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A technological imperative in high tech systems

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ECOLOGICAL INTERFACES:
A TECHNOLOGICAL IMPERATIVE IN HIGH TECH SYSTEMS?[1]

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INTRODUCTION

The topic of the present paper is the design of ecological interfaces for advanced technological systems. Ecological interfaces are characteristic by representing the interior functional structures and states of a system in the human-machine interface in a way that matches the immediate task and the cognitive characteristics of the user. It is argued that the present trend in technological development towards large, complex, and rapidly changing socio-technical systems makes this kind of interfaces important for system reliability and safety.

A TECHNOLOGICAL IMPERATIVE?

Complex, large-scale technical systems pose new requirements to the operating and maintenance staff in order to avoid major economical losses and damage to people and property in case of disturbances and maloperation. Therefore, new and difficult requirements must be met by the design of human-system interfaces. To explore why this is the case, we will have a brief look at the technological development and the changing match to the human cognitive system.

Natural environments. During millennia, evolution has granted humans an extremely effective perceptual-motor system serving control of the dynamic interaction with the environment. Being able to dynamically interact with the environment and its inhabitants was a key to primitive man's survival. Thus, the evolutionary process has resulted in the development of capabilities for very efficient feature extraction and classification, and dynamic coordination of the motor system with the environment. Some of the char-

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acteristics of this perceptual-motor system are 'hardwired' while some depend on adaptation to the characteristics of the environment during a learning phase.

In man-made environments, humans will not necessarily be able to benefit from this long evolution. When new work conditions are met (e.g., when new tools are introduced), further adaptation is necessary to supplement the product of natural evolution. Learning to use new tools involve two phases. One includes adaptation guided by exploratory behavior. The second is the adapted phase,when behavioral patterns have reached a state of equilibrium. Which of these phases is more important depends upon the characteristics of the work domain.

Stable Work Domains with moderate-size artifacts. In stable or slowly changing environments, the adaptation phase is transient and is eventually overcome with training and experience. The major part of work falls into the equilibirium phase of stereotypical working patterns which are governed by surface features of the environment, i.e., activity is guided by stereotype cue-action correlations. As a result, in traditional tools and systems, users are not in general concerned with the system's internal physical functions, but rather with the surface features of the work environment. In case of difficulties, trial-and-error exploration is acceptable, i.e., the cost of an error can be expected to be less than the value of the information gained. Consider the example of a radio receiver. Everybody will know how to operate it without knowing its functional properties.

High Technology Work Domains. A number of properties of high-tech environments raise complications for interface design. Automation of work processes moves workers to situations requiring discretionary tasks involving decision making and conscious planning and choice. In this situation, exploration of opportunities and boundaries of acceptable performance remain a part of daily work activities. In other words, the second phase of activities characterized by equilibrium is never actually reached. Instead, task demands are in a state of flux, requiring continual adaptation efforts on the part of workers.

Large-scale Systems. An additional problem is the increasingly large scale of high-tech systems. Malfunction in large systems can have unacceptable effects on people, property, and the natural environment. Therefore, learning and adaptation based on trial and error exploration is no longer acceptable. In addition, unlike the normal users of e.g., cars and radio receivers, operators of high-tech work domains are also responsible for safely controlling the system after it fails. And because the systems are so complex, there is a very large number of possible malfunction modes. Every fault will be completely unique, and therefore, cannot be anticipated. As a result, it will not be possible for operators to learn all appropriate response patterns from other persons, such as colleagues, teachers, and designers, nor can they find guide in pre-made instructions such as manuals or 'expert system.'

These factors combine to produce a new class of complex, flexible, changing work environments in which users and operators will not be able to rely on stereotypical control patterns derived from adaptation to surface properties. Instead, they will often need to select and plan their actions based on an understanding of the internal processes and functional structure of the system. The problem is that this information is typically not visible. For instance, the large internal mass- and energy flows of a power plant cannot be observed by the unaided eye and yet they are both the object of control of the operator and the basic source of large accidents. In such cases, control based on learned responses to surface features will not be possible.

In this way, advanced technology poses the following new requirements for interface design:

1. It is mandatory that the internal functions of the system are represented at the surface, i.e., the interface, in a way that they can be directly operated under unfamiliar as well as familiar conditions;
2. In order to activate the normally very effective and reliable sensori-motor system, the representation used for the interface should support direct perception and manipulation of the internal control object as well as analytical reasoning;
3. Design of interfaces can no longer be allowed to evolve empirically through trial and error, nor can they be based on general rules and guidelines applied by human factors experts; the interface design is an integrated part of the functional systems design and, like the latter, requires subject matter expertise.
4. Finally, designers of systems must have an in-depth knowledge of the cognitive context in which the system is to be implemented, in order not to choose display forms which are in conflict with the established norms, mental models, and organizational structures as communicated by text-books, drawings, and manuals of the profession and company practice.

THE CONTROL OBJECT: INTERNAL SYSTEM FUNCTION

In many modern work systems, the user or operator will frequently have to go beyond surface properties to control system behavior; the question is how far back into the system? One critical issue in interface design is that the answer to this question depends on the situation. The mode of representation necessary to support the control task will shift along a whole-part dimension concurrently as span of attention shifts from control of the entire system to manipulation of one single physical component. When span of attention changes it is also, in general, necessary to consider different representational languages corresponding to different levels in a means-ends hierarchy in order to identify the control problem and to choose means of control (Rasmussen, 1985). To illustrate this feature of technical systems, the different levels of identifying the control task in a power plant are shown in table 1. In other words, how deep into the system an operator has to go to identify the actual task depends on the situation. Therefore, an operator dynamically should be able to change interpretation of the information in the interface.

