Providing Operator Support during Monitoring for Unanticipated Events through Ecological Interface Design

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Abstract

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 marked advantage in supporting operator performance during monitoring for unanticipated events as compared to mimic-based displays. The ecological displays did not support operator performance differently for other types of tasks. These results are encouraging because EID appears to be a design solution for coping with unanticipated events, which have largely been neglected by conventional approaches. The study provides supporting evidence that EID is effective at a scale and level of complexity representative of NPP operations.

Keywords: human-system interface; ecological interface design; control room

I. INTRODUCTION

Ecological Interface Design (EID) is a theoretical framework for designing human-computer interfaces for complex socio-technical systems [1]. The framework explicitly aims to support operators with knowledge-based or problem solving tasks, which are increasingly dominating work (see, [2]). The framework consists of a formative work analysis for specifying information requirements and a taxonomy of human information processing behaviours for guiding design of perceptual features. Research on the EID framework has progressed significantly since its introduction over fifteen years ago [3]. 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 [4], 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.

Some researchers have explored EID in the power generation domain. Ham and Woon [5, 6] presented an empirical evaluation of ecological interface content in a nuclear plant simulator, but the study did not completely assess the EID framework, which typically employs configural graphics to communicate system information. Burns [7, 8] conducted empirical studies on different ecological displays for a simulated prototype fossil fuel power plant; but the findings provide guidance on designing for display integration and navigation, rather than evidence of performance benefits for ecological interfaces over conventional interfaces. Furthermore, both of these studies employed university students as participants, who might behave differently from NPP operators. In sum, the empirical studies in the open literature are insufficient to assess the merits of EID at the scale and complexity of NPP 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. [9] reported our investigation on interface design and verification, and Burns et al. [10, 11] reported the situation awareness results of our experiment. In this article, we report our empirical findings on operator task performance.

II. METHOD

A. 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. In two cases within this study, participants currently working as ROs operated the secondary side. This substitution should not affect generalization of the results given that all ROs must previously or currently hold TO licenses. Because the Ecological displays are only developed for the secondary side, the results and discussion in this paper only pertain to the performance of the TOs.

B. Experimental Environment

We used the HAlden Man-machine laboratory BOiling water reactor (HAMBO) [12, 13] as the experimental platform for this study. HAMBO, a high-fidelity simulator of a 1200MW boiling water reactor plant (in operation), offers a realistic environment of industrial nuclear processes and features for sophisticated graphics [14]. The access to licensed operators from the operating plant corresponding to the simulation was also a crucial factor for our decision to use HAMBO, as this increases the representativeness of the study. However, we confined our scope to the secondary side of the plant because of the higher availability of TOs for the future study.

B. Experimental Manipulations

This experimental study consisted of three experimental manipulations – display types, scenario types and scenario phases.

1) 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 (e.g., Figure 1). The Advanced displays are an improved version of the Traditional displays. The Advanced displays (e.g., Figure 2) 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 [12, 13].

The Ecological displays were designed according to the EID framework and are described elsewhere ([9]; e.g., Figure 3). 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. Furthermore, alarm information was communicated in the same manner across the display conditions (i.e., they have the same alarm displays). All three types of displays also share the general layout and interaction style.

