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CHAPTER 3

Representation Aiding to Support Performance on Problem-Solving Tasks

By Philip J. Smith, Kevin B. Bennett, & R. Brian Stone

A substantial literature has been developed that deals with the use of visual displays to support human problem solving. In particular, the cognitive systems engineering literature has emphasized the use of visual displays to improve performance on complex real-world tasks such as process control with the labels *direct perception, ecological interface design, representational design,* and *semantic mapping,* focusing on the use of representations that take advantage of powerful perceptual processes to support problem solving. Although the theoretical orientations and details of each approach are slightly different, they all share a fundamental core belief: The effectiveness of a graphical decision aid depends on relationships between the representation, the domain and associated task(s), and the characteristics of the agent (person). This review begins with a discussion of strategies for representation aiding, assuming that the appropriate domain semantics have been determined. It then discusses a core assumption in this literature that, in the design of complex real-world systems, designers cannot anticipate all the possible scenarios that could arise and must therefore design displays that support effective problem solving even when novel or unanticipated scenarios are encountered. Finally, the results of empirical studies of designs based on representation aiding are reviewed.

In this review, we focus on strategies for representation aiding, as discussed under several labels in the human factors/ergonomics literature, including *direct perception* (Moray, Lee, Vicente, Jones, & Rasmussen 1994), *ecological interface design* (Rasmussen & Vicente, 1989), *representational design* (Woods, 1991) and *semantic mapping* (Bennett & Flach, 1992). Zachary (1986) defined representation aids as "interface techniques which provide ways of presenting the decision problem in the aiding-system interface that are tailored to the needs and capabilities of human cognitive processes" (p. 46). Thus, representation aiding could apply to any design that seeks to improve performance on a task through some set of displays (visual, auditory, tactile, verbal, etc.) by providing interface resources that enhance human performance (Norman, 1993). Our focus will be on the design of visual representation aids as applied to the design of interfaces for operating complex, real-world systems that are designed with the following goals in mind:

- The design should enhance or leverage human cognitive and perceptual processes in support of problem solving rather than replacing these processes.
- For those tasks and scenarios that have been anticipated during the design process, displays (representations) should be developed to support skill- and rule-based processing (Rasmussen, 1983; Vicente, 2002), at least for experienced users.

- The display design should also support knowledge-based behaviors (Rasmussen, 1983; Vicente, 2002) for novel or unanticipated scenarios and for less experienced users.

These features are discussed in more detail below.

LEVERAGING HUMAN COGNITIVE AND PERCEPTUAL PROCESSES

Representation aiding as a design strategy can be contrasted with three alternatives:

a. A fully automated solution (in which the software does not merely organize information for presentation to the user and support manipulation of this information but searches for and identifies what it considers to be the solution).
b. A protocol or operating procedure that is supposed to be rigidly followed by a system operator when a given situation is encountered (e.g., Bennett, 1992).
c. A task-neutral information display in which so-called primitive data about the current state of a system or problem are displayed; the user must then combine these data in some way to make the necessary inferences to detect, understand, and solve the problem at hand.

The rationale for preferring representation aiding over automation in certain cases may be based on cost (it may be more expensive to develop and field an adequate automated software solution) or on performance (it may be difficult or impossible with existing technologies for the designer to develop algorithms that can perform as well as human perceptual and cognitive processes). In addition, it can be argued that by keeping the person involved in the routine operation of the system (through the use of representation aiding instead of automation), he or she may be more likely to detect and deal with an anomalous situation that would not have been adequately handled by the automation as designed.

Thus, one argument for using representation aiding rather than automation is that a human operator needs to be effectively involved in the task in order to provide adequate handling of cases in which an automated solution would have shown brittleness (Skirka, Mosier, & Burdick, 1999; Smith, McCoy, & Layton, 1997; Smith, Geddes, et al., 2006). The importance of this consideration is that many serious accidents are caused by circumstances that have not been predicted or planned for by the designers of a system (the so-called Achilles heel of system design).

MAPPINGS: THE AGENT, THE DOMAIN, AND THE INTERFACE

Representation aiding is an approach to display design that goes beyond simply considering the characteristics of human cognitive and perceptual capabilities. As described in the introductory section, representation aiding further emphasizes the need to consider three primary system components (domain, agent, interface) and the quality of the mappings among them. Woods and Roth (1988) referred to these three components as the *cognitive triad.* We consider each component in greater detail.

Domain

As has been emphasized in the cognitive systems engineering literature (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999), analysis and description of the domain are absolutely essential in developing effective representation aids. The goal is to achieve a detailed understanding of the "landscape" on which the work occurs, regardless of who is doing it or how it gets accomplished. The term *constraint* is used to refer to the sources of regularity in a domain and to the associated invariants that are directly relevant to certain conclusions or responses. Such constraints are often referred to as *behavior shaping* because they represent the fundamental elements of the system that must be considered for effective control. In cognitive systems engineering approaches, these constraints are often modeled using the analytical tools of the abstraction and aggregation hierarchies, including categories of information encompassing the physical, functional, and goal-related characteristics of the domain, as well as the relationships among these categories (Rasmussen et al., 1994).

Interface

A variety of representational forms can be used to present critical information in the domain. Spatial representations provide detailed information regarding the physical configuration of a system (e.g., maps and mimic displays) or the abstract properties of a system (e.g., geometrical forms that provide spatial analogies to higher-order domain constraints). Metaphorical displays use graphical representations that relate critical domain constraints to more familiar objects or concepts (e.g., the desktop metaphor). Finally, alphanumeric representations provide detailed numerical values and verbal descriptions or labels. The literature on representation aiding emphasizes the need to determine which display design will most effectively communicate the state of the constraints for the domain; the design will accomplish this by triggering automatic perceptual and cognitive processes.

In designing the interface, it is important to realize that the representations that are chosen can shape user behavior in very powerful ways. Each type of representational form produces cognitive and perceptual demands that vary in terms of the nature, focus, and amount of resources involved in its interpretation, as do the details of how that form is implemented. Even within the same class of solution, alternative realizations of a design can produce cognitive demands that are substantially different.

Agent

The cognitive agents who make the control decisions also introduce a set of constraints. Agents can be either human or computer (e.g., automation). To simplify this discussion, we will consider only those constraints associated with human agents.

Decades of research in psychology have revealed a number of constraints that characterize the human as a system component. One fairly obvious constraint is the limitation associated with working memory: Human agents can actively maintain only a small number of items in working memory. On the other hand, human agents are equipped with powerful perceptual systems and can develop new automatic processes through experience. In terms of display design, considerations of visual attention and visual form perception are particularly critical. Similarly, general modes of behavior exhibited by human agents (i.e., skill-, rule-, and knowledge-based behaviors) must be considered when making design decisions. These modes of behavior and the implications for design will be discussed in more detail later.

The net result is that the design of effective graphical representations is a complicated and intricate activity that is extremely context specific. There are no short cuts, easy solutions, or checklists. Principles of design can be described, but they must be creatively applied and adapted to the specific circumstances at hand. The domain, the interface, and the human agent—each contributes a set of mutually interacting constraints. The effectiveness of graphical decision support will ultimately depend on the quality of very specific sets of mappings among these constraints (e.g., Bennett & Flach, 1992; Bennett & Walters, 2001).

Mappings

One set of mappings involves the relationships among the constraints of the work domain and the informational content encoded into the graphical representations. The quality of these mappings is determined by the extent to which the relevant categories of domain information and the relationships among them are available in the interface. Essentially, this set of mappings determines whether or not the interface contains the information necessary to easily make effective responses. These mappings have been referred to as *correspondence* elsewhere (e.g., Bennett, Nagy, & Flach, 1997; Vicente, 1999), but we will use the term *content mapping*.

A second set of mappings involves the relationship between the visual properties of the graphical representations and the perceptual/cognitive capabilities and limitations of the observer. Essentially these mappings determine whether or not the domain constraints have been encoded or represented in the interface in a form that can be processed easily by the human agent. This has previously been referred to as *coherence mapping* (e.g., Bennett et al., 1997; Vicente, 1999); we will use the label *form mapping*.

The final set of mappings involves the relationship between the human agent and the domain. The domains of interest are usually complex and dynamic. It follows that the representations that are developed will also be complex and dynamic. The human agent must be sufficiently knowledgeable about the domain to understand and interpret the information that is presented in the representation.

REPRESENTATIONS TO SUPPORT ANTICIPATED SCENARIOS

Rasmussen (1983) described a set of general modes of behavior that are useful in considering the cognitive resources required of a human cognitive agent to complete some task: skill-, rule-, and knowledge-based behaviors. Each mode of behavior needs to be considered in the design of a representation aid, as all three need to be supported if the representation aid is to improve performance in both anticipated and unanticipated scenarios.

Skill- and Rule-Based Behavior

Skill-based behaviors are high-capacity, sensorimotor activities that can be executed automatically with little attentional demand. As an example, for a skilled driver, the information about the state of the natural environment (e.g., the road) can be specified by a set of sensory inputs that, in turn, automatically activate or trigger certain perceptions and associated responses. Thus, the environment (road) provides a reference *spatio-temporal signal* that is automatically perceived by the agent (driver). In response, the agent then automatically produces motor activity (e.g., a control input such as turning the wheel) that minimizes deviation from this signal (Jagacinski & Flach, 2003).

In rule-based behavior, the person has similarly developed associated actions that lead to effective solutions based on prior experience or knowledge. The person reacts to cues or signs that determine when a stored procedure should be executed. Continuing with the driving example, suppose the driver had obtained a set of directions for a destination. These directions consist of a set of signs to be monitored for (e.g., "when you see the billboard with the singing chicken") and rules to be followed (e.g., "turn right at the next street—Elm Street"). The driver then continues performance that is largely skill based (e.g., steering along the new course) until the next set of signs and actions (e.g., the next turn) is encountered. The key observation is that conscious deliberation is required to select from alternative courses of action at key decision points, thereby linking sets of prelearned activities. In this case, the prior experience or knowledge required for rule-based behavior exists outside the person who performs it (i.e., the supplier of the directions). In the case of experts, the required rules and knowledge will have been previously acquired.

