SUPPORTING SITUATION AWARENESS THROUGH ECOLOGICAL INTERFACE DESIGN

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ABSTRACT

A full-scope simulation study with licensed nuclear power plant operators was conducted to evaluate whether displays designed using Ecological Interface Design (EID) could support improved Situation Awareness over traditional displays. EID demonstrated performance advantages over traditional displays in beyond-design basis scenarios where operators were unable to rely on procedures. The same effects were not seen in within-design basis scenarios where procedures were available. This suggests that EID has the potential to improve SA in unanticipated situations, but that ecological interfaces should be supported with task-based displays in procedure-driven situations.

INTRODUCTION

Ecological Interface Design (EID; Vicente & Rasmussen, 1992) and Situation Awareness (SA; Endsley, 1995) have both been part of the cognitive engineering lexicon for over 15 years. The former is a design framework for complex systems and the latter is a theoretical construct for which various measures have been developed. Both EID and SA contribute to the development of information displays that improve operator insight into decision-making spaces. They share a mutual objective of designing for good decision making and good human performance in complex environments.

Despite the convergence in these objectives, EID and SA have evolved independently from one another. This is rather surprising considering that they must, at practical levels, overlap. An effective ecological interface should support SA, and high SA must depend on the conveyance of ecological aspects of the environment. Yet a review of the empirical EID and SA literature reveals next to no co-occurrences of the terms. EID researchers are not assessing SA in their studies and SA researchers are not using EID to achieve improved SA. A central aim of the study introduced here is to break through the conceptual divide between these concepts.

Being EID practitioners we decided to evaluate the first hypothesis; that good EID should support SA. Specifically, a design developed from the principles of EID should demonstrate improved SA in comparison with traditional displays. The links between the theoretical foundations of EID (Vicente & Rasmussen, 1992) and the three levels of situation awareness (Endsley, 1995) are as follows. First, we expect EID to support *perception* by making the constraints on effective action visible through graphical forms that are consistent with the perceptual capabilities and limitations of the viewer. Second, EID should support *comprehension* by communicating the purposeful structure of the system. Third, EID should support *projection* by supporting operator manipulations of the mental model that is externalized by the ecological interface. Thus, at all levels, EID should support good SA.

EID theory further predicts directional effects of interaction on SA between ecological interfaces and types of event scenarios. EID identifies information needed to support anomaly detection, decision making and action under abnormal events. Similarly, the general theory of

SA pertains to event detection and understanding. Much of the empirical literature on EID supports the theory-based prediction that the performance advantages of ecological interfaces over traditional interfaces are more pronounced in abnormal events as compared to normal events (Vicente, 2002; Jamieson, in press). The prevailing explanation for this finding is that normal events do not tax operators sufficiently to force them to rely on the additional information support provided by the ecological interface. The theory readily extends to SA as an indicator of performance.

DESIGN

A team of researchers from the University of Waterloo, University of Toronto, and the OECD Halden Reactor Project developed ecological displays for the turbine (Kwok & Burns, 2006), condenser (Lau & Jamieson, 2006), and feedwater sections of the secondary side of a nuclear power plant (as simulated in a high-fidelity simulator).

Two other display sets were available for the plant simulation. The first was a set of displays representative of many contemporary NPP control rooms. These were primarily mimic-based displays. The second set of displays added trends and some configural graphics to the traditional displays. We therefore had three display designs; Traditional, Advanced and EID.

SA MEASURES

The Halden program has developed experimental measures of SA that are tailored to the evaluation of operator performance in complex scenarios (Skraaning, 1998; 2003). The methods are based on probes of operators' SA at various points in a scenario coupled with an evaluation of the correctness of the operators' responses by process experts. The use of a process expert in the evaluation is critical because scenarios can only be controlled loosely (i.e. at the level of fault generation) and operator responses can follow many trajectories. An expert opinion is needed to assess how well the operators are performing or responding to probes. It is worth noting that the process experts are also trained performance evaluators, versed and highly experienced in their experimental roles.