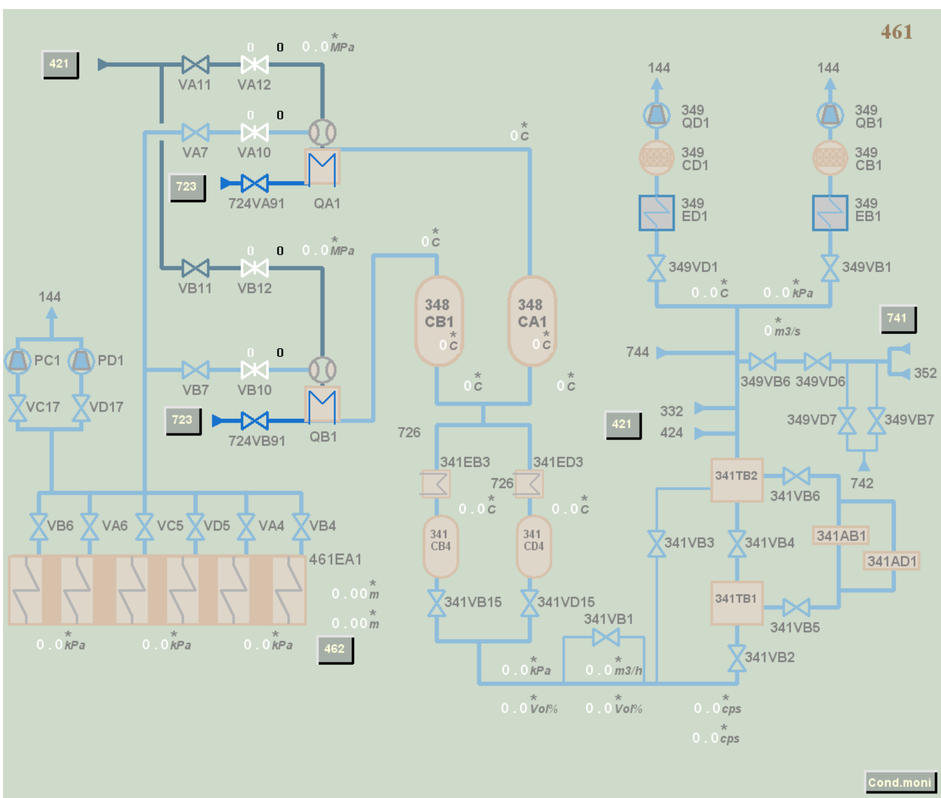

Figure 1: An example of a Traditional display.

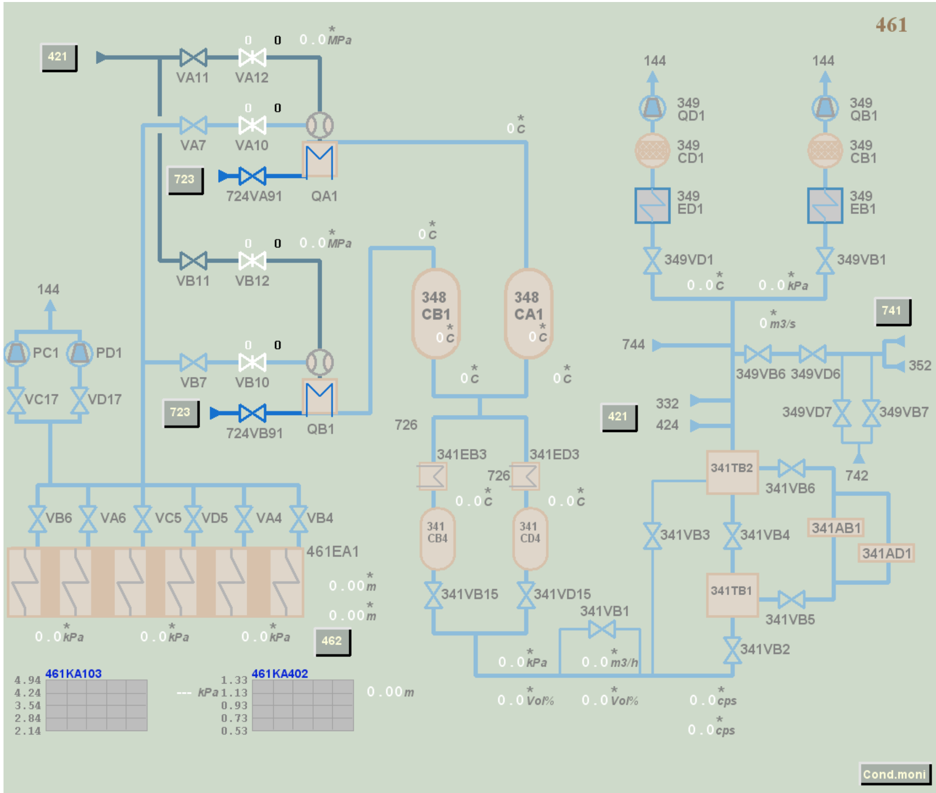

Figure 2: An example of an Advanced display.

