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AN ECOLOGICAL APPROACH TO INTERFACE DESIGN

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Four approaches to interface design are considered: technology centered, user centered, control centered, and use centered (ecological). Each perspective provides unique insights into pieces of the interface design problem. However, it is argued that the ecological or use centered approach provides a more comprehensive framework within which the other three perspectives can play important supporting roles. This approach goes beyond issues of information requirements to address meaning as an emergent property of a dynamic work ecology.

A fundamental goal of cognitive systems engineering is to design the information support needed to couple human operators and technologies into collaborative, adaptive control systems that are able to function reliably in complex work environments. In Hollnagel's words (1988), the objective is to "provide the *right* information at the *right* time and in the *right* way" (p. 221). Of course, this statement is meaningless until you can specify what "right" means in the context of a specific work environment. This paper reviews four approaches to the design of human-machine systems and the implications for what "right" means. These approaches will be reviewed and a case will be made that an ecological or use centered approach provides the most comprehensive perspective to the interface design problem.

THE TECHNOLOGY-CENTERED APPROACH

The first perspective is a *technology centered* approach. This perspective focuses on the capabilities (and limitations) of technologies. The emphasis is on what can the new technology do? How high, fast, far can the new vehicle fly or can products be produced? At what expense? How "smart" are its automatic systems? How flexible are the display surfaces? The emphasis on technology is a natural consequence of the significant role that technology plays in shaping the human experience. The development of advanced technological systems has greatly expanded the envelop of our experiences and developments in sensing, computing, and controls have had enormous implications for the efficiency and reliability of operating these systems. The emphasis of the technological centered approach is on fully utilizing the functionality offered by new technologies.

In the technology centered approach the interface typically is designed in a way that reflects the technological capabilities. There is a display for every sensor and a control axis for every control surface. This approach to display design is sometimes referred to as a single-sensor-single-indicator approach. Stokes and Wickens (1988) note that this approach can lead to a proliferation of displays that operators must process. For example in aviation this includes various warning indicators, status displays, air traffic control data links, meteorological information, navigational information, and communications data. It seems that with each new innovation in sensor or automation technology a new display is added. Stokes and Wickens (1988) express concern that this proliferation of data may exceed the information processing capacities of the operator. These potential problems in the domain of aviation may be even greater in other high technology work domains such as nuclear process control, medicine, and manufacturing where the number of state variables and the amount of uncertainty associated with these variables can be much greater.

THE USER-CENTERED APPROACH

The concerns of Stokes and Wickens (1988) lead naturally to a second perspective on human-machine systems --- a *user centered* approach. Fitts and Jones' (1947) analyses of human errors in reading instruments and operating aircraft controls illustrated the importance of the "human factor" for the proper functioning of aircraft systems. The user centered approach has tended to focus on the limitations (and capabilities) of human operators and the implication of these limitations for how systems ought to be designed. This approach has emphasized questions about how much will the humans have to perceive, do, and remember? What decisions will the humans have to make? What problems will they have to solve? What kinds of errors are people likely to make and how do design features (i.e., performance shaping factors) influence the kinds and probabilities of human error? The principal objective of this approach is to ensure that the "demands" of operating a new technology do not exceed the limited information processing capacities of its human operators.

For the user centered perspective, the capacity and expectations of the users are important concerns for designing the interface. The presentation of information should conform (where possible) to user expectations (e.g., population stereotypes or mental models) and the information should be integrated into a small number of chunks (e.g., perceptual objects) so as not to exceed the working memory capacity of the operator. Principles such as stimulus-response compatibility (Fitts & Seeger, 1953; J. Simon, 1969), stimulus/central processing/response compatibility (Wickens, Sandry, & Vidulich, 1983), and proximity compatibility (Wickens & Carswell, 1995) are representative of a user-centered perspective on interface design.

THE CONTROL-CENTERED APPROACH

The third perspective on human-machine systems is a *control-centered* approach. This approach focuses on the coupling between humans and technologies. In this perspective, the human is viewed as a controller or supervisor of the technology (or plant). The technology is generally characterized in terms of its dynamics. These dynamics can be represented by a set of first-order differential equations --- state equations. The variables in these equations are called the state variables or states of the system and the coefficients represent the action constraints that determine the mapping from current states to future states.