Table 1: Levels of Control Tasks

Means-Ends Levels of Description	Typical Control Tasks in Power Plant
Goals, purposes, and constraints.	Monitor production and safety specifications of the customers.
Abstract function; flow of mass, energy, and information.	Control of the flow of energy through the plant from source to electrical grid; Monitor major mass and energy balances for plant protection.
General functions.	Monitor and control individual functions such as coolant circulation, steam generation, power conversion from steam to electricity.
Physical processes of equipment and components	Adjust process parameters in order to align operational states of components and equipment to match requirements and limitations;
Form, location, and configuration of equipment	Connect and disconnect components; change anatomy and configuration of equipment and installations to match requirements of physical processes and activities.

Table 1. The table illustrates how identification of the control task in a power plant can take place at several levels of abstraction. In other words, how deep into the system an operator has to go to identify the actual task depends on the situation.

THE HUMAN PERCEPTUAL SYSTEM

The argument brought forward in the present paper is that it is possible to bring into action the sensori-motor system, which accounts for people's high processing capacity and reliable performance in natural environments also in complex man-made systems (Rasmussen, 1974; 1986). The high efficiency of this part of the cognitive system cannot adequately be accounted for by the production systems normally adopted by cognitive scientists (e.g., Newell and Simon, 1972; Anderson, 1983) for modeling cognitive processes (cf. de Groot, 1966; Dreyfus, 1979; Rasmussen, 1974; 1986).

In the present section, a model of the human cognitive system suggested to account for observations in field studies and analysis of human error, i.e., a cognitive engineering model, is compared with the findings of ecological psychology, in particular Gibson's 'direct perception.'

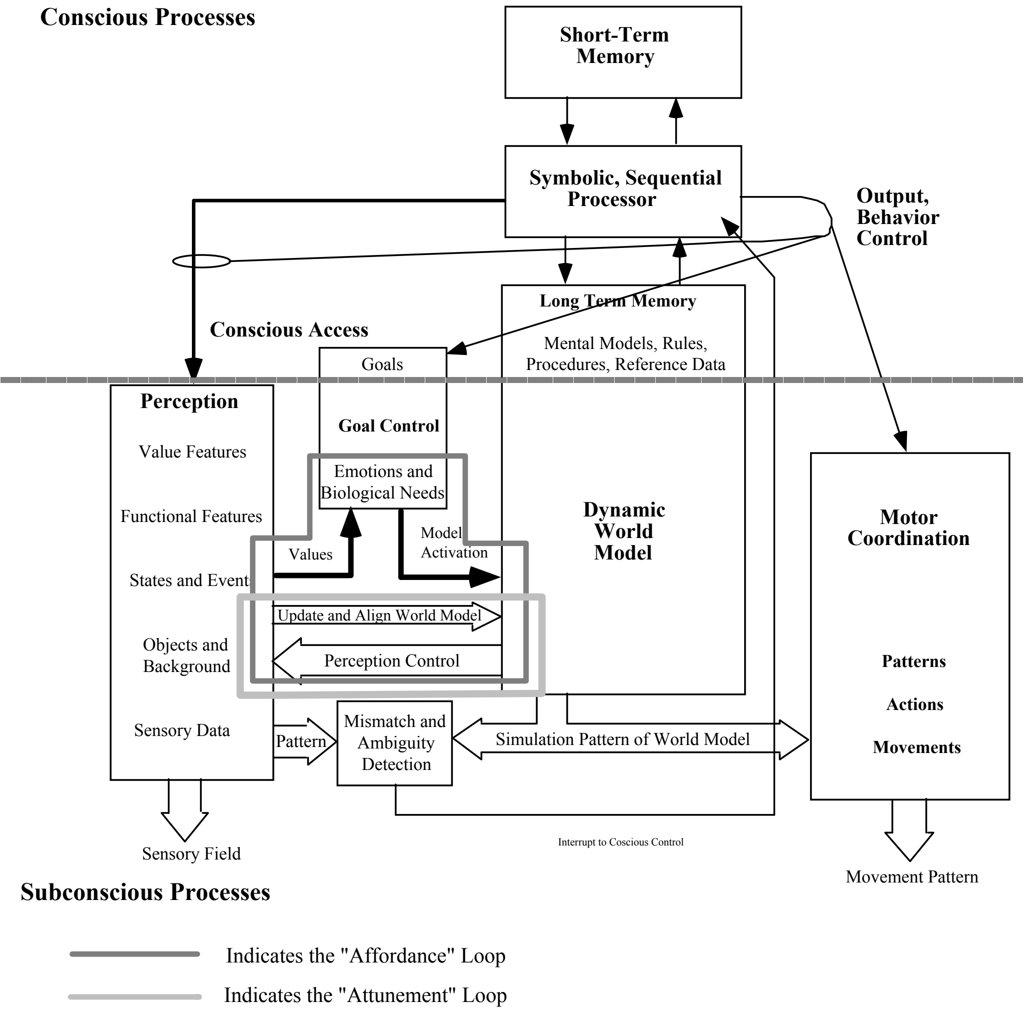


Figure 1 illustrates the interaction of the perceptive system and the internal dynamic world model which controls the active pick-up of information at different levels of abstraction. The basic figure is reproduced from Rasmussen, 1986. The complex interactions between perception, value structures and the internal world model which constitutes the affordance loop and the attunement loop in Gibson's terms are highlighted.