The cognitive systems engineering literature on representation aiding emphasizes the value of designing to support skill- and rule-based behaviors for scenarios that have been anticipated by the developer, which makes it easier for someone to complete predetermined tasks efficiently and effectively. The strategy is to identify the relevant constraint (based on the task and associated domain semantics) and to display it in a manner that allows a rich set of signals and signs (i.e., affordances for action) to be directly perceived.

This strategy is illustrated in a simple example by Vicente and Rasmussen (1990), who contrasted the use of rote sensor displays that depict "all of the elemental data that are directly available from sensors" with so-called smart displays, which are "able to directly pick up goal-relevant properties that are relevant to survival" (p. 212). Rote sensor displays "measure fundamental dimensions (e.g., mass, length, and time)," and then the person is required to use these fundamental metrics "to painstakingly derive the higher order properties of interest" (p. 215). This contrasts with a smart display, in which the critical data relationships are shown more directly on a display, indicating the goal-relevant properties as highly salient visual properties.

The assumption is that if the information about fundamental metrics is displayed separately across a number of displays (such as a hard-wired set of separate displays on a control panel), the person must shift attention from one display to another and use slower, more attention-demanding controlled processes to "recover the goal-relevant domain properties from the elemental data represented in the interface" (Vicente & Rasmussen, 1990, p. 211). As a result, "it is not possible for operators to go out and directly explore the status of the system using the powerful perceptual systems that serve them so well in the natural environment" (p. 211).

The cognitive science literature on problem solving similarly emphasizes the value of representations to support automatic, associative processes to enhance performance. Studies address direct perception in routine situations in which task-relevant information in the environment is "directly picked up without the mediation of memory, inference, deliberation, or any other mental processes that involve internal representations" (Zhang, 1997, p. 181), so that "the end product of perception is the end product of the whole problem solving process" (p. 187).

Thus, both the cognitive science and cognitive systems engineering literatures place a strong emphasis on the use of representations or displays to trigger automatic perceptual and associative processes (Shiffrin & Schneider, 1977) to enhance problem solution. Providing powerful illustrations of this, Scaife and Rogers (1996) described "the extent to which differential external representations reduce the amount of cognitive effort required to solve informationally equivalent problems" (see also Kotovsky & Simon, 1990; Simon & Hayes, 1976; Zhang & Norman, 1994).

However, Scaife and Rogers (1996) noted this caution in discussing graphical representations: "The value of diagrams…is strongly related to the experience and expertise of the individual having 'operators' that match the display… Novice physicists, for example, will not make the same inferences as experts from the same diagram" (p. 195).

An Example of Representations to Support Anticipated Scenarios

A simple example of representation aiding that takes advantage of automatic perceptual processes is provided by Cole (1986), who developed a display for monitoring patient respiration (see Figure 3.1). The relevant fundamental dimensions for this monitoring task are the volume or depth of air exchange and the rate of air exchange. However, the task-relevant concerns are the total amount of oxygen respired by the patient and imposed by the respirator and whether the patient is achieving alveolar gas exchange.

Figure 3.1 shows the display's appearance during a sequence of 11 periods. For each period, it could potentially display two rectangles: one representing the ventilator's contribution to breathing and one representing the patient's spontaneous contribution to breathing. For Periods 1–3, only the rectangle for the ventilator is shown, as the ventilator is acting alone during these times. The height of each rectangle is an indictor of the volume of air exchanged (larger rectangles indicate that more air was exchanged). Note that any given volume of air exchange can be achieved by either many rapid, shallow breaths or by fewer, deeper breaths. This is the mean rate of respiration and is represented by the width of each rectangle. Thus, for Period 6, the rectangle for the patient's contribution (right rectangle) is wide but short, representing many shallow breaths (which do not contribute as effectively to gas exchange) and a low volume of air exchange.

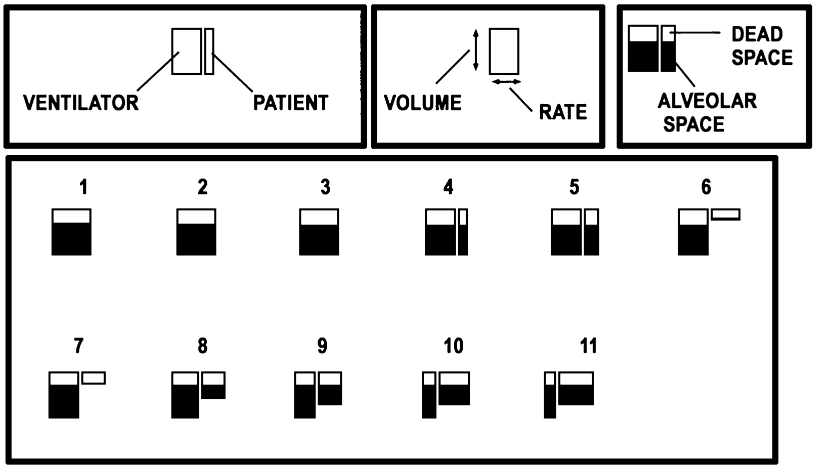


Figure 3.1. *Representation aiding to monitor patient status on a respirator (after Cole, 1986). Reprinted with permission from Association for Computing Machinery,* Proceedings of the 1986 ACM Conference on Computer-Human Interaction, *91–95. Copyright 1986 by the Association for Computing Machinery. All rights reserved.*

This display demonstrates some important principles for the design of representation aids and will be used to tie together several of the considerations that have been outlined thus far. Recall that form mapping refers to the extent to which the visual features that are present in the representations can be obtained by the human agent. A critical component of this mapping has been referred to as *emergent features* (Pomerantz, 1986). Emergent features are highly salient (e.g., notable, conspicuous, prominent) visual properties that arise from the interaction of the lower-level graphical elements of a representation. For example, Cole's display produces several different emergent features, including the width, height, area, and shape of the rectangles in Figure 3.1.

The presence of emergent features may be necessary for the design of effective representation aids, but it is not sufficient. In addition, "the emergent features must reflect the inherent data relationships that exist in the domain—that is, the highly salient emergent features must correspond to the information needed to complete domain tasks" (Bennett, Toms, & Woods, 1993, p. 73). In Cole's display, the form mapping is effective: The extent to which the air exchange is attributed to the patient or the ventilator is visually specified by the differences in the shape and size of the two rectangles. These displays are often referred to as *configural displays,* a term borrowed from the visual attention literature because of the overlap in theoretical considerations (Bennett & Flach, 1992).

Summary

Both the cognitive science and cognitive systems engineering literatures emphasize certain critical considerations in developing representations to aid problem solving for scenarios that have been anticipated by the designers. As we indicated earlier, representations need to be developed to support skill- and rule-based behavior under these conditions. In the case of Cole's display, these goals were achieved by mapping some of the key properties of this domain into geometric forms that provided spatio-temporal analogs.

The human agent interacts with this display largely at the level of skill- and rule-based control. The primary skill-based behavior is direct perception. The display has been designed so that it provides visual information that directly specifies the state of the system. For example, the shape and size of the two rectangles are spatio-temporal signals (i.e., emergent features) that specify whether the patient (e.g., Figure 3.1, Period 11) or the ventilator (e.g., Figure 3.1, Periods 1–3) is the major contributor to air exchange. Thus, the display shown in Figure 3.1 allows the human agent to directly perceive many of the domain constraints directly. This could be contrasted with an alternative representation aid in which each low-level datum was measured and presented in isolation, in the form of a digital value. Such a display would not support skill-based behavior and in fact would produce a much more difficult set of demands: The human agent would have to engage in knowledge-based behavior (e.g., computing relative rates of air exchange from the raw digital values).

The display in Figure 3.1 provides a rich set of visual cues that support rule-based behavior as well. The visual properties of the display serve as signs that suggest the appropriate control input. For example, a configuration such as that appearing in Figure 3.1, Periods 1–3 (i.e., air exchange is attributed exclusively to the ventilator) could serve as a sign that additional medical intervention is needed, especially if this appeared over a long period. Similarly, a configuration such as that represented in Figure 3.1, Period 11 could be an indication that it is time to take the patient off the ventilator.

REPRESENTATIONS TO SUPPORT PROBLEM SOLVING IN UNANTICIPATED SCENARIOS

Cognitive systems engineering researchers have posited that during unanticipated scenarios, even an expert in a complex dynamic domain may have to rely on actual problem-solving behavior (knowledge-based behaviors) when he or she is faced with a set of circumstances that have not been anticipated in the design of the operating system or in preparation through preplanned guidance, training, or operating experience. Rasmussen (1983) referred to this mode of performance as *knowledge-based behavior.* Under these circumstances, the individual must detect and identify the cause of the abnormality and consider a variety of information about the system being controlled (e.g., goals, constraints, functions, physical configuration) to compensate for the abnormality. Thus, in addition to designing to support skill- and rule-based behaviors to deal with these anticipated scenarios, the design also needs to support knowledge-based behavior (e.g., problem solving) for novel scenarios.

Vicente (2000) provided a simple but illustrative example that suggests how the process of designing for knowledge-based behavior should proceed. He contrasted verbal directions on how to travel from one point to another with the use of a map. In this analogy, the directions provide a very efficient but brittle description of how to accomplish the desired goal. The map requires more effort (reasoning) but is more flexible in the face of obstacles that might render the directions unusable. Building on this analogy, Vicente noted:

> This decrease in efficiency [of maps vs. directions] is compensated for by an increase in both flexibility and generality. Like maps, work domain representations are more flexible because they provide workers with the information they need to generate an appropriate response online in real time to events that have not been anticipated by designers. This is particularly useful when an unforeseen event occurs because task representations, by definition, cannot cope with the unanticipated. (2000, p. 115)

Before we consider how this might be achieved, we first discuss an example from the cognitive science literature that demonstrates the power of alternative representations on solving problems.

Supporting Knowledge-Based Processing by Representing the Constraints

The cognitive science literature provides some powerful examples that help in understanding the impact of external representations or displays on solving problems. An example from this literature is discussed, followed by consideration of an example from the human factors/ergonomics literature concerned with process control.

The digits game—Underconstraining the problem. The digits game (Perkins, 2000) demonstrates a design or presentation of a problem that fails to make salient the critical constraints, as a result making it difficult for a person to solve the problem (win the game).

Two players compete. Each player alternates in picking a number between 1 and 9. Once a player has selected a number, it cannot be picked again (sampling without replacement). To win, a player must be the first person to select a set that contains three numbers that add up to 15. If neither player accomplishes this, the game is a draw.

