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Mohawc Taxonomy Implications for Design and Evaluation

Jens Rasmussen & Annelise Mark Pejtersen

Risø National Laboratory, Roskilde
January 1993

Abstract. The report presents a discussion of the implications of the taxonomy for work analysis developed for the CEC project MOHAWC (Models of Human Activities in Work Context) by the Risø group. The discussion is introduced by a brief overview of the taxonomy to set the stage for new readers. Following this, different approaches to the support of performance in actual work context are discussed and it is argued that ecological information systems making visible the 'deep' structure of a work space is particularly effective for discretionary tasks in modern work systems: a map of the domain is a better guide than route instructions, that is, work procedures. The complex cognitive coupling found in such work systems is analyzed and the importance is stressed of being able to support different levels of cognitive control and perception of the work domain at several levels of abstraction.

Next, the nature of design is discussed together with the traditional lack of success of human factors guidelines. It is suggested, that rather than to try to guide the design process by guidelines and checklists, it should again be accepted that 'maps are better guides than route instructions.' That is, an attempt is made to support information system and interface designers by maps of the various design territories in stead of the usual guidelines. For this purpose, maps are suggested of 1. prototypical work-situations, of 2. knowledge representations used during design and of 3. display composition and interpretation. Further support of designers is suggested by the use of a catalogue of annotated interface formats and samples of annotated designs are presented.

Finally, the use of the taxonomy for empirical as well as analytical evaluation of prototype systems is discussed in some detail, as is the use of the taxonomy to specify the boundary conditions for psychological experiments in order to facilitate the transfer of results of such experiments to design and evaluation of information systems.

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1. INTRODUCTION

For many modern work systems, stable work procedures are not the norm. Most of the time, tasks are discretionary, explicit consideration of goals and constraints is required and an exploration of the boundaries of acceptable performance. In this case, the object of modeling no longer is the "task" but includes all the features of the work environment and the interpretation of these features by the actors, all of which in interaction create the task ad hoc. The objects of modeling, therefore, are 1) the features of the different work domains and 2) the resource and preference profiles of the individual actors who are placed in the work domains. To this end, several different dimensions of analysis are necessary and the taxonomy for work analysis developed within the framework of the MOHAWC project (MOdels of Human Activities in Work Context) is aimed at a systematic and consistent representation of work systems from several different perspectives serving to bridge between descriptions in work place terms to description in terms of human cognitive resource profiles.

The present report presents a discussion of the implications of this taxonomic development with respect to design and evaluation of advanced information systems, in particular the design of ecological information systems. The discussion is introduced by a brief overview of the taxonomy. The follows a discussion of nature of the system design process in a period with a fast pace of technological change and the special requirements to design guides in such an environment. The main body of the report is a presentation of the requirements to work support systems in modern, large scale, dynamic work systems and a proposal for a new approach to design guides in this situation.

2. THE MOHAWC TAXONOMY, AN OVERVIEW

INTRODUCTION

The formulation of the taxonomy in Rasmussen et al., (1990) is basically aimed at the *analysis* of work systems. When considering the use of the taxonomy, a slightly different point of view will be taken. The different perspectives of analysis are necessary to bridge from the work environment concepts to human concepts, as shown in figure 1. Another way to see the different perspectives of analysis is for them to be constraint envelopes at different distance from the cognitive features of the actors. Analysis of a work system will then be to identify the propagation of behavior shaping constraints through these boundaries and design of a new work system will involve the selection of the means for mediation of the work given objectives and constraints by the interfacing computer system in such a way that the result matches the resource profile of the human agent, that is, the system can be used effectively, and the subjective preferences, that is, the system will be accepted and used according to the design intentions.