Figure 1 presents a functional description of the human perceptual subsystem as part of a global model of human information processing suggested in Rasmussen (1974). In this model, the active pickup of information is made possible by an internal dynamic world model, which acts to attune the perceptual system to the invariant features that are relevant to the actual goal in the present context (Rasmussen, 1986). It is also suggested that perception can operate directly at various levels of abstraction: in terms of objects and background, possible movements, context, priorities, and even value properties. It is important to note that this hierarchical structure does not imply that higher level information is obtained from analysis of lower level data; any of the levels can be directly perceived. Nor does it imply that the model maps onto anatomical parts of the neural system, it only represents functional elements of cognition, i.e., a kind of 'grammar of action control.' In this modelling approach, great similarities can be found to Gibson's concepts of direct perception through resonance of an attuned neural network (see the discussion in Rasmussen, 1986).

ECOLOGICAL PSYCHOLOGY

The challenge that Gibson (1979; 1966; 1950) took up was to try to explain how perception of the natural environment is possible. One of the key notions that he developed was that of an affordance (Gibson, 1979). Unlike some traditional approaches which assumed that perception is a reconstructive process based on elemental sensations, Gibson proposed that higher-order properties of the environment can be perceived directly through a phenomenon referred to as resonance (Gibson, 1979; 1966). In this way, the affordances of the environment - the possibilities that it offers the organism - can be directly perceived by the attunement of the perceptual system to the invariant structure in the ambient optic array. Gibson claimed that in normal cases the meaning and value of the objects are directly perceived, not only the individual characteristics of these objects.

Value Properties: Purpose, Goal			
Survival	Pleasure	Altruism	
Priorities: Abstract Function			
Reward	Danger	Nutrition	Manufacture
Cooperation	Nurturing	Copulation	Privacy
Comfort	Pain		
Context: General Function			
Communicating	Warmth	Drinking	Eating
Washing	Bathing	Injury	Support
Fighting	Shelter	Aiding	Punishment
Locomotion			
Movement: Physical Process			
Sit-on	Bump-into	Fall-off	Get-underneath
Climb-on	Sink-into	Swim-over	Walk-on
Stand-on	Grasp-able	Barrier	Obstacle
Breathing	Pouring	Cutting	Lifting
Throwing	Piercing	Carrying	
Objects and Background: Physical Form			
Layouts	Objects	Surfaces	Substances

Table 2. The levels of affordances found in Gibson's examples. The levels are related to different aspects of the control of human activity, respectively, the goal to pursue, the activity to plan, and the movements to control.

It is useful to consider in greater detail the hierarchy of levels at which direct perception of the environment can take place. Table 2 illustrates how some of the examples provided by Gibson (1979) to explain the concept of affordances can be described with the structure suggested in Rasmussen (1986). This table emphasises the fact that the world is actually composed of a hierarchy of affordances, a point that Gibson briefly alludes to (cf. Gibson, 1979, p. 137) but does not address in any great detail. An interesting property of this hierarchy is that the relation between levels is one of means-end, very similar to the levels of the control tasks in the man-made systems presented in table 1. This has important implications for the design of 'ecological interfaces', as we will see in the example presented below. Could it be that affordances can also be structured as a means-end hierarchy, thereby being a mechanism for coping with the complexity of the natural environment? Perception of affordances at the various levels has different roles in the control of human activity. Selection of goals to pursue are related to perception of value features at the highest level, the planning of activities to perception at the middle levels, while the detailed control of movements depends on perception at the lowest level of physical objects and background.

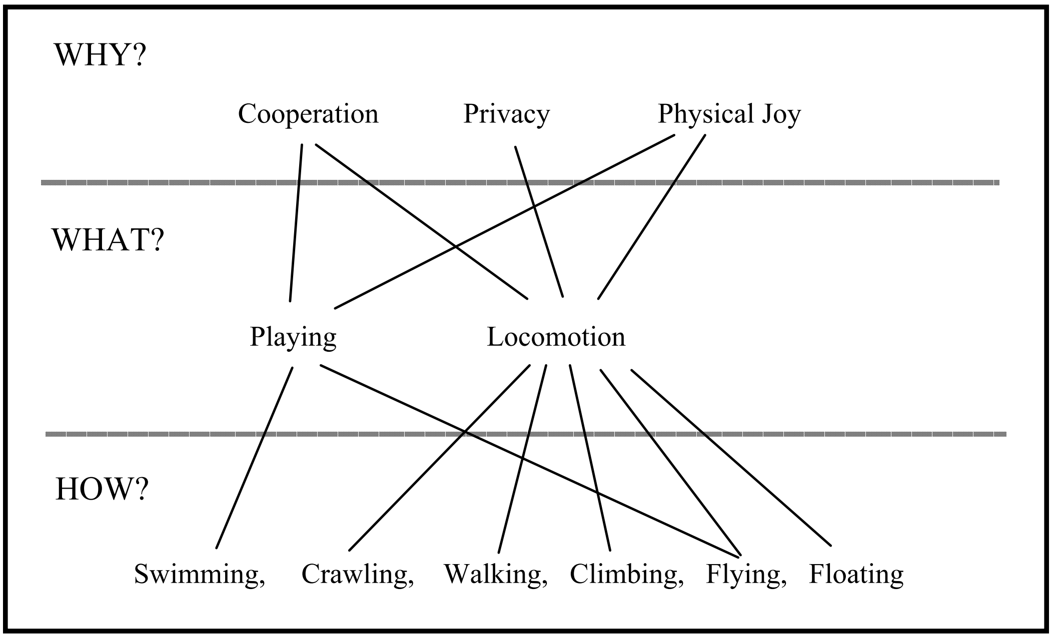


Figure 2 illustrates the many-to-many mapping between levels of abstraction in activities which will be related to environmental affordance at all levels. The three levels of abstraction in perception are relevant for control of goal setting, of activity control, and of movements respectively.