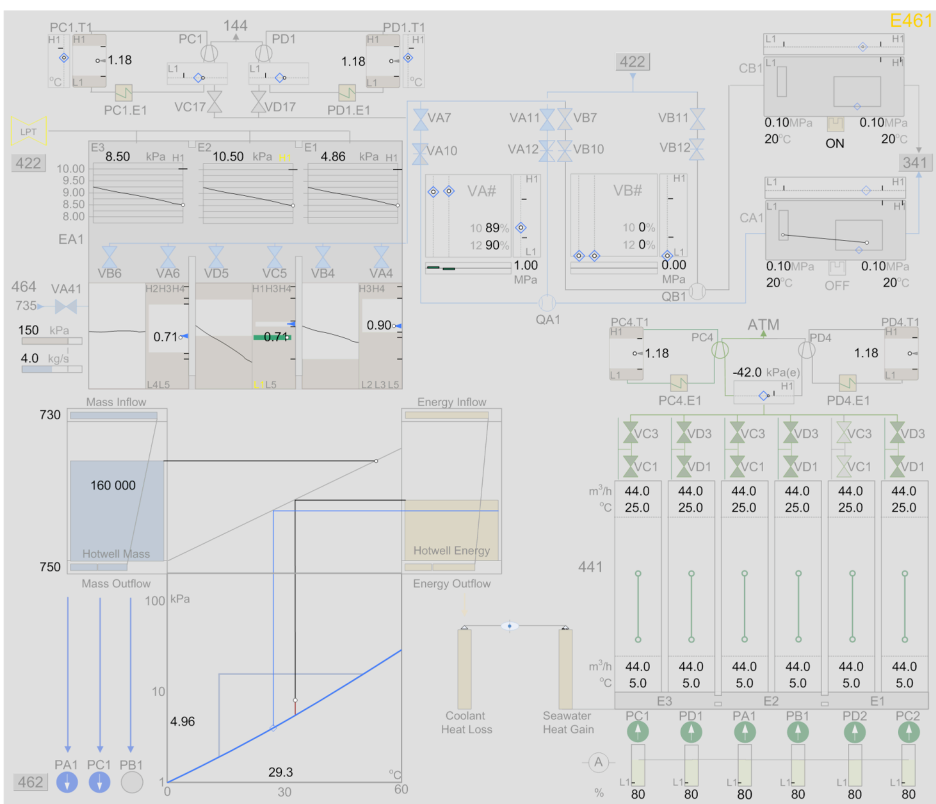

Figure 3: An example of an Ecological display.

2) Scenario Type: 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.

3) Scenario Phase: 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. (Figure 4 illustrates the detailed structure of the scenarios.) The two phases afforded separate assessments of the effectiveness of the displays in supporting both monitoring and intervention.

D. 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.

E. Hypotheses

The theoretical foundations of EID [1] and previous empirical results [3, 4] suggest that Ecological displays would support operators better than both Traditional and Advanced displays. In particular, the performance advantage of the Ecological displays was anticipated to be most pronounced in Knowledge-based scenarios, in which problem solving would be the primary means to resolving process disturbances.

F. Measures

1) Actual Task Performance: Actual task performance was captured and quantified using the Operator Performance Assessment System (OPAS) [15-17]. 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 [15] 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 discrepancy between operator performance and predefined optimal solutions to scenarios. Due to its relativistic nature, the OPAS index cannot establish any general acceptance criteria, as it is only meaningful for comparisons between indices across situations. Nevertheless, operator performance relative to the optimal level can be psychologically meaningful. OPAS assesses the degree of conformance with performance expectations that remain constant across task conditions; thus, the raw scores originating from different scenarios can be compiled into one performance index. In addition, OPAS is similar to training and licensing assessment situations in the nuclear domain, for which human performance constructs are often ill-defined and may be difficult for non-experts to understand due to domain complexity.

The ill-defined nature of human performance in complex domains is partially attributable to the fact that measures of task performance often include multiple and interacting aspects of human performance. In other words, task performance measures often cannot distinguish between interacting aspects of human performance, even though these aspects may be psychologically or conceptually distinct. In this study, we are particularly concerned with distinguishing between task performance and workload. Workload is largely driven by the nature of the scenarios, which also determines the OPAS performance items. For some scenarios, operators may experience high workload from completing many relatively simple performance items in a short amount of time. Other operators may experience high workload from completing only a few complex performance items. In either case, operators need to overcome workload demand to achieve high OPAS indices. For this reason, the influence of workload will be statistically removed from Actual task performance in this study (see *IV. Discussion*).

