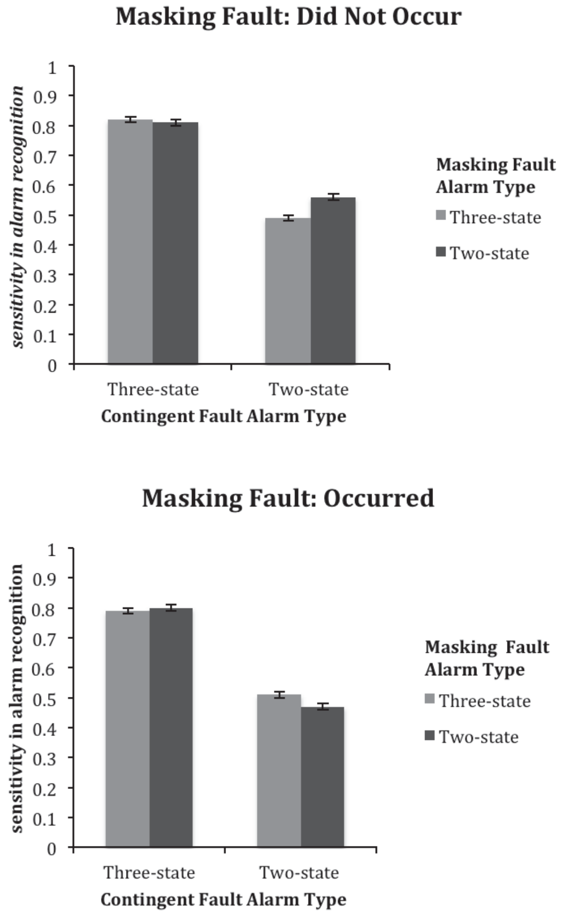

Figure 3. Sensitivity in alarm recognition for the contingent fault as a function of alarm types for the masking and contingent faults, and the state of the masking fault.

Unexpectedly, results for bias did not support our hypothesis. Alarm type did not affect participants' bias in alarm recognition.

Fault Detection

Masking fault. Sensitivity and bias were submitted to separate 2 x 2 between-groups ANOVAs with alarm type for the masking fault and the contingent fault being the two independent variables (two-state, three-state).

Results for sensitivity supported our hypothesis that sensitively would be higher in the three-state alarm condition. On average, participants had greater sensitivity when they used the three-state alarm (M = .97, SE = .00) compared to the two-state alarm (M = .92, SE = .02).

Results for bias showed three-state alarms increased bias in fault diagnosis over that of two-state alarms $F(1, 56) = 8.30$, $p < .05$, partial $\eta^2 = .13$, observed power .55. On average, participants were more biased toward making non-affirmative diagnoses when they used the three-state alarm (M = .76, SE = .07) compared to the two-state alarm (M = .30, SE = .14).

Contingent fault. Sensitivity and bias were submitted to separate 2 x 2 x 2 MANOVAs with alarm type for the masking and contingent faults (two-state, three-state), and the state of the masking fault (occurred, did not occur) being the three independent variables.

Results for sensitivity supported our hypothesis that sensitivity would be higher in the three-state alarm condition On average, participants had greater sensitivity when they used the three-state alarm (M = .76, SE = .02) compared to the two-state alarm (M = .66, SE = .02). Results also supported our hypothesis that sensitivity would be higher when participants used three-state alarms compared to two-state alarms in those conditions were indicators were potentially misleading $F(1, 56) = 20.31$, $p < .05$, partial $\eta^2 = .17$, observed power .90 (see Figure 4).

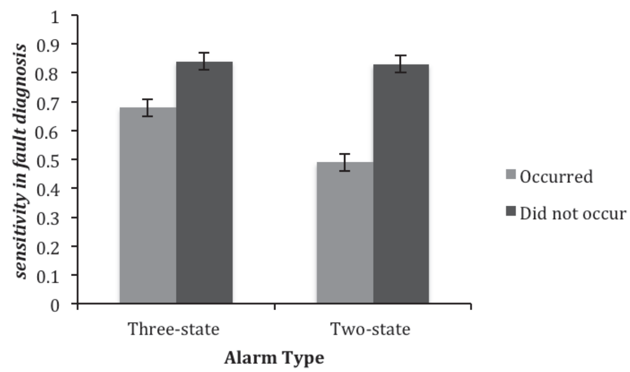

Figure 4. Sensativity in fault detection as a function of alarm type for the contingent event and state of the masking event.