In Figure 2, several relations between levels are represented in order to show how there is a many-to-many mapping between affordances at various levels. For instance, the possibility of locomotion can be fulfilled by a number of different alternatives: swimming, crawling, walking, etc. Also, a single affordance can be relevant to more than one value-related affordance. For example, swimming may be relevant when the situational context affords either playing or locomotion. Similarly, locomotion will be relevant when there is a desire for privacy (to escape from a crowd), or for cooperation (if the partner is on the other side of the pool). The important implication is that the perception of the situational context in terms of higher-order, value-related affordances can help people deal with the complexity of the environment by constraining the number of meaningful lower-level affordances which are relevant, given the current context.

Direct perception of an artifact's affordances will generally be possible if the artifact has been adapted to human needs and capabilities. This is accomplished, either by the natural evolution of cyclical redesign (Alexander, 1964), or by forethought on the part of the designer. An artifact that is well designed should, through the appropriate use of constraints, make it obvious what it is for and how it should be used (cf. Norman, 1988). In other words, its affordances should be easy to perceive.

While Gibson was concerned with the natural environment, the discipline of cognitive engineering is concerned with complex, high-technology work domains. This class of domains can be viewed as a modern, man-made ecology. Is the theory of direct perception just as applicable to high-technology work domains as it is to the natural environment?

Gibson on Natural and Man-Made Environments

In his discussion on affordances, Gibson (1979) anticipates this issue by addressing the implications of man's alteration of the natural environment (pp. 129-130). In ecological terms, man-made artifacts can be seen as efforts to change and expand the environment's affordances. In changing the substances and shapes of the environment, man has "made more available what benefits him and less pressing what injures him" (Gibson, 1979, p. 130).

In spite of these changes, Gibson makes it very clear that he does not view this trend as involving the creation of a new kind of environment:

> "This is not a new environment - an artificial environment distinct from the natural environment - but the same old environment modified by man. It is a mistake to separate the natural from the artificial as if there were two environments; artifacts have to be manufactured from natural substances" (Gibson, 1979, p. 130).

This argument against two qualitatively different types of environments is based on a belief in the primacy of the basic components of the natural environment:

> "The fundamentals of the environment - the substances, the medium, and the surfaces - are the same for all animals. No matter how powerful men become they are not going to alter the fact of earth, air, and water .... For terrestrial animals like us, the earth and sky are a basic structure on which all lesser structures depend. We cannot change it" (Gibson, 1979, p. 130).

Apparently, Gibson did not have high-technology work domains in mind, when he presented these arguments.

To conclude, in modern high-tech systems, there is no clear cut distinction between system design and operation since the operator will have to match system properties to changing demands and operational conditions. This is equivalent to performing a control design task, on-line and in real time, an activity which will require problem solving activities based on a consideration of the internal functioning and structure of the system. Thus, high-tech work domains can be considered a qualitatively different type of environment that poses unique problems that cannot be addressed by direct perception alone.

DIRECT PERCEPTION, INVARIANTS, AND SYSTEM DESIGN

Designers of complex systems must deal with human perceptual, action, and cognitive capabilities as they are - this is a given constraint. In other words: we have to observe the laws of nature of the sensorimotor system as well as of the physical environment. However, the incredible power and flexibility of information technology makes it possible to adapt the interface of the system to human capabilities. Given the remarkable effectiveness of human perception and action, a natural goal would be to design interfaces so as to take advantage of these capabilities (Rasmussen, 1974; Rasmussen and Vicente, in press; Flach and Vicente, 1989). But since, as we have argued above, high-tech systems will require operators to constantly adapt to new and unforeseen demands, it is also important that the effortful and error-prone activities of problem solving also be supported by the interface.

The primary obstacle to overcome is that, unlike the natural environment, in most modern industrial systems the goal-relevant system properties are not directly observable unless made so by means of modern information technology. In order to support direct perception, one would have to create some sort of virtual environment that would be as rich in information as the natural ecology. Operators would have to have the capability to visually explore and manipulate the objects of this artifical environment if direct perception is to be at all possible, in addition to the inevitable problem solving activities.

There are certain characteristics of complex work domains that make such an approach a feasible one. Because these are man-made systems, the design is based on intended invariants at various levels of abstraction. In other words, there is a lawful basis for describing system functioning at various levels, such as operation of components and subsystems, as well as fundamental invariant laws such as conservation of mass and energy which are relevant for control of the overall system performance. These invariants provide the basis for the construction of a virtual, natural environment. The objective fact of their existence combined with the visualization power of computer technology makes the possibility of direct perception feasible, at least in principle.

It is worthwhile emphasising how important the existence of invariants is in the operation of high-tech systems. Such systems are designed with specific purposes in mind, and these can be considered as global invariants not to be violated (e.g., to produce power safely, in the case of a power plant). The structure of the system is meant to provide a set of means (i.e., possibilities) for carrying out the higher-order goals. In addition, the invariant laws describing the operation of the system at lower levels provide further constraints that need to be considered. Respecting the intended invariants implied for normal functioning is essential, not only to maintain the desired functioning and production, but also to avoid serious accidents if changes in system structure or the behavior of individual components threaten the global invariants. Major accidents, for instance, can be caused when the intended invariants of conservation of mass or energy within system boundaries are violated (e.g., a release to the environment). Consequently, operators of advanced systems are supposed to operate the system and to cope with disturbances by redesign of the operational regime in unforeseen situations so as to maintain the necessary conditions for the intended invariants of system behavior. For the operator to pursue this aim, the interface will have to reflect the intended invariants *through a mapping of the underlying physical laws*.