As an example, consider the following sequence in which Player 1 wins:

Player 1 – selects 5
Player 2 – selects 9
Player 1 – selects 2
Player 2 – selects 8
Player 1 – selects 6
Player 2 – selects 4
Player 1 – selects 7 (Player 1 wins!)

Even with a scratch pad, this is a challenging task as framed in these instructions because, given this framing or representation of the problem, each player has to compute and consider the implications of all the various possible outcomes that could result from selecting one of the still-available digits.

An alternative representation is to embed the digits in a Tic-Tac-Toe matrix (see Figure 3.2) and to tell the competitor that he or she is playing Tic-Tac-Toe, alternating selection of particular cells in the matrix with the opponent, and trying to get a line of three

2	7	6
9	5	1
4	3	8

Figure 3.2. *Isomorphic representations: The digits game versus Tic-Tac-Toe. The three numbers along each vertical, horizontal, or diagonal line through the Tic-Tac-Toe matrix add up to 15.*

Xs or three Os before the opponent does. Thus, in terms of picking the best sequence of three numbers, playing Tic-Tac-Toe (and implicitly identifying the selected digits along the way) is equivalent to playing the digits game (i.e., they are problem isomorphs).

However, as demonstrated in a study by Zhang (1997), the necessary cognitive processes are quite different. In particular, the Tic-Tac-Toe representation implicitly indicates all the sets of three digits between 1 and 9 that add up to 15 (the triad of numbers in any row, column, or diagonal), thus displaying the constraints relevant to this problem in the external world (Hutchins, 1995; Norman, 2002). In doing so, it constrains the set of possibilities that the competitor needs to consider in trying to pick three numbers to add up to 15. It also constrains the set of possibilities that the competitor needs to consider in order to block the opponent. In short, representation of the game as Tic-Tac-Toe helps to limit search by making "the domain constraints directly perceptible" (Flach & Bennett, 1992), focusing attention on those paths that could lead to success.

As a result, even for a novice player for whom this is a novel task, the representation of the digits game as Tic-Tac-Toe significantly reduces the complexity of the reasoning necessary to successfully play the game.

The digits game—Supporting different cognitive operations. This illustration further demonstrates how the external representation of a problem can change the mental processes necessary to solve that problem. Representing this game as Tic-Tac-Toe makes it unnecessary to do any arithmetic because the goal is stated in terms of spatial reasoning instead of numeric calculations. This supports "perceptual operations, such as searching for objects that have a common shape and inspecting whether three objects lie on a straight line" (Zhang, 1997, p. 185). For in Tic-Tac-Toe, "to identify a winning triplet is to search for three circles lying in a straight line," which "can be visually inspected," and the "winning invariant [the number of potential wins for a circle] . . . is represented externally by the number of straight lines connecting a circle: 4, 3 and 2 for the center, the corners, and the sides, respectively" (p. 190).

The Tic-Tac-Toe representation also illustrates aiding through the use of an external memory aid. This aspect of representation aiding has been studied extensively; for example, Sciafe and Rogers (1996) noted that the role of diagrams as external memory aids enables "a picture of the whole problem to be maintained simultaneously, whilst allowing the solver to work through the interconnected parts" (p. 193).

Likewise, Scaife and Rogers discussed the use of external memory aids to change long-term memory demands, citing O'Malley and Draper (1992), who differentiate between

> the knowledge users need to internalize when learning to use display-based word processors (e.g., MacWrite) with that which they can always depend upon being available in the external display. The tendency, therefore, appears to be for users to learn only what is necessary to enable them to find the information they require in the interface display. Information represented in such displays is viewed as an external memory aid. (Scaife & Rogers, 1996, p. 202)

Such use of representations to support external memory aids is also highlighted in the design literature in studies of performance on real-world tasks. Hutchins (1995), for example, cited numerous examples in which external representations (such as Post-It® notes) are used as memory aids to support individual cognition and as communication tools to support distributed cognition (Zhang & Norman, 1994).

A Process Control Example

In the illustration that follows of a simple domain analysis, we discuss alternative representation aids for operating a process control system analogous to an example presented in Vicente and Rasmussen (1990). The constraints in this domain have a high degree of regularity; the cognitive demands that are produced arise from the physical, functional, and goal-related properties of the domain itself. In essence, the behavior of the system is determined primarily by the laws of nature (e.g., conservation of mass) as opposed to the intentions of the agents who control it. Using the terminology applied by Rasmussen et al. (1994), this type of domain is *law driven.*

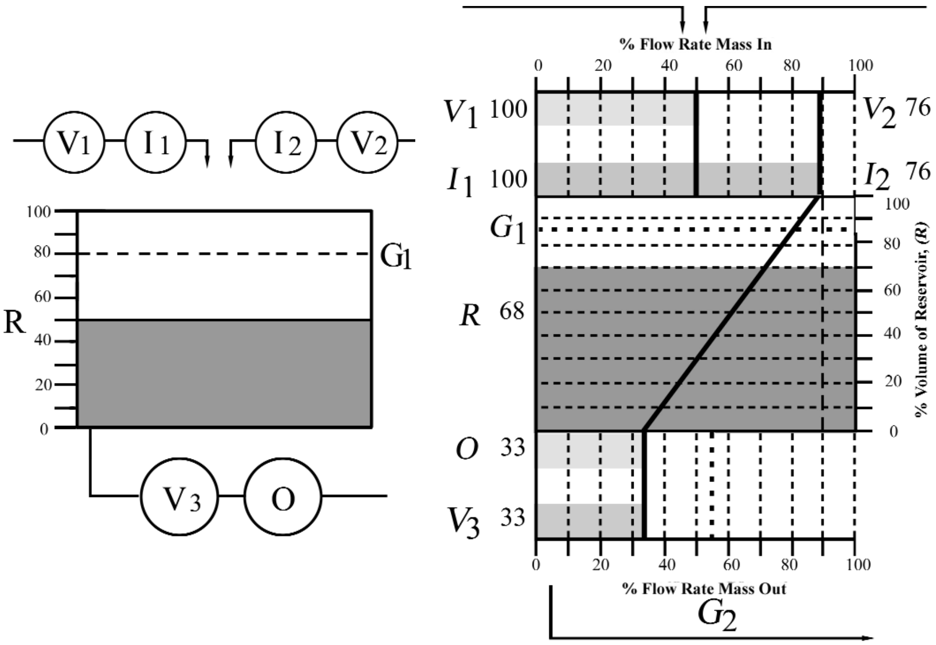
An effective representation aiding strategy for law-driven domains is to develop abstract geometrical forms that reflect the inherent goals as well as the functional and physical properties of the domain. The critical design approach involves the mapping of the domain constraints into graphic representations that provide spatial analogies to domain properties. The quality of these mappings in turn determines the effectiveness of the display. We next discuss two examples (Figure 3.3) that provide different sets of mappings and different degrees of effectiveness. (See Bennett et al., 1997, for a more comprehensive discussion.)

Consider the simplified process control system illustrated in Figure 3.3a. There is a reservoir for storing fluid, two input sources for adding fluid to the reservoir (shown on top of the reservoir), and an output source for removing fluid from the reservoir (shown underneath the reservoir). Each input has a pipe to carry the fluid, a valve to control the flow of fluid (V_1 and V_2), and a sensor to monitor the flow of fluid (I_1 and I_2) and the output (V_3 and O).

To identify critical constraints in this law-driven domain, Rasmussen et al. (1994) used an abstraction hierarchy. Such an abstraction hierarchy is an analytical tool that provides a framework for describing the critical categories of information in a domain and the relationships among these critical categories. In terms of representation aiding, they

Sample Process

Low Level Data (Process variables)	High Level Properties (Process constraints)	
T = Time	$K_1 = I_1 - V_1$	Relation between commanded flow (V) and actual flow (I or O)
V_1 = Setting for Valve 1	$K_2 = I_2 - V_2$	
V_2 = Setting for Valve 2	$K_3 = O - V_3$	
V_3 = Setting for Valve 3		
I_1 = Flow rate through Valve 1		
I_2 = Flow rate through Valve 2		
O = Flow rate through Valve 3		
R = Volume of reservoir	$K_4 = \Delta R = ((I_1 + I_2) - O)$	Relation between reservoir volume (R), mass in ($I_1 + I_2$), and mass out (O).
G_1 = Volume goal	$K_5 = R - G_1$	Relation between actual states (R, O) and goal states (G_1, G_2)
G_2 = Output goal (demand)	$K_6 = O - G_2$	



3a. Mimic display.

3b. Configural display.

Figure 3.3. *Mimic display and configural display for a process control system.*

can be thought of as the different perspectives from which the domain will need to be considered by the agents who are controlling it.

For this process control domain, there are five levels of abstraction, listed in the left column of Table 3.1. The general properties that are represented in each level of abstraction are listed in the center column of the table. These labels and general properties are adapted from Rasmussen et al. Finally, the specific properties of this simple process are listed for each level of abstraction in the right column of Table 3.1.

There are only two goals for this control system: (a) maintain the reservoir at a particular level to ensure that a sufficient volume of fluid exists and (b) maintain a specified output flow rate to provide fluid to a downstream process. Nevertheless, even this simple system has some fairly complicated dynamics. A listing of critical information is provided at the top of Figure 3.3 in two columns. The column on the left lists the low-level data associated with the process. These are the process variables that can be measured by sensors and set by the human operator using valves in order to control the process.

The column on the right lists the high-level constraints. These constraints are the important relationships among the low-level variables that are determined by the process constraints; they are critical because they are relevant to certain tasks that may have to be performed by the operator of this system (such as deciding how much to increase the flow rate using V_1 in order to regain the desired output flow rate O when it is too low).

