To appear in Proceedings of the 47th Annual Meeting of the Human Factors and Ergonomics Society. Denver, Colorado: October 13-17, 2003.

BRIDGING THE GAP BETWEEN COGNITIVE WORK ANALYSIS AND ECOLOGICAL INTERFACE DESIGN

Greg A. Jamieson
Cognitive Engineering Laboratory
University of Toronto
Toronto, Ontario, Canada

The Cognitive Work Analysis and Ecological Interface Design frameworks have garnered a great deal of attention in recent years. The former is used to analyze a complex work domain to identify the behavior-shaping constraints imposed by the work domain, control tasks, strategies, operator competencies, and socio-organizational factors. The latter informs the design of operator interfaces for complex systems. Although the two frameworks overlap, a gap remains between the analysis and design stages. This article shows one path across that gap. Aspects of both frameworks were applied to the design of an ecological interface for a petrochemical process. We discuss how the project was completed under realistic time and budget constraints, review several unanticipated obstacles that we encountered, and relate design examples to help overcome the gap between analysis and design.

INTRODUCTION

One of the challenges to acquiring design skills is that the design process cannot be described according to a set of rules that guarantees success if dutifully followed. This holds for cognitive engineers attempting to design information artifacts. Interface design in particular can be generically described as having two stages: 1) the specification of information content and structure requirements, and 2) the subsequent semantic mapping of those requirements onto visual forms. One approach to the design of cognitive artifacts uses Cognitive Work Analysis (CWA; Vicente, 1999) to inform the first of these stages and the Ecological Interface Design framework (EID; Vicente & Rasmussen, 1992) to guide the second.

In recent years, some attention has been focused on making work analysis methods more concrete. In contrast, generically applicable semantic mapping techniques appear to be a long way off. In the mean time, practitioners and researchers have present design challenges to overcome. Thus, there is value in showing successful paths through the semantic mapping stage in the hopes that they might prompt useful generalizations (see Reising and Sanderson, 2002). It is in this spirit that we review several critical aspects of an example design activity, including the resource constraints under which the project was completed, design tactics that were employed, and challenges that were encountered.

PROJECT OVERVIEW

Project Goal

We set out to design an ecological interface for an existing petrochemical process (see Jamieson, 2002a). Our sponsors wanted to know whether the performance advantages observed for non-experts using ecological interfaces in the laboratory (see Vicente, 2002) would obtain for professional operators working on actual systems. As a complement to this applied design goal, we had a theoretical problem to explore as well: How to integrate system- and task-based approaches to interface content specification in the design of a graphical interface (see Jamieson, 2002a for detail). This article focuses on the design activity.

Resource Constraints

Our project was constrained in several ways, some of them indicative of academic research and others more characteristic of an industry setting. For the design activity itself, our constraint was time. The project had already suffered a year of delay when we set out to make sense of an abstraction decomposition space (ADS) and hierarchical task analysis (HTA) completed by Miller and Vicente (1998, 1999, respectively). The sponsors were concerned that organizational support for the project would wane without clear progress being made on the design and evaluation stages. This time pressure was further compounded by an unanticipated difficulty in making use of those previously-completed analyses (see Challenges below). Thus, the designers were under constant time pressure to produce results.

Once the iterative design of the interface was completed (see Jamieson, Ho, & Reising, in press, for detail), budget constraints played a more significant role. With a limited budget and the need to hire a professional software contractor to implement the displays, only afford a partial implementation of our design concepts was possible. We therefore had to prioritize our design interventions and establish a cutoff point for what would be implemented.

In addition, there were limitations to the in-kind contributions that the industry partner could make in supporting the installation and validation of the interfaces. Plant personnel were needed to connect the novel interface to the simulator and configure the software that would record experimental data. Finally, access to the simulator and availability of the operators to complete the empirical analysis were both very limited. At any given stage in the work, any one of these limitations (i.e., in-kind contribution, simulator availability, or operator availability) could be the most limiting constraint.