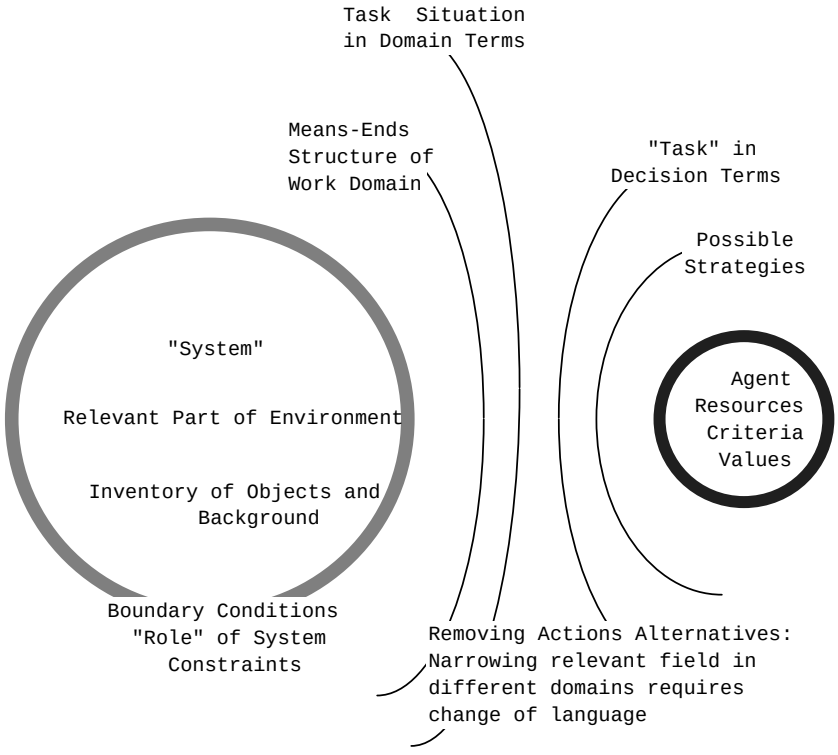


Figure 1 illustrates the problem faced when developing a taxonomy for predictive models of behaviour in a complex work context. Several layers of representation in different languages are necessary in order to be able to relate cognitive and emotional characteristics of a particular agent to the characteristics of a work environment.

From this point of view, the perspectives of analysis can be viewed as being the constraint envelopes shown in figure 2. Analysis of human activities in work involved a concurrent convergence of the focus of analysis and transformation of conceptual description to explain cognitive behavior of the involved staff. Design, in a similar way, is concerned with creation of a

consistent set of constraint envelopes from the material work environment to the actors' information environment that will ensure that actors can and will perform the decision and control task which are their raison d'aitre in the system.

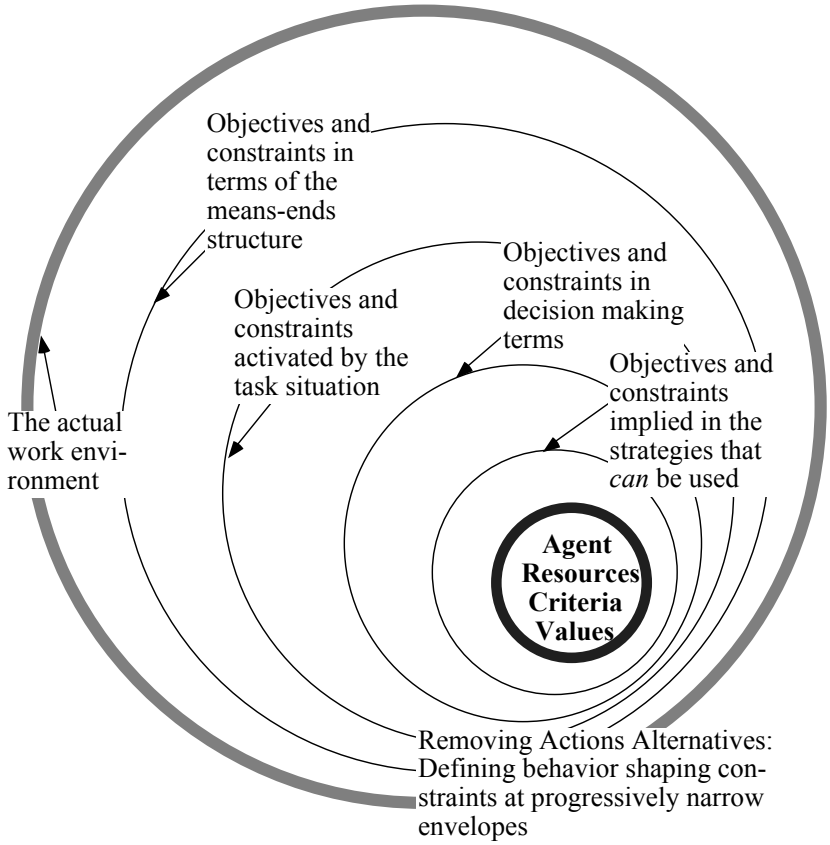


Figure 2 shows a re-interpretation of the perspectives of description of the work taxonomy as being a set of objective and constraint envelopes around an actor which can be used for generalization and transfer of knowledge during system design.

It is not possible to perform a thorough field study in the actual work system for every design project and transfer of knowledge from field studies in one known work domain or from simulated work systems to a different target domain is usually necessary. The distance of the constraint boundary around the actors at which the set of constraint can be assumed similar for the source and the target system, that is, the boundary at which transfer should take place depends upon the degree of similarity between the two systems, see figure 3.