The fundamental emphasis for the control-centered approach is on the stability of the human-machine control loops. Critical concerns include the order of control (i.e., the number of state variables needed to characterize the dynamics) and the time delays (i.e., the time it takes to respond to an input). High orders of control and/or long time delays can result in instabilities (e.g., pilot induced oscillations). From the control perspective, a fundamental concern with respect to the interface is observability --- to make sure that all state variables are measured and represented in the display and to minimize time delays and noise associated with the measurement and display process. One strategy for reducing the delays associated with human information processing is to support the operator's capacity to anticipate future states. Research from this perspective has shown that predictive displays (Jensen, 1981; Kelly 1968), quickening (Birmingham & Taylor, 1954), and compensatory formats (Poulton, 1974) can help the operator to "stay ahead" of the process. These displays result in greater stability of the human-machine control system.

Another important concern for a control theoretic approach to human-machine systems is controllability. This is typically reflected in the organization of components (human and automation) within the control system. This organization has important implications for determining the role (or mode of control) of the human operator and the associated information requirements. An important consideration is whether the human is required to function as a "manual" controller or as a "supervisory" controller. Sheridan (1996; 1992) and Weiner (1988; 1985) discuss the implications of the relative role of human and automated systems within this control-loop. In general, automation can often increase local stability by reducing the time constants in the inner loop (e.g., autopilots). However, these automated systems have been characterized as "brittle" due to the fact that they function well as long as certain global assumptions about the control context are satisfied (e.g., linearity or stationary dynamics). When these assumptions are violated (e.g., the dynamics of an aircraft can change at high altitudes) the systems can become unstable, without adaptation or intervention from a supervisor. Humans, on the other hand, have difficulty keeping up with the demands of the inner loops, but tend to be more robust in creatively responding to unexpected events (violations of global assumptions). The fundamental question is how to link human and automated systems together in a way that satisfies both the local and global constraints on stability?

THE ECOLOGICAL OR USE-CENTERED APPROACH

The first three approaches differ in terms of which constraints are emphasized --- the technology centered approach emphasizes the capabilities of the machine (e.g., aircraft and automated systems); the user centered approach emphasizes the limitations of the human information processing systems (e.g., workload); and the control centered approach emphasizes the stability constraints arising from the coupling between the human controller and the machine dynamics (e.g., observability and controllability). Despite these differences in emphasis, these alternative perspectives have a common image of the "system." For these three approaches, the system is the human and the machine (e.g., the crew and the aircraft systems or the human-computer interaction).

The fourth approach, the *ecological* (Rasmussen & Vicente, 1989) or *use centered* (Flach &

Dominguez, 1995) perspective, starts with a broader image of the system. This perspective includes the work domain (work space or problem space) as an integral component of the "cognitive system." Whereas, the first three approaches define the system relative to its structures (i.e., human and machine) the use centered approach defines the system relative to its function within a larger work or problem space (i.e., ecology).

H. Simon (1969) illustrated the importance of this broader functionalist perspective in his parable of the ant. In this parable, Simon speculates on the best approach to modeling an ant's behavior as it locomotes across a beach. He points out that when the ant's path is isolated from the beach it appears complex and the underlying rationality is not at all obvious. However, when the path is seen in the context of the beach and its objects (e.g., food, obstacles, home) the underlying rationality becomes more apparent. The point is that a model of performance must include consideration of constraints arising from both the beach and the ant.

The use-centered perspective starts with an analysis of the work domain (e.g., the beach). What are the possibilities or affordances and what are the costs and values associated with these affordances? From this perspective the human is viewed as an adaptive "meaning" processing system, rather than as a limited capacity information channel (Flach, In press). The use-centered framework assumes that the rationality which guides the actions of this meaning processing system can only be understood in relation to the "ecology," "context," or "situation." Similarly, the technology, is viewed as an "instrument" or "tool" that can best be appreciated in terms of its "function" relative to a work space (ecology, etc.). The human may often interact with the work domain through a computer or automatic control system, but it is the interaction with a work domain that is the ultimate concern. Does the "tool" make work easier or harder?

