Ecological Interface Design: Progress and Challenges

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Ecological interface design (EID) is a theoretical framework for designing human-computer interfaces for complex sociotechnical systems. Its primary aim is to support knowledge workers in adapting to change and novelty. This literature review shows that in situations requiring problem solving, EID improves performance when compared with current design approaches in industry. EID has been applied to industry-scale problems in a broad variety of application domains (e.g., process control, aviation, computer network management, software engineering, medicine, command and control, and information retrieval) and has consistently led to the identification of new information requirements. An experimental evaluation of EID using a full-fidelity simulator with professional workers has yet to be conducted, although some are planned. Several significant challenges remain as obstacles to the confident use of EID in industry. Promising paths for addressing these outstanding issues are identified. Actual or potential applications of this research include improving the safety and productivity of complex sociotechnical systems.

INTRODUCTION

The construction of complex sociotechnical systems has led to a greater demand for *knowledge workers,* people whose primary function is to engage in intellectual work that requires discretionary decision making. Routine activities that are well understood, and which can be reduced to a set of rules or an algorithm, are increasingly automated with computer technology. What will continue to be left over are the nonroutine and unanticipated situations that require worker adaptation to change and novelty. Events requiring adaptation can take many diverse forms, from the catastrophic to the mundane and everything in between. An example from the nuclear domain is a catastrophic abnormal event that is unfamiliar to operators and that has not been anticipated by designers. This situation requires operators to adapt by creating an entirely new procedure "on the fly" (Vicente & Rasmussen, 1992). This type of event occurs once in a career, if ever. A mundane example from the manufacturing domain is a minor disturbance that causes the process to behave in an unintended fashion. This situation requires operators to "work around" the disturbance so that the process goes back to working as designed. This type of event can occur three times per hour (Norros, 1996). Increasingly, the primary reason people are present in complex sociotechnical systems is to play the role of knowledge worker by engaging in adaptive problem solving.

However, few theoretical frameworks in the cognitive engineering literature explicitly aim to design interfaces to support worker adaptation. One exception is the ecological interface design (EID) framework, first introduced in journal article form by Rasmussen and Vicente (1989). More detailed theoretical formulations were subsequently put forth from ecological psychology (Vicente & Rasmussen, 1990) and cognitive engineering perspectives (Vicente & Rasmussen, 1992). Since then, a great deal of new research motivated by EID has been published. Therefore, it seems worthwhile and timely to take stock by conducting a review of this body of work (see Lee & Sanquist, 1995, and Vicente, 1996, for earlier reviews).

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This literature review serves three purposes: to clarify the terminology surrounding EID; to assess critically the progress that has been made by EID research; and to identify challenges that stand in the way of comprehensive industry-scale adoption of EID for systems design.

TERMINOLOGY

The Ecological Approach to Human Factors

There is some confusion as to what EID is because the term *ecological* has been used in two different ways that need to be distinguished. The ecological approach to human factors can be characterized by four meta-theoretical commitments (Flach, Hancock, Caird, & Vicente, 1995): (a) reciprocity of person and environment, (b) representative design of experiments and evaluations, (c) primacy of perception, and (d) start with analyzing the environment. This approach is broad in scope and can be applied to many diverse problems in human factors. For example, Mark and Dainoff (1988) adopted an ecological approach to the problem of ergonomic chair design with productive results. The EID framework is much narrower in scope. It is an example of the ecological approach to human factors that is focused on the specific problem of how to design human-computer interfaces for complex sociotechnical systems. As such, it makes reference to concepts (e.g., computer displays, problem-solving representations) that would not be pertinent to other human factors problems, such as chair design.

Ecological Interface Design

EID grew out of the research program conducted in the Electronics Department of Risø National Laboratory beginning in the 1960s (Vicente, 2001). That research led to two conceptual tools – the abstraction hierarchy (Rasmussen, 1985) and the skills, rules, knowledge taxonomy (Rasmussen, 1983) – that serve as the theoretical foundations of EID. The *abstraction hierarchy* is a framework that can be used to develop models of particular work domains. It can be defined as a stratified hierarchy characterized by a structural means-ends relation between adjacent levels. In process control, five levels of representation have been found to be of use: the purposes for which the plant was designed (functional purpose), the mass and energy topology of the plant (abstract function), the generic functions that implement that topology (generalized function), the plant equipment that realizes those functions (physical function), and the spatial location and appearance of that equipment (physical form). A detailed example for a process control microworld was provided by Bisantz and Vicente (1994).

Higher levels of an abstraction hierarchy model contain functional information, whereas lower levels contain physical information. *Physical* information describes the state of objects in a work domain (e.g., pumps, heaters, valves in a process plant). *Functional* information describes the state of the functions or purposes that those objects are intended to satisfy.

Note that an abstraction hierarchy analysis is a type of work domain analysis, not task analysis (Vicente, 1999). A task can be defined as the set of actions that can or should be performed by one or more actors to achieve a particular goal. In contrast, a work domain is the system being controlled, independent of any particular worker, automation, event, task, goal, or interface. These concepts are qualitatively different – a task is something you do (a verb), whereas a work domain is something that you act on (a noun). The abstraction hierarchy is a form of work domain analysis because it is used to analyze the controlled system, not any tasks.

This distinction is of critical importance to the aims of EID. A task analysis has benefits that are complementary to those offered by a work domain analysis (Vicente, 1999). However, task analysis can be conducted only for anticipated tasks. The reason is simple: Before you know what needs to be done, you have to know what the event or situation is. However, if the event or situation is unanticipated, then by definition it is not possible even to begin a task analysis (Vicente & Rasmussen, 1992). The same is not true of a work domain analysis because, regardless of the situation or event, the controlled system has particular properties (e.g., a limited number of components that are capable of performing only certain functions).