Table 3.1. Levels in the Abstraction Hierarchy for the Process Control Example

Means-Ends Relations	*General Properties Represented*	*Specific Properties for Process*
Purposes and constraints	Reasons for design Coupling to environment	Volume goal (G_1) and output goal (G_2) Constraints K_5 and K_6 (the difference between actual states and goal states)
Abstract functions and priority measures	Intended proper functioning Flow of information, resources, or other commodities through the system	Conservation of mass; Flow of mass through the system; K_1, K_2, K_3, and K_4 constraints
General functions	General functions to be coordinated Independent of physical implementation	Storage, sources, sink
Physical processes and activities	Physical properties necessary for control of system (adjusting, controlling, predicting)	Two feedwater streams, a reservoir for storage, a single output stream; moment to moment values and settings (V_1, V_2, V_3, I_1, I_2, O, R).
Physical form and configuration	Physical configuration, form, appearance, location, etc.	Physical locations and descriptions of components (e.g., causal connections pipe length, physical location of valves, size of reservoir)

For example, K_4 is determined by a law of nature: conservation of mass. This constraint essentially indicates that the changes in the volume of the reservoir (ΔR) will be determined by the relationship between the rate of mass flowing into and the rate of mass flowing out of the reservoir. For example, if the amount of mass flowing into the reservoir ($I_1 + I_2$) is greater than the amount of mass flowing out of the reservoir (O), then the volume of the reservoir (R) will be increasing (ΔR) at a rate that is proportional to the size of the positive net inflow (and vice versa). Alternatively, if the inflow through V_1 is 5 gallons per minute and through V_2 it is 10 gallons per minute, and the outflow through V_3 is 15 gallons per minute, then the volume stored in the reservoir will remain constant.

Representing physical form and configuration along with physical processes and activities. Suppose we start this process control task with the volume in the reservoir (R) at the desired level or goal (G_1). If the goal is to monitor the system to determine whether the current volume remains at G_1 over time, then the display shown in Figure 3.3a, using a simple analogical representation in which the geometric form of a rectangle is used to provide spatial analogies for the reservoir and its volume level, is effective. The operator can simply monitor to see whether the top of the gray rectangle (representing the filled portion of the tank) remains at the dashed line (the desired level).

Abstractly, then, the display in Figure 3.3a is a spatial representation that emphasizes the physical components and relations that characterize the system. The primary physical components are represented by the lines and labels at the top (i.e., the feedwater streams), the rectangular form in the middle (i.e., the reservoir), and the lines and labels at the bottom (i.e., the output stream). The physical relationships among the various components are emphasized (e.g., the physical placement of the valves relative to the sensors in the input and output streams).

This type of representation is often referred to as a *mimic display* because the representation mimics the physical structure of the system. Note that this type of representation provides a critical perspective for dealing with certain aspects of the system: It illustrates the physical components, the logical relationships among them, and the causal connections and structure.

Representing abstract functions and priority measures as well as purposes and constraints. Although the mimic display, representing physical form and configuration along with physical processes and activities, is effective for supporting performance for the monitoring task described earlier, it is not as useful in helping the operator to select an appropriate control input. The problem is that the information about higher-level properties or constraints is not provided in a direct fashion by the mimic display.

To make this point explicit, consider the constraint, K_4, which indicates that changes in the volume of the reservoir will be determined by the relationship between the rate of mass flowing into and out of the reservoir. For example, if the amount of mass flowing into the reservoir ($I_1 + I_2$) is greater than the amount of mass flowing out (O), then the volume of the reservoir (R) will be increasing at a rate (ΔR) that is proportional to the size of the positive net inflow. Knowledge of the state of this constraint is essential for the effective control of the system.

Consider the situation depicted in Figure 3.3a. The constraint K_5 (the difference between the volume goal and the current level) is represented graphically in the mimic display—that is, the difference between the dashed line, or $G_{1,}$ and the top of the gray-filled rectangle, or R. Thus, there is direct visual evidence specifying that a system goal is not being met (i.e., G_1 is greater than R). On the other hand, although the operator could detect an imbalance in the input and output flows by watching to see if the top of the gray-filled rectangle (representing R) goes up or down, this would take time and is therefore an inefficient method for detecting a problem with the balance between the flow in and the flow out (K_4).

The low-level data that are necessary to determine the answer (i.e., I_1, I_2, and O) are present in the mimic display, assuming there are displays embedded in the mimic display indicating each of these flow rates. However, to use these data, the human agent is forced to collect the relevant information from each of these separate displays and complete the computations necessary to derive the answer. (Note that the situation is even worse for the second system goal [G_2] and its associated constraint [K_6]: Neither the output goal nor the difference between the current value and the output goal is represented in the mimic display.)

Figure 3.3b illustrates an alternative display using the funnel display concept described in Vicente (1991). In this configural display, the variables and relationships are represented using analog geometrical formats. When the underlying information changes, it is reflected in analogical changes to these geometrical formats. At the top of the display are two sets of horizontally stacked bar graphs (showing $V_1 + V_2$ and $I_1 + I_2$). The valve settings to control the rate of mass flowing into the system (V_1 and V_2) are represented by the top stacked bar graph. The combined horizontal extent of the two bars (i.e., the length of the bars in the horizontal axis) corresponds to the total "commanded" rate of mass flow into the system.

The sensed mass flow rates into the system (i.e., the rates measured by sensors) are represented in a similar fashion by the horizontally stacked bar graph directly below ($I_1 + I_2$). In this case, the commanded and sensed flow rates are exactly the same (88%). The commanded (V_3) and sensed (O) flow rates out of the system are represented similarly in the two bar graphs that appear at the bottom of the display. The reservoir volume (R) and the goal for reservoir volume (G_1) are represented in the same manner as previously described for the mimic display.

Such a configural display can be particularly useful in representing the states of the constraints that are determined by the relationships among the low-level parameters of a law-driven domain (Bennett & Flach, 1992). Each relational invariant is represented by a high-level visual property (i.e., an emergent feature, as discussed previously for the Cole, 1982, display).

The configural display in Figure 3.3b makes extensive use of such emergent features. First, consider the mapping between one of its emergent features and the fundamental domain constraint, K_4.

The horizontal length of the stacked bar graph for the rate of mass in ($I_1 + I_2 = 88\%$), relative to the horizontal length of the stacked bar graph for mass out ($O = 33\%$) provides a visual indication of whether the flow in equals the flow out (i.e., mass balance). To make this relationship more visually salient, a bold line (more specifically, a contour) has been added to explicitly connect these two stacked bar graphs (the value of $I_1 + I_2$ is connected by a line to the value of O). A perfectly vertical indicator (connecting line) specifies that mass flow is balanced. The direction of the indicator's deviation from the vertical directly specifies whether more mass is flowing into or out of the reservoir. A clockwise rotation of the indicator from vertical, as illustrated in Figure 3.3b, specifies a positive net inflow; a counterclockwise rotation from vertical specifies a negative net inflow. Furthermore, the degree to which the indicator deviates from vertical is a direct visual indication of the magnitude of the difference between the rate of mass flow into and the rate of mass flow out of the reservoir, as shown in Figure 3.4. Thus, the slant or orientation of this line is an emergent feature that provides direct visual evidence specifying both the direction and magnitude of the net flow of mass into or out of the reservoir. This visual evidence allows the operator to directly perceive mass balance rather than requiring him or her to calculate it.

This configural display contains similar emergent visual features to indicate the status of most of the other relevant domain constraints. Three of these domain constraints (K_1, K_2, and K_3) describe the relationships between commanded rates of flow (i.e., valve settings) and sensed rates of flow (i.e., sensor readings). The emergent features corresponding

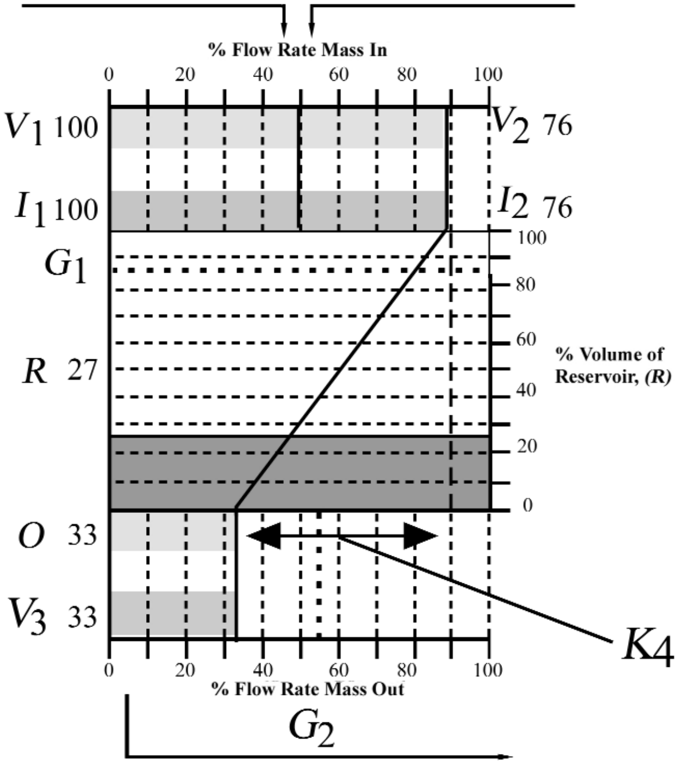


__Figure 3.4.__ Example with the configural display for the process control system showing a positive net inflow (with more mass entering the reservoir than leaving the reservoir).

to these constraints are the bold lines connecting the ends of the associated bar graphs (i.e., V_1 to I_1, V_2 to I_2, and V_3 to O). Similar to the mass balance indicator, the orientation of each of these lines is an emergent feature that visually indicates the status of the corresponding constraint. When these lines are vertical (as in Figure 3.3b), it is a direct visual indication that the associated commanded mass flows are equal to the measured mass flows. See Figure 3.5 for an example in which K_2, the difference between the measured flow I_2 and the commanded flow based on the valve setting V_2, indicates a problem.

The final two constraints (K_5 and K_6) are goal related and describe the difference between a goal and the current value of the associated variable. For example, the constraint on mass inventory (K_5) is shown using the relative height of the filled area to represent volume within the reservoir and the bold, dashed horizontal line to represent the goal level G_1.

Supporting problem solving in anticipated scenarios. The configural display just described is clearly based in part on a desire to assist operators in dealing with certain predefined scenarios, such as detecting an imbalance between the total inflow and outflow.

