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EMPIRICAL EVALUATION OF AN INDUSTRIAL APPLICATION OF ECOLOGICAL INTERFACE DESIGN

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ABSTRACT

Abnormal events in production plants cost the petrochemical industry billions of dollars annually. In part, these events are difficult to deal with because current interfaces do not adequately inform operators about the state of the process. Ecological human-machine interfaces aim to provide information about higher-level process functions. Several laboratory simulator studies have shown that, in comparison with contemporary process interfaces, ecological interfaces can lead to faster fault detection, better root-cause diagnosis, and more effective control responses. However, an empirical evaluation of these findings for professional operators in more realistic plant settings has been absent from the literature. In this study, two ecological interfaces were created for a representative petrochemical refining process. One was a traditional ecological interface based on a system-based analysis and the other was an ecological interface augmented with additional task-based information. Professional operators used the novel interfaces in an industrial simulator to monitor for, diagnose, and respond to several types of process events. In comparison to operators using the current process interface, participants in both ecological interface conditions showed better control performance, while the participants using the augmented ecological interface provided more accurate fault diagnoses than either of the other two groups. The results shed light on practical implications for the use of ecological interfaces in the process industries.

INTRODUCTION

The Chemical Incident Report Center (CIRC) provides a database of incident reports from the chemical industry (http://www.chemsafety.gov/circ/index.cfm). Each day, CIRC is updated with new fire, explosion, and release reports, many of which involve worker injury or death. Despite the regularity of these reports, they are only a subset of the frequent process disturbances that require operator action to restore the plant to a normal operating condition. Cochran & Bullemer (1994) refer to such disturbances as *abnormal situations*. They estimate economic losses from abnormal situations in the petrochemical industry alone to be $10B (US) annually.

Abnormal situations fall into two main categories, those that are *anticipated* by process engineers and those that are *unanticipated* (Vicente and Rasmussen, 1992). Typically, a plant has emergency operating procedures (EOPs) that prescribe an appropriate response to anticipated abnormal events. Similarly, standard operating procedures (SOPs) prescribe responses to normal events. However, writing a procedure for an unanticipated abnormal event is a logical impossibility. When such events occur, the operations team is left to generate a response procedure for the disturbed process in real time; a challenge that Rasmussen and Goodstein (1987) dubbed ‘completing the design’. Historically, the most severe events in process operations have fallen into the category of unanticipated abnormal (Vicente and Rasmussen, 1992).

In part, the difficulty in responding to abnormal events (either anticipated or unanticipated) reflects a failure of user interface technologies to match advances in automation technology and plant complexity (Bullemer & Nimmo, 1994). Many of the digital information systems employed in current petrochemical plants are of the single-sensor, single indicator variety (Goodstein, 1981). Mimic diagrams and trend packages are the most common graphical information presentation tools in use. The industry is, however, showing interest in new approaches to graphical interface design.

ECOLOGICAL INTERFACES

One such approach is Ecological Interface Design (EID; Vicente & Rasmussen, 1992). Laboratory results from several studies have shown that, in comparison to contemporary interfaces, ecological interfaces can lead to faster fault detection, better root-cause diagnosis, and more effective control responses (see Vicente, in press). These promising results have drawn the attention of petrochemical producers. However, although prior studies have striven to create representative experimental conditions, it is unclear how well those results will generalize to a production environment. For example, there is currently no literature that addresses the use of ecological interfaces in realistic process environments with professional plant operators. In addition, previous studies of EID have not included the use of prescribed operating procedures, a mainstay of industry practice. Finally, the EID research performed to date has not clearly distinguished between anticipated and unanticipated abnormal events. Each of these limitations is overcome in the present study (see Table 1).

Prior EID Research	Present Study
Primarily laboratory simulations (cf. Ham & Woon, 2001a, 2001b)	Industrial simulation
Typically non-expert operators (cf. Sharp & Helmicki, 1998)	Professional operators
No procedures	Both SOPs & EOPs
"Fault" events not clearly distinguished	Anticipated and Unanticipated events

Table 1: Contrasts between existing EID research and the present study.

One of the reasons that the type of study described in the right hand column of Table 1 has not been conducted is that the resources required to do so are substantial. The time, money and expertise required to complete the necessary analyses, design and implement the interface, and deploy them in an industry simulator can rarely be aligned.

