Enhancing Operator Task Performance during Monitoring for Unanticipated Events through Ecological Interface Design

Nathan Lau[1], Gyrd Skraaning jr.[2], Greg A. Jamieson[1], Catherine M. Burns[3]
[1]Cognitive Engineering Laboratory, University of Toronto, Toronto, ON, Canada
[2]Man-Technology-Organization, OECD Halden Reactor Project, Halden, Norway
[3]Advanced Interface Design Laboratory, University of Waterloo, Waterloo, ON, Canada

A full scope simulator study with licensed Nuclear Power Plant (NPP) operators was conducted to evaluate the effectiveness of ecological displays in supporting operators with different types of tasks. The results suggest that ecological displays have a advantage in supporting operator performance during monitoring for unanticipated events as compared to mimic-based displays. Furthermore, ecological displays seem to achieve this performance advantage without imposing workload increases. This study provides supporting evidence that EID is effective at a scale and level of complexity representative of NPP operations.

INTRODUCTION

Low carbon emission and stable fuel supplies are rekindling interest in nuclear power (see e.g., Kennedy, 2007; Toth & Rogner, 2006). At the same time, Nuclear Power Plants (NPPs) are undergoing significant modernization to both extend plant lifecycles and increase electricity generation (see e.g., Watford, 2005; World Nuclear Assoc., 2005). This period of global and local change presents a unique opportunity for the industry to shift toward advanced technologies, including those that support the cognitive workload challenges of control room operators.

Ecological Interface Design (EID) is a theoretical framework for designing human-computer interfaces for complex socio-technical systems (Vicente & Rasmussen, 1992). The framework explicitly aims to support operators with knowledge-based or problem solving tasks, which are increasingly dominating work (also see, Vicente, 1999). Research on the EID framework has progressed significantly since its introduction over fifteen years ago (Vicente, 2002). Proof-of-concept ecological interfaces have been reported in many domains and performance benefits have been demonstrated in many laboratory studies. Despite its theoretical strength and accumulating research evidence, EID has yet to be widely adopted by the nuclear industry.

One factor precluding the nuclear industry from gaining the knowledge and confidence to adopt EID is a shortage of representative empirical studies that assess the practical benefits that EID could bring to the nuclear domain. The study most representative of industrial settings was conducted by Jamieson (2007), who evaluated an ecological interface in a full-scope simulator with licensed operators. While the results corroborated many of the findings of the laboratory studies, the study was situated in the petrochemical domain.

Other researchers have explored EID in the process industries. Ham and Woon (2001a; 2001b) presented an empirical evaluation of ecological interface content in a nuclear plant simulator, but the study did not employ configural graphics to communicate system information. Burns (2000a; 2000b) conducted empirical studies on different ecological displays for a simulated prototype fossil fuel power plant. However, the findings provide guidance on designing for display integration and navigation, rather than supporting evidence for performance benefits of ecological interfaces over conventional interfaces. Furthermore, both of these studies employed university students as participants, who might behave differently from NPP operators. A few other empirical studies on advanced visualization techniques for process operations do exist (e.g., Li, Sanderson, Memisevic, & Wong, 2007; Woods, Wise, & Hanes, 1981) but the configural displays in these studies were not specifically developed through the EID framework. In sum, the empirical studies in the open literature are insufficient to assess the merits of EID at the scale and complexity of nuclear power plant operations.

To address this, the University of Toronto, University of Waterloo and the OECD Halden Reactor Project established a research program to provide design, verification and validation evidence for EID in the nuclear domain. The research program involved designing ecological displays for the secondary side of an operating boiling water reactor (BWR) plant and evaluating them against mimic-based displays in a full-scope simulator with licensed operators. Lau et al. (in review) reported our investigation on interface design and verification, and Burns et al. (2007; in review) reported the situation awareness results of our experiment. In this article, we report our empirical findings on operator task performance and workload.

METHOD

Participants

Six licensed operator crews (n=6) were recruited from a BWR power plant identical to the simulated process. Each crew consisted of one reactor operator (RO) and one turbine operator (TO), responsible for the primary and secondary side of the simulated process, respectively. Because the Ecological displays were only developed for the secondary side, the results and discussion in this article only pertain to the performance of the TOs.

