Ecological Interface Design for Petrochemical Process Control: An Empirical Assessment

Greg A. Jamieson, *Member, IEEE*

***Abstract*—Abnormal events in process plants cost the petrochemical industry billions of dollars annually. In part, these events are difficult to deal with because contemporary interfaces do not adequately inform operators about the state of the process. Laboratory simulator studies have shown that, in comparison with contemporary interfaces, ecological interfaces can lead to more effective monitoring and control behavior. However, ecological interfaces derived from work-domain analysis differ from more traditional human-centered interfaces that use a task analysis to inform the design process. A companion paper demonstrated an ecological interface that integrates both work-domain- and task-based information. A second ecological interface was created, drawing exclusively from the traditional work-domain-based analysis. Professional operators used the novel interfaces in an industrial petrochemical process simulator to monitor for, diagnose, and respond to several types of process events. Operators using the work-domain-based ecological interface completed trials more quickly and executed fewer control actions than their counterparts using the current process displays. Operators using the integrated (task- and work-domain-based) ecological interface also showed these benefits and, in addition, showed improved fault diagnoses and better performance scores. The implications and opportunities for introducing ecological interfaces into industrial control rooms are discussed.**

***Index Terms*—Graphical user interfaces, petroleum industry, process control, man–machine systems.**

I. INTRODUCTION

THIS paper is situated at the intersection of a practical problem in process control and a theoretical problem in cognitive engineering. The practical problem is the management of abnormal situations by process operations personnel. Bullemer and Nimmo [1] defined an abnormal situation as any process disturbance that requires an operator action to restore the plant to a normal operating condition. Their estimate placed the annual cost of abnormal situations in the petrochemical industry at US $10 billion in preventable losses. One challenge in recovering those losses is overcoming the failure of user interface technologies to match advances in automation technology and plant complexity.

Having identified user interface technologies as an area for improvement in addressing losses due to abnormal situations, we encounter a theoretical problem in cognitive engineering. That is, 1) what work analysis methods should be used to generate the design requirements for these interfaces and 2) how can those requirements be translated into effective visual forms? In a companion paper [2], we explored these questions in detail, providing an account of an effort to produce an innovative ecological interface that integrated the results of both system- and task-based work analyses.

In this paper, a second ecological interface that draws exclusively from the system-based work analysis is introduced. Results of an empirical assessment of both of the ecological interfaces and a third interface—the one currently used to control the target process—are reported. That assessment combines the practical and theoretical problems noted above and yields insight into the interaction of event classifications and interface design approaches.

A. Classifications of Abnormal Situations

A fundamental distinction for the research described in this paper is the classification of events that occur in process operations. Vicente and Rasmussen [3] classified events according to two dimensions: 1) whether the event is *familiar* or *unfamiliar* to an operator and 2) whether an event is *anticipated* or *unanticipated* by designers of the process. Based on these two distinctions, they identified three event classes: 1) familiar and anticipated events (often addressed by standard operating procedures); 2) unfamiliar but anticipated events (often addressed by emergency operating procedures); and 3) unfamiliar and unanticipated events (not addressed by procedures).[1] The most severe accidents in process operations have historically fallen into the category of unfamiliar and unanticipated events [3].

Although Vicente and Rasmussen [3] spoke of events in terms of whether they are familiar or unfamiliar to operators, empirical studies of ecological interface design (EID) have distinguished between events from a systems perspective as either *normal* or *fault* events. Industry tends to share this system-centric view, typically using the terms *normal* and *abnormal* (see the definition above). While acknowledging that an abnormal situation could conceivably be familiar to operators (however undesirable that might be) or vice versa, the similarity between the terminology in prior empirical work and in industry suggests that the terms are largely consistent. In this work, the terms Familiar and Unfamiliar are employed, as

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The author is with the Department of Mechanical and Industrial Engineering, University of Toronto, Toronto, ON M5S 3G8, Canada (e-mail: jamieson@mie.utoronto.ca).

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[1] The fourth category, namely, events that are familiar to operators but unanticipated by designers might include known deviations from proscribed operating practice. This category of events is not discussed by Vicente and Rasmussen [3] and is not addressed here.

opposed to Normal and Abnormal. The difference appears to be minor and not highly relevant in this case.

EID theory predicts that ecological interfaces will be most beneficial in supporting operators in managing events that are both abnormal and unanticipated by designers [3]. Several studies have confirmed that ecological interfaces lead to better performance in such events [5]. However, the scenarios employed in those studies have not explicitly distinguished unfamiliar events that are anticipated by designers (Anticipated/Unfamiliar) from unfamiliar events that are unanticipated (Unanticipated/Unfamiliar). Rather, these studies only distinguish "normal" events from "fault" events. Thus, the current EID literature fails to adequately distinguish between performance advantages for these two subcategories of unfamiliar events as predicted by theory.

B. Work Analysis Frameworks

Much of the academic work on human–machine interfaces can be categorized as addressing one of two questions: 1) What information content should the interface communicate? 2) What form should the information take? In a companion paper [2], we posited that a primary differentiator of content-specification methods is whether they take a work-domain- or task-based perspective. We employed both perspectives in an intensive analysis of an acetylene hydrogenation reactor (referred to as "the reactor" henceforth)—a representative industrial petrochemical production system. Despite the marked theoretical differences between the perspectives, the information requirements derived from the two sets of analyses proved to be largely complementary; a replication of earlier findings from analyses of simpler systems [4].

The companion paper continued by demonstrating a sample ecological interface form that integrated the work-domain- and task-based requirements for an advanced controller. The complete interface for the target system fully integrated those requirements both within process views and between process views, with some graphical forms drawing exclusively from one type of analysis and other forms combining information from both types of analysis.

As this brief account suggests, the companion paper discusses both theoretical issues surrounding the specification of information content and a case study of that process. This paper builds upon that foundation by 1) presenting a variant of the reactor interface that excludes task-based information and 2) relating the results of an empirical evaluation of both interfaces.

C. Conclusion

Taken together, the two fundamental issues noted above form the foundation of the work described here. The objective is to determine the possible relationship between three different categories of process events and two different approaches to interface content specification. In this study, the three event categories (i.e., Anticipated/Familiar, Anticipated/Unfamiliar, and Unanticipated/Unfamiliar) were distinguished and experimentally evaluated between interfaces that either included or excluded task-based information. Thus, important theoretical predictions of EID (e.g., that ecological interfaces are most beneficial in supporting unanticipated unfamiliar events) were tested.

D. Corollary Issues

In addition to the two core issues of event classification and design approaches, this paper addresses several corollary issues of importance to cognitive engineering research.

1) State of the Art in Operator Support Tools in Practice: Contemporary interfaces in the petrochemical process industry generally fail to provide higher level information to operators in a form that is both effective and usable [6]. The existing interface for the target process tested here is typical of contemporary process displays. The display scheme is based primarily on a process mimic graphic that places some setting and flow values in their physical context. Trending capability and tabular alarm summary pages are provided to support the mimic displays. Very little higher order information is made available, and designers rarely employ human factors standards for interface design. In most cases, experienced operators designed these displays based on reviews of piping and instrumentation diagrams and drawing from their prior experience as users. Such an approach is not uncommon in industry practice. This research represents an alternative approach to this interface design practice and thereby furthers the state of the art.

2) Fidelity and Scale: Much of the EID research completed to date has been conducted with a single representative process control microworld simulation with several interface variations [7]–[12]. Reising and Sanderson [13] also constructed a novel ecological interface for a laboratory process simulation of similar complexity and extended the research by investigating the impact of sensor reliability and availability [14]. Burns [15], [16] designed an ecological display (i.e., with no operator control capability) for a more complex desktop process simulation and evaluated different approaches to display integration. Ham and Yoon [17], [18] conducted an empirical evaluation of ecological interface content in a nuclear plant simulator, but without employing the configural graphics that have typified the visual form of other ecological displays. All of these studies employed undergraduate students as participants. Further examples of EID applications span a range of levels of complexity, without including empirical evaluations. For example, both Dinadis and Vicente [19] and Jamieson and Vicente [6] have presented ecological interfaces for safety-critical process subsystems, but without undertaking empirical evaluations. Scaling up the design problem, Toshiba has developed an ecological interface for a full-scale nuclear power simulation [20]. Similarly, Yamaguchi and Tanabe [21] describe an interface for a shipboard nuclear power simulator. However, no empirical evaluations of these interfaces have been published.

Ecological interfaces have also been tested outside of the process control domain. Sharp and Helmicki [22] tested ecological displays for neonatal intensive care monitoring with medical residents, fellows, and attending physicians. Burns *et al.* [23] and Duez and Vicente [24] have separately developed novel ecological interfaces for computer network management and evaluated those displays with nonexpert

TABLE I
PARTICIPANT DEMOGRAPHICS

	Mean (years)	Standard Deviation (years)	Range (years)
Age	44.5	6.7	(31,57)
Industry Experience	19.7	5.9	(9,36)
Control panel operating experience (all processes, throughout career)	6.6	2.9	(0.75,12.83)
Tenure at sponsor company	16.4	5.4	(3.7,24)
Control panel operating experience on target process	3.6	2.4	(0.75,10)

participants. Finally, applications of EID in the aviation domain are emerging in the literature (for example, [25]–[27]), although the initial evaluations are limited.