We leveraged prior work by Miller & Vicente (1998, 1999) to get a jump-start on developing two novel ecological interfaces. The traditional EID approach calls for a Work Domain Analysis (WDA) to specify both physical (P) and functional (F) information to be included in the interface. We created a P+F interface based on a WDA of a petrochemical refining process conducted by Miller and Vicente (1998). In an effort to extend the EID approach to include task-based information (T), we also incorporated two additional analyses. The first was a Hierarchical Task Analysis (HTA) of the existing SOPs and EOPs for the AHR (Miller & Vicente, 1999). The second was a Control Task Analysis (CTA) of the regulatory and advanced automation employed in the process. We augmented the P+F interface with information from both of these analyses to more effectively support task-based activity, producing a P+F+T interface (see Figure 1). Details of the CTA and the iterative design process used to create both interfaces are described elsewhere (Jamieson, Reising, & Hajdukiewicz, 2001), as are the two novel ecological interfaces (Jamieson & Ho, 2001).

METHOD

Interfaces

The interface graphics were implemented as a set of ActiveX controls written in Microsoft Visual Basic 6.0. Each control comprises a process view that, in combination with other controls, make up the P+F and P+F+T interfaces. The P+F+T interface contains all of the controls, while the P+F interface leaves out the graphics that were created based on the task-based analyses.

A third interface was used in the study; the Current process interface. The Current interface is representative of the current state of the art in the industry, consisting of two annotated mimic diagrams and a trending capability.

Platform

All three interfaces were connected via an emulated digital control system to a full-scope industrial plant simulator. A subset of that simulator, the acetylene hydrogenation reactor (AHR) process, served as the experimental platform. The AHR is a production- and safety-critical step in the ethylene refining process wherein acetylene, a contaminant, is removed from the process in an exothermic, catalyzed reaction.

Approximately 250 dynamic process variables were represented. The experimental platform closely approximates the appearance, behavior, and capabilities of the actual working environment. However, the auditory indications from the alarm summary software were disabled to force the operators to rely on the graphical interfaces to detect and diagnose upsets.

Participants

30 professional operators participated in the study. The participants were all male and ranged in age from 31 to 57, with a mean age of 45 and a standard deviation of 6.7 years. Their AHR operating experience ranged from 0.5 (operator in training) to 10.0 years, with a mean of 3.6 years and a standard deviation of 2.4 years. Their industry experienced ranged from 9 to 36 years, with a mean of 19.7 years and a standard deviation of 5.9 years.

Event Scenarios

Three process events were created to correspond to the taxonomy of normal and abnormal events described above. The Anticipated/Normal (A/N) event involved redirecting process flow from one reactor to a parallel reactor. There is an SOP for this event. The Anticipated/ Abnormal (A/A) event was a reactor temperature runaway. The EOP for this event provides guidance to prevent the situation from progressing from dangerous to catastrophic. The Unanticipated/Abnormal (U/A) event was a leak in a heat exchanger. The leak interrupts the exchanger function and inhibits the heating of the process stream. No EOP is available for this event and quick decision-making and prompt control action are required to avoid a shutdown.

Experimental Design

A 3x3 split-plot factorial design was employed, with Interface Group (Current, P+F, P+F+T) as a between participants factor and Scenario (A/N, A/A, U/A) as a within participants factor. The assignment of participants to interfaces and the order of presentation of the scenarios were both randomized.

Hypotheses

In keeping with previous empirical results (see Vicente, in press), we expected to see performance advantages for operators using either of the ecological interfaces to manage either of the abnormal events (A/A and U/A). We also anticipated that operators using the P+F+T interface (i.e., augmented EID) would enjoy an additional performance advantage over the P+F interface (i.e., traditional EID). This is because relevant task-specific information had been included in the display. Although the study did address Scenario effects and interactions, only the main effects of Interface are described in this article.