The project was therefore constrained along several dimensions, making it a fairly realistic application of CWA and EID to the design of an operator interface for a complex system. At every stage of the project, we would have liked to have had more time to check our work, improve our analyses or designs, and receive feedback from our collaborators.

To appear in Proceedings of the 47th Annual Meeting of the Human Factors and Ergonomics Society. Denver, Colorado: October 13-17, 2003.

Despite these constraints, however, the design effort was both productive and successful, as noted in the Evaluation section.

Challenges Leading to a Change in Approach:

Throughout the project, several unanticipated problems arose that required changes in our project plan. Two of these are described here. First, despite having prior experience with constructing an ADS and building an ecological interface for a petrochemical process (Jamieson & Vicente, 2001), we found it very difficult to familiarize ourselves with the domain given the ADS analysis completed by Miller and Vicente (1998). When we examined the analysis, the nodes and links made sense; however, we were unable to reconstruct a comprehensive understanding of how the process worked. It was necessary to return to both the source material and to domain experts to reconstruct the knowledge that had been acquired by the original analysts. We realized that much of the benefit to the ADS lies in performing the analysis.

We faced a second unexpected challenge in employing the results of the task analysis. We discovered that the HTA did not address the behavior of the automated controllers used in the process. This is because the primary knowledge source for the HTA was the operating procedures and the procedures assume that the behavior of the controller is a) known to the operator, and b) reliable. The AH had not captured the activity of these controllers either because CWA assigns control constraints to the task domain. The effect of this combination of analyses was that the role of the automation had not been analyzed. This was clearly a problem as these controllers are an important part of the operations activity. Thus, we added a control task analysis (CTA) to identify content requirements pertaining to the automation (see Jamieson, in press).

DESIGN EXAMPLES

The challenge to interface design lies in mapping the information requirements identified by the work analysis onto graphical forms. In this section, we offer two perspectives (one product, one process) on this problem. First, we present a detailed example of how one set of information requirements is instantiated in a graphical product. Second, we discuss several tactics for the process of crossing the gap from infomation requirements to graphical forms.

Information Requirements in Graphical Forms

In this section, the graphical elements that are comprised of information requirements for a critical sub-process of the target plant are examined in detail to exemplify how the requirements were parsed into graphics.

H2 flow control information requirements. In Table 1, the information requirements that relate to the control of hydrogen flow into a chemical reactor are consolidated from the three work analyses. Jamieson (in press) describes in detail the challenge of integrating the information requirements obtained from the ADS, HTA, and CTA. Here, we restrict ourselves to a discussion of the connection to the graphical form.

The set of requirements in Table 1 defines the information that the graphical elements must communicate. The left-most column of the table contains a number to facilitate the description of how these requirements were mapped onto a graphical form.

# on Figure 1	Information requirement to be shown	ADS	HTA	CTA
1.	FV413 (appearance and location)	●●	●●	●●
2.	FV413 setting	●●	●●	●●
3.	The effect of FV413 setting on flow through the valve	●●	●●	●●
4.	The flow of CO into the reactor	●●	●●	●
5.	The flow of H2 into the reactor	●●	●●	●
6.	The flow of C2H2 into the reactor	●●	●●	●
7.	The flow of C2H4 into the reactor	●●	●●	●
8.	The flow of C2H6 into the reactor	●●	●●	●
9.	The effect of the setting of SDV413a on the flow of H2 to the C2 stream	●●	●	●●
10.	The effect of the state of PV441 on flow of H2/CO through TV440 (to the C2 stream)	●●		●
11.	The effect of the setting of TV440 on flow of H2/CO through CV6 and (to the C2 stream)	●●	●●	●●
12.	H2/CO Heat and Supply Input	●●	●	●
13.	C2 Heat and Supply Input	●●	●	●
14.	H2/C2 weight ratio SP		●●	●●
15.	H2/C2 weight ratio PV		●●	●●
16.	H2/C2 weight ratio error (SP -PV)			●●
17.	H2/C2 weight ratio OP (to FC413 SP)			●●
18.	FC413.SP		●	●●
19.	FC413.OP		●	●●
20.	Error (FC413.SP -FC413.OP)		●	●●
21.	ZSC-413 A status			●●
22.	TIC440.OP	●	●	●●
23.	Low flow limit on FC411.PV of 40 Mg/hr	●	●●	●

Table 1: Information Requirements for the ratio controller and surrounding process.