This paper builds upon all of these efforts in terms of fidelity and scale. In terms of the number of process variables, the target system is of a complexity comparable to that employed by Burns [15]. However, the use of a full-scale industrial simulator allowed for the development of interactive interfaces (i.e., with both display and control capabilities). The use of professional operators, as opposed to students, gives the study face validity in generalizing results to industry. In a further enhancement to generalizability, this study included proceduralized events, both normal and abnormal. Prior studies of EID have not included events for which procedures were established and known to the operators. Finally, the simulator used in the present study runs on the same digital instrumentation and control system that is employed in the actual plant. Thus, the challenges of implementing an ecological interface in practice have been realistically addressed and overcome. This scaling up brings EID closer to industrial practice and operations than prior investigations [5].

II. METHOD

A. Participants

Thirty male professional operators participated in the study. Table I reflects the broad range of experience of the participants, both in the domain and on the target process. Participants were compensated indirectly for participation in the study, which took place during work hours allocated to regular training.

B. Experimental Platform: Process Simulation

A high-fidelity model-based industrial process simulation served as the experimental platform.[2] The system boundaries of the simulation (i.e., the ethylene refining unit) were much broader than the boundaries of the subsystem for which the novel interfaces were designed (i.e., the reactor section). For the purposes of this study, the operators were instructed to monitor and control only the reactor section. The operators controlled the simulator through an emulated instrumentation and control system, including a suite of eight 21-in monitors and five keypad stations, that is effectively identical to that used in the actual unit. In sum, the experimental platform closely simulated the appearance, behavior, and capabilities of the actual working environment.

Auditory indications from the alarm summary software were disabled in the simulator. This forced the operators to rely on the graphical interfaces (new or old) to detect and diagnose upsets. This artificial manipulation was necessary because a key performance variable was event detection time. Auditory alarms would have made many event detection tasks trivial and thereby subverted the evaluation of the interfaces. There is also an alarm panel in the simulator display suite that was visible to all participants and could not be silenced or covered. One or both of the panel alarms sounded during the Anticipated/Unfamiliar scenario, but never before the operator had detected the induced disturbance or manually cut off hydrogen flow to stop the reaction.

C. Experimental Platform: Interfaces

Three interfaces were employed in the study; the P + F + T, the P + F, and the Current. The letters P, F, and T refer to the Physical, Functional, and Task information content. The P + F + T interface, which is described in the companion paper [2], integrates the physical and functional information (identified through the work-domain analysis) with the task information (identified through the task analyses). In the literature to date, an "ecological interface" is one that contains both physical and functional information that is derived from a work-domain analysis. Thus, the P + F + T interface is an ecological interface that is supplemented with task-based information.

The second interface, i.e., the P + F interface, was formed by removing from the P + F + T interface the two process views and three graphical elements that contained task-based information. The upper monitor for this interface is shown in Fig. 1; the lower monitor is identical to that of the P + F + T interface. The following graphical elements and views are not drawn in the P + F interface:

1) procedure view;
2) motor-operated valve (MOV) view;
3) H2 balance view: weight ratio control graphic;
4) H2 balance view: analyzer update timers;
5) H2 balance view: set point and output data on control valves.

Because it retains the physical and functional information derived from a work-domain analysis, the P + F interface serves as an example of EID as broadly practiced in the literature.

The existing interface for the reactor served as the third interface and a baseline case. This Current interface was highly typical of the state-of-practice in the industry. It was based on

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[2] The ethylene refining process, in general, and the acetylene hydrogenation reactor, in particular, are described in the companion paper [2].

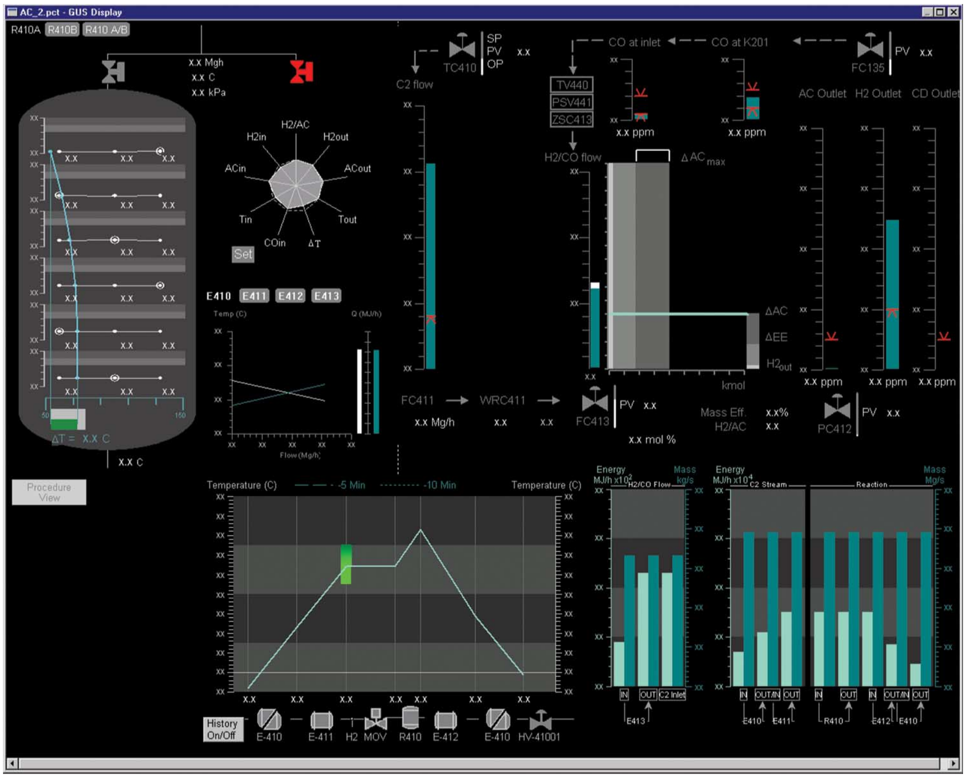

Fig. 1. P + F interface upper monitor.

a mimic diagram concept with dynamic color-coded text to denote equipment states and process values. The Current interface does not lend itself to clear characterization according to the P, F, and T labels. It contains most of the physical information contained in the P + F and P + F + T interfaces, but the states of many rarely used components are excluded. The Current interface contains some basic functional information (e.g., flow rates and reactor efficiencies), but much less than that contained in the two ecological interfaces. Finally, the Current interface has evolved to contain information specific to the performance of anticipated tasks, although it is not meant to provide a direct task support.

Although the creation of a P + T interface was considered for the study, it was not pursued for two reasons. First, a P + T interface would not qualify as an ecological interface, and the purpose of this study was to test ecological interfaces in an industrial setting. Second, an additional interface would have complicated the experimental design and demanded additional participant resources that were in short supply. Thus, the study was performed with three interface types.

D. Experimental Platform: Implementation and Process Tracing

A professional software contractor implemented the views comprising the upper monitors of the P + F and P + F + T interfaces as a set of ActiveX controls written in Microsoft Visual Basic 6.0. The controls were designed to be compatible with Honeywell's Global User Station Display Builder, which was used to implement the views of the lower monitor. This approach allowed the two sets of visual components to be incorporated in the same workspace. This implementation strategy allowed the interfaces to be connected to either the plant or a process simulator via a Honeywell Total Plant Solution system.

Commercial process history software was employed to record samples of the variables associated with the simulated process. These included the controlled variables (e.g., regulatory and advanced controls) and process variables (e.g., pressures, temperatures, and analyzer readings). Samples of the full suite of parameters were taken approximately every 5 s.

E. Event Scenarios

For the purposes of this study, the dimensions of Familiarity and Anticipatedness were defined as follows. Any event for which a procedure had been written was deemed Anticipated. Events for which no procedure was written were considered to be Unanticipated. Familiar events were those that were scheduled in the plant, regularly practiced in the simulator, and would likely have been executed by an operator in practice. Unfamiliar events were those that were unscheduled, were rarely practiced, and most operators would never have encountered in operations. A description of each of the events is given below.

1) Anticipated/Familiar: A reactor "swing" served as the event for this category. Swinging the reactors involves redirecting process flow from one reactor to a parallel reactor. In actual operations, a reactor swing takes place two to four times a year. The procedure is also regularly practiced in simulated operations. The scenario requires several control actions and requires continual monitoring of a dynamic plant state. All of the activities are localized to the reactor section and are typically reviewed in advance by the operator.