Experimental Environment

The HAlden Man-machine laboratory BOiling water reactor (HAMBO) (see, Karlsson et al., 2001; Øwre, Kvalem, Karlsson, & Nihlwing, 2002) was employed as the experimental platform for this study. HAMBO, a high-fidelity simulator of a 1200MW BWR plant (in operation), offers a realistic environment of industrial nuclear processes and features for sophisticated graphics.

Experimental Manipulations

The study consisted of three experimental manipulations:

Display Types. Three display types – Traditional, Advanced, and Ecological – were selected for comparison. The Traditional displays are the computerized version of the hard-wired wall panels originally installed in the operating nuclear plant. The Advanced displays are an improved version of the Traditional displays. The Advanced displays retain the mimic-diagrams of the Traditional displays; however, they also contain some configural graphics and "mini-trends" strategically developed or inserted by process experts (Karlsson et al., 2001; Øwre et al., 2002).

The Ecological displays were designed according to the EID framework and are described elsewhere (Lau et al., in review). The design scope was limited to the secondary side of the plant; hence, for plant processes that were not represented by the Ecological displays, the participants had access to the Traditional displays.

Scenario Types. This study contained three Procedure-guided and three Knowledge-based scenarios. For the purpose of this study, Procedure-guided scenarios were defined by a set of disturbances that could be resolved by referencing plant procedures. Scenarios in which disturbances could not be resolved by procedures were classified as Knowledge-based. In other words, equipment failures anticipated by the utilities and job responsibilities familiar to operators characterized the Procedure-guided scenarios, while unanticipated and unfamiliar ones characterized the Knowledge-based scenarios.

Scenario Phases. Each scenario started with a "Detection" phase, a time period just before the first alarm sounded, and then ended with a "Mitigation" phase that consisted of all subsequent events. The two phases afforded separate assessments of the effectiveness of the displays in supporting both monitoring and intervention.

Experimental Design

A 3x2x2 within-subjects design was employed with treatments of display type (Traditional, Advanced and Ecological), scenario type (Procedure-guided and Knowledge-based), and scenario phase (Detection and Mitigation). The treatments were completely crossed and counterbalanced using a Latin-square technique.

Hypothesis

The theoretical foundations of EID (Vicente & Rasmussen, 1992) and previous empirical results (Jamieson, 2007; Vicente, 2002) suggest that Ecological displays would support operators better than both the Traditional and Advanced displays. In particular, the performance advantage of the Ecological displays should be most pronounced in Knowledge-based scenarios, in which problem solving would be the primary means to resolving process disturbances.

Measures

Actual Task Performance. Operator task performance is selected over plant performance because operator behaviors could more clearly reflect the support facilitated by the different display types. Plant behaviors, in contrast, could be affected by factors besides operator actions, such as automation. (For a discussion, refer to Braarud & Skraaning jr. (2006).) Operator task performance was captured and quantified using the Operator Performance Assessment System (OPAS) (Skraaning jr., 2003; Skraaning jr. et al., 2007). OPAS provides a structure for the assessment of whether operators carry out their task work in accordance with scenario solutions prescribed a priori by experts in control room operation.

Prior to data collection, process experts analyzed the scenarios and developed optimal solutions by identifying items that expressed the desired performance. These items could differentiate between levels of task performance across experimental conditions relating to omissions, commissions, response time, and strategies. A simple scoring system was used, where the operators earned points for completing performance items. Each item depicted alternative operator activities that were rewarded by 0, 1, 2 or 3 points.

During the experiment, a process expert registered the points earned by operators in completing the predefined activities within each performance item based on observations of operator verbalization, physical behaviors, problem solving, and system states. Studies have shown that real time expert rating is comparable to objective data logs (e.g., simulator logs and video recordings) and that a single expert rater is adequate given the high inter-rater reliability (Skraaning jr., 2003) of the OPAS instrument. The employed performance index is the unweighted average of all performance items defined for a scenario. The OPAS index reflects the degree of conformance between operator performance and predefined optimal solutions to scenarios.