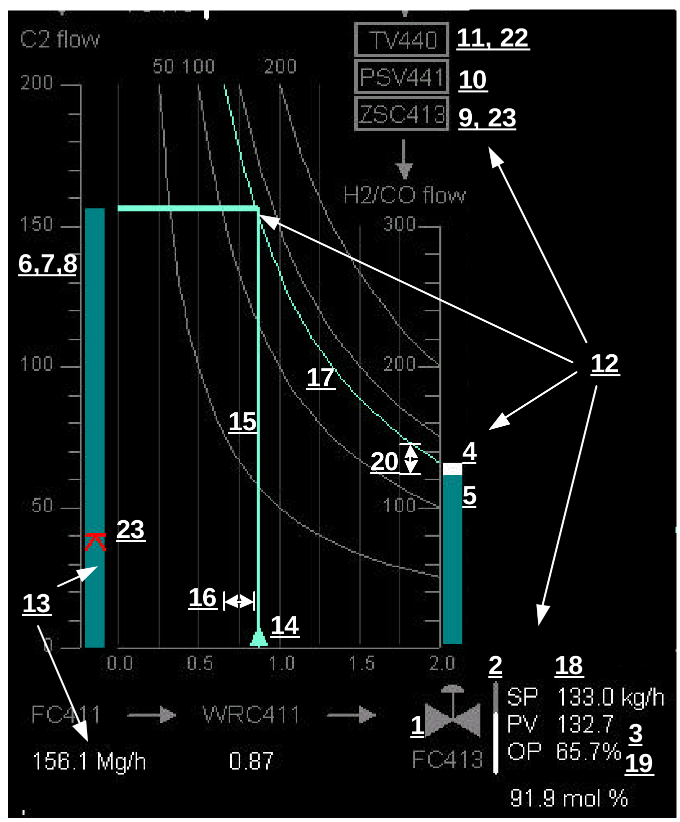

Figure 1: The ratio controller graphic. Numbers correspond to information requirements in Table 1.

Ratio controller graphic. An annotated description of the appearance and behavior of the graphic (Figure 1) exemplifies how the requirements were instantiated. The ratio controller graphic allows the operator to monitor the control of the incoming hydrogen (H2) and carbon monoxide (CO) stream. Two flow-rate graphics are used to display the flow-rate of the feed (C2) stream [13] and the H2/CO stream [4, 5]. Each graphic has a gray fixed scale, ranging from 0 to 200 in Mg/hr for the C2 flow (tag name FC411) and 0 to 300 in kg/hr for the H2/CO flow (tag name FC413). Above each of the scales, the type of flow is denoted. A minimum limit for the FC411 process variable is set at 40 Mg/hr [23]. The limit is indicated by red limit arrow formed by a chevron below a horizontal line segment.

For the C2 flow, a cyan bar indicates the flow rate [13]. A divided cyan [5] and white [4] bar is used to describe the flow rate of the H2/CO stream. The cyan portion of the bar represents the amount of H2; the white portion represents the amount of CO and impurities.