2) Anticipated/Unfamiliar: A reactor temperature runaway was used for this event category. The procedure has been employed only a few times in the history of the plant. It is practiced by operators, although infrequently. Some interaction with the outside operator is advisable (although not required), several timely control actions are called for, and continual monitoring of plant state is critical. Of the eligible procedures, the runaway had the most activities concentrated in the reactor section of the process. The event was instigated by a dual equipment failure caused by a localized fire in the unit. Ten minutes of steady-state operation preceded the onset of the fault.

3) Unanticipated/Unfamiliar: A leak in the feed preheat exchanger served as the event in this category. The leak raised the pressure in the shell side of the exchanger and inhibited the heating of the process stream. A cooler stream is less reactive, causing the reactor temperatures to fall. Close monitoring, quick decision making, prompt control action, and interaction with the outside operator were all required. Most of this activity was expected to be confined to the reactor section of the process. Seven minutes of steady-state operation preceded the onset of the fault.

F. Selection of Experimental Scenarios

Each of the above scenarios was selected based on a set of explicitly defined criteria. A review of the tradeoffs made in selecting the scenarios may address some criticisms.

Four criteria were used for selecting the two Anticipated events. First, they had to be events for which procedures were already written (as per the definition in Section II-E). Second, as far as possible, their causes and mitigations had to be constrained to the reactor section of the process. Third, scenarios requiring several control manipulations were desired. Fourth, the events had to be capable of being modeled in the simulator. Using these four criteria, and with the aid of two domain experts, all of the procedures and existing fault simulations for the target process were evaluated for use.

Of the five qualifying Anticipated Familiar procedures, only the reactor swing had several control actions required within the reactor section. Of the nine Anticipated Unfamiliar procedures, four were signaled by hard-wired alarms (which would have made detection a trivial task), and of the remaining five, the temperature runaway stood out in terms of prescribed control actions within the reactor boundaries.

Selecting an Unanticipated Unfamiliar event and an instigating cause for the Anticipated Unfamiliar event was a more difficult challenge. In the case of the Unanticipated Unfamiliar scenario, the event had to follow the second and third criteria listed above (i.e., several steps confined to the reactor section). In addition, it had to be as close to novel as possible, as well as functionally meaningful. The tube leak was a good compromise in this case. There was no existing procedure for dealing with it and no procedure for dealing with the functional impact.

The functional meaningfulness criterion made it particularly challenging to create an initiating cause for the Anticipated Unfamiliar event because most of the plausible causes for a runaway have either been targeted by hard-wired alarms (e.g., compressor trips)[3] or are familiar to the operator (e.g., certain failures that can lead to temperature runaway). The subject-matter experts eventually managed to generate a plausible root cause that could be modeled in the simulator. However, it required a pair of component failures.

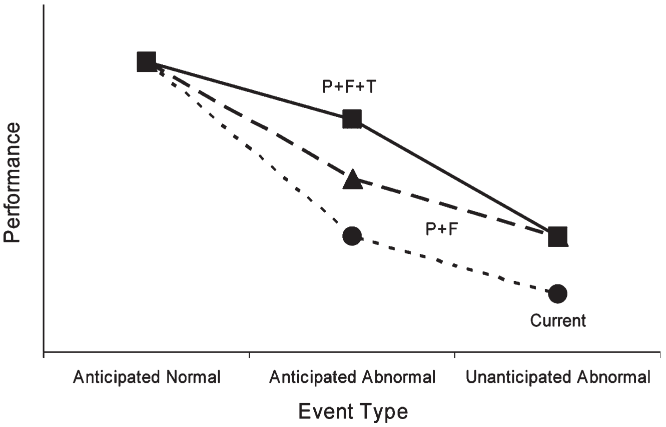

Fig. 2. Hypothesized performance effects of the Interface × Scenario interaction.

In sum, the effective engineering of the information systems and operating procedures currently in use in the plant made it difficult to select events that truly fit the theoretical categories.

G. Experimental Design

A 3 × 3 split-plot factorial design was employed, with Interface Group (P + F + T, P + F, Current) as a between-participants factor and Scenario (Anticipated Familiar, Anticipated Unfamiliar, Unanticipated Unfamiliar) as a within-participants factor. The order of presentation of the scenarios was randomized. An equal number of participants were randomly assigned to each of the three interface conditions (although participant cancellations led to a slight upset of this balance).

H. Hypotheses

The initial hypotheses for relative performance as a function of Interface type and Scenario are shown in Fig. 2.

1) H1: An interaction between Interface type and Scenario classification was predicted. Operators using the P + F + T interface were expected to perform better than those in the Current and P + F conditions in the Anticipated/Unfamiliar scenario. The rationale for this prediction is that the additional task information in the P + F + T interface should provide comparatively more support for anticipated events than either the Current or P + F interfaces. In addition, the P + F and P + F + T interface users were expected to outperform the Current interface users for the Unanticipated/Unfamiliar condition. In this case, the P + F and P + F + T interfaces should equally support abnormal event management because

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[3] The hard-wired alarms are distinct from the software-driven alarm summary, which was disabled in the simulator. The hard-wired alarms appear on a fixed alarm panel and could not be universally silenced.

both include functional information (and task information will not be relevant), whereas the Current interface lacks much of the functional information required to support abnormal events.

2) H2: A Scenario effect was predicted. The two Unfamiliar conditions were expected to induce poorer performance than the Familiar condition because they should require problem solving. Furthermore, the Unanticipated/Unfamiliar condition was expected to yield the worst performance because no procedure exists to direct the operator's response. Thus, the operator would need to generate a response, as opposed to following an instruction.

3) H3: An Interface effect was predicted. The ecological interfaces were expected to lead to better performance (although see H1).

I. Experimental Team

The author and a collaborator comprised the experimental team. The author administered the questionnaires, provided training, controlled the audio equipment, and operated the data collection software.

A former operator of the process served as a collaborator in the experiment. The collaborator was a qualified operator and was known to all of the participants. His role was threefold. First, he acted as the simulated field operator, interacting with field equipment and instruments (as they are represented in the simulator) and communicating with the participants in a way that closely resembled the dynamic of an operations team. Second, he acted as the simulated control room operator for the units immediately upstream of the target process. Third, the collaborator controlled the process simulation and introduced faults as required by the protocol.

The collaborator was the regular administrator of the simulator and had five years of experience in this role. No other person in the plant was qualified to run the simulator, and his participation was therefore necessary. Prior to the start of the experiment, the collaborator was briefed on the purpose of the experiment to a similar extent as the participants. That is, he knew that the purpose of the study was to compare the new interfaces to the Current interface across normal and abnormal scenarios. He was not, however, aware of the hypothesized results and was not privy to the data collection beyond what he could observe while running the simulator. Moreover, the collaborator had been provided with no operational training on the new displays.

During the data collection, the collaborator and experimenter were seated in a room adjacent to the simulator room, out of the direct line of sight of the participants. Communication between the participants and the collaborator was conducted verbally through an open door. The collaborator was aware of which scenario was presented to the operator because he initiated each one in the simulator. He was advised that his interaction with the participants could bias their actions and admonished not to assist with fault diagnosis. The participants were similarly instructed to treat the collaborator as a novice operator who would provide accurate reports of plant conditions and correctly execute control actions in the field, but would not assist with detection and diagnosis of any disturbances.

J. Training and Supplementary Materials

Participants assigned to the $P + F$ and $P + F + T$ interface conditions were given approximately 2 h of training on their respective interface. The training addressed the purpose, appearance, and behavior of the interface views. Each participant in these conditions was given 45 min of self-directed practice with the novel interface. The practice session included observing the effects of an example process disturbance in the interface provided. At the end of the practice session, the participants were asked to complete several monitoring and control tasks, as well as to predict the expected appearance of the graphics under generic process anomalies. Refresher training was provided until each operator was able to complete all of these tasks without aid and provide correct predictions of the appearance of all views for the anomalies. Neither the training disturbance nor the proficiency questions related directly to any of the experimental scenarios.

All of the written procedures that pertain to the reactor section were made available to the operators in the study. One of those procedures is relevant to each of the Anticipated scenarios. The rest were not directly relevant to any of the scenarios.

K. Experimental Task

At the beginning of the experimental session, the operators were told that the test scenarios were all localized to the reactor section of the simulated process. They were advised that no disturbances would be introduced in other subunits that would typically be part of their purview. Otherwise, they were instructed to complete each of the three scenarios as if they had encountered the event in their normal operating capacity. They were told at the beginning of each scenario whether there was a planned activity (the Anticipated Familiar scenario) or not (the two Unfamiliar scenarios). In the latter cases, they were to monitor for and respond to any process disturbances. They were also instructed that disturbances could occur at any time during any of the scenarios or not at all.