These control requirements have important implications for interface design, if we are to design systems that: a) allow operators to exploit direct perception in normal conditions, and b) reveal affordances during unfamiliar system conditions as well. Vicente and Rasmussen (1988a; 1988b; Rasmussen and Vicente, 1989) have proposed a theoretical framework, called ecological interface design (EID), that attempts to meet the goals and requirements described above. The primary goal of EID is to allow operators to take advantage of perception and action, while at the same time providing the necessary support for problem solving activities. In this section, we will concentrate on the aspects of EID that bear on exploiting direct perception. The ensuing discussion is also based on Flach and Vicente (1989), who treat the problem of supporting skilled behavior through interface design in greater detail.

ECOLOGICAL INTERFACE DESIGN

The aim of ecological interface design can be described as trying to make the interface transparent, i.e., to support direct perception directly at the level of the user's discretionary choice, and to support the level of cognitive control at which the user chooses to perform. The mapping across interfaces which will support the user's dynamic switching among levels of focus and control must support control of movements, acts, and plans simultaneously. To do this, the designer must create a virtual ecological environment which maps the intended invariants of the functional system design onto the interface.

One of the points made earlier is that the level at which state identification and intentions are expressed by people varies depending on the actual circumstances (see Table 1). In natural environments, all observable information is available all of the time. Thus, the level of abstraction at which the environment will be perceived can be varied at will by the actor. The degree of perceptual chunking is discretionary and will be related closely to the level at which the agent will express an intention to act which, in turn, is determined by the complexity of the automated patterns of movements available to the agent for the particular activity.

A good example, which will help to make these ideas more concrete, is that of musical skill (cf. Vicente and Rasmussen, 1988a). Skilled sensorimotor performance with an instrument is characterized by integrated patterns of movements resulting in a very high capacity and speed in performance. As the musician's level of proficiency increases, movements are aggregated together into higher order chunks. Whereas the novice must control at the level of individual actions, skilled musicians can work at the level of complex sequences of actions. The key requirement for attaining this type of skill seems to be the mapping between the musical notation and the associated actions. Thus, experienced musicians are able to form higher order visual chunks of notes and then directly map these onto a concurrent chunking of movements. A similar situation can be found in the skilled use of an abacus (Vicente and Rasmussen, 1988a).

This suggests that, in order to facilitate skilled sensorimotor performance in complex work domains, a similar mapping should be built into the interface. Thus, the interface should be designed in such a way that the aggregation of elementary movements into more complex routines corresponds with a concurrent integration (i.e., chunking) of visual features into higher level cues for these routines. In other words, the structure of the displayed information should be isomorphic to the part-whole structure of movements. This can be accomplished by revealing higher level information as an aggregation of lower level information (e.g. *through appropriate perceptual organization principles*). In this way, multiple levels are visible at the same time in the interface and the operator is free to guide his attention to the level of interest, depending upon his level of expertise and the current domain demands. Developing such a hierarchical visual structure should facilitate the acquisition of skill by encouraging the chunking process. At the same time, flexibility is maintained by not constraining people to attend to a specific level.

Another important aim of ecological displays will be that this kind of displays can be interpreted at several cognitive levels. Since it is transparent, i.e., it represents that internal functional relationships which are to be controlled, it will support knowledge-based, analytic reasoning and planning. Furthermore, because it reflects this relationship in a perceptual pattern, cues which will be correlated to familiar action sequences are likely to be defining patterns rather than convenient signs and, therefore, effectively can prevent 'under-specified' action mistakes. Finally, the faithful representation of the control object will invite the evolution of reliable 'direct manipulation' skills.

In developing graphic designs that will meet these requirements, it is likely that the graphic representations engineers and physicists have developed through decades to understand and to teach the lawful behavior of technical systems will be a useful starting point for interface design. Examples of such well established graphical representations are easily found. For instance, thermodynamic experts have, through decades, been guiding the evolution of graphic and other symbolic representations for communicating the principles underlying design to students and colleagues (e.g., rankine cycles, bode-plots, root-locus plots, etc.).

AN EXAMPLE: RANKINE CYCLE DISPLAY

A good example of an interface that is based on a standard engineering representation (temperature-entropy plot) and that can be read at several levels of abstraction and decomposition according to the operator's discretion is Beltracchi's (1987; 1989) Rankine cycle display for water-based heat engines. A variation of that interface, developed by Lindsay and Staffon (1988), is illustrated in Figure 3. These displays are developed concurrently and independently of our work on ecological discplay design principles. They are, however, consistent with the principles and offer good examples for illustration.

The interface is based on the display of primary sensor data in such a way that the shape of the emerging graphical patterns supports perception of higher level functional features. Graphical patterns show the circulation paths of coolant and water. Also, the temperature in different point of the paths can be read on the common scale on the left. To the knowledgeable operator, the patterns immediately show the temperature rise and fall in core, heat exchanger, etc. At the same time, temperature differences across heat exchangers can also be read. Figures 4 and 5 illustrate how propagation of a disturbance in the energy flow through the system can be directly perceived. At the same time, primary data can be easily compared and the total thermodynamic loop can be visually decomposed in correspondence with the physical component which can be chosen for control, since the data are superimposed on a symbol of the core and the heat exchangers.