Thus a work domain analysis provides a more robust basis for supporting workers in adapting to novelty and change because it has the flexibility that is required to cope with these situations. Accordingly, EID begins with work domain analysis.

The *skills, rules, knowledge* (SRK) taxonomy describes three qualitatively different ways in which people can interact with their environment (Rasmussen, 1983). Skill-based behavior involves parallel, automated, direct behavioral interaction with the world. Rule-based behavior involves associating a familiar perceptual cue in the world with an action or intent, without any intervening cognitive processing. Knowledge-based behavior involves serial, analytical problem solving based on a symbolic mental model.

The twofold objective of EID is to encourage the use of skill- and rule-based behavior (to save on scarce cognitive resources) while providing support for otherwise more effortful and error-prone knowledge-based behavior (to cope with unfamiliar and unanticipated situations requiring adaptive problem solving). To achieve this aim, the framework comprises three design principles, each directed at supporting a level of the SRK taxonomy:

- *Skill-based behavior:* Workers should be able to act directly on the interface.
- *Rule-based behavior:* There should be a consistent one-to-one mapping between the work domain constraints and the perceptual information in the interface.
- *Knowledge-based behavior:* The interface should represent the work domain in the form of an abstraction hierarchy to serve as an externalized mental model for problem solving.

Summary

An interface can fail to be a "pure" example of EID by violating any one of its three principles – that is, if (a) there is no capability for direct manipulation, (b) the perceptual forms do not map uniquely onto work domain constraints, or (c) the interface content does not represent all of the information identified by an abstraction hierarchy model of the work domain. Interfaces that satisfy a subset of the EID principles have been constructed to test parts of the framework.

PROGRESS: WHAT HAS BEEN LEARNED SO FAR

This section addresses five questions: (a) Does EID improve performance compared with the industry state of the art? (b) Why does EID improve performance? (c) How can EID be leveraged via training or selection? (d) Can EID be applied to large-scale problems across diverse application domains? (e) How successful has EID been in transferring technology to industry?

Does EID Improve Performance?

EID has consistently improved performance compared with the industry state of the art. For example, Reising and Sanderson (1998, 2000a, 2000b) conducted a 2 × 2 experiment with two interfaces (EID and conventional) and two sensor sets ("max" and "min") in the context of a pasteurization microworld. The EID display presented both physical and functional information and tried to take advantage of emergent feature graphics, whereas the conventional interface presented physical information using a piping and instrumentation diagram (P&ID) – the industry standard in process control. The min condition had the minimum number of sensors required to display the information identified by an abstraction hierarchy analysis of the microworld, requiring many variables to be derived rather than sensed. The max condition had the maximum number of sensors, thereby reducing the need for derivation. Equipment and sensor failure scenarios were included in the experiment, creating situations in which information was being derived from faulty sensor data (particularly in the min conditions).

The results showed that the EID-max condition was the best overall for fault trials. However, there was no significant impact of interface or sensor set on mean control performance during routine (i.e., nonfault) trials. Thus the value added by EID seems to be in situations requiring adaptive problem solving. The conventional-max and conventional-min interfaces led to better fault management performance than did the EID-min interface, thereby showing the importance of sensor selection in an EID interface. There is no point in presenting higher-level functional information in an EID interface unless the sensors that are required to present that information reliably are present.

Sharp and Helmicki (1998) tested the value added by EID in the context of neonatal intensive care unit (ICU) monitoring and diagnosis. Their EID display presented both physical and functional information and tried to take advantage of graphical forms, whereas their conventional interface presented physical information using an alphanumeric format – a typical display form in medicine. Participants were selected according to three levels of expertise: residents, fellows, and attending physicians. Their task was to diagnose acute clinical situations. The results indicated that the EID interface led to the best level of performance overall. Only 1 of the 16 participants performed better with the existing (and more familiar) interface. However, there was also a significant interaction with expertise. The least experienced group (the residents) performed significantly better with the EID interface, but the interface effect was not significant for the most experienced group (the attending physicians). These results could be attributable to three reasons: (a) the attending physicians had years more experience with the existing display than with the EID, (b) the value added by EID diminishes with experience, or (c) the experimental power was too low. Regardless, the findings showed that EID adds value for less-experienced practitioners in neonatal ICU compared with the industry state of the art.

A number of experiments evaluating the value added by EID have also been conducted in the context of DUal REservior System Simulation (Vicente, 1992) and DURESS II (Christoffersen, Hunter, & Vicente, 1996, 1997, 1998; Pawlak & Vicente, 1996), thermal hydraulic process control microworlds. Two interfaces (see Pawlak & Vicente, 1996; Vicente & Rasmussen, 1990) were compared in each study. The P+F interface was based on EID, contained both physical and functional information, and took advantage of emergent feature graphics. The P interface presented physical information using a P&ID format.

These experiments have already been reviewed elsewhere (Vicente, 1996), so only a summary of the major findings are presented here. On fault trials, the P+F interface led to faster detection and more accurate diagnosis performance than did the P interface. Moreover, the P+F participants exhibited a more sophisticated and effective set of fault management strategies than did the P participants. On normal trials, there was no statistically significant difference between the two interfaces in terms of mean task completion times. However, the P interface led to significantly less consistent performance than did the P+F; P participants occasionally took twice as long as usual to complete the required tasks, even after 5.5 months of quasi-daily practice. Knowledge elicitation measures showed that the P interface can lead to a shallow knowledge base consisting of a rote set of rules for controlling the process. In contrast, the P+F interface can lead to a functionally organized knowledge base, but only if participants actively reflect on the feedback they get from the interface. If participants adopt a surface approach to learning, then the P+F interface can lead to a shallow knowledge base that is tied to the perceptual features of the interface.