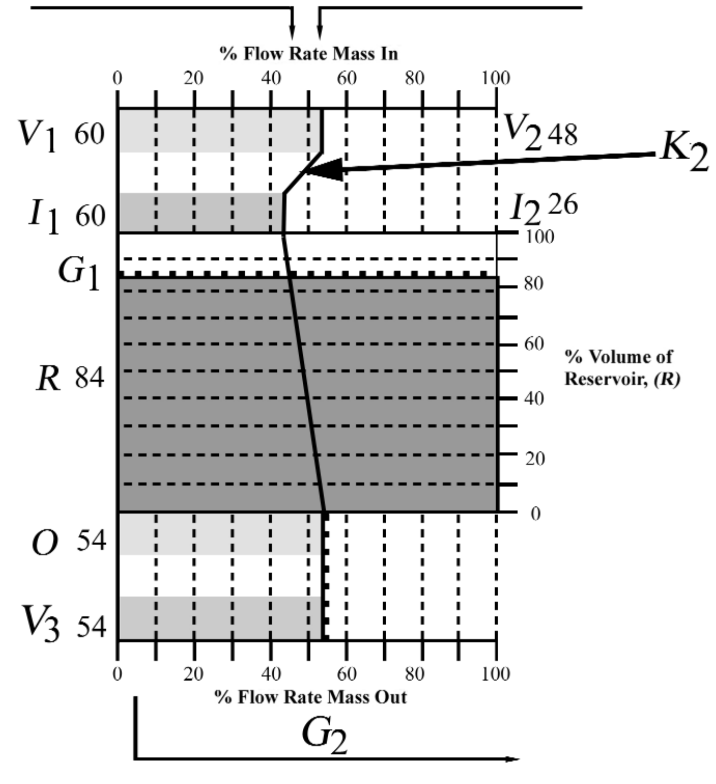


Figure 3.5. *Example with the configural display for the process control system showing an imbalance in K_2 (the difference between the expected inflow V_1—based on the valve setting—and the sensed flow I_1).*

It does so by providing salient perceptual cues (detecting vertical vs. slanted lines) that are direct indicators of certain imbalances. Thus, the user can directly perceive the constraints in the domain, making it unnecessary to perform the computations that would be required if the mimic display (with associated meters) in Figure 3.3a were used instead of the configural display in Figure 3.3b.

Supporting problem solving in unanticipated scenarios. A configural display like the one just described is also very helpful in solving unanticipated scenarios in this process control setting. As an illustration, contrast this configural display with a simple expert system that is brittle (Smith et al., 1997) because the designers developed it to correctly detect and diagnose the failure of a single sensor but not a simultaneous failure of two or more sensors. Although this might be unlikely for this simple process control system, it is not at all implausible that the designers of the expert system could overlook one of the myriad potential interactions that could occur within a complex, large-scale process control system. Similar to instructions on how to get to some unfamiliar location, the expert system could make the user's job easier for scenarios in which the software is fully competent. However, when a scenario arises that is outside the expert system's range of competence, the user could be faced with a very difficult problem-solving task, assuming he or she even recognizes that this has happened.

In contrast to the expert system, the configural display requires more active participation by the operator in terms of monitoring for and dealing with anticipated problem scenarios, because the operator has to visually scan the configural display for an indication of a problem instead of simply waiting to be alerted by the expert system. However, like the map used to get to an unfamiliar location, assuming that all the relevant constraints have been effectively represented, the configural display is likely to provide better support when dealing with an unanticipated scenario because the configural display has been explicitly designed to make salient a deviation of any of the critical constraints from its expected value (see Figure 3.5).

In terms of completeness, these critical constraints have been derived by representing the domain in a means-ends or abstraction hierarchy adapted from Rasmussen et al. (1994), with several levels of detail (see Table 3.1). These levels can be thought of as different perspectives on the domain that need to be considered by the operator who is controlling it. They provide a model, or a description, of the domain in terms of different types of information and the relationships among them. Ideally, displays should have complementary graphical representations of domain-related information at each level of the abstraction hierarchy if effective support is to be provided during knowledge-based behavior. These displays will then provide a graphical "explanation" of how the domain constraints are broken and the alternative resources that could be used to fix them.

Summary

The foregoing discussion introduced two additional points that offer concrete assistance to designers:

First is the use of a means-ends analysis to develop an abstraction hierarchy to identify the critical domain constraints and guide the development of a design that supports direct perception of violations of these constraints. This enables the use of skill- and rule-based processes to deal with many unanticipated scenarios even though they have not been explicitly considered in the design, because they have been implicitly considered through the identification of the domain constraints. Thus, for unanticipated scenarios, if the violation of critical constraints is made more salient via automatic perceptual processes, this should make it easier to apply knowledge-based processes to complete problem solving because the direct perception of the violated constraints helps to focus the attention of these controlled processes on critical aspects of the underlying abnormality.

Second is the use of geometric forms to produce configural displays that support automatic perceptual processing of information relevant to problem-solving goals; they reflect the constraints introduced by certain functional and physical properties of the domain.

A Caution

Powerful representation aids focus attention and influence the user's cognitive processes. As a result, if some skill- or rule-based process is triggered by a given design at an inappropriate time, the user may be induced to fixate on the wrong hypothesis (if it is a diagnosis task, for instance) or to perform the wrong action.

The magnitude of the biasing effects that visual representations can impose has been illustrated in a number of studies (Larson & Hayes, 2005; Smith, Geddes, et al., 2006). For instance, Smith et al. (1997) demonstrated that graphical presentation of a recommended reroute around weather by a flight-planning system to experienced airline dispatchers and pilots caused 35% of them to bias their situation assessment of the weather (a type of justification bias). This changed their mental model of the situation and thus influenced their evaluations of alternative routes around the weather.

Thus, if a representation emphasizes inappropriate aspects of the domain constraints for a particular scenario, it can actually hinder problem solving (the proverbial double-edged sword). For example, placing independent and noninteracting variables into a configural display (i.e., a single graphical object with contours driven by the individual variables) will produce emergent features that are highly salient, are difficult to ignore, and suggest higher-order properties that do not exist in the domain (e.g., Bennett & Fritz, 2005).

The intent of this caution is not to say that designs should not be developed that trigger automatic perceptual processes (that, in fact, is one of the goals of representation aiding). Rather, our point is that designers need to be aware of the influences their designs can have on how users solve problems, and they must think carefully about how to support performance for both anticipated and unanticipated scenarios.

INTERACTION DESIGN: CRAFTING THE DETAILS

The representation aiding literature reviewed in the earlier sections is concerned with certain high-level concepts, such as designing representations that support direct perception in dealing with anticipated scenarios and that also support effective controlled processing to deal with scenarios that were not specifically anticipated in the design. The representation aiding literature also provides guidance on the use of certain more specific design concepts, such as the use of configural displays (Bennett et al., 1993; Carswell & Wickens, 1987; Goettl, Wickens, & Kramer, 1991; Wickens & Andre, 1990).

Ultimately, however, this high-level design guidance must be translated into a detailed interaction design for a given application that specifies the underlying functionality of the product, as well as the look and feel of the interface with that functionality (Burns et al., 1997). The broader literature on display design provides a great deal of guidance when making these more detailed decisions to support skill- and rule-based behaviors. It also provides guidance on how to craft displays to support knowledge-based behaviors. This guidance comes from a number of different overlapping fields, which have produced literatures with the labels *human factors, human-computer interaction, industrial design,* and *visual communication*. Some of these findings are based on rigorous empirical studies and evaluations; others have developed into accepted principles through practice.

Based on analysis and accepted practice in much of the design world, Tufte (1983, 1990, 1997), for instance, suggested and illustrated a number of guiding concepts for visual display design:

- Often the most effective way to describe, explore, and summarize a set of numbers—even a very large set—is to look at pictures of those numbers. (Tufte, 1983, p. 9)
- Erase non-data-ink, within reason. (Tufte, 1983, p. 96)
- Reveal the data at several levels of detail, from a broad overview to the fine structure. (Tufte, 1983, p. 13)

Note that many of these types of design principles are based on judgments developed through practical experience rather than controlled empirical evaluations, and that such practice-based evaluation is how many fields develop such guidance. It should also be noted that such principles almost always require that the designer use judgment regarding whether and how to apply such principles to a specific application.

The human factors/ergonomics literature provides other empirically supported and generally complementary design concepts, summarized by Wickens, Lee, Liu, Becker, & Gordon (2004, pp. 187–191) with recommendations focusing on issues such as these:

- avoiding absolute judgment limits
- designing to support top-down processing
- designing consistent with pictorial realism (Roscoe, 1968)
- minimizing information access cost
- providing predictive aiding
- ensuring consistency.

In a review of the literature on visual displays, Bennett et al. (1997) further characterized display design based on four approaches concerned with aesthetic, psychophysical, attentional, and problem-solving perspectives. This review provides illustrations of how detailed design concepts developed from each of these perspectives can contribute to design, such as this: “To support the extraction of low-level data, the graphical elements of the [configural] display must be made more salient perceptually through a variety of techniques, including emphasis of scale, spatial separation, and color-coding” (Bennett et al., 1993, p. 71).

The cognitive systems engineering and human-computer interaction literatures further emphasize consideration of mental models in the design of complex systems. These literatures stress the importance of developing an interface or representation that helps the user to develop a correct mental model of how a product or tool functions and provides him or her with guidance about how to interact with it to complete various tasks. Researchers in these domains also discussed the importance of developing the design so that the user will maintain a correct mental model of the world that is viewed (in part) using the tool as an interface (Van Der Veer & Melguizo, 2003). This emphasis on mental models applies to the design of representation aids to support knowledge-based processing to deal with novel scenarios.

A substantial literature under the heading of *heuristic analysis* provides guidance on developing effective display designs (Badre, 2002; Krug, 2000; Nielsen, 1994, 1997, 2000; Silver, 2005; Spool, Scanlon, Snyder, DeAngelo, & Schroeder, 1998). For instance, Smith, Stone, and Spencer (2006) reviewed heuristics such as these:

> **a.** How is the "focus of attention influenced by the display? Does it support completion of the alternative goals that users may have when looking at that display?"
> **b.** "Are external memory aids provided to help the user remember or determine what actions to take or to remember what steps in some process have already been completed?"
> **c.** "Are the relationships among associated controls and displays indicated through some form of functional grouping?"
> **d.** "Does the product look and behave consistently?"
> **e.** "Is the navigation robust enough to support the easy completion of alternative tasks, while still clear enough to help the user navigate along the correct paths without getting lost?"
> **f.** "Are landmarks provided to help the user remember where he or she is within the system (relative to the overall navigational structure), and to understand where he or she can go next to complete different tasks?" (p. 24–13)

Note that such heuristics were developed to support a variety of display design contexts, not with a focus on the design of representation aids as discussed in this review. However, many of these heuristics are applicable to the design of the specific features of representation aids within a display, as well as the selection of strategies for embedding representation aids within some larger system design.