In the use-centered perspective the focus shifts from the interaction between humans and machines to the interaction between humans and work. The constraints that matter in terms of the work become fundamental, and the constraints on human information processing, on technology, or on the control loops become secondary. This does not mean that information processing constraints, technological constraints, or control constraints are not real or that they are irrelevant to the interface design problem. Rather, the point is that these constraints can best be appreciated relative to a situation --- in Suchman's (1987) terms these constraints are "situated" (See also, Flach & Rasmussen, In press).

Rasmussen and Vicente (1989) coined the term "ecological interface design" (EID) to characterize a use-centered approach to display design (See also Rasmussen 1998 for extensive discussion of ecological interfaces). The term "ecological" was adopted to emphasize the focus on constraints arising from the work ecology--- a focus shared by "ecological" approaches to human performance (e.g., Brunswik, 1959; Gibson, 1979). The term "ecology" is used (instead of environment) to emphasize the reciprocal dynamic between the operator and his work niche. The term "environment" tends to be used for things outside of (or extrinsic) to the system. The term ecology is used to explicitly include the work domain as an intrinsic part of the distributed cognitive system (see Hutchins (1995) for an excellent discussion of distributed cognitive systems). Woods (1991) used the term "representational aiding" to emphasize that the displays were "representations" of the work or problem space. Thus, it was important that the displays be designed to reflect the "structural truths" (Wertheimer, 1959) of the problem (work) space. Bennett and Flach (1992) used the term "semantic mapping principle" to emphasize that the constraints of the work ecology reflect the task "semantics" of the work domain. In other words, salient distinctions within the display ought to map to meaningful distinctions within the workspace.

The general implications of a use-centered approach to the issues of "right information," "right time," and "right way" are that the questions must be framed in the context of a dynamic distributed cognitive ecology. The limitations of technologies, humans, and control systems are important considerations --- but the significance of these limitations can only be appreciated relative to the functional demands of a work domain.

The question of "right information" is not adequately addressed by making the "state" variables available to the operator. For example, it is not enough for the pilots to know the current altitude. They must also know the significance of that altitude relative to their flight objectives (e.g., landing, evading detection from enemy radar, etc.) and relative to the dynamic capabilities of the aircraft (e.g., Cessna or F-16). They must know whether they are "too low" or "too high." Flach (In press) presents a preliminary design concept for a configural flight display that attempts to explicitly represent some of these boundaries to the field of safe travel. Vicente (e.g., 1988, 1992; Bisantz & Vicente, 1994; Vicente, Christoffersen & Pereklita, 1995; Vicente & Wang, 1998) shows how Rasmussen's abstraction hierarchy can be utilized to help define the "right information" for a process control interface. This program of research has contributed important empirical evaluations of the ecological framework and demonstrates how that framework can be used to make sense of a wealth of empirical research on expert performance. Itoh, Sakuma, and Monta (1995) and Vicente, Moray, Lee, Rasmussen, Jones, Brock, & Djemil, (1993) demonstrate how Rasmussen and Vicente's insights can be generalized to complex systems outside the laboratory. Work is continuing to further develop and evaluate these display concepts in the context of a full scale nuclear reactor system (Tanabe, Yamaguchi, & Rasmussen, 1998; Yamaguchi, Furudawa, & Tanabe, 1998). These studies illustrate the development of ecological interfaces for nuclear power plant control rooms and provide empirical support for the approach.