Critical analysis. Collectively, these studies suggest that EID can lead to better performance than can contemporary interfaces, as long as the required sensor set is available. No interface design technique can make up for the fact that important information is not being sensed and thus is not available. The primary value added by EID seems to be localized to more complex tasks, a finding that is consistent with the framework's emphasis on supporting worker adaptation in situations that require discretionary decision making. There is no disadvantage to EID on less complex tasks, despite the added visual complexity compared with traditional designs.

In all of the experiments reviewed so far, an EID interface was compared with an interface that represents contemporary industry practices. Given that value added has now been consistently demonstrated, cognitive engineers can aim higher by comparing EID with other interface design frameworks that also aspire to replace the industry state of the art. The only study that falls in this category is the one conducted by Chéry, Vicente, and Farrell (1999; to be discussed later), but that comparison was based on an analytical, not an empirical, evaluation. EID should be compared with more stringent baselines so that its value can be clearly differentiated from other interface design approaches that also aim to support worker adaptation to novelty and change.

Why Does EID Improve Performance?

Not just form. Differences in visual form were not controlled for in the studies reviewed so far. Other studies have shown that the benefit of EID is not attributable merely to differences in form. For instance, Xu, Dainoff, and Mark (1999) compared two interfaces for Hyper-Ergo, a hypertext database of ergonomic workstation design principles based on an American National Standards Institute standard. Their conventional interface organized the nodes in the database according to part-whole relations (e.g., a backrest is part of a chair). The EID interface also organized the same nodes according to structural means-ends relations identified by an abstraction hierarchy analysis of the work domain (e.g., seat pan height is a structural means for achieving the end of body comfort). The visual forms for the two interfaces were the same (i.e., text and diagrams).

Xu et al. (1999) evaluated these interfaces experimentally on three types of information retrieval tasks: (a) a problem-solving task that required participants to explore the entire database to solve a workstation design problem, (b) a complex search requiring participants to find several related facts, and (c) a simple search requiring participants to find a single isolated fact in the database. The EID interface was expected to provide a better basis for supporting goal-directed problem solving because it organizes the hypertext nodes using a functional approach.

The results showed that the EID interface led to significantly faster search times and significantly less disorientation on both the complex and the problem-solving tasks. Moreover, the magnitude of the advantage of the EID interface increased significantly with task complexity. However, the interface effect was not significant for the simple search task. Thus, even when differences in form are controlled for, using EID to design a hypertext database can lead to better performance on more complex tasks.

Ham and Yoon (2001b) also found that the benefits of EID cannot be attributed solely to differences in visual form. They conducted an evaluation of EID using a simulation of the secondary cooling system of a pressurized water reactor nuclear power plant. The task was to diagnose unfamiliar faults. Three different displays were compared: a P display, which represented physical information; a PG display, which represented physical information as well as the generalized function level of the abstraction hierarchy (i.e., flow and heating functions); and a PA display, which represented physical information as well as the abstract function level of the abstraction hierarchy (i.e., mass and energy balances). All displays used simple bar charts and alphanumeric forms to present information, thereby controlling for differences in visual form.

The results showed that the PG display was the best, whereas the P display was the worst. The PA display led to an intermediate level of performance. Thus, both the generalized function and abstract function levels added value, although the former had a bigger impact for the scenarios used in this study. These results again show that EID can lead to improvements in performance in the absence of sophisticated graphical formats. Ham and Yoon (2001b) also found that the advantage of the PG and PA displays was greater in complex scenarios than in simpler fault scenarios. These results reinforce those reviewed earlier and suggest that the primary benefit of EID is in supporting complex tasks requiring discretionary decision making.

Collectively, these studies provide evidence that the benefit of EID, compared with the industry state of the art, is not attributable merely to differences in visual form.

Functional information is critical. The studies reviewed so far all show that adding functional information identified by an abstraction hierarchy analysis can lead to improved performance, regardless of whether emergent feature graphics are also used. Several other studies provide converging evidence showing that functional information plays a key role in improving performance with an EID interface. In a follow-up experiment, Ham and Yoon (2001a) compared the performance of three displays for a nuclear power plant secondary system simulation: the PG display used in their earlier experiment; a PGA display, which contained all levels of the abstraction hierarchy; and a PGA2 display, which also contained all levels of the abstraction hierarchy but, unlike the PGA display, grouped together information according to structural means-ends relations. Participants performed a control task as well as a fault diagnosis and compensation task concurrently. The results showed that the PGA2 display was the best overall, whereas the PG display was the worst. The PGA display led to an intermediate level of performance. Thus performance can be significantly enhanced merely by grouping existing functional information according to structural means-ends relations.

Vicente, Christoffersen, and Pereklita (1995) conducted a verbal protocol study using the P+F interface for the noninteractive DURESS simulation. They found that effective problem-solving performance was generally characterized by initiating search at a high level of abstraction, spending time overviewing the problem at a high level of abstraction, and searching through the relations defined by the abstraction hierarchy model in a coherent and connected manner. Conversely, ineffective problem-solving performance was generally characterized by initiating search at a lower level of the abstraction hierarchy and examining individual components that were all highly interconnected.