Results for bias did not support our hypothesis that it would be higher in the two-state alarm condition when the contingent indicators were potentially misleading. Rather, participants had more bias in the three-state alarm condition $F(1, 56) = 5.5$, $p < .05$, partial η2 = .05, observed power .39. On average, when the masking fault occurred, participants tended to make more affirmative diagnoses when using three-state alarms (M = .96, SE = .01) compared to two-state alarms (M = .77, SE = .06).

DISCUSSION

This research effort found evidence that three-state alarms may assist nuclear power plant operators in appropriately allocating attention, and thereby may increase the effectiveness and efficiency of plant operations.

Theoretical Implications

Alarm Recognition. Three-state alarms improved performance in alarm detection over two-state alarms for both faults. This finding shows the benefits of three-state alarms over two-state in helping operators allocate attention. Furthermore, this study showed important theoretical implications for the principles of probability matching (Bliss et al., 1995) and urgency mapping (Edward & Loxely, 1991) when operators interact with multiple faults and alarms. Although three-state alarms generally improved sensitivity, there were times when it did not. For instance, when the masking fault had a three-state alarm and the contingent fault had a two-state alarm, participants tended not to monitor the masking event indicators and confirm the state of this fault. Furthermore, not confirming if the state of the masking fault made alarm recognition more difficult for the contingent event. Therefore, although three-state alarms better assisted participants in allocating attention during false alarms, two-state alarms better assisted participants in diagnosing faults during false alarms.

Fault Diagnosis. Participants performed better in fault diagnosis for both events when they used the three-state alarm compared to the two-state alarm. Furthermore, when the contingent fault had potentially misleading indicators, participants performed better in diagnosing faults when they used the three-state alarm. This finding shows that three-state alarms play an important role in assisting operators in diagnosing faults when those fault indicators have the potential to be misleading. It appears the urgency mapping of the alarm advisories contain additional diagnostic information that assists operators in diagnosing complex faults.

Participants also showed more bias in not making affirmative diagnoses for the contingent fault when using three-state alarms because they tended not to respond to 'Warning' advisories, thereby reducing the rate at which they monitored fault indicators and made affirmative diagnosis.

Practical Application

The implementation of three-state alarms within nuclear power plants may have important practical applications as operators systematically monitor numerous indicators to diagnose critical faults. The effectiveness of plant operations may improve as three-state alarm advisories guide operators more appropriately through the emergency operating procedures. By using the advisories to guide them, operators would give more time and attention to those procedures corresponding to faults that have high magnitude and/or probability of occurring.

Limitations and Future Research

Two potential limitations of this research were the low fidelity of the simulated environment and the nature of the sample—college students participating in the study were not professional nuclear power plant operators. High fidelity nuclear power plant simulators are rare and expensive (Boring, 2009) and were not feasible for this study. Previous research suggests people make decisions differently depending on their level of experience (Klein, 1998); furthermore, the way in which nuclear power plant operators make decisions may be significantly different from the participants used in this study.

This research had limitations that lead to suggestions for future research. First, future research could be done with high-fidelity simulators and actual nuclear power plant operators. One way to increase the fidelity of the simulation is to tether the alarm-monitoring task with the processing control task. Another way to increase the fidelity is to set the reliability levels of alarms to more accurately replicate that of a nuclear power plant.

Conclusion

Similar to past research (Bustamante, 2008; Clark & Bustamante, 2008; Clark, et al., 2010), the findings in this study provide further support for the benefit of three-state alarms within false alarm prone systems. Findings also showed the benefit of three-state alarms in providing additional diagnostic information to assist operators in diagnosing faults that may have misleading indicators. Finally, findings from this research effort may have strong theoretical foundations that will generalize and guide future research within the domain of nuclear power plant control.

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