2) Workload: Workload is generally accepted to have a significant impact on performance. Improved task performance at the expense of higher workload is usually not desirable; thus, we collected workload data using a *subjective task-complexity scale* developed by the OECD Halden Reactor Project [18]. The scale is a self-rating instrument focusing on task-related difficulties that control room operators experience while they work. Participants rate five items (Table 1) in a seven-point Likert scale anchored by 'very difficult' (1) and 'very easy' (7). Several psychometric evaluations and experimental studies indicate that the scale is more reliable and predictive of task performance in representative nuclear process control settings [16] than the NASA-TLX [19]. [20] discusses the subjective task-complexity scale in detail.

Table 1: Workload items of the subjective task-complexity scale.

Workload items	How difficult was this scenario period with respect to:
Item 1	Vague or ambiguous process displays, misleading or missing process information
Item 2	Ambiguous, misleading or missing feedback on operator actions
Item 3	Time for planning and controlling the work
Item 4	May parallel tasks (several disturbances or process events) that complicated the execution of every single task
Item 5	Collection and utilization of much information to perform the work

G. 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 as depicted in Figure 4. 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 for 30 to 40 minutes, followed by another administration of the subjective task-complexity questionnaire at the end of the scenario.

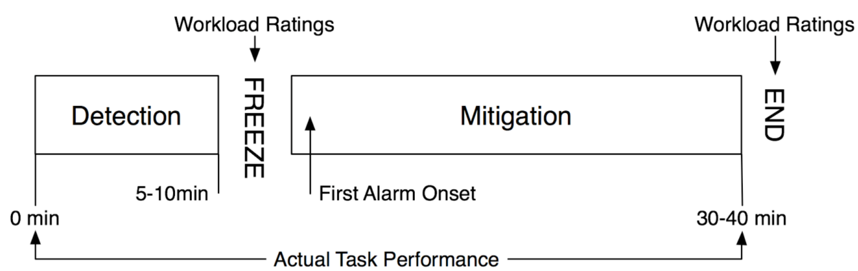

Figure 4: Basic structure of the scenarios.

III. RESULTS

We applied analysis of variance and analysis of covariance to analyze Workload and Actual task performance, respectively. For the purpose of examining interface support for knowledge-based work, we omit the analysis and results on Workload, which are reported elsewhere [21, 22]. It is worth noting that Workload is statistically shown to be an appropriate covariate given its high inter-item reliability (α=0.89) and its low correlation ($r(72)=0.31, p<0.01$) with Actual task performance.

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.

This analysis explores the fixed effects on Actual task performance controlled for Workload, assessing the support for problem solving provided by each display type independent of the variation in task demand. Table 2 presents the results of the ANCOVA for all effects. 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 for Actual Task Performance with Workload as the covariate.

Fixed Effects	SS	df	MS	df for Error	MS for Error	F	P
Display	1.00	2	0.50	9.48	0.50	0.99	0.41
Scenario	0.82	1	0.82	4.94	0.44	1.88	0.23
Phase	0.03	1	0.03	14.60	0.22	0.14	0.72
Display*Scenario	3.81	2	1.91	9.86	0.97	1.97	0.19
Display*Phase	4.40	2	2.20	10.55	0.27	8.09	0.00
Scenario*Phase	1.11	1	1.11	5.37	0.57	1.95	0.22
Display*Scenario*Phase	1.64	2	0.82	9.00	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 5 suggests that the Ecological displays enhanced Actual task performance in the Detection phase of Knowledge-based scenarios. The performance difference between interfaces in other experimental conditions appeared negligible. The three-way interaction effect accounts for 12% of the total variance ($\omega^2=0.12$).