Janzen and Vicente (1998) also obtained evidence of the value of higher-level functional information in EID. They created a divided interface for the interactive DURESS II simulation that contained all levels of the abstraction hierarchy. Instead of having all of these levels integrated in one display, as in the P+F interface, the divided interface consisted of four different windows, each presenting information at a different level of the abstraction hierarchy. Participants could view only one window at a time, allowing Janzen and Vicente to determine how often and how long participants consulted each level of abstraction. These coarse process-tracing measures were correlated with performance under normal and abnormal conditions. Participants who made more frequent use of functional levels of information exhibited more proficient control under normal trials and more accurate diagnosis performance under fault trials. Also, participants who made efficient use of functional information exhibited faster fault compensation times. In contrast, participants who made infrequent or inefficient use of functional information exhibited poorer performance on both normal and fault trials.

Collectively, these studies provide strong evidence that the benefit of EID is, in part, attributable to the value of higher-order functional information in supporting problem solving.

Spatial rather than verbal resources. There is also some empirical evidence bearing on the type of mental resources induced by an EID interface under normal operating conditions. Pawlak and Vicente (1996) included two secondary tasks in their experimental design, one spatial and the other verbal, to see what type of cognitive resources for DURESS II were loaded by the P and P+F interfaces. The results revealed an interaction between interface type and resource category. The P interface loaded more on verbal resources than did the P+F interface, presumably because of the mental processing required to integrate the raw data presented by the perceptually impoverished P interface. In contrast, the perceptually rich P+F interface loaded more on spatial resources than did the P interface, presumably because the participants in the former group attended to the emergent feature graphics in the P+F interface.

Higher-level control. There is also some evidence suggesting that EID leads to a qualitatively different type of control than does a traditional interface. Hajdukiewicz and Vicente (2000) found that P participants tend to focus on lower levels of the abstraction hierarchy when controlling DURESS II. In contrast, P+F participants tend to focus on high levels, specifically the abstract function level representing the work domain in terms of first principles (i.e., mass and energy balances). This type of higher-level control is indicative of the flexible, adaptive behavior that is the hallmark of robust coordination skills (Bernstein, 1996). Thus the P+F interface appears to provide a stronger basis for helping people adapt to novelty and change, which is the primary objective of the EID framework.

Critical analysis. The value added by EID can be attributed to several related factors: (a) information content, not just visual form; (b) functional information identified by an abstraction hierarchy analysis; (c) loading more on spatial than on verbal resources; and (d) higher-level control. It is important to note, however, that there are sometimes strong individual differences in these patterns. Some participants were able to effectively exploit the benefits of an EID interface, but some were much less adept at doing so.

A concise and coherent theory that integrates all of these findings under a single rubric has yet to be published. In the original theoretical development of EID, more emphasis was put on practical design principles than on fundamental theory. The data collected since that time should now be used to build a more mature theoretical foundation for EID.

How Can EID Be Leveraged?

Can anything be done to make sure that all participants are able to attain the comparatively higher levels of performance already exhibited by the most proficient EID participants? The research program centered on DURESS II investigated three potential means of leveraging EID.

Model-based training. Hunter, Vicente, and Tanabe (1996) explored the role of model-based training in improving performance. They conducted a 2 × 2 experiment comparing two interfaces (P and P+F) and two types of training (none and model-based training). Participants in the model-based training conditions received several days of instruction, during which they learned to use the concepts identified by the abstraction hierarchy representation for DURESS II. This study was the first to show that model-based training using the abstraction hierarchy was helpful in improving performance. The P and P+F groups benefited equally, but there were still substantial individual differences. Thus, although training based on the abstraction hierarchy is helpful in making the most of EID, there is still additional room for improvement.

Self-explanation. Howie and Vicente (1998) explored a second way of trying to leverage EID. In their experiment, one group of participants reviewed a videotaped replay of their control actions immediately after completing a trial, a second group was instructed to explain aloud the reasons for their control actions while reviewing them, and a third group merely performed the control task without any review or self-explanation. On normal trials there were no substantial differences among the three groups. However, on fault trials, self-explanation (SE) led to the best overall performance. Howie and Vicente also performed a post hoc median split of the SE participants. An analysis of the verbal protocols produced during self-explanation revealed that the SE participants who performed well showed more signs of self-explanation in their protocols than did the SE participants who performed poorly. These results show that self-explanation can help people leverage EID. However, there were still substantial individual differences among participants in the SE group.

Holist cognitive style. These two studies suggest that instruction may not completely eliminate the substantial individual differences observed with the P+F interface for DURESS II. Perhaps these differences are caused in part by stable, unalterable psychological traits that cannot be influenced by instruction. Torenvliet, Jamieson, and Vicente (2000) explored this possibility by conducting linear regression analyses to identify the best predictors of performance on normal and fault trials on DURESS II. Based on previous work, they suspected that the serialist/holist cognitive style distinction (Pask & Scott, 1972) might be a mediator of performance with the P+F interface. People who are *holists* tend to be system thinkers, focusing on the big picture and information integration. People who are *serialists* tend to be detailed thinkers, focusing on individual facts. Torenvliet et al. found that the strongest and most consistent predictor of performance was the interaction between a holist cognitive style score and use of the P+F interface. Participants who used the P+F interface and who had high holist scores were the best performers overall. It seems that these individuals have the relational thinking ability that is required to exploit the value of the higher-level functional information provided by the P+F interface. Because cognitive style cannot be trained, this empirical result may have practical implications for worker selection.

Critical analysis. A few techniques have been explored for raising the performance of participants using the P+F interface for DURESS II. Model-based training and self-explanation are both forms of instruction that seem to improve performance, although they do not completely eliminate the strong individual differences observed in earlier studies. The holist cognitive style appears to be an important prerequisite for fully enjoying the benefits of the P+F interface. It seems that training and selection may each have a unique role to play in making the most of EID. The generalizability of these results needs to be tested outside of DURESS II.

Can EID be Applied to Large-Scale Problems across Diverse Application Domains?