L. Performance Measures

Most of the performance measures have been used in prior studies of EID [5]. These include fault detection and diagnosis times, diagnosis accuracy and control action counts. Superior performance is assumed to be indicated by prompt detection of events, quick and accurate deduction of the root cause of events, and efficient control behavior. The performance score was a new measure suggested by the availability of procedures to identify a canonical set of steps to be completed. The scoring method was conceived *a priori* with the assistance of two highly experienced operators. A perfect score could be achieved by completing all of the expected steps (see Section III-E). Two additional new measures were acetylene and hydrogen throughput. These measures were added to assess possible differences between the interfaces in terms of economic performance. Acetylene passing through the reactor can contaminate the process stream, and it is desirable to reduce excess hydrogen to reduce waste and prevent unwanted reactions. Thus, better

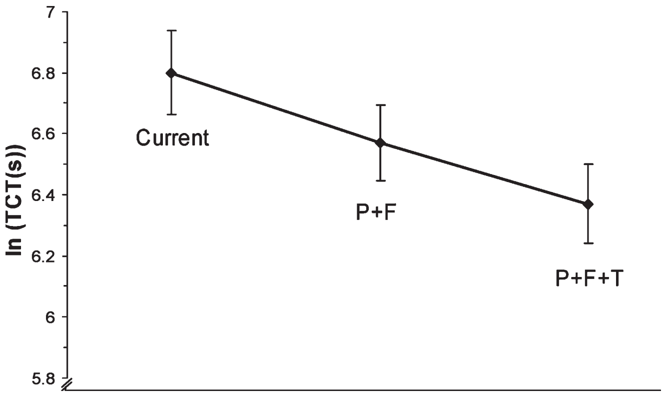


Fig. 3. Log-transformed trial completion time by interface.

performance would be associated with low values for these measures.

III. RESULTS

A general linear model was constructed to describe the data collected from the study. Results from this model are reported with 95% confidence intervals where possible (as suggested in [28]). These intervals are expressed in the error bars. For each outcome measure, least squares means (lsmeans) were calculated to measure the true effects of Interface and Scenario after adjusting for the effects of covariates that are listed in Table I. The plots reflect these adjusted means. A detailed discussion of the covariate results is excluded from this paper for two reasons. First, there were very few significant covariates, and their effects accounted for a small portion of the observed variance. Second, none of the significant covariates were of interest to the research questions posed by the study.

In many cases involving time-based measures, counts of control actions, and throughput, Shapiro–Wilks tests revealed that the data were distributed in a nonnormal fashion. The spread of values increased as the mean of the values increased (i.e., there was a right skew to the data). This is a common observation in measurements with a zero baseline and monotonic trend. In these cases, log transformations of the data values were employed to improve the normality of the distributions. In cases where the transformation is used, the vertical axis is labeled as "ln(parameter(unit))." The axis itself is linear in all cases.

A. Trial Completion Time (TCT)

A TCT for each trial was calculated based on the process tracing data. The Anticipated Familiar trial started and ended when the operator started and completed the procedure. The two Unfamiliar trials started with the event onset and ended when the participant had either secured or recovered the process.

Fig. 3 shows the results of the adjusted log-mean TCTs by Interface (note the nonzero horizontal axis). The graph shows a steady decrease in TCT between interfaces. The difference between the Current and P + F + T levels of Interface is significant, whereas the difference between the Current and P + F levels is not significant, although nearly so. The difference between the P + F and P + F + T interfaces is not significant.

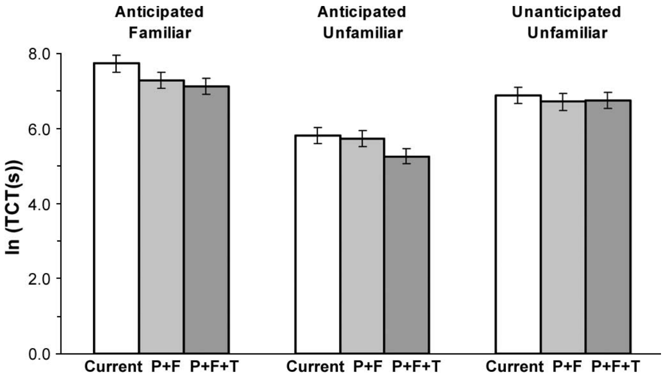


Fig. 4. Log-transformed trial completion time.

TABLE II
CONFIDENCE INTERVALS FOR DIFFERENCES IN TRIAL COMPLETION TIME

	Best Estimate (log scale)	C.I. Range (log scale)	Best Estimate (geometric mean)	C.I. Range
Current-P+F	0.24	(0.05, 0.41)	1.70	(1.11, 2.59)
Current-P+F+T	0.44	(0.24, 0.62)	2.70	(1.75, 4.14)
P+F-P+F+T	0.20	(0.02, 0.04)	1.60	(1.05, 2.39)

There are also some significant differences in the Interface × Scenario interaction (see Fig. 4). In both the Anticipated Familiar and Anticipated Unfamiliar conditions, the P + F + T interface yielded significantly faster TCTs than the Current interface condition. The P + F interface did not differ significantly from the Current interface in these two Scenarios, although the difference is very nearly significant in the Anticipated Familiar case. All three displays showed similar TCTs in the Unanticipated Unfamiliar condition.

Table II shows the best estimates and confidence intervals for each of the differences between the P + F + T, P + F, and Current interfaces. These intervals are returned to the original scale (i.e., seconds, as opposed to log seconds) to facilitate comparison (using a procedure outlined in [29]). Thus, the best estimate indicates that participants in the Current condition took 1.70 times as long (in seconds) to complete the trials as those in the P + F condition, and 2.70 times as long as those in the P + F + T condition. Participants in the P + F condition took 1.60 times as long to complete trials compared to those using the P + F + T interface. Despite these differences, care should be taken to note that the lower bounds on the confidence intervals for the Current–PF and PF–PFT comparisons are very close to including zero (on the log scale).

Finally, the differences between the log-transformed mean TCTs for each scenario were all significant. However, these means are not particularly interesting because they primarily reflect a difference in the dynamics of the events, as opposed to any differences in the difficulties of dealing with the particular types of scenario.

B. Anticipated Unfamiliar and Unanticipated Unfamiliar Trial Completion

One of the difficulties in establishing TCTs came from the differences in the outcomes of the two fault scenarios. In the Anticipated Unfamiliar case, for example, some of the

TABLE III
HYDROGEN ISOLATION PASS/FAIL IN ANTICIPATED UNFAMILIAR SCENARIO

Interface	Fail to Isolate	Isolate	Total
Current	5	5	10
P+F	2	8	10
P+F+T	0	9	9
Total	7	22	29

TABLE IV
PROCESS RECOVERY PASS/FAIL IN UNANTICIPATED UNFAMILIAR SCENARIO

Interface	Fail to recover	Recover	Total
Current	4	6	10
P+F	7	3	10
P+F+T	3	7	10
Total	14	16	30

operators never identified the large hydrogen source into the reactor. Of those who did, only a subset managed to isolate that source. This motivated an alternative consideration of trial completion performance. The number of participants who failed or passed the hydrogen isolation criterion in the Anticipated/Unfamiliar scenario is listed in Table III. Performance against the criterion was assessed by reviewing the process data for the variable associated with the hydrogen flow rate into the reactor. If that value was reduced to 0 following the onset of the fault, isolation was confirmed. A Fisher's Exact Test on the pass/fail proportions indicates that the success or failure in isolating the hydrogen source is affected by the Interface $(p < 0.05)$. More participants in the $\mathrm{P+F}$ and $\mathrm{P+F+T}$ groups managed to isolate the fault.

A similar criterion-based evaluation was attempted for the Unanticipated Unfamiliar scenario. The proportion of operators recovering the process or failing to recover was recorded and tested using the Fisher's Exact Test. The result for the data shown in Table IV is not statistically significant $(p < 0.30)$.

C. Control Actions

More significant differences were observed in terms of the number of control actions made by the operators. Operator control actions on the five primary controlled variables in the reactor section were identified from the process data.

1) Total Control Actions: Fig. 5 shows the log-transformed total number of control actions by Interface. There is a decrease in the number of control actions as the amount of information provided in the interface increases. Participants in the $\mathrm{P+F}$ and $\mathrm{P+F+T}$ conditions took significantly fewer control actions than the participants in the Current condition. The difference between the $\mathrm{P+F}$ and $\mathrm{P+F+T}$ groups was not significant.

Table V shows the best estimates and confidence intervals for each of the differences between the $\mathrm{P+F+T}$ or $\mathrm{P+F}$ interface and Current interface. As with the TCTs, these intervals are returned to the original scale (i.e., moves, as opposed to log moves) to facilitate comparison. Thus, the best estimate indicates that participants in the Current condition made three times as many control actions as those in the $\mathrm{P+F}$ condition, and almost four times as many control actions as those in the $\mathrm{P+F+T}$ condition.

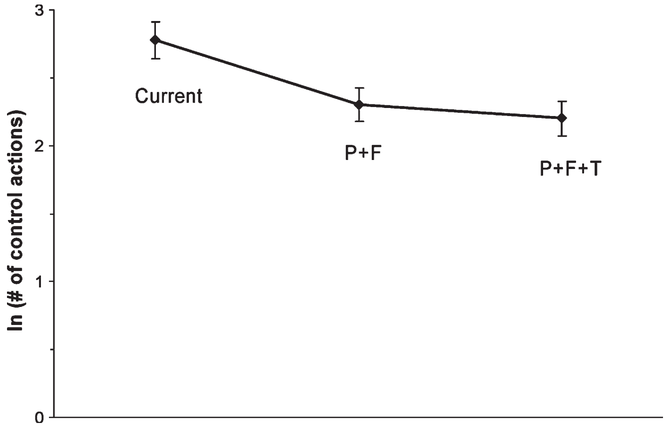


Fig. 5. Log-transformed total control actions by interface.