The taxonomy has two important implications for such a transfer. First, it serves to define the objective and constraint envelope at which direct transfer is possible and, second, it points to the properties of the target and source systems which must be taken into account during design. Another use of the taxonomy is a prediction of the response of the personnel to changes in work conditions, such as new tools, new organizational structures or new institutional policies. In that case, the envelope of constraints, that is, the set of boundary conditions, that can be considered stable and which is used for transfer, depends on the scope of the re-design of the work system. It should, however, be considered that even when only a new tool is introduced such as a replacement of a type writers by a word processor, the entire task situation can be influenced

and, more often than normally considered, even the division of work and coordinating pattern will be changed.

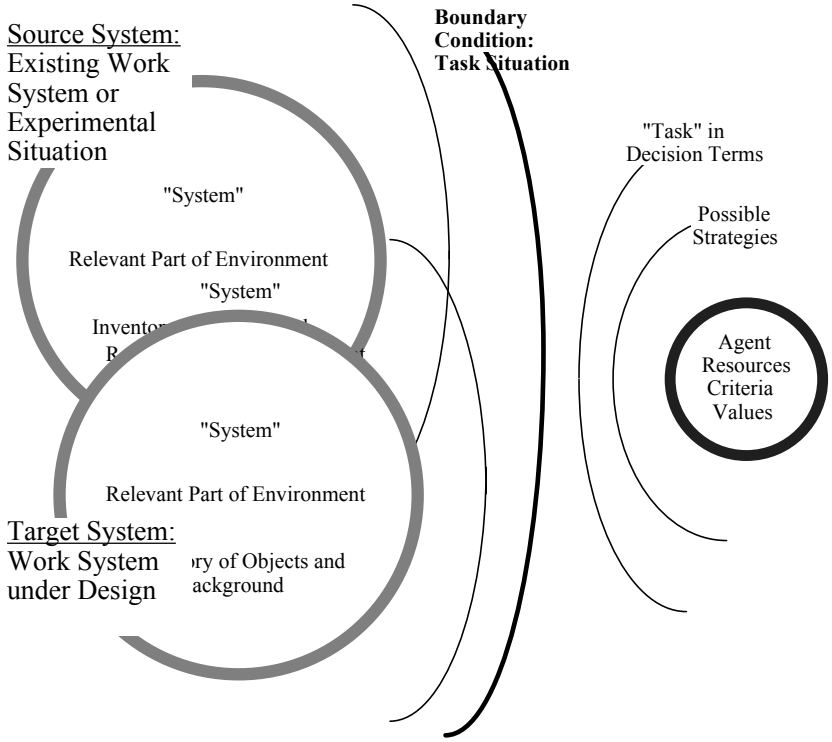


Figure 3. Transfer of conceptual descriptions and data between a source domain (existing work system, experiment) and the target system (another work system). For such generalization and transfer, we need to define the boundary conditions, that is, the behaviour-shaping constraints which define the "cut" around an experimental situation and the properties of the possible alternative worlds into which these boundary conditions transfer. The figure shows transfer at the "task situation" boundary level.

A brief summary of the basic perspectives of the taxonomy is given in the subsequent paragraphs as a basis for the discussion of the implications of the taxonomy for system design and evaluation.

THE PERSPECTIVE OF THE TAXONOMY

The taxonomy is intended to serve analysis and design of modern, dynamic work environments, that is, work systems in which the staff and the organization are subject to a fast pace of technological change and living in a dynamic, competitive environment. In this work context, adaptation to new requirements is often needed, a stable and generally accepted work practice may not have time to emerge, and, consequently, the work practice is likely to vary among individuals and to change with the work conditions. The actual approach taken the work requirements cannot be reliably predicted by a designer and, consequently support of work by normative decision tools and advice systems may not be effective. Therefore, information systems should be considered to present the state of affairs in the work domain with reference to the objectives and constraints to be respected, that is, to *make the ecology of the work visible*. One solution to this problem is a presentation of a map of the territory of work at a level of

representation relevant for the particular task situation, that is, make visible *what is up*, in stead of giving advice with respect to *how* to work.

Design of a visible ecology of work depends on a framework for analysis able to capture the basic behavior shaping constraints governing the evolution of the work practice and to predict the kind of performance which will be likely to evolve in response to the changes resulting from new work tools. Basically, human actors are goal directed, adaptive mechanisms. Great diversity in behavioral patterns is found among the members of an organization. No two individuals are occupied by the same activity nor will a task be performed in exactly the same way twice. The variety of options with respect to 'what to do when and how' in many work situations is immense. In order to predict why a particular piece of behavior is chosen instead of another possible pattern, we have to understand how the degrees of freedom, that is the action alternatives in a particular situation, are eliminated such that one unique sequence of behavior can manifest itself. As long as action alternatives remain, behavior is indeterminate until a choice is made. In other words, we have to identify the *constraints* which shape behavior by guiding the choices taken by the individual together with the *subjective performance criteria* which are applied by the individual actors to resolve the remaining degrees of freedom. A problem in identifying behavior shaping constraints by studies of work performance is that they will not all be active at the time of the behavior they control. Behavior has a prehistory. Patterns of behavior evolve they are shaped by prior decisions and choices. When a piece of behavior is planned by situation and goal analysis and by a consideration of the alternative options for action, the behavior shaping constraints are being compiled into flexible cue-action patterns and will not be active in later situations, when the particular pattern of behavior is re-used. It is, however, necessary to identify these 'hidden' constraints in order to predict and understand behavior even if they are no longer needed for the control of behavior.