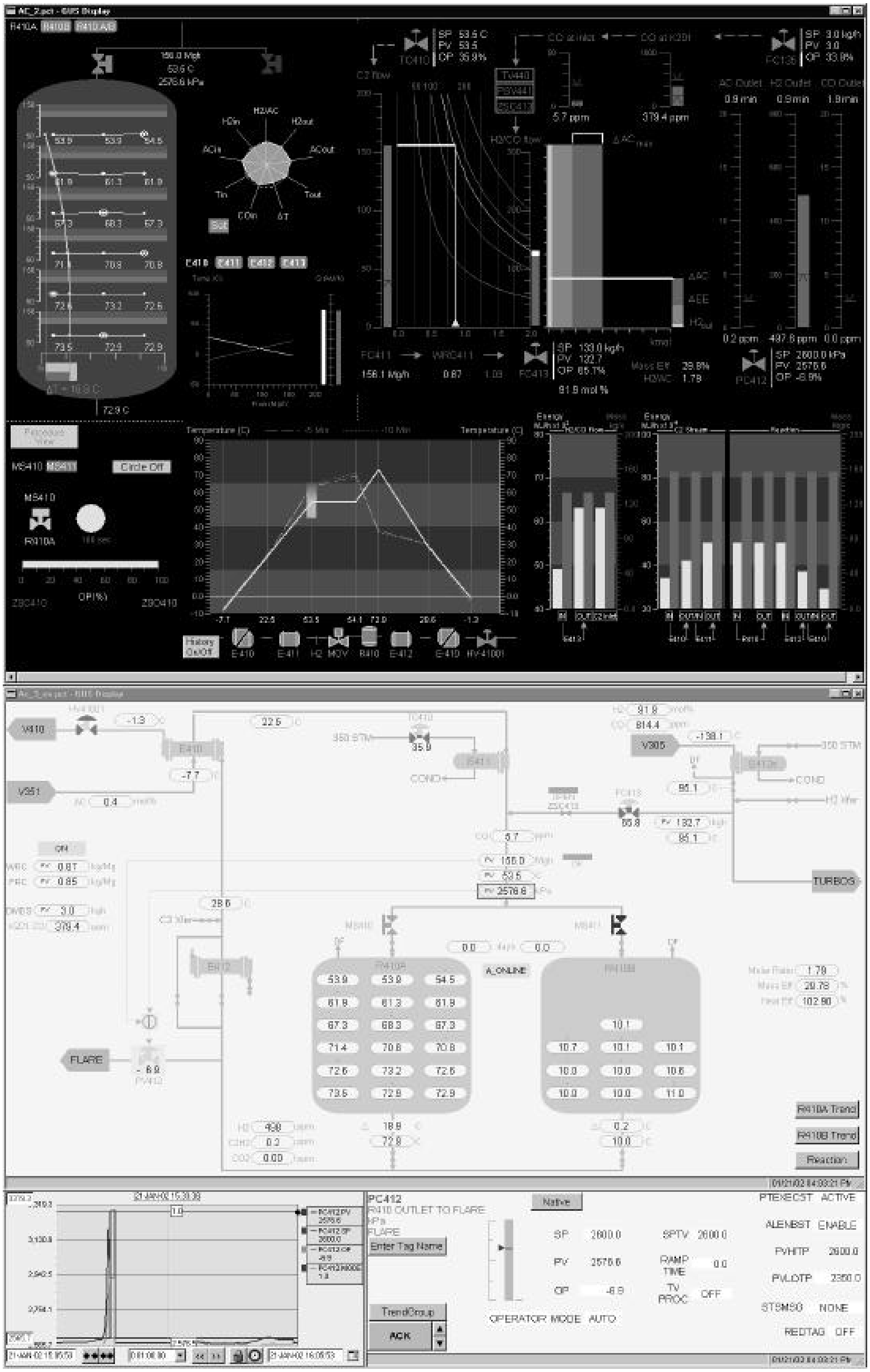

Figure 1: The P+F+T interface in greyscale. The P+F interface is formed by removing the (T)ask information.

RESULTS

Trial Completion Time

Trial completion time was measured for each of the trials. Although the participants were not instructed to complete the trials quickly, they have been trained to limit the time in which the plant is in a transition phase, regardless of whether an event is anticipated or unanticipated. Thus, faster trial completion times are associated with better performance.

Figure 2 shows the mean log transformed trial completion times for each of the three Interface groups. The plot shows that times were faster in the P+F and P+F+T conditions compared to the Current condition, although only the Current versus P+F+T difference is statistically significant.

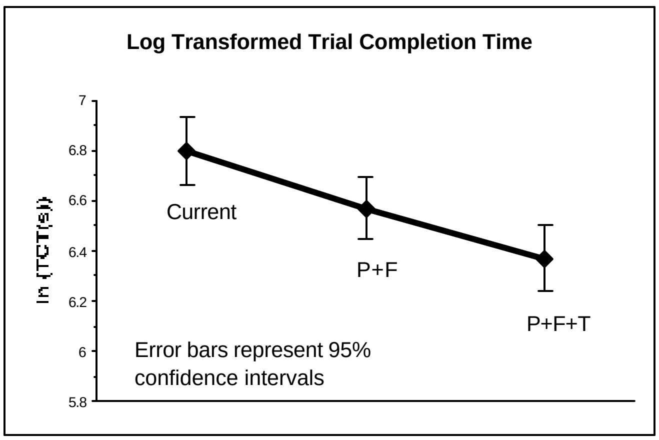

Figure 2: Mean log transformed trial completion times.

Control Actions

Figure 3 shows the mean log transformed number of control actions for each of the interface groups. There is a trend toward fewer control actions as the information content of the interfaces increases. The differences between the Current interface and both the P+F and P+F+T displays are statistically significant, whereas the difference between the two ecological interfaces is not.