2) MOV Control Actions for the Anticipated Familiar Scenario: The reactor swing procedure involves opening and closing two MOVs in steps. Direct support of this task was provided in the $\mathrm{P+F+T}$ interface MOV View. In addition, the $\mathrm{P+F}$ and $\mathrm{P+F+T}$ displays provide functional information about the two reactor temperature profiles, which are directly affected by these valve movements. Therefore, the number of control actions taken during this procedure may reveal some performance differences between operators in each of the Interface conditions. In particular, it may reveal a difference between the $\mathrm{P+F}$ and $\mathrm{P+F+T}$ interfaces, since the former did not contain the detailed information to support the MOV move task.

Fig. 6 presents the number of MOV control actions by Interface for the Anticipated Familiar scenario. Similar to the count of total number of control actions, the plot shows a significant difference between the Current and $\mathrm{P+F+T}$ groups, and a nearly significant difference between the Current and $\mathrm{P+F}$ groups. However, although the $\mathrm{P+F+T}$ group made fewer control actions than the $\mathrm{P+F}$ group, this difference is not statistically significant.

This particular comparison was of interest because control of the MOV is directly supported by the MOV view, which the $\mathrm{P+F+T}$ interface included and the $\mathrm{P+F}$ interface did not. Thus, a view that was drawn exclusively from the task-based work analyses is associated with a large drop in the number of control actions that make up the task. However, there is also a nearly significant effect for the $\mathrm{P+F}$ group, and no difference between $\mathrm{P+F}$ and $\mathrm{P+F+T}$. A possible explanation for this is that both displays contain the reactor temperature profile view. The primary criterion for selecting the timing and magnitude of inputs to the MOV is the temperature profile in the reactor. Thus, both ecological interfaces support the assessment of the function whose state is the primary driver of MOV control actions. Operators using either of these displays show at least marginally significant reductions in the number of control actions to the component that affects that function. Participants in the $\mathrm{P+F+T}$ group show a further reduction in control actions when using an interface that explicitly supports execution of that action, although the additional reduction is not statistically significant.

3) Control Actions by Scenario: Similar to the TCT metric (Section III-A), the main effect of control actions by scenario

TABLE V
CONFIDENCE INTERVALS FOR DIFFERENCES IN THE NUMBER OF CONTROL ACTIONS

	Best Estimate (log scale)	C.I. Range (log scale)	Best Estimate (geometric mean)	Range
Current-P+F	0.477	(0.285, 0.8753)	3.00	(1.52, 5.92)
Current-P+F+T	0.580	(0.1823, 0.7723)	3.80	(1.93, 7.50)

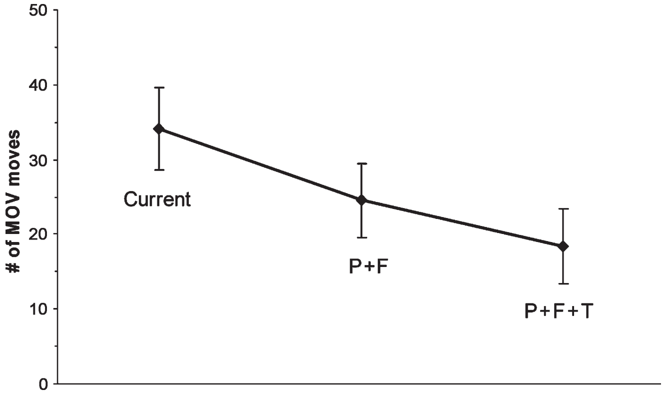


Fig. 6. MOV control actions in the A/F scenario.

was also significant, but not highly informative. More control actions were taken in the Anticipated Familiar scenario than in either of the other two Scenarios. The difference between the number of control actions in the Anticipated Unfamiliar and Unanticipated Unfamiliar is very nearly significant. However, these differences reflect differences in the nature of the tasks. The Anticipated Familiar scenario involves a stepwise opening and closing of two valves accompanied by several temperature setpoint changes over a long scenario. The Anticipated Unfamiliar scenario demands a few well-timed control actions to isolate the reactor. The Unanticipated Unfamiliar scenario offers opportunities for several moves to protect the stability of the process while the operator either diagnoses and corrects the fault, or enters into the isolation steps. Thus, the three Scenarios call for control actions under three very different task conditions and comparing between them to assess categorical differences between the scenario types would have low face and construct validity.

D. Diagnosis Accuracy

Diagnosis accuracy was assessed based on written descriptions completed by the participants immediately after the scenarios. These descriptions were scored using a scaling technique described by Pawlak and Vicente [30] and adapted to this application. The scoring criteria are listed as follows.

0) The operator says nothing relevant to the fault.
1) The operator provides a vague but correct description of the effects of the fault. For example: "The inlet temperature to the reactor is falling."
2) The operator provides a correct statement of the specific functional impact of the fault. For example: "I seem to be losing heat exchange in E411."
3) The operator provides a correct localization of the faulty component. For example: "There must be a noncondensable fluid on the shell side of E411."

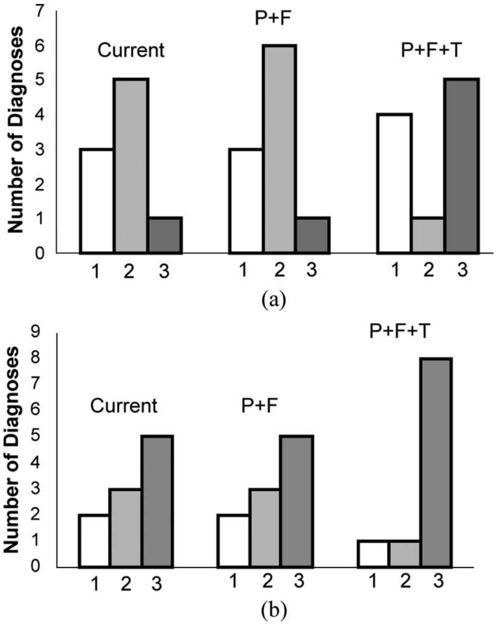


Fig. 7. Fault diagnosis accuracy scores. (a) Anticipated Unfamiliar scenario. (b) Unanticipated Unfamiliar scenario.

Scores for the two fault scenarios are presented in Fig. 7. In previous studies of EID [15], nonparametric tests have been performed on diagnosis data of this type by combining the scores from the scenarios and applying a chi-square test. However, the present case presents a challenge to one of the criteria for employing the chi-square test. Siegel and Castellan [31] point out that the expected frequency table that is calculated in the preparation of the chi-square test statistic should not have cell values that are too small (i.e., no more than 20% of the cells should have an expected frequency of less than 5). The distribution of diagnosis scores that were obtained in this study yields an expected frequency table that fails to meet this criterion. A solution to this problem lies in combining categories to raise the expected cell values [31]. When applied to the present data, a combination of the 1 and 2 scores leads to an expected frequency table with no cell values less than 5 (with the exception of the cells for the zero scores, which were excluded from the following test). The contingency table with the combined categories is shown in Table VI.

The contingency table is statistically significant $(\chi^2 = 6.35, df = 2, p < 0.05)$, thus indicating that the diagnosis score depends on the Interface treatment. In both scenarios, there are more 3 scores and fewer 1 or 2 scores in the $\mathrm{P + F + T}$ condition. In contrast, the Current and $\mathrm{P + F}$ conditions look virtually indistinguishable from one another.

TABLE VI
FREQUENCY OF DIAGNOSIS SCORE ACROSS INTERFACE
(SCORES OF 1 AND 2 COMBINED)

	Display			
Score	Current	P+F	P+F+T	Row Total
0	0	0	0	0
1 or 2	13	14	7	34
3	6	6	13	25
Column Total	19	20	20	59

E. Performance Score

The performance of each operator on all three trials was scored on a scale from zero to four according to the criteria listed in Table VII. The steps for the Anticipated Familiar and Anticipated Unfamiliar scenarios were drawn from the written procedures. Although these procedures call for a specific order of operations, only step completion was used in determining the performance scores because the constraints on the order in which steps were completed were very weak (i.e., the step order in either scenario could be changed without negative consequences). The scoring criteria for the Unanticipated Unfamiliar scenario could not be based on an existing procedure and were therefore developed by the collaborator and the senior operator in charge of procedures. The scale for this scenario was based on a combination of their expert judgment and a review of the range of responses observed.