In short, as noted in the introduction, the goal of this review is not to review the entire display design literature. Rather, it emphasizes the unique aspects of the literature that have developed within the cognitive systems engineering literature under the label of *representation aiding*. However, the details of a specific design still must be crafted and are critical to successful representation aiding. It is not enough simply to ensure that information on the relevant domain constraints is available somewhere within an interface. This information must be presented in a fashion that helps the user to make use of the appropriate skill-, rule- and knowledge-based processes when alternative scenarios arise.

REPRESENTATION AIDING: EMPIRICAL EVALUATIONS

As discussed earlier, the success of a particular representation aid depends on two critical aspects of the design:

- identification of the semantics of the domain and the constraints that need to be represented in the display to support skill-based, rule-based and knowledge-based behaviors;
- crafting of the interface through which the design strategies based on representation aiding are realized in a specific implementation.

It is therefore important to keep in mind that both of these aspects of the design could affect the results of an evaluation of a given design that incorporates representation aiding. In addition, it is important to understand the focus of the evaluation itself.

Regarding the nature and focus of the evaluation, Rasmussen et al. (1994) provided a framework that consists of five levels for categorizing alternative types of evaluation settings. These boundary levels are defined in terms of the *boundary conditions* or *constraint envelopes* that are present.

In describing boundary conditions, Rasmussen et al. (1994) stated that "the innermost boundary [Level 1] corresponds to the evaluation of actor-related issues in an environment that corresponds most closely to the traditions of experimental psychology. The remaining boundaries successively 'move' the context further from the actor to encompass more and more of the total work content" (p. 205). Next, we describe these five levels briefly, then follow with the results from a set of specific evaluations of certain representation aiding designs, which are framed in terms of these five levels to identify the extent to which they can be used for generalization.

Boundary 1: Controlled Mental Processes

Rasmussen et al. (1994) described the evaluations performed at this level as controlled laboratory investigations. The goal is to investigate the relationships between specific design features and the basic capabilities and limitations of participants. The experimental tasks to be performed are somewhat artificial, in the sense that there is little "direct concern for the eventual contexts of the end users" (p. 218). Because of the simplicity of these tasks, the strategies required for their completion are well defined and extremely limited. In Rasmussen et al.'s words,

> The formulation of the subject's instruction is at the procedural level and is very explicit. It serves to define the constraint boundary around the experimental situation and isolate it from (1) the general, personal knowledge background, and performance criteria of the subject, and (2) any eventual higher level considerations within the experimental domain itself. (p. 218)

In terms of display design, evaluations conducted at this level often examine the relationship between particular visual features that have been used to encode information into a display or graph and how well participants can extract or decode this information. Thus, the tasks to be performed are defined in terms of the physical characteristics of the display itself; performance is usually measured in terms of the accuracy and latency of responses. Prototypical examples of evaluations performed at this level can be found in the work of Cleveland and his colleagues (Cleveland, 1985; Cleveland & McGill, 1985); they systematically varied the visual features employed in alternative representations and ranked participants' abilities to make discriminations using these visual features.

Boundary 2: Controlled Cognitive Tasks

This level of evaluation is designed to assess performance at experimental tasks that are approximations of those found in real-world domains. The focus is on isolated "decision functions, such as diagnosis, goal evaluation, planning and/or the execution of planned acts" (Rasmussen et al., 1994, p. 219). These experimental tasks are typically more complex than those found at the previous level of evaluation.

To complete these tasks, a participant must consider more than the physical characteristics of the display alone—that is, he or she must consider the information presented and determine what this information means in the context of the task to be performed. At this level of evaluation, a participant's general knowledge of the task and the particular strategies that he or she develops and employs will become more important (relative to Boundary 1). Therefore, individual differences will have a more pronounced influence on the levels of performance that are obtained.

Performance assessment typically involves measures other than accuracy and latency. Prototypical examples of display evaluations performed at this level can be found in MacGregor and Slovic (1986) and Goldsmith and Schvaneveldt (1984). MacGregor and Slovic employed a multicue probability judgment task that required participants to consider multiple cues (age, total miles, fastest 10 km, time motivation) with varying degrees of diagnosticity to predict the amount of time runners would take to complete a marathon. The display formats used to present this information were varied, and performance measures (e.g., an achievement index) were calculated and analyzed using Brunswick's (1956) lens model.

Boundary 3: Controlled Task Situation

In contrast to the previous boundary levels, Boundary 3 evaluations incorporate a very direct link between the experimental tasks to be performed and the specific tasks that exist in a particular real-world domain. Analyses of real-world scenarios are used to develop causal or mathematical simulations that capture some portion of their inherent complexity.

Correspondingly, the experimental tasks to be completed at this level will be more complex than those encountered in the previous two boundary levels. The tasks may involve consideration of physical/functional characteristics of the domain, competing goals, limited resources to achieve these goals, and performance trade-offs. As a result, an individual's general knowledge of the domain, specific knowledge of the task(s) to be performed, and efficiency of the strategies employed will play a more important role in the findings that are obtained. The measures that are used to assess performance will be defined by the domain itself and will therefore be relatively domain specific.

Prototypical examples of display evaluations performed at this level can be found in the work of Moray, Lootsteen, and Pajak (1986) and Mitchell and Miller (1983, 1986).

Boundary 4: Complex Work Environments—Microworlds

Rasmussen et al. (1994, p. 224) described this evaluation boundary in the following fashion:

> A more recent category of experiments has been focused on human problem-solving behavior in complex simulated work environments in which the entire decision process is activated, including value formation, goal evaluation, and emotional factors.

Simulations at this level could certainly be more complex than those at the previous level. However, additional complexity alone is not the primary distinguishing factor. Rather, it is critical that the boundary conditions of the evaluation be set up to determine the influence of the interface on the participant's goal formulation and performance criteria. Typically, the participant is presented with a relatively open-ended task and will be free to formulate the task and goals on his or her own. For example, operators might be instructed to "run a power plant" in a full-scale simulator without explicit specification of the task situation.

Note that the utilization of work domain experts is essential for evaluation at this boundary level.

Boundary 5: Experiments in Actual Work Environments

At this boundary, the display or interface evaluation is conducted using real practitioners in the actual domain (field studies). Rasmussen et al.'s (1994) evaluation of a library information retrieval system, the BookHouse, is an excellent example. This system assists librarians and patrons in the selection of fiction books from a library. This system was evaluated in a public library during a six-month period. Numerous measures of performance were obtained, including "(a) a questionnaire, (b) on-line logging of all dialogue events (mouse clicks, etc.), (c) observation, and (d) interviewing by the librarians who (e) also kept a logbook with reports of user responses, system behavior, and so on" (p. 319).

As these descriptions indicate, moving from one boundary to another involves changes in many dimensions, including complexity, fidelity, knowledge, strategies, and values. Inherent trade-offs are involved when conducting evaluations at the various levels. The primary concerns center on experimental control and the generalization of results. At lower levels in the framework, more experimental control can be exerted. The tasks are well defined, the knowledge to complete them is straightforward, and the strategies that can be executed are limited. Thus, the chances of achieving statistically meaningful results are increased.

The situation is reversed at higher levels of evaluation. On the other hand, the chances that the results that are obtained will actually transfer to applied settings are increased as experiments are conducted at higher levels of evaluation.

To summarize, these five levels of evaluation represent a continuum of settings that needs to be considered in the evaluation of displays and interfaces that are intended for the real world. Different issues in design are addressed at each level. No single level is, a priori, more or less important than any other level. Regardless of the boundary level, effective performance will depend on whether or not the constraints introduced by the three system components mentioned earlier (i.e., domain, agent, interface) are well matched. Furthermore, the generalization of results between boundary levels will depend on extremely complex relationships among these three components.

The bottom line is that care must be taken in choosing a particular level to evaluate a display. Even more care must be taken when one attempts to generalize beyond the confines of the specific situational factors that were involved in a particular evaluation.

Evaluations of Designs Based on Representation Aiding

To illustrate these points, we next describe the results of several evaluations in the context of the framework outlined earlier.

Example 1. A number of factors in display design were evaluated in three empirical evaluations contrasting a configural display based on representation aiding concepts with other display designs (Bennett et al., 1993, 2000; Bennett & Walters, 2001). The factors included the general representational format employed (configural displays, bar graph displays, and digital displays) and a variety of display design techniques (color coding, perceptual layering, visual separation, graphical extenders, and display grids). All three display evaluations used the same experimental task environment: a part-task simulation of a steam generator in a nuclear power plant.

The evaluations were conducted at two of the levels outlined earlier. The experimental tasks in the Boundary Level 1 evaluations were defined in terms of the physical characteristics of the display: Participants were required to provide quantitative estimates of either individual variables (e.g., steam flow) or relationships between variables (e.g., mass balance). Performance on these tasks was graded with respect to how well the reported estimates corresponded to the displayed information (accuracy) and how long the estimates took (latency).

The second level of evaluation was conducted at Boundary Level 3. The tasks to be performed, and therefore the measurements that were obtained, were defined in terms of a part-task simulation as opposed to the display itself. Thus, the quality of the displays was determined by whether or not they assisted the agent in controlling the system under normal operating conditions (e.g., time on task, root mean square error) or detecting the presence of faults (e.g., sensitivity and false alarms) and compensating for them.

The task constraints associated with the Boundary 1 evaluation were simple: Provide a quantitative estimate of a variable or the difference between two variables. The display design techniques that contributed a matching set of constraints were effective in improving performance. More specifically, performance was improved to the extent that a technique contributed visual structure, allowing perceptual processes to be substituted for controlled cognitive processes. The digital value technique (the annotation of the analog geometrical format with digital values) provided the best support for the Boundary 1 task: The need for any visual estimates or mental computations was eliminated. In contrast, the visual structure provided by color-coding and layering techniques (i.e., chromatic and luminance contrast) did not eliminate the mental estimates or mental computations and therefore did not improve performance.