OVERVIEW OF THE TAXONOMY

The framework must serve to represent both the material characteristics of the work environment and the subjective interpretation of this environment by the humans involved. As mentioned, several different *perspectives of analysis* and *languages of representation* are necessary to bridge from a description of the behavior shaping constraints in work domain terms to a description of human resource profiles and subjective preferences, see figure 1.

In the following sections, an overview of the different perspectives of analysis is given from the perspective of system design, that is, in terms of a coherent description of the propagation of behavior shaping constraints through the constraints envelopes of figure 2, which must be considered for design of information systems serving to "interface" people effectively with their work environment.

1. Work Domain Constraints

A representation of the territory of work should identify the entire network of means-ends relations relevant for all activities relevant for system design. That is, in Ashby's (1962) terms, the world of 'possibilities' or 'the requisite variety' which is necessary to cope with all the requirements and situations which may appear during work. Changes caused by introduction of

information systems are likely to propagate to all coupled activities and an overview of the means-ends network of an entire work organization can be useful to judge the likely propagation.

This domain representation defines the functional inventory of the work system, i.e., the functional territory within which the actors will navigate. The means-ends representation is structured in several levels of abstraction as follows: The lowest level of abstraction represents the physical anatomy of the system and the appearance of its elements, that is, its material configuration. The next higher level describes the physical activities and processes of the various elements in a language related to their specific material properties (e.g., physical, mechanical, electrical, or chemical processes). At the level above this, work functions are represented by more general concepts without reference to the physical processes or parts by which the functions are implemented. At the level of abstract function the functional implications are found which are used to set priorities and coordinate resource allocation to the various general work functions and to compare their results with the goals and constraints formulated at the upper level. This level of abstract functions represents functionality / intentionality in terms of flow of values for which laws of conservation are valid, such as monetary values, energy, material, people, etc. (For a detailed discussion of the means-ends hierarchy, see e.g., Rasmussen, 1986, Rasmussen et al., 1991). An important feature of this complex means-ends network is the many-to-many mapping found among the levels. If this was not the case, there would be no room or need for human decision or choice.

At the lower levels, elements in the description represent the material properties of the system. When moving from one level of abstraction to the next higher level, the change in system properties represented is not merely a removal of detailed information about physical or material properties but information is added on higher-level principles governing the co-functioning of the various elements at the lower level. In man-made systems, these higher-level principles representing co-functions are derived from the purpose of the system, i.e., from the reasons and intentions behind the design, see figure 2.

A change in level of abstraction involves a shift both in the concepts and the structure of the representation. It is important to realize that the different levels represent information about the same physical world. The information used for representation at the various levels is chosen so as serve as a set of links between the representation of the material work environment and its resources on one hand and the representation of the ultimate human goals and objectives on the other. Thus, the means-ends hierarchy is formed by a progressive set of conceptual transformations.

The levels of abstractions are illustrated in figure 4 which also shows the different *sources of regularity* of system behavior underlying the representations at the various levels together with an indication of the directions of the propagation of changes. The higher levels of abstraction represent properties connected to the purposes and intentions governing the work system, whereas the lower levels represent the causal basis of its physical constituents. Consequently, perturbations of the system in terms of changes in company goals, management policy, or general market conditions will propagate downward through the levels, giving 'rules of rightness' (Polanyi, 1958). In contrast, the effect of changes of the material resources, such as

introduction of new tools and equipment or break down of major machinery will propagate upwards, being causes of change.

Another way to look at the sources of regularity of the behavior of a goal oriented system is to consider them being *behavior shaping constraints* to be respected by actors working in the system. Any actor striving to control the state of affairs within a work system will have to operate on and through the internal constraints of the system. Control involves a change of the parameters of relational constraints in order to introduce a propagation of effects ultimately bringing the system into the intended goal or target state. This control involves operation on the *causal constraints* of the physical part of a system, or on the *intentional constraints* originating in the other actors of the system. Whether one or the other mode of control is dominant, depends on the task situation and the structure of the system.