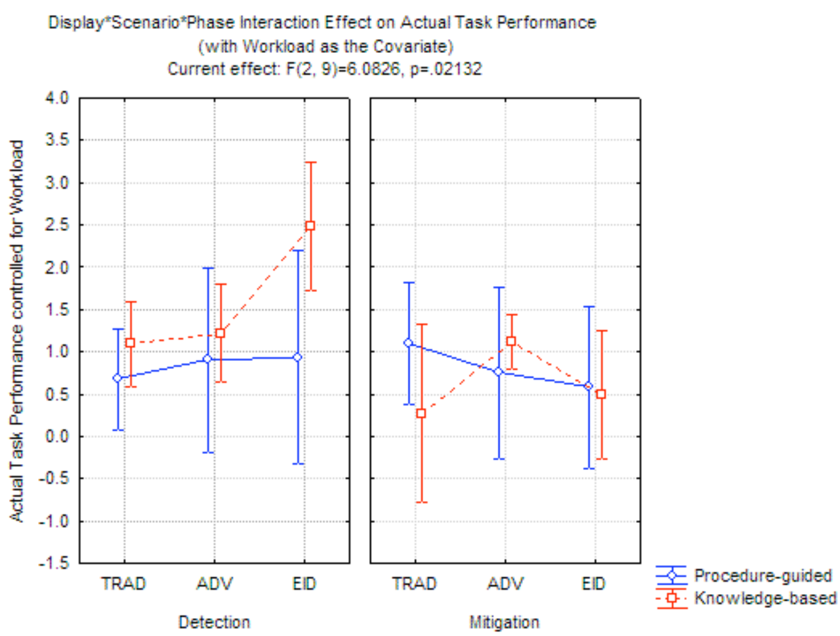

Figure 5: Interaction plot of Display, Scenario and Phase for Actual Task Performance controlled for Workload. The plot is drawn according to the method proposed by [23] to remove within-subject variance. (Note that overlaps between confidence intervals do *not* necessarily indicate that the means are not significantly different. See [24, 25] for a discussion.)

IV. DISCUSSION

A. Validation Evidence: Actual Task Performance Controlling for Workload

The theoretical foundations and accumulated empirical results pertaining to EID indicate that the primary contribution of introducing ecological displays would be superior support for knowledge-based or problem solving tasks relative to displays based on conventional approaches. However, as mentioned, task performance as defined by OPAS is likely to include the influence of workload, which is of secondary interest here. To limit the influence of workload while assessing the level of support for problem solving tasks provided by the displays, we conducted an ANCOVA on Actual task performance with Workload as a covariate. The ANCOVA removed the variance of workload in each scenario from the Actual task performance. Given that both the Advanced and Ecological displays appear superior to the Traditional displays in terms of Workload according to the ANOVA results [21], this analysis approach was appropriate and meaningful as new visualization techniques do not seem to induce excessive Workload. In essence, the ANCOVA results provided a purer indication of *performance on problem solving tasks* in comparison to an ANOVA on Actual task performance.

The ANCOVA results corroborate the general findings of the previous EID studies [3, 4] supporting the theoretical claim [1, 2] of improving operator performance for knowledge-based or problem solving tasks. The three-way interaction plot (Figure 5) illustrates a marked advantage for the Ecological displays in the Detection phase of Knowledge-based scenarios over both Traditional and Advanced displays (though not in the Mitigation phase of Knowledge-based scenarios as suggested by theory). Other performance differences were relatively negligible.

The advantage for the Ecological displays in the Detection phase of Knowledge-based scenarios indicates that EID could lead to displays which 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 from developing into major disturbances or even accidents (see [26, 27]). Furthermore, investigations have repeatedly indicated that major accidents are often preceded by unanticipated events [28, 29]. 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 theoretical foundations of EID [1, 2, 30] support the argument that the framework could contribute to this benefit in two ways. First, the information content and structure identified by the Work Domain Analysis are explicitly selected to support operators in coping with all events, including unanticipated ones. In contrast, conventional approaches only explicitly identify information requirements of anticipated events. While all of these design approaches could effectively support monitoring for anticipated events (as suggested by the negligible performance difference between display types in the Detection phase of Procedure-guided scenarios), the information content and structure in Ecological displays should better support operators in coping with unanticipated events. Second, the graphical forms in Ecological displays followed the SRK taxonomy, which served as an overarching framework to guide design towards high compatibility with human information processing (for all levels of cognitive controls). On the other hand, conventional approaches usually contain specific, rather than overall, design heuristics and principles (e.g., [31]) to ensure compatibility with information processing. Thus, Ecological displays could communicate process information more effectively to operators than displays based on conventional approaches. This advantage would also be most prominent for information related to knowledge-based rather than rule-based decision making when common monitoring strategies may be insufficient.

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.

B. 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.

C. 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 [30] and investigated in [32], 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, in both laboratory and industrially representative settings.

V. 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. [14] reports our effort in demonstrating that the EID framework can lead to visualization features and verification criteria that are valuable for supporting and ensuring effective monitoring during both anticipated and unanticipated events. Together with [10], this article presents the first empirical evaluation of ecological displays in a setting representative of a nuclear power plant control room with professional operators. The results support the conclusion that ecological displays could provide a marked advantage for monitoring for unanticipated events over other conventional displays while other performance differences between the interfaces are relatively negligible. This conclusion marks a promising beginning of 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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