If the EID framework is to be of broad use to industry, then two key questions must be addressed: Can EID be applied to industry-scale problems beyond laboratory microworlds, the original focus of EID research? Can EID be applied across a diverse range of application domains beyond process control, also the original focus of EID research? These issues are reviewed together here because they have tended to be investigated in tandem.

Whether examining increase in scale or diversity of domains, three nested criteria can be applied (see Rouse, 1991): (a) *Proof of principle* – can EID be applied? (b) *Analytical evaluation* – does EID lead to new information requirements not found in existing interfaces? (c) *Empirical evaluation* – does EID lead to better performance? The answers to these questions cannot be taken for granted, so it is important to address all of them. The remainder of this section reviews these issues by application domain.

Process control. The studies already reviewed showed that EID can be applied to several process control microworlds (e.g., pasteurization, thermohydraulics), resulting in novel information requirements and improved performance. Ham and Yoon's (2001b) work led to similar findings but was conducted in the context of a nuclear power plant secondary system simulation. This complex test bed is composed of four subsystems: the steam generation system, a turbine operation system, a condensation system, and a feedwater supply system. The simulation was designed to be representative of industrial processes and thus provides a more stringent test of the scalability of the EID framework.

There have been several proof-of-concept attempts to scale up the EID framework within process control to work domains that are closer to industry-scale problems. This research is important because in the early work on DURESS II, many researchers justifiably questioned whether EID could be used to tackle problems that were much larger in scope and complexity.

Olsson and Lee (1994) developed a prototype EID interface for a chemical engineering process known as a single-stage forced circulation evaporator system. Van Paassen (1995) developed a prototype EID interface for an industry-scale simulation of a cement milling plant. Dinadis and Vicente (1996) developed a prototype interface for the feedwater subsystem of an industry-scale simulation of a conventional power plant. Jamieson and Vicente (2001) developed a prototype EID interface for an industry-scale simulation of a fluidized catalytic cracking unit. Burns (2000a, 2000b) developed three different EID interfaces for an industry-scale simulation of a conventional power plant consisting of 402 variables. Reising, Sanderson, Jones, Moray, and Rasmussen (1998) developed a subset of a prototype EID interface for the start-up of a commercial nuclear power plant. Yamaguchi and Tanabe (2000) developed a prototype EID interface for a full-scope simulator of a ship-based nuclear power plant with a rated core power of 36 MW. These proof-of-concept tests were all successful, showing that EID can be applied to large-scale problems that are closer to those found in the process control industries. All of these efforts also led to the identification of new information requirements, thereby analytically showing that EID has value added over current interfaces. However, with the exception of Burns's work (2000a, 2000b; to be discussed later), none of these efforts has been empirically evaluated.

These proof-of-concept tests were very useful in providing some insight into what it takes to implement EID on a large scale. The work of Dinadis and Vicente (1996) provides a representative example. They found that EID needs to be, and can be, supplemented by more specific interface design principles (e.g., Mumaw, Woods, & Eastman, 1992; Woods, 1984) if it is to be applied to industry-scale problems. This same point was made in almost all of the other proof-of-concept tests just reviewed.

One of the biggest problems in scaling up EID is that not all of the information will fit on one display or monitor. One inevitably runs into the problem of visual momentum (Woods, 1984) – how to parse the data set effectively into collections of variables that will be displayed together on a single display or monitor, and how to facilitate transitions across those screens or monitors. The three EID design principles described earlier do not address this issue, because Vicente and Rasmussen (1992, p. 591) deliberately excluded this aspect of the interface design problem from their theoretical scope.

Burns (2000a, 2000b) appears to be the only one to have investigated empirically how to improve the visual momentum of an EID interface. She compared three different ways of integrating information in a EID interface for a medium-scale industry simulation of a conventional power plant. All three displays were based on an abstraction hierarchy analysis but presented the same data in different ways. One display showed each level of the abstraction hierarchy at the same time but in a different window. Thus the screen was divided into four equal-sized windows, one for each level. A second display showed only one level of the abstraction hierarchy at a time. Thus the screen could be used to display one window at a time with serial access across windows. Finally, a third display overlaid the four levels of abstraction in parallel into a single integrated view. To the untrained eye, this last display looks extremely complex and cluttered and seems like an extreme example of the frequently discussed "data overload" problem. Indeed, the serial access, one-level-at-a-time display led to the fastest detection times. However, the messy-looking, highly integrated display surprisingly led to the fastest and most accurate fault diagnosis performance.

These findings reinforce those of Ham and Yoon (2001a) by pointing to the importance of spatially and temporally integrating the structural means-ends relations across adjacent levels of the abstraction hierarchy. It appears that performance with an EID interface will be enhanced to the extent to which the display integrates these critical relationships, rather than requiring workers to integrate them mentally.

Aviation. Two proof-of-concept tests of EID have been conducted in military aviation. There are many differences between process control and aviation (e.g., time available for action, reliance on procedures), so it was unclear whether or not EID could be applied or could make a unique contribution. Dinadis and Vicente (1999) developed a prototype EID interface for the fuel and engines of a Lockheed Hercules C-130 Model E-H aircraft. This interface is radically different from those currently available on the C-130 because it puts much more emphasis on presenting higher-level functional information identified by an abstraction hierarchy analysis.

Chéry et al. (1999) applied EID to the control display unit interface for radio communication of the CH-146 Griffon helicopter. They developed a prototype EID interface as well as a second prototype developed using another interface design approach, perceptual control theory (PCT; Powers, 1973). Both prototypes contained information not found on the existing control display unit interface for the Griffon. The EID and PCT prototypes were then compared analytically using representative scenarios in a cognitive walk-through methodology (Lewis & Warton, 1997). Both interfaces supported radio exchanges under normal conditions, although the PCT prototype provided more guidance because it was tailored to known tasks. Both interfaces also supported the detection of failures impeding successful radio communication. However, the EID prototype provided a better basis for fault diagnosis than did the PCT prototype, probably because the former was deliberately designed to support adaptation to novel events that are unanticipated.