For this experiment, the process expert had been an operator of the physical power plant being simulated for over 10 years. Furthermore, over the 10 years preceding the experiment he had developed the NPP simulator and conducted numerous simulator experiments. Given his experience with the power plant and the simulator as well as his prior analysis of the scenarios, his rating of the OPAS items should be accurate and reliable.

Workload. We collected workload data using a *subjective task-complexity scale* developed by the OECD Halden Reactor Project (Braarud, 2000). The scale is a self-rating instrument focusing on task-related difficulties that control room operators experience while they work. Participants rate five items in a seven-point Likert scale anchored by 'very difficult' (1) and 'very easy' (7).

Procedure

The participation of each crew was divided over three consecutive days. The first day was dedicated to the training program after obtaining informed consent and demographic information. Six hours of training occurred on the first day.

The second day started with a one-hour training session to refresh the materials presented on the first day, followed by three scenarios with fifteen-minute breaks in between. The third day started with three scenarios also with fifteen-minute breaks in between, followed by a debriefing/closing session.

For all scenarios, crews were asked to maintain the original power level and safe operation. A process expert registered OPAS scores to corresponding performance items at various points of the scenarios by observing the participants while they monitored system states and resolved disturbances. The participants also responded to the subjective task-complexity questionnaire during a short simulator freeze and at the end of each scenario. The simulation freeze occurred at the end of the Detection phase, which took up the first five to ten minutes of the scenario. The scenario then continued with the Mitigation phase, which was marked by the onset of the first alarm within the first minute. The Mitigation phase usually lasted 30 to 40 minutes, followed by another administration of the subjective task-complexity questionnaire at the end of the scenario.

RESULTS

Workload

Workload was confirmed to have a sufficiently high inter-item reliability (α=0.89) for further analysis. Workload was analyzed in an ANOVA with fixed factors of display type (Traditional, Advanced and Ecological), scenario type (Procedure-guided and Knowledge-based), and scenario phase (Detection and Mitigation), and with a random factor of crew.

A significant main effect of phase ($F(1,5)=23.03$, $p<0.01$), and significant two-way interaction effects for display and phase ($F(2,10)=5.39$, $p<0.05$), and scenario and phase ($F(1,5)=8.59$, $p<0.05$) were observed (Table 1).

Table 1: ANOVA results on Workload.

Effects	SS	df	MS	SS_{er}	df_{er}	MS_{er}	F	p
Display	1.42	2	0.71	12.1	10	1.21	0.59	0.57
Scenario	0.29	1	0.29	1.60	5	0.32	0.92	0.38
Phase	22.9	1	22.9	4.97	5	0.99	23.0	0.00
Display*Scenario	0.71	2	0.35	10.9	10	1.09	0.32	0.73
Display*Phase	3.97	2	1.98	3.68	10	0.37	5.39	0.03
Scenario*Phase	3.12	1	3.12	1.82	5	0.36	8.59	0.03
Display* Scenario*Phase	1.27	2	0.64	8.50	10	0.85	0.75	0.50

For the purpose of evaluating EID, we only present the two-way interaction plot as it relates to display types. The display and phase interaction plot (Figure 1) illustrates no practical difference in Workload between the three display types in the Detection phase, although the Workload increase from the Detection to the Mitigation phase is highest with the Traditional displays and lowest with the Advanced displays.

Actual Task Performance controlled for Workload

Actual task performance (i.e., the OPAS indices) was analyzed in an ANCOVA with fixed factors of display type (Traditional, Advanced and Ecological), scenario type (Procedure-guided and Knowledge-based) and scenario phase (Detection and Mitigation), a random factor of crew, and a covariate of Workload.

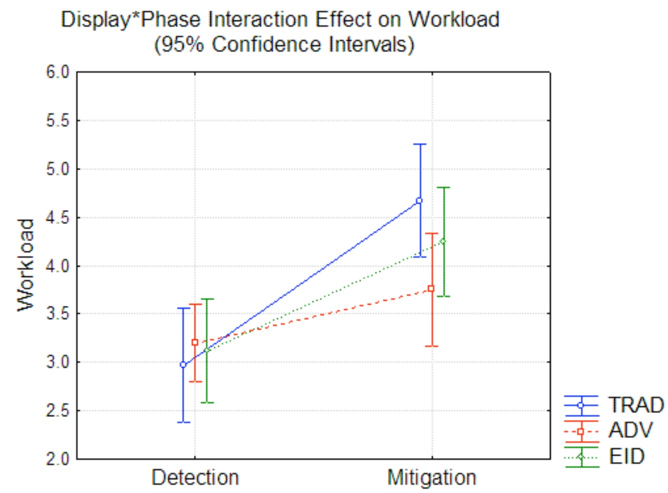

Figure 1: Interaction plot of display and phase on Workload. The confidence intervals throughout the article are based on the method proposed by Cosineau (2007) to remove within-subject variance.