The behavior of the ratio controller is represented by a graphic that lies between the two flow rate bars [15, 17]. The baseline of the graphic reflects the value of the weight ratio controller (i.e., the automation) setpoint. It is drawn in a medium gray and has a range of 0.0 to 2.0. Darker vertical gray lines extend from the baseline at 0.25 unit increments, extending to a point equal to the maximu m values of the C2 flow scale. Four curved constant value lines are drawn in medium gray on the plot at values of 50, 100, 150, and 200 kg/hr. At every point along each of the lines, the product of the value along the baseline and the value along the C2 flow scale is a constant. The lines are static. A fifth constant value line is drawn in green [17]. The value of this line is determined by the current value of FC413 process variable [4,5]. A small green triangle [14] rests on the baseline at the present value of the setpoint of the weight ratio controller. A green line [15] extends vertically from the horizontal axis at the present value of the controller, up to the present constant value line. The difference between the position of this vertical green line and the green triangle is the error signal [16]. A second green line is drawn horizontally from the top of the C2 flowrate column across to the current constant value line. The two lines meet at the current constant value line defined by FC413process variable [17].

Implication. The point of providing this detailed description is to demonstrate that the information content requirements identified by the three work analyses are indeed contained in the interface graphics. Thus, there is a direct correspondence between analysis and design. However, this product description does little to aid in the process of establishing the semantic mapping. Some tactics for completing this process are discussed below.

Design Tactics

Finding the inspiration to create the integrated graphical displays that characterize EID is not easy. Reising and Sanderson (2002) summarized sources of design inspiration into three categories: Borrow, Adapt, and Invent. In this section, examples illustrate each of those techniques in our design.

Borrow. Early in the design effort, it is often useful to look for an opportunity to Borrow from previous designs. It is often relatively easy apply a graphical tool with which the designer is familiar. Examples include the polar star (Wolff, 1967) or annotated trend charts. As designers, we trust these tools because we believe that we know their strengths and weaknesses. It is therefore important to be current and familiar with the work of other designers. The mass and energy display (Figure 2) that we designed for the present project is borrowed from Burns's ecological interface for a simulated power generation system (Burns, 2000). This simple display shows pairs of mass and energy flows at critical points in the process.

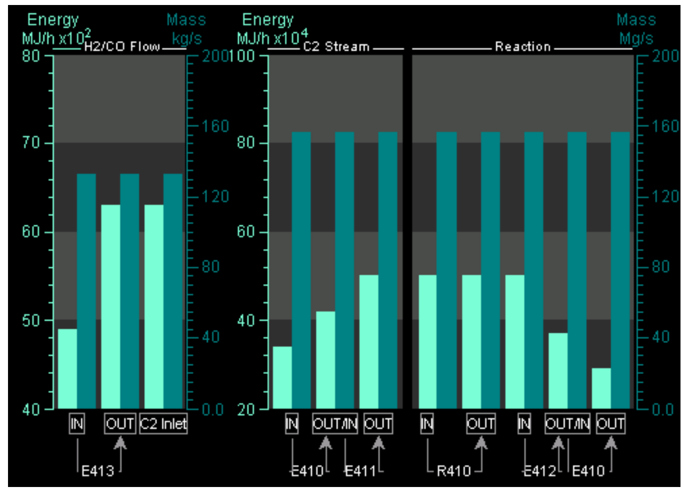

Figure 2: The mass and energy display (adapted from Burns, 2000).

Adapt. Compelling design often comes from Adapting concepts that are inherent to the domain. One example of this practice is the temperature profile view that we developed for the chemical reactor in our target system. During the data collection phase for the ADS and HTA analyses, several operators and engineers drew the same diagram to explain how temperatures should be spatially distributed through the reactor (see left side of Figure 3). They were describing the two sets of constraints that needed to hold for the reactor to perform properly. 1) The horizontal temperature distributions at each of six levels should be consistent. 2) The temperatures in the vertical dimension of the reactor should gradually increase and then stay constant. Some deviations from these temperature distribution patterns were known to indicate process upsets that required operator action. We recognized that these characteristics formed the basis for a display (right side of Figure 3). The inspiration was provided by the domain experts; the rest was merely execution.