These two examples show that EID can be applied to at least some industry-scale design problems in aviation and, by doing so, that new information requirements may be identified. Experiments are required to determine whether these new requirements improve performance.

Network management. Burns and her colleagues (Burns, Barsalou, Handler, Kuo, & Harrigan, 2000; Kuo, 2001; Kuo & Burns, 2000) initiated a research program applying EID to the domain of computer network management. Computer networks have a number of unique characteristics that posed a challenge for the EID framework (e.g., rapid technological change, extreme decentralization, the existence of "soft" components, the absence of mass and energy conservation laws as a goal-relevant constraint). Burns and her colleagues were the first to show that it was possible to overcome these challenges. For example, in place of mass and energy conservation laws, information (i.e., entropy) conservation was identified as a goal-relevant constraint in an abstraction hierarchy analysis for this new domain. Kuo (2001) built a prototype EID interface for network management that contains information requirements that are not currently found in existing interfaces. Experiments have yet to be conducted.

Software engineering. Leveson (2000), a pioneer in the area of software for safety-critical systems, adapted part of the EID framework to important problems facing the software engineering industry. Software development and evolution is notoriously difficult and time consuming. According to Leveson, one reason for this is that the specifications that people have to work with are not tailored to support human problem solving. Once again, the application of EID to a new domain poses a unique set of challenges. Software engineering has a set of characteristics (e.g., the existence of "soft" components, the absence of useful mass and energy balance relations) that are quite different from that of process control. Thus it is important to demonstrate that EID is robust enough to accommodate these differences.

Leveson (2000) used part of EID to create an approach, referred to as *intent specifications,* that satisfies these unique needs. Intent specifications are based on an abstraction hierarchy representation that tries to support the problem-solving activities of software engineers. The specification provides an audit trail that can be used to perform key software engineering tasks (e.g., program understanding, information search, design criteria and evaluation, minimize effects of changing requirements, design of run-time assertions, safety ensurance, software maintenance and evolution). Leveson conducted an ambitious proof-of-concept test of the approach by applying it to an industry-scale problem of considerable magnitude, namely the software specification for the Traffic Alert and Collision Avoidance System II part of the U.S. air traffic control system. The resulting intent specification document was more than 800 pages long. As with the cases described earlier, new information requirements were identified: "We found while constructing the TCAS intent specification that having to provide these [means-ends] links identified goals and constraints that did not seem to be documented anywhere but were implied by the design and some of the design documentation" (Leveson, 2000, p. 30). Experimental evaluations of intent specifications have yet to be conducted.

Medicine. The work of Sharp and Helmicki (1998) on neonatal ICU, described earlier, initially encountered several obstacles in applying EID to medicine. First, Sharp and Helmicki found that the labels that had been developed for the various levels of the abstraction hierarchy in process control were not meaningful for medicine. They overcame this obstacle by redefining the levels to capture medical constraints while remaining faithful to the structural means-ends relations across levels. Second, Sharp and Helmicki found that neonatal ICU is a highly distributed work domain for which the available models are not as detailed or as robust as the well-known physical laws that govern many process control plants. This obstacle was overcome by limiting the abstraction hierarchy analysis to the coarse level made possible by the biomedical models found in medical textbooks.

Finally, Sharp and Helmicki (1998) also found that the number of sensors available in neonatal ICU is determined a priori and is highly limited (many relevant variables cannot be sensed). Vicente and Rasmussen (1992) had identified this as a potential problem with EID and suggested a potential remedy: "In some systems, there may be certain variables (particularly higher order functional information) that cannot be measured with existing sensors. In some cases, however, it may be possible to overcome this limitation by the use of analytical techniques" (p. 600). Accordingly, Sharp and Helmicki dealt with this obstacle by classifying variables identified by the abstraction hierarchy analysis into four categories: (a) those that can be sensed directly, (b) those that can be derived analytically from sensed variables, (c) those that can be derived heuristically from sensed variables, and (d) those that cannot be sensed or derived. Hajdukiewicz, Vicente, Doyle, Milgram, & Burns (2001) encountered a similar set of obstacles in developing an abstraction hierarchy of the human body for anesthesiology in the operating room, and they were able to deal with them successfully in the same way as Sharp and Helmicki. As mentioned earlier, Sharp and Helmicki's experimental results showed that EID adds value for less-experienced practitioners in neonatal ICU compared with the industry state of the art.

Command and control. Rasmussen, Pejtersen, and Goodstein (1994) made a distinction between work domains that are governed primarily by physical laws and those governed primarily by human intentions. Most EID research has been conducted on physical work domains. Some have argued that EID cannot be applied to intentional systems (Wong, Sallis, & O'Hare, 1998), so it was important to test this hypothesis. Military command and control is an application domain that has both physical and intentional aspects, so it provides a suitable context for investigation.

Burns, Bryant, and Chalmers (2000) conducted a feasibility study for the Canadian HALIFAX class naval frigate. They pointed out that "there were several aspects of naval command and control that differ from nuclear power plant control that could make the application of this framework challenging, and indeed, could require that the framework itself develop further in order to meet this new domain" (p. 2229). Some of the challenging characteristics were the difficulty in defining a precise boundary for the work domain; the lack of clear purpose caused by many mission types; scaling up to a very large scale; and the fact that part of the environment (i.e., the enemy) has a dynamically shifting intent.