A bar chart of the performance score distribution for the Anticipated/Familiar scenario is shown in Fig. 8. A visual inspection of the scores indicates that there is almost no difference between the Interfaces for the Anticipated/Familiar scenario. Given the high rate of complete task performances (i.e., scores of 4) across the groups, a possible explanation for not observing a benefit for the P + F + T Interface is that there is a ceiling effect for the Familiar scenario. This is corroborated by the observation that nearly all of the participants read the procedure before they started the trial.

Bar charts of the performance score distributions for the Anticipated/Unfamiliar and Unanticipated/Unfamiliar scenarios are shown in Fig. 9. A combined chart is shown in Fig. 10. The scores for these two scenarios were entered into a contingency table to conduct a chi-square test (see Table VIII). Once again, issues with minimum cell values in the expected frequency table were observed (which is why the two scenarios could not be examined independently). To compensate, performance scores of 0, 1, and 2 were combined and compared against scores in the 3 and 4 categories. The contingency table is statistically significant ($\chi^2 = 10.62, df = 4, p < 0.05$): Performance scores in the abnormal scenarios depend on the Interface condition. However, the cause of this difference is less clear than in the case of the diagnosis score. It appears that the P + F + T display is generating the greatest number of complete performances. However, the Current Interface has a fair number of complete scores in the Unanticipated/Unfamiliar case as well. Notably, the distribution of scores in the Unanticipated/Unfamiliar condition is wider and possibly multimodal for the Current and P + F + T interfaces.

F. Fault Detection Times and Time to Diagnosis

The time elapsed between event start and the first indication that the operator noticed an anomaly is captured as fault detection time. The detection indications were sometimes overt but were often judged by the experimenter. An indication could include any oral or physical behavior that conveyed surprise (e.g., "Uh oh!"), alerting (e.g., sitting up sharply), or confusion (e.g., "What the …?"). Because faults were only presented in the two Unfamiliar Scenarios, only times for these two Scenarios are included in the Group means and confidence intervals presented in Fig. 11. Although the detection times for the two ecological interfaces were faster than the Current interface, the mean differences were not significant.

In several previous studies, the time to reach a complete diagnosis (i.e., a score of 3) with an ecological interface was observed to be significantly faster than the time to reach the same level of diagnosis with a contemporary interface. Thus, time to diagnosis was included as an outcome measure in this study. For the Unanticipated Unfamiliar scenario, no differences in the mean time to diagnosis were suggested in the data. This comparison could not be made for the Anticipated Unfamiliar scenario due to an underrepresentation of complete diagnoses.

G. Acetylene and Hydrogen Output

Given that the functional purpose of the reactor is to keep acetylene concentration below 5 ppm, a measure of the amount of acetylene passed during a scenario is a measure that offers a high degree of face validity. In addition, an operational constraint on the process is to keep the concentration of hydrogen in the reactor effluent below 200 ppm. Thus, the total amount of acetylene and hydrogen output from the reactor was measured for each scenario. However, no main effects or interactions were found for either of these measures.

IV. DISCUSSION

A. Hypotheses

1) H3—An Effect of Interface Was Predicted: The results of this study show several significant performance advantages for the two ecological interfaces (i.e., P + F and P + F + T) over the Current interface in an industrial process simulation with professional operators. These advantages include significant (P + F + T) or nearly significant (P + F) reductions in TCTs, more successful trial outcomes for the Anticipated Unfamiliar scenario (P + F + T only), fewer control actions taken across all scenarios (P + F and P + F + T), significant (P + F + T) or nearly significant (P + F) reductions in MOV control actions in the Anticipated Familiar scenario, more accurate fault diagnoses (P + F + T only), and somewhat better control performance scores for abnormal scenarios (P + F + T only). The advantages were more pronounced in the P + F + T condition, although there was no statistic on which a direct P + F to P + F + T comparison showed statistical differences. This suggests that the additional task-based information was only moderately beneficial to effective control.

TABLE VII
PERFORMANCE SCORING CRITERIA

Scenario	Scoring Criteria
Anticipated Familiar	1 point given for each of the following steps: Open MS410 Close MS411 Reduce inlet temperature < 58° C Increase hydrogen flow ratio
Anticipated Unfamiliar	1 point given for each of the following steps: Close MS410 Open Flare Valve Reduce inlet temperature Close HV41001
Unanticipated Unfamiliar	0. No action relevant to the fault 1. Response to surface characteristics of the fault (e.g., manipulate TC410.SP) and fail to execute flare procedure when TI417.PV>130.0° C 2. Response to surface characteristics of the fault (e.g., manipulate TC410.SP) and execute flare procedure correctly when TI417.PV>130.0° C 3. Vent non-condensables from E411 shell and execute flare procedure correctly when TI417.PV>130.0° C 4. Vent non-condensables from E411 shell and recover process without going to flare

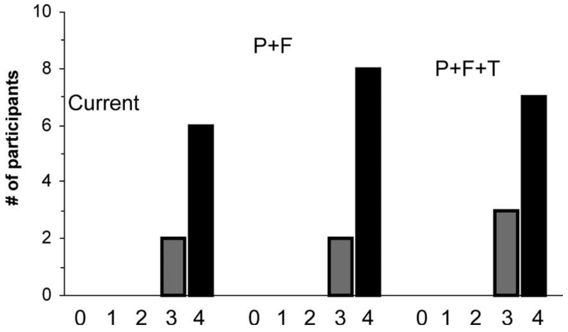
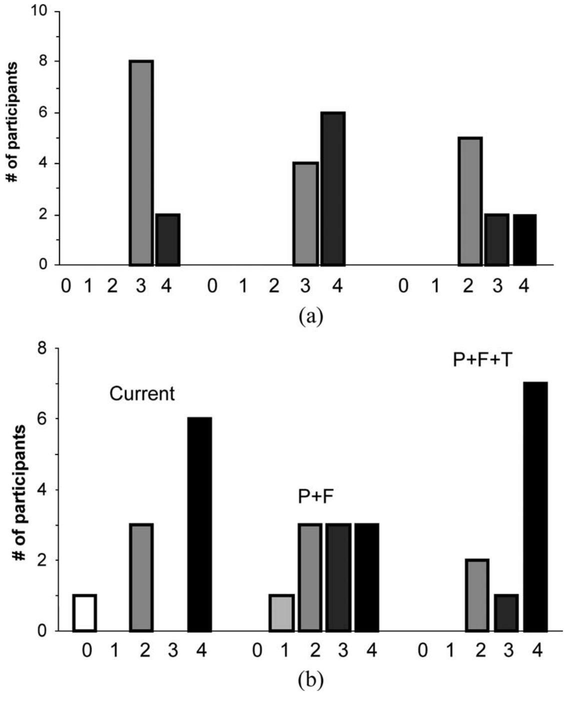


Fig. 8. Performance score distribution for Anticipated/Familiar scenario.



(a)

(b)

Fig. 9. Performance score distributions. (a) Anticipated Unfamiliar scenario. (b) Unanticipated Unfamiliar scenario.

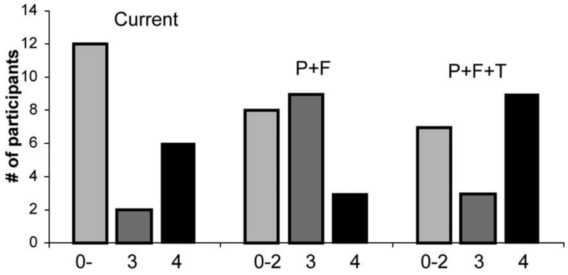


Fig. 10. Performance score distribution for combined Anticipated Unfamiliar and Unanticipated Unfamiliar scenarios.

TABLE VIII
FREQUENCY OF PERFORMANCE SCORES ACROSS INTERFACE FOR UNFAMILIAR SCENARIOS

	Display			
Score	Current	P+F	P+F+T	Row Total
0, 1, or 2	12	8	7	27
3	2	9	3	14
4	6	3	9	18
Column Total	20	20	19	59

Despite the trend toward improved performance in the ecological conditions for these measures, performance on several other outcome measures was not differentiated by Interface. For example, no significant fault detection time differences were observed, although the trend in the data suggested faster detections for the ecological interfaces. Furthermore, no time-to-diagnosis benefit was observed for the ecological interfaces in the Unanticipated Unfamiliar scenario. In addition, the two process measures of hydrogen and acetylene throughput were not sensitive to group differences. In retrospect, however, the relatively short exposure times of the scenarios (compared to actual process operations) and the overrepresentation of fault scenarios may not have been sufficient to expose any differences between the Interface groups for these latter two measures.