The task constraints associated with the Boundary Level 3 evaluation were much more complicated. To complete the system control and fault detection/compensation tasks successfully, the participant had to consider individual variables, higher-level properties/relationships, competing goals/constraints, and the physical/functional characteristics of the system. Far fewer significant effects were found at this boundary level because of the factors outlined earlier. The primary findings were that the presence of the analog configural display improved performance relative to the digital-only display (9 of the 10 significant results).

The analog configural format supported performance at Boundary Level 3 because it represented the critical domain semantics directly. For example, the critical system properties of energy and mass balance were represented by highly salient emergent features (i.e., the height and width of a rectangle). Additional emergent features (shape, size, and location of the rectangle) made it possible to view critical properties in the context of system goals (e.g., how close is the indicated level to the goal or trip set points?). In essence, participants could utilize powerful pattern recognition capabilities to assess current system state and, to some degree, to determine the correct control input.

In contrast, the digital-only display (this display had only digital values) imposed a truly severe set of constraints. The route to underlying meaning was much less direct. Participants could not use pattern recognition capabilities to complete tasks because the domain semantics (relationships, properties, goals, and constraints) were not directly visible in the digital format. Instead, the participants were forced to derive the current system state mentally using the digital values in conjunction with their conceptual knowledge about the system. (See Bennett & Flach, 1992; and Bennett et al., 1997, for a more detailed discussion of similar considerations.) Thus, the constraints introduced by the digital-only display made it much more difficult to assess system state, to determine appropriate control input, and to gauge the appropriateness of the system dynamics. As a result, performance suffered.

The collective results of these evaluations provide a fairly clear message: The evidence supporting the generalization of results between boundaries was extremely limited. There was only one significant contrast indicating that a single display manipulation produced improved performance at both boundaries, and this result failed to be replicated in the second experiment. The overall lack of generalization across boundaries is particularly striking given the five experiments, dozens of display manipulations, and hundreds of statistical comparisons.

The implication is twofold: First, designers must ask which of the boundary levels considered in the study best match the generalizations they wish to make. If the goal is to gain insight into how alternative display designs are likely to affect performance by trained practitioners on tasks such as fault diagnosis and system control in a process control system, then it could be argued that the Boundary Level 3 results in this study are more predictive than Boundary Level 1 results. This conclusion is supportive of the concepts underlying representation aiding—such as the representation of critical system properties like energy and mass balance by highly salient emergent features (i.e., the height and width of a rectangle), and the use of additional emergent features (shape, size, and location of the rectangle)—such that the critical properties can be viewed in the context of system goals. It suggests that these design features become more dominant determinants of performance when the system operator must consider individual variables, higher-level properties and relationships, competing goals and constraints, and the physical and functional characteristics of the system.

Example 2. Reising and Sanderson (2002) evaluated the design of a pasteurization microworld based on representation aiding and used configural displays that presented information on all the constraints identified in an abstraction hierarchy for that domain. This supported inquiries "at any level of abstraction or decomposition" (see Figure 3.6). They contrasted this with a mimic display. The participants were students (domain nonexperts) who were given only limited training on the use of these alternative interfaces. Thus, this would be categorized as a Boundary Level 3 evaluation. They concluded that "fault diagnosis was better with the ecological [representation aiding] interface than with a conventional (or mimic-only) interface" (p. 242).

Results on a follow-up questionnaire suggested that the reason was that although "the mimic display within the ecological interface was the most highly valued" (Reising & Sanderson, p. 242), the indication of boundary regions in the energy flow and goals displays were very important. Participants further indicated that although they perceived the straight line emergent features of the mass display to be useful for telling whether or not the mass flow was normal, this information was less important overall for control. The researchers also noted, however, that "some participants found certain configural displays hard to understand at first but learned to make good use of them"; participants made comments such as "At first, the mass and energy displays were hard to understand, but later it became one of my most reliable interfaces" (p. 243).

This Boundary Level 3 evaluation thus further supports the use of representation aids to support higher-level tasks (such as fault diagnosis) in a process control setting. However, remember that this is still just a Level 3 evaluation—meaning that generalizations to knowledgeable operators in the field should be made with caution—and that the focus was on scenarios that had been anticipated during the design.

Example 3. Burns et al. (2003) evaluated a representation aiding design for a network management system. This included several displays meant to support performance at different levels in the abstraction hierarchy described in Table 3.1. Figure 3.7 illustrates a polar display meant to support diagnosis of faults at the generalized function level.

The evaluation compared this tool against an industry tool (which provided a variety of displays based on tabular, timeline, and network topology formats) for both detection tasks and diagnosis tasks using students with a background in computer science and computer networks. For this Level 3 evaluation, detection times were faster using the industry display, but diagnoses were faster and more accurate using the displays based on representation aiding design strategies.

Example 4. In a final example of the evaluation of representation aiding, Jamieson (2002a, 2002b) conducted a Level 4 evaluation using an industry simulator of a petrochemical system with professional operators. New interfaces were integrated into this simulator, which was part of the operational system for the testing and training of operational staff (Miller & Vicente, 1998). The researchers studied 30 professional operators in this domain, who operated within this industry simulator using three different interfaces; the current display used in actual operations, a representation aiding display developed using a domain analysis based on ecological interface design methods, and a combination of this ecological interface with displays designed to support performance on specific tasks. This latter display is shown in Figure 3.8.

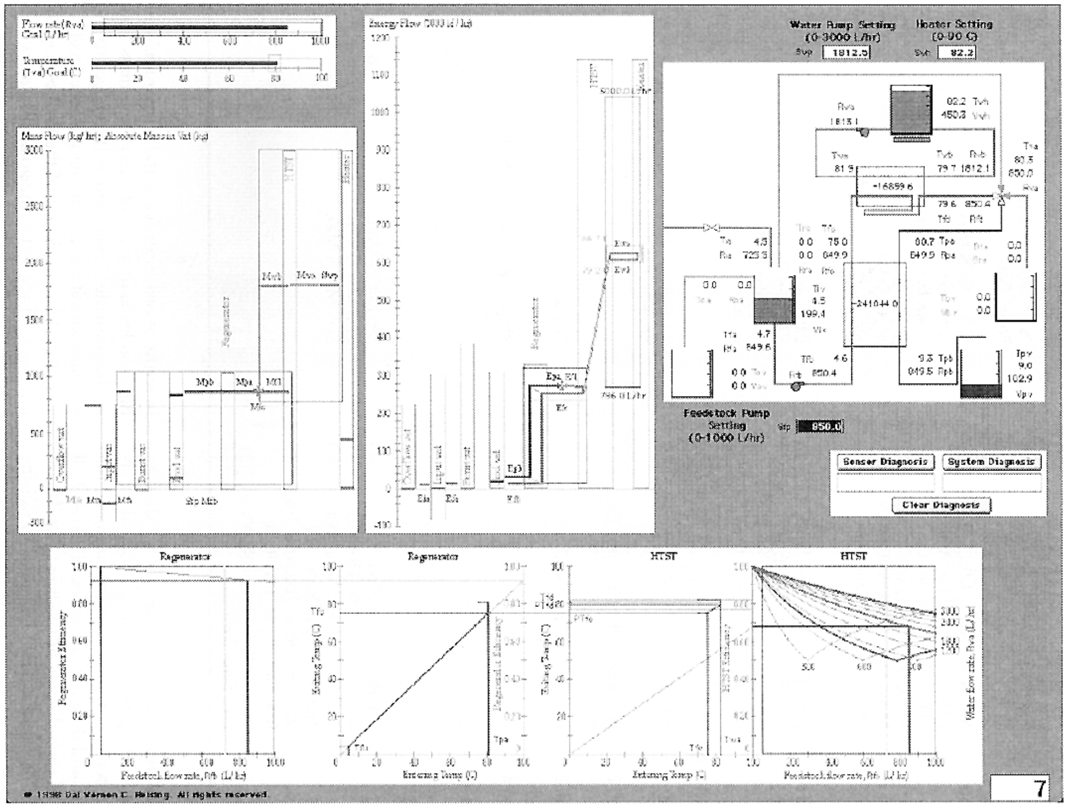


Figure 3.6. *Interface design for the pasteurization system, reproduced at smaller size than viewed during actual operation to show the overall layout. From Reising and Sanderson (2002). Reprinted with permission from* Human Factors, *44, 222–247. Copyright 2002 by the Human Factors and Ergonomics Society. All rights reserved.*

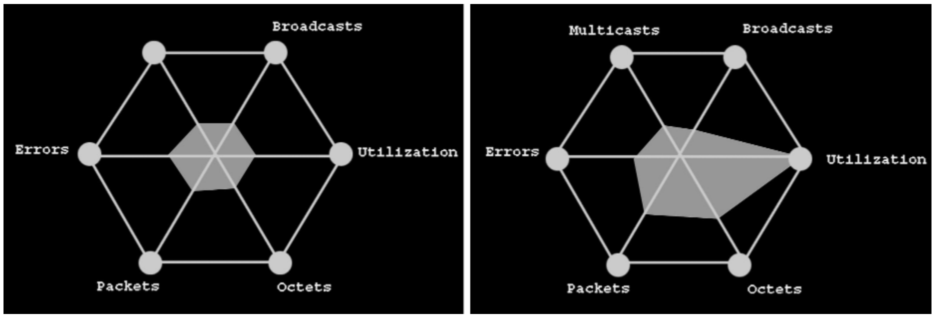


Figure 3.7. *Polar display from a network management system to support diagnosis of faults at the generalized function level. The polar graphic shows the states of critical variables sensitive to network functioning along the different axes. Different shapes of the graphic are diagnostic of significantly different system states. Based on figure from* Computer Networks, *43, Burns, C., Kuo, J., & Ng, S., Ecological interface design: A new approach for visualizing network management, 369–388, copyright 2003, with permission from Elsevier.*

These participants were studied when operating the plant under normal and abnormal conditions. The results showed that the times for operators to complete their tasks were slowest using the current display and fastest for the combination of the ecological interface with displays designed to support performance on specific tasks, with average time for the ecological display in between. Only the difference between the current display and the combination of the ecological interface with displays designed to support performance on specific tasks was significant.