Burns, Bryant, et al. (2000) were able to overcome these obstacles in developing an abstraction hierarchy representation for the HALIFAX. Their most innovative contribution was to divide the work domain representation into three subsets: (a) the constraints associated with the frigate, (b) the constraints associated with enemy contacts, and (c) the constraints associated with the physical environment (e.g., seaways). Burns, Bryant, et al. (2000) compared the information identified by their work domain analysis with the information now being displayed in the existing decision support system for the HALIFAX. They found that the information requirements identified by the abstraction hierarchy analysis included many variables that were not currently displayed with the existing design, thereby analytically showing the added contribution of the EID framework compared with current industry design practices. No interface prototype was built or tested.

Roth, Gualtieri, Easter, Potter, and Elm (2000) applied EID as part of their work on the Defense Advanced Research Projects Agency's Command Post of the Future program. They developed an innovative prototype display for military command and control and found that it, too, provided new information requirements, although no experimental test was conducted.

Information retrieval. Document information retrieval is an application domain that has an even stronger intentional component than does military command and control. There are no physical equipment, conservation laws, or mathematical equations to describe the work domain constraints. In this sense, this domain provides a stronger test of the breadth of the EID framework. As Vicente and Rasmussen (1992) noted, however, these differences need not be an insurmountable obstacle for EID: "The primary prerequisite for applying the framework is that the designer have a description of the goal-relevant constraints governing the work domain. In principle, it is irrelevant what those constraints are, as long as they can be described in some way so that they can then be mapped onto perceptual features of the display" (p. 600).

The work of Xu et al. (1999), reviewed earlier, supported this claim. It showed that EID can be applied to information retrieval, that doing so can identify new information requirements, and that this new information can improve performance on more complex tasks.

The applicability of EID to information retrieval is also shown by Pejtersen's (1992) work on information systems for retrieving fiction books in a public library. The Book House, an innovative full-scope document retrieval system that was made available as a commercially available product and introduced in several public libraries in Scandinavia, is consistent with the principles of EID. Although fiction retrieval is not a physical application domain, Pejtersen was able to identify qualitative constraints that could be captured by an abstraction hierarchy analysis and mapped onto salient perceptual features of the interface form. The Book House was evaluated in public libraries in Denmark with representative users. Subjective ratings indicated that the new design was preferred to traditional means of retrieving fiction.

Critical analysis. EID can be applied to industry-scale design problems, but it needs to be complemented by more specific design principles. Visual momentum is particularly important. The available data suggest that performance can be improved by integrating structural means-ends relationships spatially and temporally, but this issue needs more research attention.

Proof-of-concept tests have shown that EID can be applied to a diverse set of application domains, spanning both physical systems (e.g., nuclear power plants) and intentional systems (e.g., hypertext information retrieval). In every case, analytical evaluations showed that EID uncovered novel information requirements that were not captured by existing designs. In every case tested so far, empirical evaluations have shown that EID can improve performance in a diverse range of application domains (e.g., pasteurization, thermohydraulics, nuclear power cooling, neonatal ICU, hypertext information retrieval). However, empirical tests of EID have yet to be conducted in several application domains (e.g., aviation, network management, software engineering, military command and control). Future research should be targeted at this empirical gap in the literature.

Has EID Led to Technology Transfer to Industry?

Honeywell Technology Center and AECL Research incorporated portions of the P+F interface for DURESS II into demonstration prototypes that represented the state of the art in advanced interface design. In Japan, Toshiba adopted EID as the basis for designing its advanced control room for a next-generation boiling water reactor plant (Itoh, Sakuma, & Monta, 1995). It also incorporated and adapted specific features of the P+F interface for DURESS II (e.g., the mass balance graphics) into some of the displays. This application is notable because it was implemented at a very ambitious scale (i.e., a full-scope nuclear power plant simulator), thereby showing that EID can be applied to at least some industry-scale design problems.

Critical analysis. The transfer of EID technology to industry achieved so far is encouraging. However, no industry-scale implementation of EID has been rigorously evaluated empirically using professional workers, although several such efforts are being planned (e.g., Yamaguchi & Tanabe, 2000). This is an important obstacle to industry acceptance because few companies are willing to adopt a new design approach without first testing it at a realistic scale of implementation.

CHALLENGES: UNADDRESSED ISSUES

Several other issues that stand in the way of the confident use of EID in industry have yet to be investigated. Until these challenges are overcome, cognitive engineers cannot claim to know how to implement the EID framework effectively in operational settings.

Time and Effort to Conduct the Analysis

Considerable time and effort are required to conduct an abstraction hierarchy analysis of a work domain. If companies do not believe that these costs are outweighed by tangible benefits, then they will not adopt EID as a basis for systems design.

Several paths should be pursued to overcome this obstacle. First, software tools could be developed to reduce the amount of time and effort associated with analysis (Sanderson, Eggleston, Skilton, & Cameron, 1999). Second, domain-specific templates may be developed and reused to reduce the analysis effort (Vicente, 1999). Third, libraries of various objects that are used frequently in a particular application domain (e.g., routers for network management, valves for process control) may also be developed and reused to reduce the analysis effort further. Finally, quantitative data on the benefits of EID for industry-scale problems should be collected, whether it be in terms of safety, productivity, or worker health.

Choice of Form

Another obstacle to the implementation of EID is that the choice of visual form remains largely an art rather than a science (Reising & Sanderson, 1998). A great deal of creativity is involved in going from an abstraction hierarchy model of the work domain to a particular interface form. Some guidance can be obtained from perceptual organization principles (e.g., Mumaw et al., 1992), but there are still many remaining degrees of freedom. Engineering design of any type will always be a creative effort, but designers will be more ready to adopt EID if this ingenuity gap is reduced. Zhang (1996), Hansen (1995), Reising and Sanderson (1998), and Pedersen and Lind (1999) have all started to address this issue.