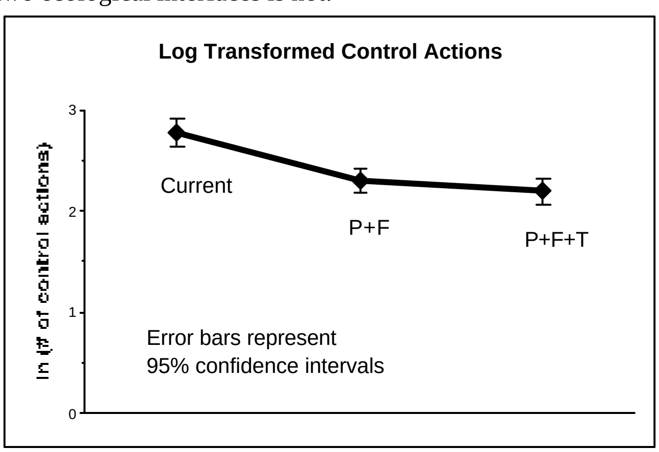

Figure 3: Mean log transformed number of control actions.

Diagnosis Accuracy

For each of the Abnormal events, participants provided written fault diagnoses. These diagnoses were scored according to an ordinal scale introduced by Pawlak and Vicente (1996).

0. The operator says nothing relevant to the fault.
1. The operator provides a vague, but correct description of the effects of the fault.
2. The operator provides a correct statement of the specific functional impact of the fault.
3. The operator provides a correct localization of the faulty component.

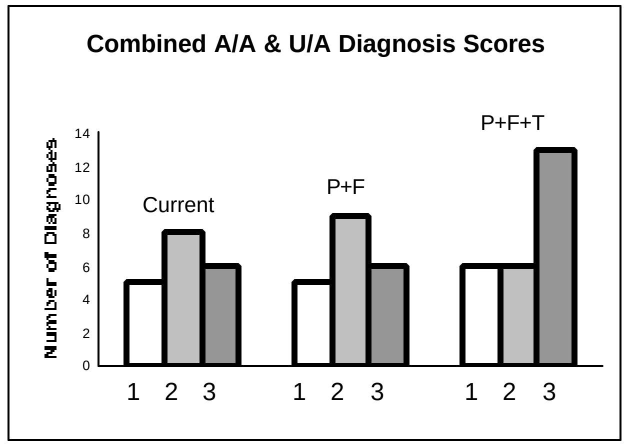

Figure 4: Diagnosis scores by Interface.

There were no zero scores in any of the Interface conditions for either of the Abnormal Scenarios. In order to meet the minimum cell criterion for application of a Chi-square test, the scores from both of these events were combined and scores of 1 or 2 compared to scores of 3. The resulting contingency table is statistically significant ($?^2$=6.35, *df*=2, p<0.05) and we conclude that the diagnosis score depends on the Interface treatment. From Figure 4, we can see that there were more diagnosis scores of 3 in the P+F+T condition, whereas the Current and P+F conditions were indistinguishable.

DISCUSSION

The results of the three outcome measures presented here are encouraging for several reasons. First, for trial completion times and number of control actions, we observed the hypothesized performance benefits for the two ecological interfaces over the Current interface. These findings are consistent with earlier studies of EID. Additionally, the participants using the P+F+T interface provided more accurate fault diagnoses than those in the Current and P+F conditions. Thus, Miller and Vicente's (1998, 1999) contention that system- and task-based methods of work analysis complement each other by identifying unique and useful information requirements is supported with empirical evidence.

Another reason to find encouragement in these results is that the performance benefits were observed for skilled operators with thousands of hours of experience with the Current interface. Moreover, the benefits persist for the two

Anticipated trials for which the operators have pre-defined operating procedures to guide their actions. This suggests that domain experts working under representative task conditions can benefit from EID.

Third, the results largely corroborate previous findings in laboratory simulations with novice operators. This suggests that the growing body of EID literature, despite its methodological limitations, is producing results that generalize to industry. This final message is important for both researchers and industry consumers. It assures the former that empirical conditions used to date are sufficient to continue their microworld research, and it gives the latter the confidence to accept the results of those studies.

Limitations

Although this study is the most realistic evaluation of ecological interfaces in an industry setting to date, there are still several limitations to consider. First, only one process event in each of the three event categories defined by Vicente and Rasmussen (1992) was examined. Limitations on experimental resources and the difficulty of matching events to the categorical criteria presented significant challenges. Second, the participants in this study were not exposed to the interruptions that are common in the control room. The role of interruptions in task performance is an emerging issue in cognitive engineering. Third, operating a petrochemical plant is a group task whereas this experiment placed a single operator in an individual problem-solving situation. To date, collaborative use of ecological interfaces remains as an outstanding research issue.

Future work

The results presented above show a pattern of improved operator performance with ecological interfaces over a cotemporary process display. However, these results reflect only statistical significance. In order to make a business case to industry in support of ecological interfaces, we must establish the practical significance of these results in domain-relevant terms. Thus, our next step is to use cost-benefit models of this process environment to estimate the economic impacts of EID in industry application.

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