Table 2 presents the results of the ANCOVA. The significant effects on Actual task performance after controlling for Workload are the two-way interaction of display and phase ($F(2,10.55)=8.09$, $p<0.01$), and the three-way interaction of display, scenario and phase ($F(2,9)=6.08$, $p<0.05$).

Table 2: ANCOVA Results on Actual Task Performance.

Effects	SS	df	MS	SS_{er}	df_{er}	MS_{er}	F	p
Display	1.00	2	0.50	5.05	10	0.50	0.99	0.41
Scenario	0.82	1	0.82	2.19	5	0.44	1.88	0.23
Phase	0.03	1	0.03	0.85	5	0.22	0.14	0.72
Display*Scenario	3.81	2	1.91	9.29	10	0.97	1.97	0.19
Display*Phase	4.40	2	2.20	2.80	10	0.27	8.09	0.00
Scenario*Phase	1.11	1	1.11	3.24	5	0.57	1.95	0.22
Display* Scenario*Phase	1.64	2	0.82	1.21	9	0.13	6.08	0.02

Because the two-way interaction only provides limited and redundant information, we present the three-way interaction plot. Figure 2 suggests that the Ecological displays enhanced Actual task performance in the Detection phase of Knowledge-based scenarios. The performance difference between displays in other experimental conditions appeared negligible.

DISCUSSION

Workload

For the purpose of evaluating EID for the nuclear industry, our discussion on Workload excludes the phase main effect, and scenario and phase interaction effect. The display and phase interaction effect indicates that both the Advanced

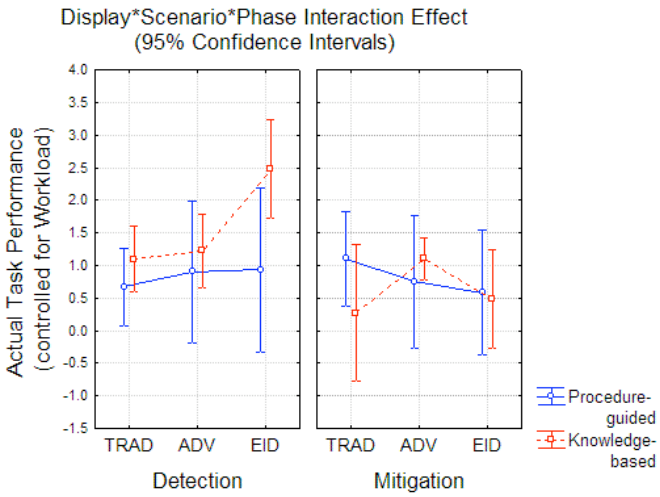

Figure 2: Interaction effect of Display, Scenario and Phase on Actual Task Performance controlled for Workload.

and Ecological displays appear to induce smaller increases of Workload from the Detection to Mitigation phase than the Traditional displays. This finding is encouraging in that the new visualization techniques do not result in higher Workload. The least Workload increase was unexpectedly observed with the Advanced displays. We postulate that the evolutionary improvements based on the user-centered approach for the Advanced displays may be concentrated on improving efficiency and thereby reducing Workload. In contrast, the ecological approach emphasizes improving interface effectiveness and thereby strengthening operator performance during unanticipated events. This approach may not necessarily alleviate Workload. Also for this reason, we focus our discussion on the Actual task performance, which includes an assessment of problem solving.