SA Measure 1: Process Overview

After the completion of each scenario period, the turbine operator in each crew was asked whether important process parameters had increased, decreased, or remained stable over the preceding few minutes. The simulator was frozen, and the user interface unavailable to the operators while they responded to these questions. In parallel, the process expert scored the actual drift of the process parameters by inspecting trend diagrams, event lists and other simulator data. Because this evaluation was focused on how well operators perceived various plant parameters, the process overview is primarily a measure of Level 1 SA using the definition of Endsley (1995).

The operators were given the score 1 whenever there was agreement between the process expert and the operator rating (e.g., both said that the pressure in the condenser had decreased). When the operators disagreed with the process expert, the score 0 was given (e.g., the operator believed that the reactor temperature had increased, while the process expert concluded that the temperature was stable). The number of parameters scored varied between 9 and 12 depending on the scenario characteristics. The process overview score was calculated as the percentage of correct operator responses per scenario.

SA Measure 2: Scenario Understanding

During short mini-freezes of the scenarios, operators were phoned by the experiment leader acting in the role of plant management and questioned on their understanding of the plant situation. These questions probed operator awareness of what was happening, whether things were normal and how they expected plant conditions to change in the future. In this way, this measure probed for Level 2 and Level 3 SA following the definitions of Endsley (1995). The probes were open probes so operator responses were not constrained. Probes were selected from a list in a way compatible with the context of the experimental run. The simulator was frozen during the probes so that the operators were not under excessive workload or pressure to control the plant while responding. Again, the operators' answers to the probes were scored by the process expert.

EVALUATION

Participants for the experiment were recruited from a boiling water reactor nuclear power plant located in Sweden. The power plant licensee is a member of the Halden Reactor Project (HRP). A total of six (n = 6) licensed control room operating crews with roles ranging from supervision to reactor operation agreed to participate on a voluntary basis. Each crew consisted of one reactor operator (RO) and one turbine operator (TO).

Scenarios

Operators faced six scenarios of two types. Three "within-design basis" scenarios were typical of scenarios the operators had faced before and for which procedures were available. In contrast, the operators had never experienced the three "beyond-design basis" scenarios before and did not have procedures they could follow. We anticipated that the EID displays would be more effective at supporting SA in the beyond-design basis scenarios (Vicente & Rasmussen, 1992). The effects were expected to be less noticeable in the within-design basis scenarios since the procedures provide additional performance support.

Scenarios were broken into two phases, a detection phase before the first alarm came in, and a mitigation phase signified by the first alarm. A short break between these phases was used to administer the process overview probes. Process overview probes were also administered at the end of the mitigation phase. The scenario understanding probes were administered during the scenarios and before the process overview probes at the break in the scenario and at the end of the mitigation phase.

Training

The operators received a full day of training on all displays before participating in the experiment. This included training on the probes and freezes used in the experiment.

RESULTS

The evaluation of the experiment investigated the effect of three independent variables: Interface Type (Traditional, Advanced and EID), Scenario Type (Within-Design Basis and Beyond-Design Basis), and Scenario Period (Detection Phase and Mitigation Phase).

Process Overview

A significant three way interaction was found between Interface Type, Scenario Type and Scenario Period (F=0.41, 2, p=0.02). The figure below shows the effect on Process Overview by Interface Type and Scenario Type, separated by Scenario Period.

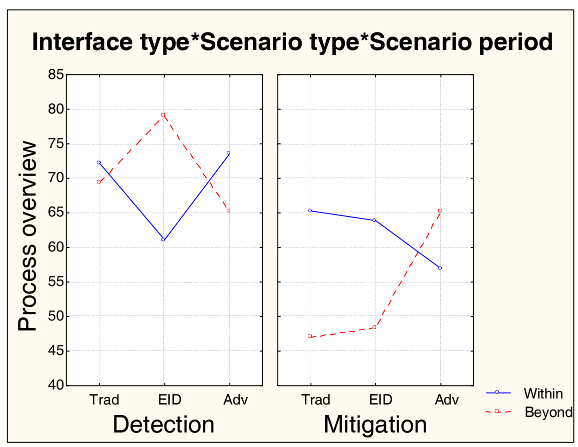

Figure 1. The effect of Interface and Scenario Type on Process Overview.