As a final comment on H3, it is notable that the Current interface was not significantly better than either of the two

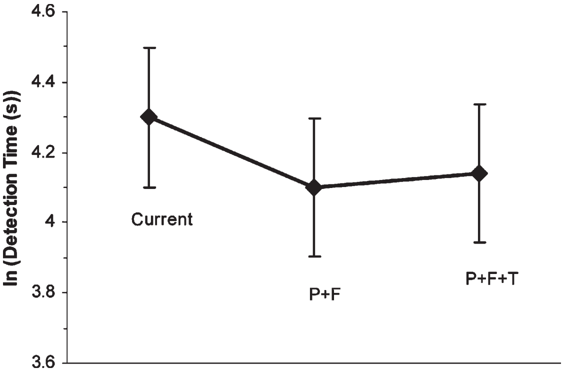


Fig. 11. Log-transformed fault detection time.

ecological interfaces on any of the outcome measures. This is surprising, as the participants had, on the average, 3.6 years of operational experience with this display. Most of them had more years of experience (an average of 6.6) with displays of similar design. In contrast, participants in the P + F and P + F + T groups were given 2 h of training and 1 h of practice with the novel interface prior to the experimental trials. It would be reasonable to expect that one or more of the outcome measured would have shown some benefit for the Current interfaces. No evidence to confirm this expectation was seen.

2) H2—An Effect of Scenario Was Predicted: With regard to the hypothesis of a main effect of Scenario, the results obtained provide no valid evidence. Although several of the measures (e.g., TCT, number of control actions, and hydrogen and acetylene throughput) were sensitive to scenario type, these differences appear to be best explained by the characteristics of the particular scenarios, as opposed to characteristics of the scenario types or the classes of process events that they were intended to exemplify. There is no consistent trend among these results, despite their consistent statistical significance.

It is unlikely, however, that a more comparable set of scenarios could have been developed while meeting the constraints of the scenario taxonomy. This is an inescapable challenge of having used a simulator study, particularly one that so closely aligns itself with a combination of known events. Our experience here suggests that this question would be better addressed in a more controlled experimental environment.

3) H1—An Interaction Between Interface and Scenario Was Predicted: The hypothesized interaction between the interface content and scenario type is only weakly suggested by the data. The mean TCT for P + F + T in the Anticipated Unfamiliar scenario was faster than that for the other two displays, there were more complete diagnoses for P + F + T in the Anticipated Unfamiliar scenario, and all participants in the P + F + T group successfully isolated the hydrogen source in the Anticipated Unfamiliar scenario. All three of these observations are consistent with the expected added benefit of task-based information for anticipated events. However, there is no Interface × Scenario interaction for number of control actions. In addition, the evidence suggests some benefit for task-based information where none was expected. For example, the slight P + F + T advantage in performance score stems primarily from differences in the Unanticipated Unfamiliar scenario, where one would not have expected to see a difference compared to P + F.

The relative absence of this expected interaction is surprising, considering that two of the procedures used to identify the task-based information requirements were directly pertinent to the Anticipated Familiar and Anticipated Unfamiliar scenarios. Thus, although the interface designs themselves demonstrate that task-based information can be effectively integrated into an ecological interface, the advantages appear to be, at best, only loosely coupled to anticipated events. Rather, it appears that the advantage is more generally derived either from the presence of the additional information, regardless of the event, or the better integration of that data [15].

The hypothesized interaction is also not clear with respect to the benefit of functional information. The expected benefit for the P + F group compared to the Current group in managing Unfamiliar events is not visible in the TCTs for the Anticipated Unfamiliar event, and diagnosis accuracy scores for both fault events are indistinguishable from the Current interface. Moreover, neither ecological interface led to faster TCTs compared to the Current interface in the Unanticipated Unfamiliar scenario. These mixed interaction results suggest that added functional information is not always conducive to improved performance on abnormal events.

B. Unexpected Result

One unusual observation made here was that of a performance advantage of ecological displays over the Current display in a Familiar event condition. Most of the previous studies of EID in laboratory settings have failed to show mean differences between Interfaces under normal operations. In a notable counterexample to this trend, Janzen and Vicente [32] showed that, under normal operating conditions, attention to abstract function information was positively correlated with faster TCTs. However, a direct comparison between that study and the one presented here is not possible because neither of the present ecological interfaces were parsed according to the levels of the abstraction hierarchy (as was the interface in [32]).[4]

There are several possible explanations for this observation. For example, it is possible that the increased level of domain complexity in this study, coupled with the use of professional operators, revealed an effect that does not manifest itself in less complicated laboratory simulations. Alternatively, the particular Anticipated Familiar scenario that was used in this study may have been complex enough to require problem solving—a characteristic of abnormal events for which ecological interfaces are designed to provide support. A third possible explanation is a combination of the first two. Perhaps, there are few events in highly complex systems that do not require some degree of problem solving (although some results suggest that the benefit of functional information content increases as task difficulty increases [17], [18]). This explanation raises the possibility that operators faced with any event in a complex

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[4] Janzen and Vicente [32] modified an ecological interface to present information pertaining to only one level of abstraction at a time. This allowed them to control the abstraction levels from which information was provided in a scenario.

system may benefit from an ecological interface and that the distinction between Familiar and Unfamiliar events may be less important than the criteria for what qualifies as an Event, as opposed to Routine.

C. Limitations

There are several limitations to the conclusions drawn from this study. First, the scenario selection criteria and the need to match scenarios to the event taxonomy overconstrained the choice of events. None of the Scenarios was a perfect match for the theoretical category that it exemplified. Although the best matches were selected, only one scenario in each event category was possible. Another potentially important factor was that the Anticipated Unfamiliar event was caused by a dual fault, whereas the Unanticipated Unfamiliar event was caused by a single fault. Finally, it is also worth noting that this study is similar to many other studies of fault management in quasi-realistic settings in that it vastly overrepresents the frequency of fault occurrence.

A second limitation to the interpretation of the findings of this study is the paucity of training provided to the users of the novel interfaces. Whereas participants in the Current interface condition had years of experience with their information system, participants in the $\mathrm{P + F}$ and $\mathrm{P + F + T}$ conditions had a few hours. It is unlikely that this difference could be entirely remedied in any study with expert users of an information system.

Finally, although this study created an experimental environment that is more realistic than that afforded by prior studies of EID, the scope remains limited in comparison to the environments in which the participants regularly work. The role of auditory alarms (intentionally removed in this study), collaboration (actively discouraged in this study), and influences of different work cultures (held constant here) are all factors that affect supervisory control performance [33]–[35]. These issues remain largely unexplored in EID research [5].

D. Contributions

Despite these limitations, this study makes several novel and significant contributions to the EID literature. Most importantly, it appears to be the first empirical evaluation of the EID approach in a simulated industrial setting with professional operators. This is important because it begins to address the question of whether the benefits that have been observed with ecological interfaces in laboratory settings scale up to industry applications. One particular aspect of such applications is the use of operating procedures. The results obtained here confirm that performance benefits for ecological interfaces (as compared to a contemporary interface) persist even when detailed operating instructions are available to operators prior to and during the execution of the events addressed by those procedures. A second characteristic of industry settings is the presence of skilled operators. This study showed no consistent pattern of results to suggest that an operator's age or experience precludes him from, or preferences him toward, benefiting from an ecological interface.

E. Future Directions

1) Return to the Laboratory: A key shortcoming of this study is that the anticipated interaction between event type and interface content was not observed. Although it is possible that no such effect exists, it is more likely that the additional sources of variability in the more realistic setting prevent us from seeing small interaction effects. In order to take a closer look at this question, it may be necessary to return to the laboratory where the experimenter can exert greater control over participant assignment, train the operators to criteria, take advantage of greater flexibility in creating scenarios and procedures that meet the theoretical event categorizations, and increase contact time with the participants.

2) Procedures: Operating procedures are and will continue to be a key component of the information suite available to professional operators. Solution providers in the industry are developing tools to automate procedures or support them with electronic media in the control room and the field. The potential role for EID in supporting automated or electronic procedures should be investigated to further the relevance and impact of the design approach.

3) Operator Strategies: In light of our success in integrating task-based information into EID, a next meaningful challenge would be to integrate support for various control strategies. This represents an important challenge for the approach because it may be extremely difficult to identify strategy constraints that can provide meaningful guidance to operators across a range of process events.

V. CONCLUSION

The objective of this study was to determine whether, and under what conditions, there is an advantage to adding task-based information requirements to work-domain-based EID for petrochemical process control. Empirically answering this question in the context of a high-fidelity process simulation with professional operators was attempted. The data suggest that operators using an ecological interface containing task-based information showed broader performance benefits compared to the Current interface than a traditional ecological interface. However, the traditional ecological interface group also showed performance benefits compared to the Current interface for some of the same outcome measures. The study was less successful in articulating whether the event conditions of anticipatedness and familiarity interacted with the information content of the two ecological interfaces.

Aside from this main objective, this study makes contributions to two corollary issues. First, implementing ecological interfaces for a representative petrochemical process furthers the state of the art of interface design in this domain. That performance benefits were obtained with these displays confirms that ecological interfaces have a role to play in improving the safety and productivity of industry operations. Second, the study raises the fidelity and scale of the empirical study of EID. A majority of prior EID research has been conducted in microworld settings with students. In this study, professional operators used ecological interfaces implemented in a commercial process instrumentation and control environment to monitor for and respond to realistic process events. These characteristics enhance the generalizability of the study to industry applications.