Actual Task Performance

The ANCOVA results corroborate the general findings of previous EID studies (Vicente, 2002) that support the theoretical claim of improving operator performance for knowledge-based or problem solving tasks (Vicente & Rasmussen, 1992). The three-way interaction plot (Figure 2) illustrates a marked advantage for the Ecological displays in the Detection phase of Knowledge-based scenarios over both Traditional and Advanced displays, whereas other performance differences were relatively negligible. This unique performance advantage also directly translates to the significant two-way interaction effect between display type and scenario phase (in which the Ecological displays demonstrated better performance in the Detection phase than the other displays).

The advantage for the Ecological displays in the Detection phase of Knowledge-based scenarios indicates that EID could lead to displays that better support operators in monitoring for unanticipated events or early phases of problem solving (i.e., problem identification and formulation) than mimic-based displays. Monitoring for critical events evolving from ‘normal’ operating states is a key part of supervisory control. Effective monitoring facilitates early intervention that can prevent process deviations developing into major disturbances or even accidents (see, Burns, 2006; Mumaw, Roth, Vicente, & Burns, 2000). Furthermore, investigations have repeatedly indicated that major accidents are often preceded by unanticipated events (e.g., Rasmussen, 1969; Reason, 1990). Thus, the unique advantage of the Ecological displays demonstrated in this study is encouraging in that EID could be a design solution for coping with unanticipated events, which have largely been neglected by conventional approaches.

The performance advantage of the Ecological displays, however, did not persist in the Mitigation phase of Knowledge-based scenarios, as predicted by the framework and observed in previous empirical studies. Two factors that could have contributed to such an outcome are particularly worth highlighting. First, the Mitigation phase could contain proportionally fewer knowledge-based tasks than the Detection phase, thereby attenuating the reliance on the support for problem solving provided by the Ecological displays. During the Mitigation phase, operators may have engaged in some rule-based decision-making, even in the Knowledge-based scenarios (e.g., executing control actions according to their planned solutions). In other words, the Mitigation phase inherently included tasks other than problem solving even in Knowledge-based scenarios. Second, the designers did not invent an EID-based interaction style for taking control actions in the Ecological display conditions. The interaction style was taken from the Traditional displays and was consistent across display conditions, potentially resulting in similar operator behaviors. These factors would be expected to yield Ecological display performance during the Mitigation phases that is similar to that of the Advanced and Traditional displays, which are mainly intended to support rule-based decision-making and taking control actions.

Limitations

The Ecological displays employed in this study are, in fact, a hybrid Ecological-Traditional interface. The reliance on a hybrid implementation raises the question of compatibility between the two display types that has not been investigated in the open literature. A comparison of displays that included ecological displays for the primary side would provide a more accurate assessment of the merits of the ecological approach. It is worth noting that, although a hybrid implementation is not ideal from an experimental perspective, it is actually quite representative of industry practice.

Future work

Subsequent studies should address several unattended issues. The scope of future assessments should be expanded to include the primary side and other operator support tools (e.g., large screen displays). Studies employing alternative performance measures (e.g., system efficiency) are also needed to obtain both convergent and discriminant validity. A complete set of human performance measures would also illustrate the particular facets of work best supported by EID. A more extensive set of scenarios is also needed to explore the consistency of support provided by ecological displays in other operating modes (e.g., start-up, shut-down, and re-fueling). As recommended by Burns and Hajdukiewicz (2004) and investigated by Jamieson et al. (2007), our findings suggest that integrating other approaches into the EID framework to explicitly provide procedural support may result in efficient and robust interfaces that may not be achieved with any one design technique. Thus, future studies also need to assess integrated techniques, probably in both laboratory and industrially representative settings.

CONCLUSION

The objective of our ongoing research program is to collect design, verification and validation evidence to assess the merits of EID in the nuclear domain. This article presents an empirical evaluation of ecological displays in a setting representative of a NPP control room with professional operators. The results indicate that ecological displays could provide a marked advantage in monitoring for unanticipated events over other conventional displays while other performance differences between the interfaces are relatively negligible. Furthermore, ecological displays seem to achieve this performance advantage without any workload increments. This conclusion marks a promising beginning for EID validation in the nuclear domain. These results together are particularly encouraging because EID appears to be a design solution for coping with unanticipated events, which have largely been neglected by conventional approaches. This study, therefore, is an important step in the ongoing effort to improve human-system interaction in the nuclear industry.

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