There is incredible richness in complex work domains to be exploited, and it is orders of magnitude easier to Adapt existing ideas than it is to Invent new ones. As with Borrowing, to be an effective adapter, a designer has to know what other people have done. However, a designer must also be able to extract the essence of a form and manipulate it to meet the designer's needs. Many of the design ideas behind the MPC Elucidator (Guerlain, Jamieson, Bullemer, and Blair, 2002) are adaptations of forms appearing in Tufte's books (1983, 1990, 1997).

To appear in Proceedings of the 47th Annual Meeting of the Human Factors and Ergonomics Society. Denver, Colorado: October 13-17, 2003.

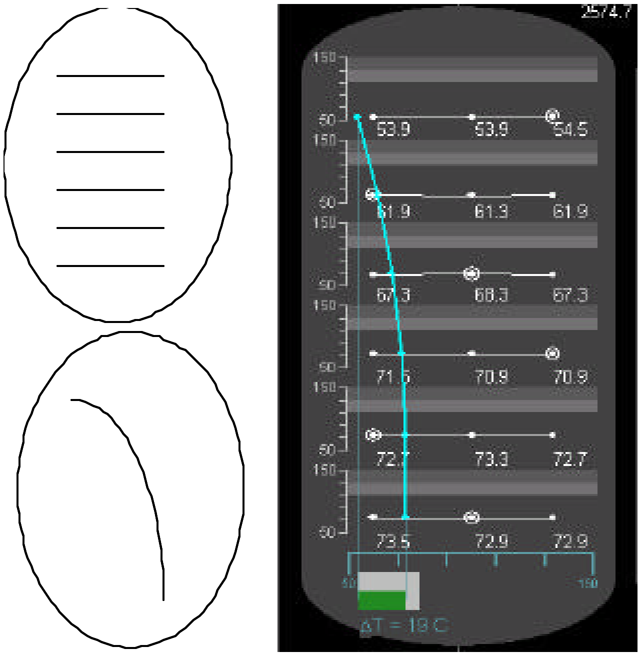

Figure 3: At left, a conceptual view of temperature distributions; at right, the resultant display.

Invent. Inventing novel graphical displays is difficult and time consuming and should be used as a last resort. It is also prone to error. For example, we spent scores of hours on the design of a display to represent the steady state first law of thermodynamics for heat exchange (see Figure 4). However, we (designers and domain experts included) focused too much on the graphical constraints and not enough on the physical ones. We were seeking to convey a multiplicative relationship between three terms (i.e., a=xyz), but actually created a display that showed one term summed with the product of the other two (i.e., a=x+yz). The design passed review by over 25 domain experts.

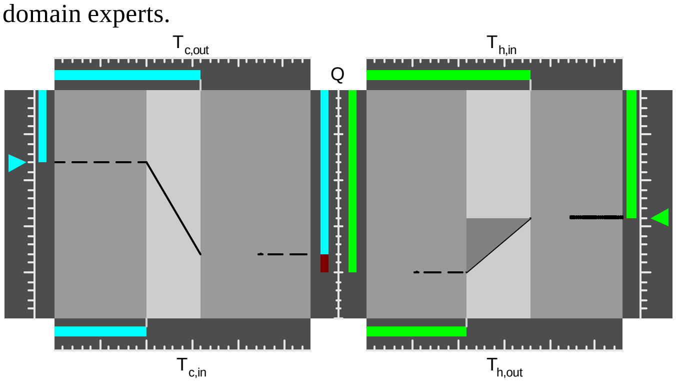

Figure 4: An erroneous design for the steady state, first law of thermodynamics for heat exchange.

Invent. Sometimes, however, invention is a must. When that's the case, several tactics can prove useful. First, scanning through library books on the topic of interest (in this case, heat exchange) can be a source of inspiration. These sometimes contain graphical descriptions of the concept that must be conveyed. The design of a graphic for flow control valves (see Figure 5) combines a valve characteristic curve (i.e., a manufacturer's specification of how valve position relates to percentage of flow) with measured and commanded values. The combination is based on the equation relating flow to valve characteristics, position, and pressure differential.