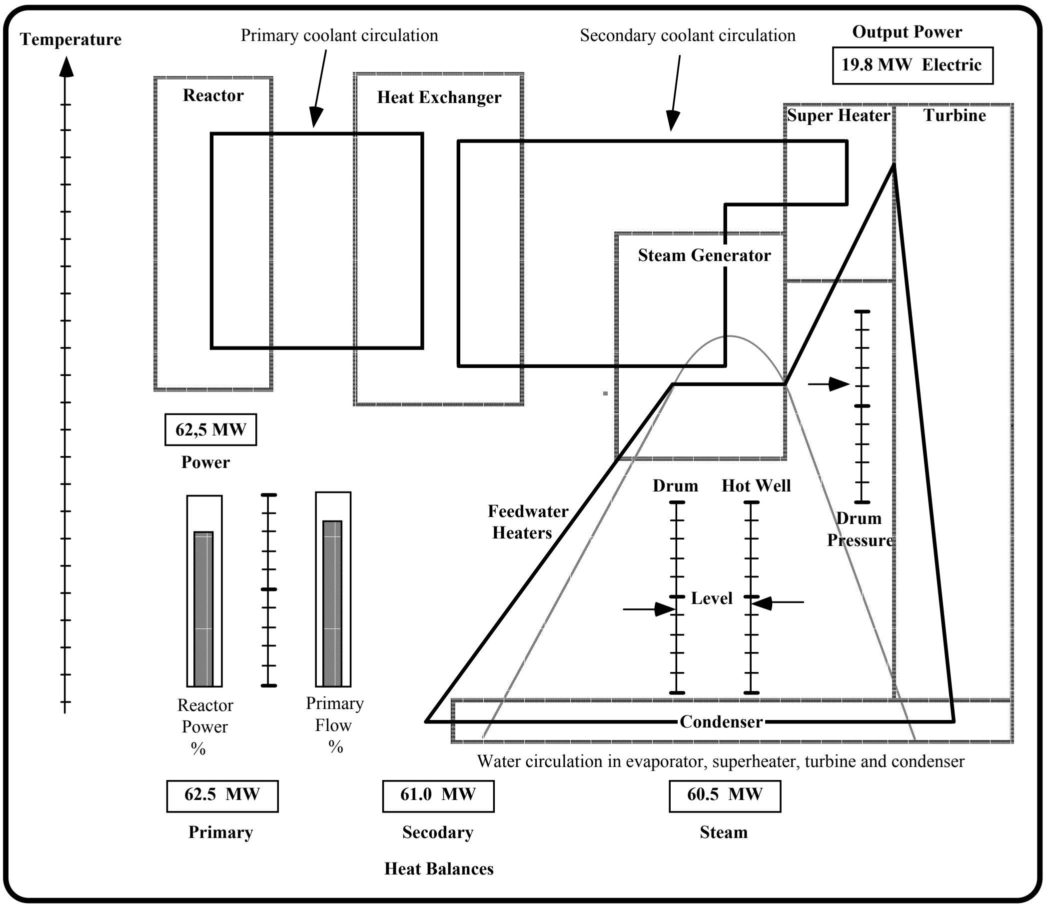


Figure 3. An experimental overall display for a nuclear power reactor. The display is based on primary measuring data used to modulate the shape of graphical patterns which support perception of higher level functional features. Graphical patterns show the circulation paths of coolant and water. The temperature in different point of the paths can be read on the common scale. The patterns, therefore, immediately show the temperature rise and fall in core, heat exchanger, etc., at the same time as temperature differences across heat exchangers can be read. Figures 7 & 8 illustrate how propagation of a disturbance in the energy flow through the system can be directly perceived. At the same time, primary data can be easily compared and the total thermodynamic loop can be visually decomposed in correspondence to the physical component which can be chosen for control. (Reproduced from Lindsay and Staffon 1988).

The symbols used in the display is explained in figure 4 to 8. Figure 4 explains the display of the coolant circuit displays, while figure 5 and 6 illustrates the complex pressure-temperature relationships in a boiler, i.e., a steam generator. Note that the primary measurements are shown, and still the functional status of the system can be directly read from the interrelationships between data.

The phase diagram of a water-steam mixture as it is found in a boiler, is shown on figure 5. To the left is water, to the right only steam, and within the curve is found a boiling water-steam mixture. This relationship is the basis of safe boiler control. Figure 6 shows the function of the steam turbine of a power plant, i.e. the Rankine cycle, with reference to the phase diagram. Water is boiling within the curve, and the operating point of a steam generator should be safely within it. At the right side of the curve, the boiler becomes dry, at the left side it will be full of water, it "goes solid" in the term of operators. Both cases are dangerous because control of temperature, respective pressure is difficult and an accident is likely. Since safety is closely related to the complex relationships between pressures and temperatures in the phase diagram, the graphic representation is well suited for monitoring purposes. After leaving the boiler, the steam is heated further in a 'superheater' before it goes to the turbine where it cools down, delivering its energy content to the turbo-generator.