It can be seen from Figure 1 that the ecological interface enhanced process overview in the detection phase (period 1) of beyond-design basis scenarios, but impaired the overview in the detection phase of within-design basis scenarios. Advanced displays improved the process overview in the mitigation phase (period 2) of beyond-design basis scenarios, while traditional and ecological displays facilitated process overview in the mitigation phase of within-design basis scenarios.

Scenario Understanding

A significant three way interaction was found for the effect of Interface Type, Scenario Type and Scenario Period on Scenario Understanding (F-21.07, 2),, p<0.001).

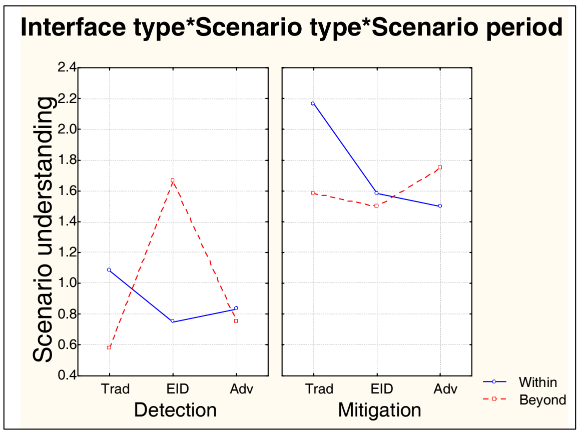

Figure 2. The effect of Interface Type on Scenario Understanding.

It can be seen from Figure 2 that the ecological interface enhanced Scenario understanding in the detection phase of beyond-design basis scenarios. Traditional displays seemed to improve Scenario understanding in the mitigation phase of within-design basis scenarios. These tendencies are consistent with the effects on process overview (scenario understanding and process overview are uncorrelated dependent variables (r^2=0.0)).

DISCUSSION

Our study produced some evidence that EID can support SA in complex problem solving situations. The effect was noticeable only during the detection phase of the beyond-design basis scenarios and was seen on both measures, process overview and scenario understanding. However, although the effect was only see in the beyond-design basis scenarios, it was consistent and a strong effect.

We argued that the SA based measure of process overview reflected Level 1 SA. In reality though, we expect that some degree of process understanding or Level 2 SA is required to answer the Level 1 SA probes. As well, good Level 1 SA is required to correctly generate the Level 2 and 3 SA that we measured in our Scenario Understanding measure. Our measures however were not correlated and therefore were measuring unique aspects of operator situation awareness.

EID did not improve SA in within-design basis scenarios on either measure. This highlights the concern that EID based solely on WDA, while providing useful information visualizations, does not particularly help operators to perform procedural tasks. When using the EID approach, designers must take care to integrate a task based approach (such as GDTA, or Control Task Analysis) in order to support procedural tasks properly (see Jamieson, in press).

EID primarily improved SA in the detection phase of the beyond-design basis scenarios. In particular, the improvement in scenario understanding brought the operator’s scenario understanding up to the level of their understanding during the mitigation phase of the scenario, which was a very promising result.

Process overview in beyond-design basis scenarios dropped dramatically during the mitigation phase with both the EID and Traditional displays. While it can be argued that this is not important, since operators are now focused on solving a problem and not maintaining a large view of the process, the Advanced display showed an improvement in process overview. This display should be examined further to determine what features might be providing this benefit.

In both measures, it was clear that beyond design basis scenarios are much more challenging for operators to handle than scenarios where there is procedural support. The potential of EID to dramatically improve

SA in these situations is quite important since serious accidents are most likely of this unanticipated type of situation. We anticipate, however, that the optimal solution will combine EID with a task-based support method.

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