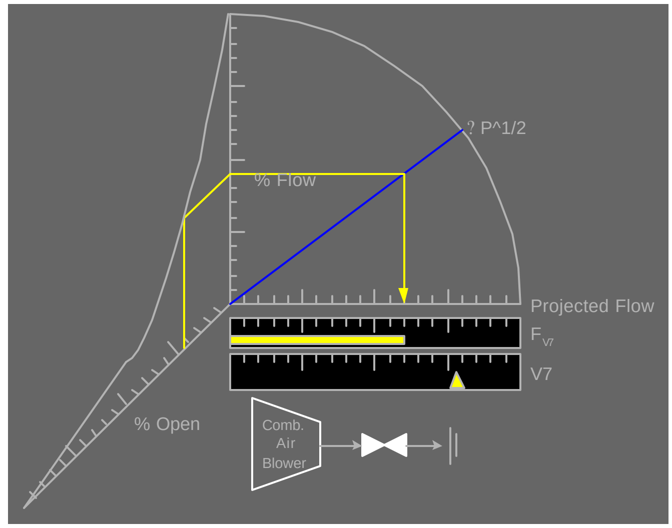

Figure 5: A representation of the relationship between valve position, valve characteristic, pressure, and flow rate. A measured flow allows for analytical redundancy.

A second tactic is to talk to the person to whom the operators go when they need something explained. These reflective experts sometimes provide explanations that plant seeds for design concepts. We sometimes returned to the same few operators for repeated descriptions of how they viewed a specific process. These conversations lead to several graphical concepts that advanced our designs.

If all else fails and we needed to generate design ideas from scratch, we started asking ourselves the following questions: How did I come to understand how this works? How can I explain it to someone else? What type of relations do I have to convey and what graphics have similar dimensionality? It can also be useful to ask why certain ideas *won't* work and what that says about the solution.

EVALUATION

We evaluated the complete interface developed for this project in a full-scope industry simulator with 30 professional operators as participants (Jamieson, 2002b). Participants using the ecological interfaces demonstrated faster trial completion times, more accurate fault diagnoses, and more effective control responses than those using the contemporary displays. The results obtained mimic those summarized by Vicente (2002) for laboratory evaluations of EID.

LESSONS LEARNED

Several of the preceding comments suggest lessons from which other designers may benefit. First, to the extent possible, the same team should be tasked with both the information requirements generation and design stages. In all previous applications of EID (with which we are familiar), the designers of the visual form have been the analysts. This was not the case with this design effort and it was costly. Using the same people for both stages reduces the time invested in learning the meaning of the analysis results and thus reduces the project costs.

Second, there is further advantage to be gained from having domain experts act as the analysts and designers. Such individuals will clearly benefit from their prior expertise with the target process. Of course, this approach would require that the analysts be familiar with the analysis and design techniques. There are, however, at least two potential disadvantages to this approach. First, persons who are highly familiar with current process operations may fail to exploit the strengths of the analyses. CWA and CTA are extremely meticulous (if properly executed). Persons highly familiar with operations for the target domain would almost certainly be drawn into contrasting the process of the analyses with current practice. This could easily lead to focusing on the process as it is practiced, as opposed to a high level examination of how the unit was designed and what the functions and operations afford in terms of process behavior. A second disadvantage is that very few people are skilled domain experts, skilled analysts, and skilled designers.

Finally, designers should consider the difficulties that domain experts may have in relating their knowledge to an unfamiliar graphical representation. If the design team is relying on these workers to catch errors in the representational forms, then great care should be taken in not leading the workers down a garden path. Our failure to elicit a more critical evaluation of the heat exchanger graphic lead to wasted design and prototyping effort.