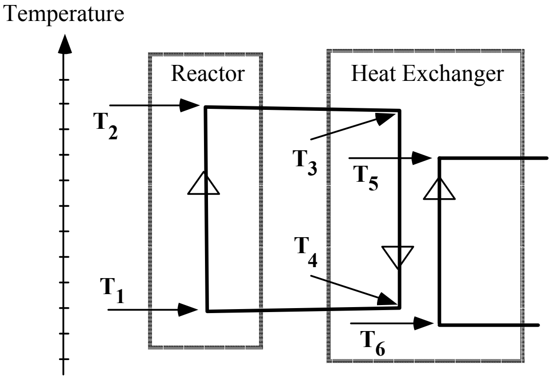


Figure 4 shows the basic graphic symbol for a cooling circuit. The background boxes represent the heat producing reactor core and the primary heat exchanger. The rectangular overlays represent the cooling circuits with arrows indicating the coolant flow direction. The sides of the rectangles indicate temperatures with reference to the scale: The reactor heats the coolant from temperature T1 to T2. The coolant temperature drops a little in the pipe to the heat exchanger, from T2 to T3 and further from T3 to T4 when delivering energy to the heat exchanger. The cold coolant looses further a little temperature T4 to T1 on its way back to the reactor.

Figure 7 and 8 illustrate how the graphic patterns can support an overview of the propagation of changes through the system in case of disturbances. Figure 7 shows the change in the coolant flow/temperature pattern when the primary coolant flow is suddenly increased. The power production can now be transported by the coolant with a lower temperature rise and the temperature profile of the primary collapses, as compared to Figure 3. The secondary circuit is not yet affected and its higher temperature forces power backwards through the heat exchanger. This can be seen directly from the change in sign of the temperature difference between secondary and primary side of the exchanger.

Figure 8 presents the state of the system a little later. The transient has now reached the secondary circuit while the primary circuit is restoring due to an increase in power production caused by the decreased temperature and a negative power-temperature coefficient. Note that the individual temperature representations of the display, such as for instance, output temperature from core and input temperature in heat exchanger, are based on separate sensors. Inconsistency from sensor failure, therefore, can be seen directly if a slope appears of the horizontal lines representing pure coolant transport in pipes.

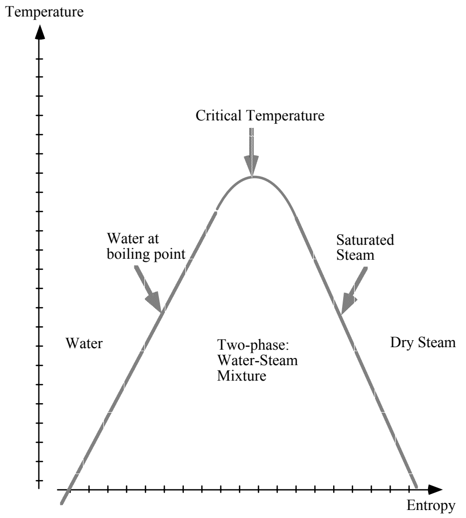


Figure 5 shows the two-phase diagram of a water boiler.

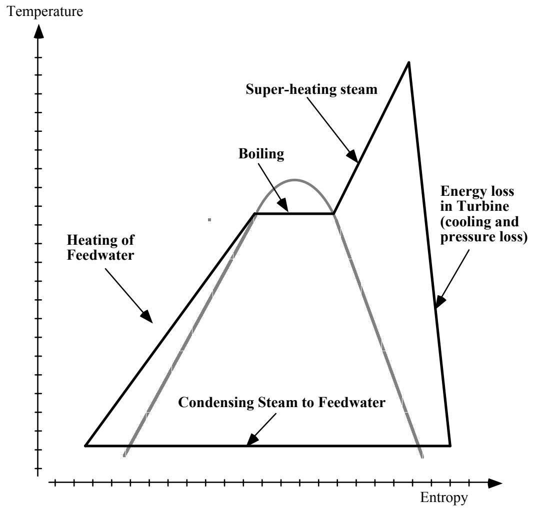


Figure 6 shows the Rankine-cycle of a power plant.

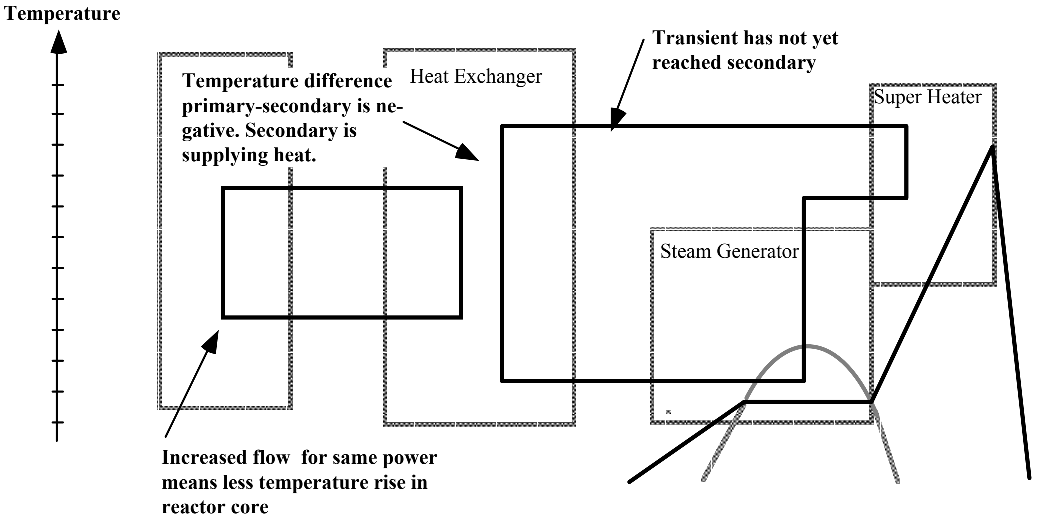
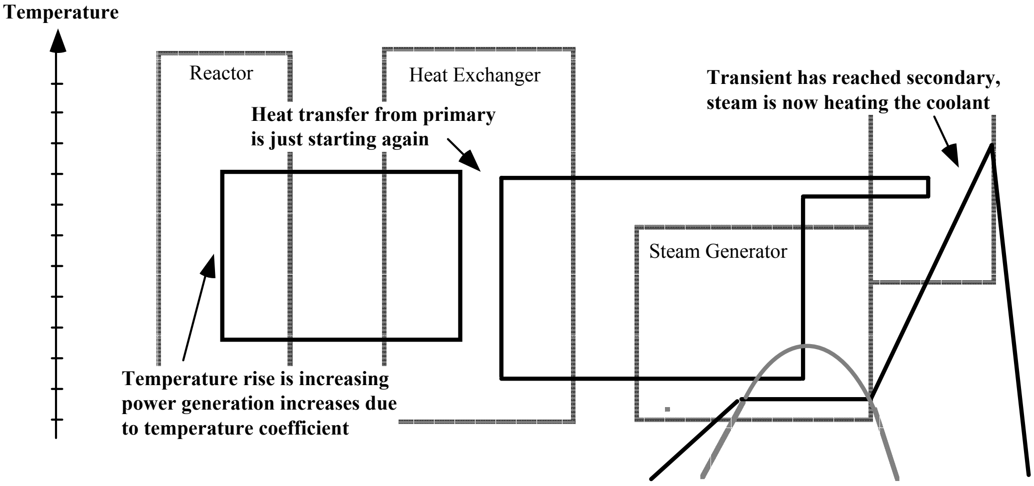