Our findings represent a conservative estimate of the potential benefits of EID in an industry setting. These benefits would likely increase if the level of training and experience on the ecological interfaces were comparable to that on the Current interface. For experienced process operators (with thousands of hours of training and operational experience on the Current interface) to have demonstrated better performance with an ecological interface with which they had only a few hours of training and practice is encouraging. It suggests that their control expertise is robust to changes in information presentation and, more importantly, that their expertise can be better supported with ecological interfaces.

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REFERENCES

[1] P. T. Bullemer and I. Nimmo, "Understanding and supporting unfamiliar situation management in industrial process control environments: A new approach to training," in *Proc. IEEE Int. Conf. Syst., Man, Cybern.*, 1994, pp. 391–396.

[2] G. A. Jamieson, C. A. Miller, W. H. Ho, and K. J. Vicente, "Integrating task- and system-based work analyses in ecological interface design: A process control case study," *IEEE Trans. Syst., Man, Cybern., Syst. Humans,* to be published.

[3] K. J. Vicente and J. Rasmussen"Ecological interface design: Theoretical foundations," *IEEE Trans. Syst., Man, Cybern.*, vol. 22, no. 4, pp. 1–18, Jul./Aug. 1992.

[4] C. A. Miller and K. J. Vicente, "Comparison of display requirements generated via hierarchical task and abstraction–decomposition space analysis techniques," *Int. J. Cogn. Ergon.*, vol. 5, no. 3, pp. 335–356, 2001.

[5] K. J. Vicente, "Ecological interface design: Progress and challenges," *Hum. Factors*, vol. 44, no. 1, pp. 62–78, 2002.

[6] G. A. Jamieson and K. J. Vicente, "Ecological interface design for petrochemical applications: Supporting operator adaptation, continuous learning, and distributed, collaborative work," *Comput. Chem. Eng.*, vol. 25, no. 7, pp. 1055–1074, Aug. 2001.

[7] K. J. Vicente, "Operator adaptation in process control: A three-year research program," *Control Eng. Pract.*, vol. 5, no. 3, pp. 407–416, Mar. 1997.

[8] J. R. Hajdukiewicz and K. J. Vicente, "Designing for adaptation to novelty and change: Functional information, emergent feature graphics, and higher-level control," *Hum. Factors*, vol. 44, no. 4, pp. 592–610, 2002.

[9] O. St-Cyr and C. M. Burns, "Mental models and ecological interface design: An experimental investigation," in *Proc. Hum. Factors and Ergonomics Society 46th Annu. Meeting*, 2002, pp. 270–274.

[10] A. Garabet and C. M. Burns, "Collaboration with ecological interface design," in *Proc. Hum. Factors and Ergonomics Soc. 48th Annu. Meeting*, 2004, pp. 543–546.

[11] O. St-Cyr and K. J. Vicente, "Sensor noise and ecological interface design: Effects on operators control performance," in *Proc. Hum. Factors and Ergonomics Soc. 48th Annu. Meeting*, 2004, pp. 538–542.

[12] O. St-Cyr and K. J. Vicente, "Sensor noise and ecological interface design: Effects of increasing noise magnitude on operators performance," in *Proc. Hum. Factors and Ergonomics Soc. 49th Annu. Meeting*, 2004, pp. 417–421.

[13] D. V. C. Reising and P. M. Sanderson, "Ecological interface design for Pasteurizer II: A process description of semantic mapping," *Hum. Factors*, vol. 44, no. 2, pp. 222–247, 2002.

[14] D. V. C. Reising and P. M. Sanderson, "Minimal instrumentation may compromise failure diagnosis with an ecological interface," *Hum. Factors*, vol. 46, no. 2, pp. 316–333, 2004.

[15] C. M. Burns, "Putting it all together: Improving display integration in ecological displays," *Hum. Factors*, vol. 42, no. 2, pp. 226–241, 2000.

[16] C. M. Burns, "Navigation strategies with ecological displays," *Int. J. Human-Comput. Stud.*, vol. 52, no. 1, pp. 111–129, Jan. 2000.

[17] D. H. Ham and W. C. Yoon, "The effects of presenting functionally abstracted information in fault diagnosis tasks," *Reliab. Eng. Syst. Saf.*, vol. 73, no. 2, pp. 103–119, Aug. 2001.

[18] D. H. Ham and W. C. Yoon, "Design for information content and layout for process control based on goal-means domain analysis," *Cogn. Technol. Work*, vol. 3, no. 4, pp. 205–223, 2001.

[19] N. Dinadis and K. J. Vicente, "Ecological interface design for a power plant feedwater subsystem," *IEEE Trans. Nuclear Sci.*, vol. 43, no. 1, pp. 266–277, Feb. 1996.

[20] J. Itoh, K. Monta, A. Sakuma, and M. Makino, "An ecological interface design for intelligent man–machine systems for BWR plants," in *Proc. Topical Meeting Nuclear Plant Instrum., Control and Man–Mach. Interface Technol.*, 1993, pp. 97–103.

[21] Y. Yamaguchi and F. Tanabe, "Creation of interface system for nuclear reactor operation; practical implication of implementing EID concept on large complex system," in *Proc. IEA/HFES Congr.*, 2000, vol. 3, pp. 571–574.

[22] T. D. Sharp and A. J. Helmicki, "The application of the ecological interface design approach to neonatal intensive care medicine," in *Proc. 42nd Annu. Meeting Hum. Factors and Ergonomics Soc.*, 1998, pp. 350–354.

[23] C. M. Burns, J. Kuo, and S. Ng, "Ecological interface design: A new approach for visualizing network management," *Comput. Netw.*, vol. 43, no. 3, pp. 369–388, Oct. 2003.

[24] P. Duez and K. J. Vicente, "Ecological interface design and computer network management: The effects of network size and fault frequency," *Int. J. Human-Comput. Stud.*, vol. 63, no. 6, pp. 565–586, Dec. 2005.

[25] M. H. J. Amelink, "Visual control augmentation by presenting energy management information in the primary flight display: An ecological approach," Tech. Univ. of Delft, Delft, The Netherlands, Sep. 2002.

[26] S. B. J. Van Dam, A. L. M. Abelos, M. Mulder, and M. M. van Passen, "Functional presentation of travel opportunities in flexible use airspace: An EID of an airborne conflict support tool," in *Proc. IEEE Int. Conf. Syst., Man, and Cybern.*, 2004, pp. 802–808.

[27] N. Dinadis and K. J. Vicente, "Designing functional visualizations for aircraft systems status displays," *Int. J. Aviat. Psychol.*, vol. 9, no. 3, pp. 241–269, 1999.

[28] K. J. Vicente and G. L. Torenvliet, "The Earth is spherical ($p < 0.05$): Alternative methods of statistical inference," *Theor. Issues Ergon.*, vol. 1, no. 3, pp. 248–271, 2000.

[29] F. L. Ramsey and D. W. Schafer, *The Statistical Sleuth: A Course in Methods of Data Analysis*. Belmont, CA: Duxbury Press, 1997.

[30] W. S. Pawlak and K. J. Vicente, "Inducing effective operator control through ecological interface design," *Int. J. Human-Comput. Stud.*, vol. 44, no. 5, pp. 653–688, May 1996.

[31] S. Siegel and N. J. Castellan, *Nonparametric Statistics*, 2nd ed. New York: McGraw-Hill, 1988.

[32] M. E. Janzen and K. J. Vicente, "Attention allocation within the abstraction hierarchy," *Int. J. Human-Comput. Stud.*, vol. 48, no. 4, pp. 521–545, Apr. 1998.

[33] N. Yuji and E. Hollnagel, "Enhancing operator control by adaptive alarm presentation," *Int. J. Cogn. Ergon.*, vol. 5, no. 3, pp. 367–384, 2001.

[34] P. M. Jones and C. M. Mitchell, "Model-based communicative acts: Human–computer collaboration in supervisory control," *Int. J. Human-Comput. Stud.*, vol. 41, no. 4, pp. 527–551, Oct. 1994.

[35] N. A. Stanton and M. J. Ashleigh, "A field study of team working in a new human supervisory control system," *Ergonomics*, vol. 43, no. 8, pp. 1190–1209, Aug. 2000.

Greg A. Jamieson (M'03) received the B.S. degree in mechanical engineering and in psychology (with distinction) from the University of Illinois, Urbana-Champaign, in 1996 and the M.A.Sc. and Ph.D. degrees in mechanical and industrial engineering from the University of Toronto, Toronto, ON, Canada, in 1998 and 2002, respectively.

From 1998 to 1999, he was a Research Intern at Honeywell Laboratories, Minneapolis, MN, and subsequently held the position of Research Scientist from 1999 to 2002. He is now an Associate Professor in the Department of Mechanical and Industrial Engineering, University of Toronto.

Dr. Jamieson is a member of the Human Factors and Ergonomics Society and the IEEE Systems, Man, and Cybernetics Society, where he serves as a Member of the Human–Machine Systems SMC Technical Committee. He is a licensed Professional Engineer in the province of Ontario, Canada.