Control theoretic analyses help to define the time requirements (e.g., minimum delays) for stable control. However, the "right time" for presenting information cannot be determined based on stability requirements alone. If the human operator is in the control loop, then whether and how the information is perceived and whether the information is remembered depends critically on the context of presentation? For example, Neisser and Becklan's (1975; also see Fischer, Haines, & Price, 1980) work on attention illustrates clearly that human are actively interrogating the available information. If the information is not relevant to the questions that the operator is asking at the time, then there is a strong likelihood that it will not be perceived. In the Fischer, Haines, and Price study, pilots failed to see an aircraft incursion onto a runway that they were approaching when attending to a head-up display. The information was above threshold, it was within the field of view in ample time to make evasive maneuvers, but it was not perceived because it did not fit with the questions that the pilots had framed in the context of their interaction with the head-up displays. The key point here is that operators are actively seeking information --- thus, the cognitive operators are integral components within the dynamic system. They are not just additional sources of noise and time delay. Dynamic or temporal considerations about the information coupling must be framed in the context of the distributed cognitive system. The questions that the human operators ask are shaped by the situation (i.e., the context or work domain).

Analyses of how humans chunk information suggest that the "right way" is to integrate information into "perceptual objects." However, research by MacGregor and Slovic (1986) illustrates that creating perceptual objects is not enough. In that study, integral face displays gave both the best and worse performance depending on the mapping of elements within the perceptual object to decision variables. Performance was best when the critical decision variables were mapped to salient features within the perceptual object. The appropriate mapping of variables to features of a display is critical to the success of a configural display. Bennett & Flach (1992) illustrate how ecological principles can help to make sense of a wide range of empirical studies that have evaluated graphical interfaces (See also Bennett, Nagy, & Flach, 1997; Flach & Bennett, 1996; Sanderson, Flach, Buttigieg, & Casey, 1989; Wickens & Carswell, 1995). The criticality of information must be determined relative to the functional demands of the dynamic work environment and the mapping of information to features of a configural graphic must reflect the semantic structure of the work domain. The nesting of information within a configural graphic should reflect the nesting of meaning as characterized by the abstraction hierarchy.

CONCLUSIONS

Hollnagel's (1988) statement about the objectives of interface design at the start of this paper --- "provide the *right* information at the *right* time and in the *right* way" (p. 221) --- is often mistaken for the answer to the interface design question. Actually, it is simply a restatement of the problem --- the fundamental question is to define "right." Rasmussen (1998) reviewed trends in research to understand human and organization performance in ways that will help designers to determine what "right" means. Early in research programs "right" has been defined with respect to normative, prescriptive models of performance (e.g., optimal control). Then as observations accumulate, deviations from normative models have been observed and these have led to descriptive theories in which deviations from the norm were attributed to human limitations (e.g., heuristic decision models). Eventually, increasing amounts of evidence of systematic patterns of performance have suggested an intrinsic rationality (different from the extrinsic rationality of normative models). At this phase, descriptive models of cognitive processing have begun to replace the normative models (e.g., recognition primed decision model). Finally, as behavior is observed across many different contexts (from laboratory paradigms to performance in natural work environments), there is increasing appreciation of the adaptive, context sensitive nature of performance. At this stage, models are just beginning to shift from a focus on internal human rationality to a more expansive view of the "eco-logic" shaping the patterns of adaptation.

There are multiple layers to the question about what is "right" that reflect the different approaches to human factors (Rasmussen, 1998). Of course, the ecological approach assumes that the eco-logic (reflecting constraints and affordances of situations) is at the heart of the problem. This does not mean that other layers do not provide valid insights into the phenomena of human work. It is simply a matter of depth of analysis. The ecological approach assumes that the eco-logic provides the deepest insights into the invariant nature of adaptive cognitive systems. The convergence of numerous fields supports this assumption (e.g., the evolution of decision making research from normative logic, to heuristic models, to naturalistic decision making).

In sum, questions about the right information, the right time, and the right way cannot be adequately addressed within the narrow scopes defined by either the technology, the human information processing system, or the control system. Each of these components must be considered within the larger context of the work ecology or eco-logic (i.e., the dynamic coupling between intelligent agents and the functional demands of a work domain). The first step to building intelligent interfaces is to uncover the meaningful properties that emerge from the dynamics of that ecology. In the end, it is the ability to represent meaning, not information that is the test of an interface. The ecological approach is a framework for addressing meaning as an emergent property of a dynamic work ecology.

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