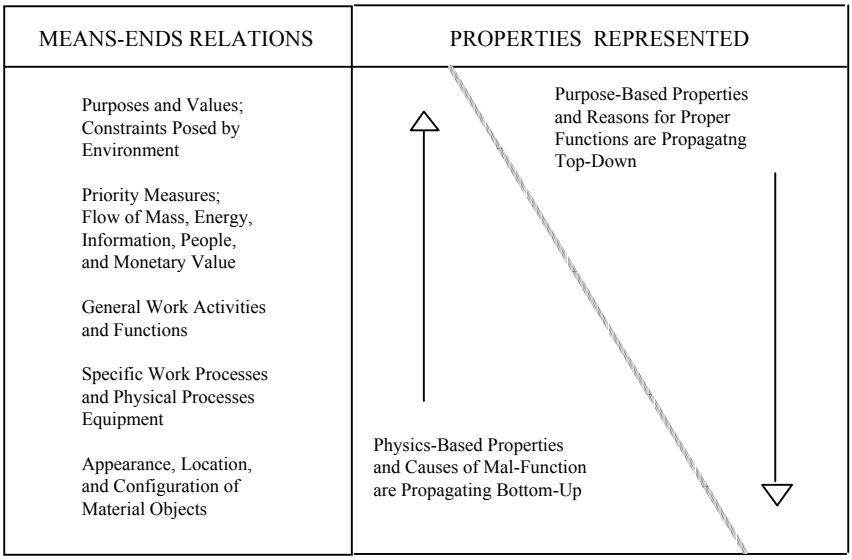


Figure 4. Any system can be described at several levels of abstraction each representing a different set of behavior shaping objectives and constraints. At the higher levels, the source of constraints is primerily found in intentional structures, institutional or individual and subjective, at the lower levels, physical causality and laws of nature are the source of functional constraints.

Two examples, a tightly coupled technical system (a process plant) and a more loosely coupled social system (a city), are briefly examined to illustrate the difference found between the kind of systems for which information and decision support systems are often designed:

In a *tightly coupled technical system,* such as, e.g., a power plant, the intentional structure will be hard-wired into a complex, automatic control and safety system, serving to maintain the functions of the entire system in accordance with the high level, stable design goals, that is, to produce power as requested by customers, and to do it as economically and safely as possible through the lifetime of the system. The physical processes of an automatic control system is only a medium for processing this intentional information and, consequently, will be of no significance except to the repair staff. The task of the operating staff is basically to make sure that the function of the automatic control actually represents the intentionality of the original design.

In contrast, in *loosely coupled work places*, such as e.g., an office, a manufacturing workshop or a hospital, also the functional coordination depends on the intentionality brought to work by

the actors of the system. A city can be taken as an example of a loosely coupled work system and be used to illustrate the role of the functional and the intentional constraints represented by the means-ends hierarchy, see figure 5. At the bottom level of the means-ends hierarchy the representation is found of the material objects present in a city. The intentional element at this level is only represented in the selection and configuration of objects necessary to supply the requisite variety for the higher level functions. In a city, people and houses, furniture and tools, cars and street lamps are plentiful, whereas large boulders, wild animals and village ponds are avoided or, at least, kept at controlled locations. The next level represents the processes of a city, such as moving goods and people, sleeping, feeding, shaping and assembling products, chemical and physical production processes. The intentional aspect is the control of the configuration and boundary conditions of the material world so as to support the required processes. One level up, the functions of a city are found such as transport, trade, health care, administration, public education. The intentional element serve to coordinate the lower level processes so as to serve the various functions. At the level of abstract functions, the implications of the functions are represented in terms of values and resources absorbed. The intentional element represents the efforts to set priorities and to direct the flow of money, people, goods so as to serve the higher level goals, such as the prosperity of the city, the well-being of the people and the pride of the mayor.

MEANS-ENDS RELATIONS	FUNCTIONALITY	INTENTIONALITY
Purposes and Constraints	Goals and objectives.	Explore opportunities and constraints.
Abstract Functions	Implications of the functions in terms of values and resources absorbed.	Setting priorities and directing flow of money, people, goods to serve the higher level goals.
General Functions	Functions of a city: transport, trade, health care, administration, public education.	Coordinate lower level processes to serve the various functions.
Physical Processes and Activities	Processes of a city: moving goods and people, sleeping, feeding, shaping and assembling products, chemical and physical production processes.	Control of the configuration and boundary conditions.
Physical Form and Configuration	Material objects: people and houses, furniture and tools, cars and street lamps.	Selection of objects.

Figure 5. The role of the functionality and intentional structures of a loosely coupled socio-technical system exemplified by a city.