Figure 7 illustrates the change in the coolant flow/temperature pattern when the primary coolant flow is suddenly increased. The power production can now be transported by the coolant with a lower temperature rise and the temperature profile of the primary collapses, compared to figure 3. The secondary circuit is not yet affected and its higher temperature forces power backwards through the heat exchanger. This can be seen directly from the change in sign of the temperature difference between secondary and primary side of the exchanger.

The important point to gather from this example is that the opportunity to choose the level of decomposition in perception of the state of affairs that was discussed in the music example is present in the Rankine cycle display. The display can be perceived at the level of flow of energy, of state of the coolant circuits, of the physical implications of temperature readings, etc. at the discretion of the observer. At the same time, the display takes advantage of a standard format (i.e., a temperature-entropy plot) that is used by engineers to graphically display the thermodynamic properties of heat engine cycles. Another important feature, as mentioned previously, is that this kind of graphic display can be interpreted at several cognitive levels. Since it is transparent, i.e., it represents that internal functional relationships which are to be controlled, it will support knowledge-based, analytic reasoning and planning. Furthermore, because it reflects this relationship in a perceptual pattern, cues which will be correlated to familiar action sequences are likely to be defining patterns rather than convenient signs and, therefore, effectively can prevent 'under-specified' action mistakes. Finally, the faithful representation of the control object will invite the evolution of reliable 'direct manipulation' skills.



Heat transfer from primary is just starting again

Transient has reached secondary, steam is now heating the coolant

Temperature rise is increasing power generation increases due to temperature coefficient

Figure 8 presents the state a little later. The transient has now reached the secondary circuit while the primary circuit is restoring due to an increase in power production caused by the decreased temperature and a negative power-temperature coefficient. Note that the individual temperature representations of the display, such as for instance, output temperature from core and input temperature in heat exchanger, are based on separate sensors. Inconsistency from sensor failure, therefore, can be seen directly if a slope appears of the horizontal lines representing pure coolant transport in pipes.

CONCLUSION

Ecological psychologists and cognitive engineers are both conerned with studying people performing practical and meaningful activities, albeit in two very different settings. Perhaps it is this link which has led to the similarity in how the two disciplines view the human perceptual system. In this paper, we have tried to bring out this common ground and show how the ideas of Gibson can be interpreted within the framework of cognitive engineering.

In doing so, we have also argued that there are some characteristics of high-tech work domains which present problems that the theory of direct perception cannot cope with. Nevertheless, the concept of an affordance and the idea of direct perception both have considerable relevance to the design of interfaces for human-machine systems. While not providing a comprehensive answer to all of the demands that are faced in complex systems, the ideas of ecological psychology can be extended and adapted to provide useful answers to the applied problems being faced by cognitive engineers.

There is no doubt that the work that ecological psychologists are doing is important. Man's ability to effortlessly navigate and locomote in the natural environment remains, for the most part, a mystery to be solved. Nevertheless, the message that we would like to leave in closing is that the set of issues that is faced in designing information systems for complex work domains provide a mine of opportunities for ecological psychology. For one, it provides a new setting for showing the utility of the ideas proposed by Gibson. The duality of actor and environment is obvious to anyone who has studied the work activities in technical systems such as a power plant or a social system like a hospital. Also, as we have tried to show, these domains have properties that are quite different from the natural environment, and thus they can lead to new insights that can increase the scope and power of ecological theory. There are certain classes of problems which simply do not exist in navigating and locomoting in the natural environment that must be continually faced in high-tech work domains. For all of these reasons, and many more, an interaction between the ecological psychology and cognitive engineering communities is bound to be fruitful. While there are a few small steps being taken in this direction (e.g., Rasmussen and Vicente, in press; Vicente and Rasmussen, 1988a; 1988b; Flach and Vicente, 1989; Vicente, 1989), cognitive engineering, for the most part, is still an unexplored ecological frontier.

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