CONCLUSION

Cognitive engineering practitioners have repeatedly asked researchers for more detailed guidance in applying analysis and design frameworks. It can be frustrating for people on both sides that this practice is so difficult to distill. In this article, we have stepped away from the effort to provide concrete, replicable design instructions and instead offered an account of a prototypical design effort. In effect, rather than attempt the leap from design art to design science, we have treated interface design as a craft that can be passed from those with prior experience to those with a desire to learn and a willingness to practice. The challenge of establishing repeatable design methods remains.

ACKNOWLEDGEMENTS

This work was sponsored by NOVA Chemicals, Ltd. and the Natural Science and Engineering Research Council of Canada. Operators and engineers from the NOVA Joffre, Alberta site contributed their immeasurable expertise. The 'we' used in this article is not a colloquialism. Wayne Ho, Chris Miller, Dal Vernon Reising, and Kim Vicente all contributed to one or more of the insights noted here.

REFERENCES

Burns, C. M. (2000). Putting it all together: Improving Display Integration in Ecological Displays. Human Factors, 42, 226-241.

Guerlain, S., Jamieson, G.A., Bullemer, P., Blair, R. (2002). MPC Elucidator: A case study in the design for human-automation interaction. IEEE Transactions on Systems Man and Cybernetics: Part A, 32, 25-40.

Jamieson, G.A. (2002a). Ecological interface design for petrochemical process control: Integrating task- and system-based approaches (CEL-02-01). Cognitive Engineering Lab: University of Toronto.

Jamieson, G. A. (2002b). Empirical Evaluation of an Industrial Application of Ecological Interface Design. In Proceedings of the 46th Annual Meeting of the Human Factors and Ergonomics Society (pp. 536-540). Santa Monica, CA: Human Factors and Ergonomics Society.

Jamieson, G. A. (in press). Information requirements in ecological interface design. To appear in Proceeding of the XVth Triennial Congress of the International Ergonomics Association.

Jamieson, G. A., Ho, W. H., & Reising (in press). Ecological interface design in practice: A design for petrochemical processing operations. To appear in Proceedings of the 10th International Conference of Human-Computer Interaction.

Jamieson, G. A., & Vicente, K. J. (2001). Ecological interface design for petrochemical applications: supporting operator adaptation, continuous learning, and distributed, collaborative work. Computers and Chemical Engineering, 25, 1055-1074.

Miller, C. A., & Vicente, K. J. (1998). Abstraction decomposition space analysis for NOVA's E1 acetylene hydrogenation reactor (CEL-98-09). Cognitive Engineering Lab: University of Toronto.

Miller, C. A., & Vicente, K. J. (1999). Comparative Analysis of display requirements generated via task-based and work domain-based analyses in a real world domain: NOVA's acetylene hydrogenation reactor (CEL-99-04). Cognitive Engineering Lab: University of Toronto.

Reising, D.V.C., & Sanderson, P. M. (2002). Ecological Interface Design for Pasteurizer II: A Process Description of Semantic Mapping. Human Factors, 44, 222-247.

Tufte, E.R. (1983). The visual display of quantitative information. Cheshire, CT: Graphics Press.

Tufte, E.R. (1990). Envisioning information. Cheshire, CT: Graphics Press.

Tufte, E.R. (1997). Visual explanations. Cheshire, CT: Graphics Press.

Vicente, K. J. (1999). Cognitive work analysis: Toward safe, productive, and healthy computer based work. Mahwah, NJ: Erlbaum.

Vicente, K.J. (2002). Ecological interface design: Progress and challenges. Human Factors, 44, 62-78.

Vicente, K. J., & Rasmussen, J. (1992). Ecological interface design: Theoretical foundations. IEEE Transactions on Systems, Man, and Cybernetics, SMC-22, 1-18.

Wolff, H. S. (1967). Signal received but not understood. In Proceedings of the IEE Professional Group 6 Colloquium on the Interpretation of Biological Signals (pp. 14-16).