The example illustrates how the functional aspects of the material world are represented up through all the levels, but in increasingly abstract and global terms. The intentional component is becoming increasingly influential at the higher levels and increasingly complex as more global functions are considered. It is also seen, that the intentional part of the domain representation constitutes a hierarchical control function, serving to structure the functional implications of the material world at all levels. These functional implications propagate up-ward through the levels, whereas an explication of the intentional control criteria will propagate downward. Decision making at each level will be directed toward the discrepancies between the functional state of affairs and the intentions derived from the ultimate goals. To visualize the

ecology of work it is, therefore, necessary that the abstract representation of the functional implications match the presentation of the intentional explications at each level.

For the individual decision maker, the intentional element is a very real part of the domain, being embedded in the form of the behavior shaping constraints present in the institutions and the accepted rules of conduct of the work system. In this way, the intentional system of a city is pretty well established. It is, however, still flexible, and public debates, political parties, and efforts of the local government serve to modify the structure in response to the results of experiments made by political activists and people violating rules of conduct (e.g., by stressing tax laws), social scientists, etc.

The properties of different work domains represent a continuum from tightly coupled, technical systems where the intentional properties of the work domain in embedded in the functions of a control system, through systems where intentionality is represented by social rules and values, to systems in which the entire intentional structure depends on the actual users' subjective preferences. The relationship between the causal and intentional structuring of a work system, and the degree to which the intentionality of the system is embedded in the system or brought to work by the individual actor is an important characteristic of a work domain to be considered in the design of ecological interfaces, see section xyz.

2. Work Situation Aspects

Activities in Domain Terms. Viewed from the task situation perspective, the work domain description discussed in the previous section is a stationary, situation independent representation of the options for choice among alternative means-ends relations. The representation is an inventory map of the options of the actors in all relevant work situations. It will, in general, be very complex simply because all "possibilities," should be included even if they are only implicitly present in the established work practice at the time of analysis.

Traditionally, the identification of work requirements in a particular situation is done in terms of a task analysis to produce a normative work procedure. As mentioned, this is no longer an adequate approach when tasks are discretionary. Instead, activities must be decomposed and analyzed in terms of a set of problems to solve or a set of prototypical work situations which represent recurrent, natural islands of activity which have reasonably well defined boundaries. The activities are labeled in work domain terms, that is in the language of the staff met in a manufacturing company, a library, or a hospital. For each of these work situation, the relevant sub-set of the means-ends relations, that is, the "actualities" will be instantiated and control the behavior of the involved staff.

The identification of the sub-set of behavior shaping *functional* constraints which are relevant in a particular situation by analysis of the physical resources and their use is rather straight forward. This is not the case for the *intentional* constraints. In most loosely coupled work systems, many degrees of freedom are found at the intermediate levels, and institutional intentional constraints propagating top-down will be dressed-up by local, situation and person dependent criteria. Therefore, identification of the local, intentional behavior shaping constraints by an actor depends on the ability to identify the state of affairs at the work places of cooperators and the actual intentions and personal preferences of these colleagues. In many cases, members of a team perceive the intentions of their cooperators through non-verbal

channels or establish, if necessary, informal communication channels for that purpose (see figure 6, reproduced from Rasmussen et al., 1990). This kind of intentional communication is a key problem for design of computer support of cooperative work.

Activities in Decision Making Terms. In the previous section, activities are analyzed in work domain terms. At a certain level of analysis, however, it is necessary to switch to a description in decision making terms in order to determine the information requirements of a task and to find a representation which can serve the formulation of mental strategies and a subsequent analysis of the match between the requirements of the various strategies and the competence and cognitive resources of the individual actor.

Decision making is more manageable when decomposed into subroutines connected by more or less standardized key nodes. Such prototypical nodes represent states of knowledge about different features of a task and are very useful for linking different processes, for bringing results from previously successful subroutines into use in new situations and, for communicating with cooperators in decision making. This is important since a complex decision task may be shared, not only by a number of cooperating team members but also, across time with procedure designers, system programmers and computers.