The results further demonstrated improved fault diagnosis with the design that was a combination of the ecological interface with the displays designed to support performance on specific tasks. There was no significant difference in the accuracy of fault diagnosis for the current design (the design used in actual operations) alone and the ecological display alone. These results regarding fault diagnosis applied both to scenarios considered during the design of the ecological interface and the task-based interface and to scenarios that were not anticipated during the design process.

Summary

Studies like those just reviewed, and others summarized in Burns and Hajdukiewicz (2004), provide support for the potential value of representation aiding as a design strategy to support the operation of complex systems for tasks such as fault diagnosis and process control. Although they do not provide data based on Boundary Level 5 evaluations, which would provide the greatest face validity for the results, there are findings that are supportive at Levels 3 and 4.

However, although all the aforementioned studies are supportive of the value of representation aiding as a design strategy, Jamieson's study also provides evidence that additional, complementary design strategies (such as the design of displays based on cognitive task analyses) may further enhance performance when combined with designs based on the principles discussed in this review on representation aiding.

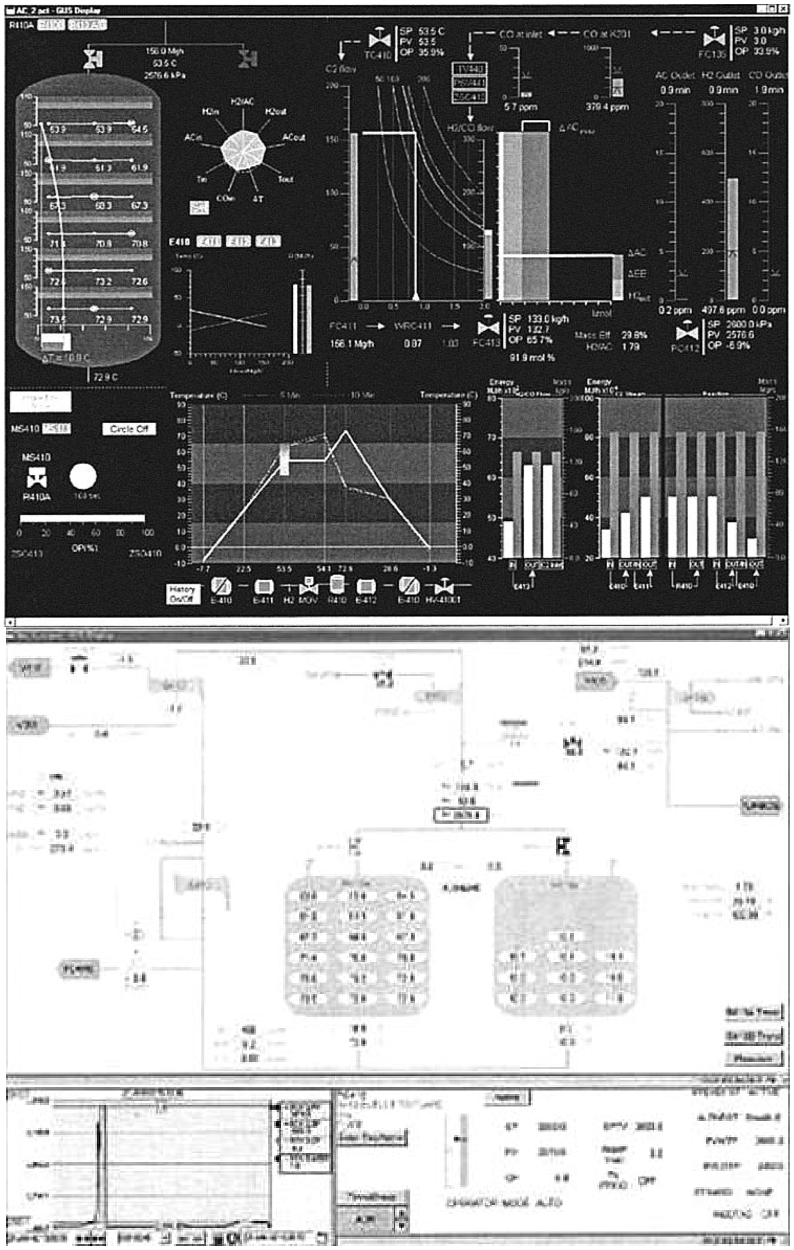


Figure 3.8. *Graphical displays from a representation aiding display with a task-based display for process control of an acetylene hydrogenation reactor. The display presents information about the physical state of the system and its functioning, as well as information based on procedures to support specific tasks. From Jamieson, 2002a. Reprinted with permission from* Proceedings of the Human Factors and Ergonomics Society 46th Annual Meeting, *2002. Copyright 2002 by the Human Factors and Ergonomics Society. All rights reserved.*

CONCLUSIONS AND FUTURE RESEARCH

The literature on representation aiding reviewed in this chapter is grounded on a model that identifies direct perception as a key process underlying expert performance. This model asserts that in many real-world tasks, experts become attuned to patterns in the environment that afford direct perception (Vicente & Rasmussen, 1990) of the diagnosis or solution to a problem, without the need for slower, controlled reasoning processes that must be applied to some internal representation of the problem.

Designs Based on Representation Aiding for Anticipated Scenarios

Based on this model, this literature provides the following guidance to designers: For known scenarios, develop representation aids that enable direct perception, allowing the user of the system to employ skill- and rule-based processes to conduct routine operations and to detect, diagnose, and deal with abnormalities. Such representation aids support performance when the system is operating correctly or when some malfunction arises, because they support direct perception of the diagnoses or responses necessary to maintain proper functioning and to respond to abnormalities.

This literature goes a step further and provides illustrations of how to develop such representations. One of the most significant examples is the use of configural displays (Bennett et al., 1993), in which the critical features that support direct perception emerge from carefully designed data displays that indicate the state of relevant domain properties or constraints.

There is strong empirical evidence that attention to this guidance on the use of representation aiding to support direct perception in known scenarios can lead to the design of more effective displays. These findings have repeatedly shown that in a variety of simulated worlds for different domains, for those scenarios that have been predicted by the designer, displays incorporating representation aiding lead to better fault diagnosis than do systems in use in these domains and better than other alternatives, such as mimic displays (Burns & Hajdukiewicz, 2004; Vicente, 2002).

Evidence regarding the use of representation aiding to support performance in anticipated scenarios would be further strengthened by future research if Boundary Level 5 evaluations (studying experienced practitioners at work using representation aiding designs for their everyday operations) were conducted and provided similar results.

Designs Based on Representation Aiding for Unanticipated Scenarios

The ecological interface design literature on representation aiding goes beyond helping designers develop displays to deal with anticipated scenarios, however. It starts with the premise that we need to develop decision support systems (Smith et al., 2006) that keep the human expert in the loop because of the potential brittleness of the technologies used to operate complex systems (Larson & Hayes, 2005; Smith et al., 1997). It then provides a method for doing so, first by identifying the critical constraints for the domain of interest (Vicente, 2002) and then by supporting direct perception to enable the user to directly perceive a constraint that has been violated.

In some cases, knowledge that a particular constraint has been violated may be sufficient to directly diagnose or solve the problem, even in an unanticipated scenario. In other cases, however, direct perception of which constraint or constraints have been violated helps focus the user's attention as controlled, knowledge-based processes are employed to reason about the underlying problem.

Thus, representation aiding makes the violation of critical constraints associated with the domain more salient via automatic perceptual processes. This, in turn, should make it easier to apply controlled processes to complete problem solving, with critical aspects of the problem solving that once required knowledge-based behavior translated into skill- and rule-based behaviors and thereby made more efficient. This is consistent with findings in the cognitive science literature regarding the value of diagrams for problem solving.

Scaife and Rogers (1996), for instance, discussed the value of diagrams for improving performance "through directing attention to key components that are useful or essential for different stages of a problem-solving or a learning task" (p. 207). Similarly, this is analogous to the representation of the digits game as Tic-Tac-Toe, as discussed earlier, in which the interface indicates key constraints and further serves as an "externalized mental model for problem solving" (Vicente, 2002, p. 64).

However, with regard to the use of representation aiding to make violations of domain constraints salient, note that we said they "should make it easier to apply controlled processes to complete problem solving." We include this caveat because there is a need for further research along three dimensions in order to further support this hypothesis.

First, more research is needed at Boundary Levels 3–5 using test cases in which scenarios that were not anticipated in the design are developed.

Second, more detailed models are needed to characterize the nature of the knowledge-based processes that are engaged when an unanticipated problem arises in a system that supports direct perception to detect violations of domain constraints, and that provides an externalized mental model to further support these controlled reasoning processes. Much of the literature on representation aiding was developed in contrast to traditional symbolic reasoning models based on models of direct perception to support performance instead of on models involving the applications of cognitive operators to internal models (Hegarty, 2004; Keodiger & Nathan, 2004; Koffka, 1935; Newell & Simon, 1972; Ormerod, 2002; Sternberg & Davidson, 1995; Zhang & Wang, 2005). Vicente (2002) noted, however, that "knowledge-based behavior involves serial, analytical problem solving based on a symbolic mental model" (p. 64). This raises an interesting question: To what extent does the cognitive science literature on problem solving as symbolic reasoning provide insights into knowledge-based processing when using representation aids to deal with an unanticipated scenario?

Third, at present, discussions of representation aiding provide examples of specific forms that can be used to support direct perception. There is, however, a need for stronger guidance and supporting empirical data on how to craft the interface for a specific application, especially with respect to supporting both skill- and rule-based behaviors for anticipated scenarios and knowledge-based processes for novel or unanticipated scenarios.

Additional Research Issues

Most work to date on representation aiding has focused on the operation of a system by a single person. In order to deal with cognitive complexity, however, many complex systems involve teams of operators. Thus, a wide-open research question concerns how and when to apply representation aiding concepts to support distributed work.

In addition, most research on representation aiding has compared either the design of an operational system or a system based on some so-called pure design strategy (such as the use of a mimic display) with a pure design based on representation aiding. An exception was the study by Jamieson (2002a, 2002b), described earlier, in which the best performance on fault diagnosis tasks was found to be provided by a design that combined displays based on representation aiding and task-based displays developed using a cognitive task analysis. This exception raises the interesting question of whether and when hybrid solutions are likely to be most effective and indicates the need to develop a model that helps to understand and guide such design decisions.

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