Note that the principles of EID do not refer to a specific perceptual channel. Nevertheless, almost all of the work conducted to date has been focused solely on the visual modality. Given the multimodal character of natural human interaction with the environment (Gibson, 1966; Stoffregen & Bardy, 2001), it seems that a great deal of benefit could be obtained by expanding the implementations of EID to other modalities. The auditory channel is an obvious choice in several respects. First, it can serve an orienting function that complements the information obtained from the visual channel. Second, relatively low-cost hardware and software are now available to develop auditory interfaces. Watson, Russell, and Sanderson (2000) developed the first auditory implementation of the EID framework. No experimental results have been obtained yet, but anecdotal evidence suggests that the approach is promising.

Sensor Noise and Failure

From the viewpoint of industry, one of the most worrisome concerns in adopting EID is the potentially negative impact of sensor noise and failure on worker performance (Watanabe, 2001). This obstacle was identified by Vicente and Rasmussen (1992): “data from sensors are inherently noisy and therefore uncertain…. Empirical research is needed to determine how robust performance with an interface based on an abstraction hierarchy is with respect to these sources of uncertainty” (p. 600). Reising and Sanderson’s (2000a, 2000b) results suggest that EID is not especially susceptible to sensor noise, given that the EID-max interface led to better fault management performance, despite the presence of imperfect and uncertain information. However, no experiment conducted to date has investigated the impact of the presence or magnitude of sensor noise and variability on performance with an EID interface.

It could be argued that an EID interface should be robust because of the redundant constraints identified by the abstraction hierarchy analysis. It could also be argued, however, that if attempts are made to make constraints easy to perceive, workers might confuse the displayed state of the work domain with its true state. Because of sensor noise and failure, these two states can diverge significantly in operational settings. If this latter argument is correct, then EID could actually lead to worse performance in practice. Thus this issue is a high-priority research item.

Integrated Systems Design

Any interface will not realize its full potential unless it is implemented as part of an integrated approach to systems design. The interface, decision support, automation, training, selection, alarms, procedures, and team collaboration all need to be designed in a coordinated manner using a common philosophy. There has been some empirical work on how to leverage EID (as described earlier), but for the most part this issue has not received much attention. Because the philosophy behind EID (i.e., designing for worker adaptation) is qualitatively different from that of traditional approaches to systems design, an EID interface cannot be expected to have its full impact unless corresponding changes are made to other system design elements.

Some theoretical work can be used to move in this direction. In terms of analysis, the cognitive work analysis framework provides an integrated basis for expanding the scope of EID beyond the work domain constraints alone (Rasmussen et al., 1994; Vicente, 1999). In terms of design, Goodstein (1985) described a functional approach to the design of alarm systems that is based on the abstraction hierarchy and, thus, is highly compatible with the philosophy of EID. This approach appears to have influenced the Westinghouse AWARE alarm system (Woods, Elm, & Easter, 1986). Also, Reising et al. (1998) and Vicente (1999) have outlined an approach to procedure design that is geared toward supporting worker adaptation. However, none of these design efforts has been investigated empirically.

There is also some innovative experimental work that can be used to transform EID into a broader integrated approach to systems design. Guerlain et al. (1999) developed and tested an approach to the design of decision support systems that is compatible with EID. Furukawa and Inagaki (in press) developed and tested an approach based on EID to make automation more transparent. Roth et al. (1998) developed and tested an approach based on EID to design computer-supported cooperative work. The results of all three empirical studies showed a performance improvement compared with more traditional design approaches. These new design ideas can help expand the scope of EID.

Critical Analysis

The obstacles discussed in this section show that despite the progress demonstrated to date, EID is an immature technology from the perspective of industrial implementation. Many important issues have yet to be addressed, let alone solved. Some of these issues, such as sensor failure, may turn out to be "show stoppers." Without more research, the adoption of EID for operational settings cannot be recommended.

Eventually, the EID framework as currently defined should fade in importance because the primary goal will increasingly be to develop an integrated approach to sociotechnical system design, not just a better human-computer interface (see Rasmussen et al., 1994; Vicente, 1999).

CONCLUSIONS

The ability to effectively perform knowledge work is a core requirement in complex sociotechnical systems. If cognitive engineers are to have a positive impact, then they must design systems that help workers perform intellectual work requiring discretionary decision making. This is equivalent to helping workers adapt to novelty and change (e.g., unanticipated events that fall outside of the scope of predefined procedures and automation). This design challenge is exceedingly complex and will not be satisfied in an ad hoc or piecemeal manner. A systematic and integrated approach to systems design is essential.

The EID framework was deliberately developed to meet this challenge, initially in process control (Vicente & Rasmussen, 1992). The progress made to date suggests that the approach is a promising one and can be applied to a diverse set of application domains. Some technology transfer to industry has been achieved. Although these are encouraging signs, the literature on EID has important limitations, and some critical obstacles have not even begun to be addressed. If EID is to be part of a principled basis for integrated systems design for complex sociotechnical systems, then these limitations need to be overcome and those obstacles circumvented. In the meantime, the evidence suggests that the EID framework continues to generate scientific knowledge, increasing understanding of the relationship among workers, technology, and environments.

In the end, this scientific progress is what matters most. Increasing understanding in new and useful ways is more important than being right or getting the final word. To continue to move forward, cognitive engineers should keep their eyes fixed on the practical problems to be solved rather than on the existing conceptual means for solving them.

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