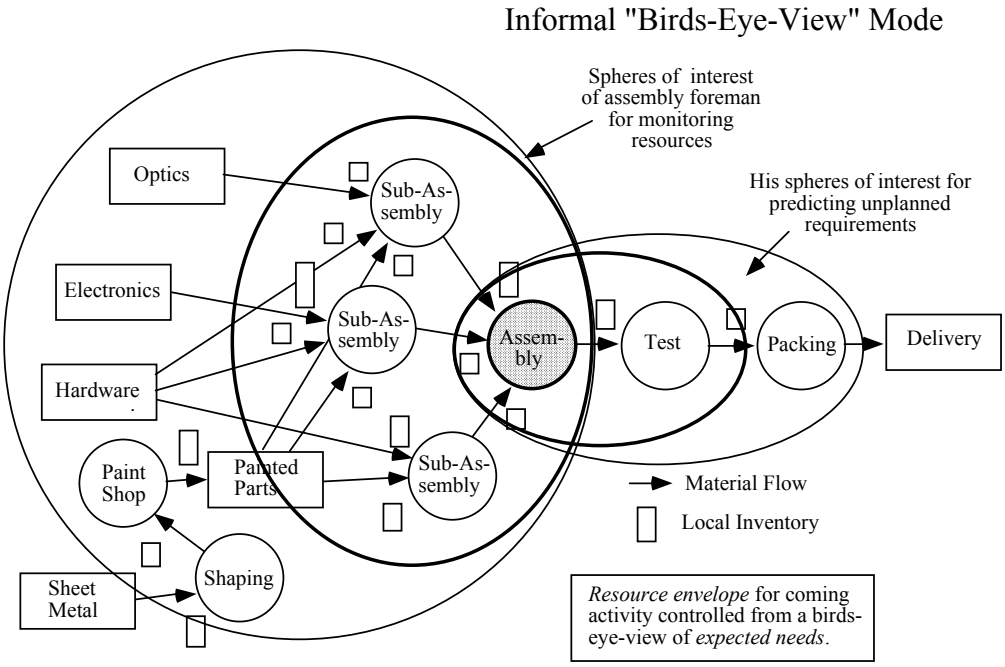


Figure 6. The varying attention horizons of a shop foreman's informal information network in a work system for just-in-time production. The network serves to monitor the adequacy of his resource envelope for oncoming requests and to predict disturbances from 'rush orders.'. In the formal system, the production control depends on a feedback control of the flow of resources to a work place. However, requests for supply propagates along the flow lines in the form of paper forms and consequently delays are found. The foremen's informal network serves to give a birds-eye view and a prediction of the likelihood of inadequate resources. This makes the system much more responsive to rapid disturbances.

The basic categories of decision functions to be considered for a more focused identification of behavior shaping constraints include information retrieval, situation analysis and diagnosis, priority judgment and goal evaluation, planning, execution and monitoring because these decision functions involve basically different information processes. The identification of these

processes is necessary to identify the mental strategies that are likely to be chosen by an actor in a particular work situation. This choice will influence an actor's interpretation of the constraints found in the work domain.

The 'objective' behavior shaping constraints as identified by analysis of the work domain and task situations are transformed by the interpretation of the individual actor through the choice of mental strategy to use. This transformation not only depends on the level of representation of the work system, the actor selects to consider, but also on the representation of the constraints implicitly found in the actor's repertoire of heuristics derived from previous encounters. That is, the perception of the work environment changes as constraints become implicit in work strategies and, therefore, embedded in a tacit and subjective representation of the work context. In consequence, it is necessary to study the various analytical and empirical strategies brought to work by the actors depending on the level of expertise.

3. Aspects of Mental Strategies.

This perspective of analysis serves to identify the mental strategies which *can* be used and are likely to be chosen by an actor. The context of reasoning, that is, the causal and/or intentional field within which analytic reasoning and perceptual judgment will take place, depends on the mental strategies applied. The choice of strategy depends on the competence and performance criteria of the individual actor and, therefore, determines the behavior shaping constraints at the detailed level.

It is well known that several, basically different mental strategies can be used for a decision task. This has been studied for diagnosis (Rasmussen, 1991) and libraries (Pejtersen, 1979). Analysis of diagnostic strategies (Rasmussen, 1991) demonstrates that the context in which diagnostic reasoning takes place within the various strategies can be of a very different nature. In search by recognition, the context is only implicitly defined in terms of the pool of episodic experience possessed by the diagnostician. In decision table search, the diagnostic context is a hierarchically ordered set of categories found by induction (typical for medicine) or deduced from a model of the functional structure of the system (as typical for operating instructions for technical systems). For diagnosis by hypothesis and test, the diagnostic context is a representation of the functional structure of the system used for deduction of symptoms from a postulated cause to be matched with the observed symptoms. In topographic search for the location of a fault, the diagnostic context is a representation of the physical or functional anatomy of the system.

In consequence, the manifestation of the properties of a particular system in terms of 'behavior shaping constraints' to be considered for modeling behavior and for system design will vary significantly with the perspective taken through the choice of mental strategy by the individual actor. This problem is even more complicated, because the strategies, their context, and the perspective taken by the actor will change dynamically during a decision task.

A 'mental strategy' is an abstraction describing one consistent reasoning approach characterized by a certain kind of mental representation and a particular interpretation of observations. The concept of a 'formal' strategy serves to formalize the information processes, their information requirements and the cognitive load involved. The 'natural' strategies applied in actual work situations, for several different reasons, will involve very frequent shifts among

such formal strategies caused by very subjective and situation dependent factors. One reason to shift between strategies is their very different resource requirements with respect to time taken, type of mental model available, number of observations necessary, etc. Shifts in strategy is a very effective way to circumvent local difficulties along the path of work.

Another reason for shift of strategy in a particular work scenario will be that the diagnostic objective will change during a session. Initially a medical doctor or a process operator will be concerned with the question whether he is confronted with a need for rapid compensatory action, i.e., he is concerned with the potential consequence of the present state. Next, he will be concerned with the choice of a function to control for compensation. Then he will be concerned with the correction of the present abnormality and, finally, he may be concerned with prevention of a repetition (Rasmussen, 1991). This means that a diagnostician may need to shift between strategies and thus change perspective in the interpretation of constraints several times during a task. An important implications of this discussion is, that information system should support of all the strategies relevant for a task to allow users to shed mental work load by shifts among strategies. Forcing users to *work through* the difficulties met using a particular strategy, preferred by the designer, rather than to *pass around* them by switching to another strategy will impair their acceptance of a system. It is, therefore, important to study how the *choice* of and *shifts* among mental strategies influence the interpretation of behavior shaping constraints and their proper representation in interfaces of information systems.

To sum up, the *means-ends map* represents the structure of the work system and the conceptual levels at which the functional and intentional constraints can be formulated (more or less) objectively, as seen from the system point of view. Analysis of *task situations* characteristic of the work system, serves to select those constraints which are active at certain times and for certain work functions and identification of *decision functions* serves transfer to the information processing domain. The analysis of *mental strategies* which *can* be used serves to identify the subjective interpretation of the behavior shaping constraints related to different subjective performance criteria and cognitive resource profiles.

4. Aspects of Cognitive Resources

This dimension of analysis serves to uncover the competence and cognitive resources of the actors and their subjective performance criteria.

Humans have different modes of control of their interaction with the environment. During familiar circumstances, interaction is based on a real-time, multi-variable, and synchronous coordination of physical movements with a dynamic environment. Quantitative, time-space signals are continuously controlling movements. The automated patterns are activated and chained by cues perceived as signs, no choice among alternatives is required. During skill-based performance, higher-level conscious control may be concerned with rehearsal of previous scenarios to prepare the world model for future demands by updating the state of the dynamic world model and preparing it for the proper response when time comes. This anticipatory updating of the internal model is equivalent to Gibson's (1966) attunement of the neural system underlying direct perception of invariants of the environment in terms of 'affordances'.

When this intuitive reaction to the context is no longer effective, a mismatch will be experienced between the state of affairs in the environment and the intuitive expectations of an

actor. In this case, a skilled professional will normally perceive a small number of alternatives for action and efforts will be focused on search of information which can resolve the ambiguity. The important point to consider here is that an expert will need no more information than is necessary to resolve the choice between the perceived action alternatives. If only two alternatives are perceived to be present, only one bit of information is needed as long as the actor is embedded in the context, even when it is a complex work environment (Rasmussen, 1991).

An important implication for interface design is that decision makers are not subject to 'information input' from an environment which has to be analyzed, they are asking very specific questions. They are, in a Gibsonian sense, able to consult 'invariants' in the environment by direct perception if the environment is well structured and transparent. In this way, performance in a familiar environment can be represented by a cue-response hierarchy, based on the human ability to read off cues at several levels of abstraction in the means-ends representation.

To sum op, the internal constraints which are the sources of regularity of the behavior of a work environment also are functioning as constraint envelopes within which the behavior of the individual actor will unfold, governed by the personal intentions and preferences. The problem of the design of work support systems is to represent the sources of the regularity of the work system so as to make them directly available by an actor both consciously and analytically as symbolic representations and perceptively as cues for actions.

3. WORK SUPPORT SYSTEMS

INTRODUCTION

The present section presents an overview of different kinds of work support systems to give a basis for a discussion of the role of the taxonomy in design of such systems. Different approaches to work support have an emphasis on different functions in the mediation of the work content by a computer based work station. Figure 7 is an illustration of the cognitive coupling of a person to the work content. The focus of efforts to support work varies widely and can be placed on the situation analysis at the input, on the decision process itself, or on the implementation of the decisions by acting at the output. Support can be given by automatic computer functions, such as diagnostic algorithms or heuristic programs (expert systems) at the input side and automatic planning and sequence control programs at the output side, as shown in the figure. Another more traditional way is to rely on the cognitive processes of the user and eventually support these by normative decision algorithms. A third approach is to rely on the human sensori-motor system and to match the interface coding to the characteristics of this system - that is, use the ecological interface approach which is advocated in this book. In a way, this approach can be seen as an extension of Shneiderman's direct manipulation concept.

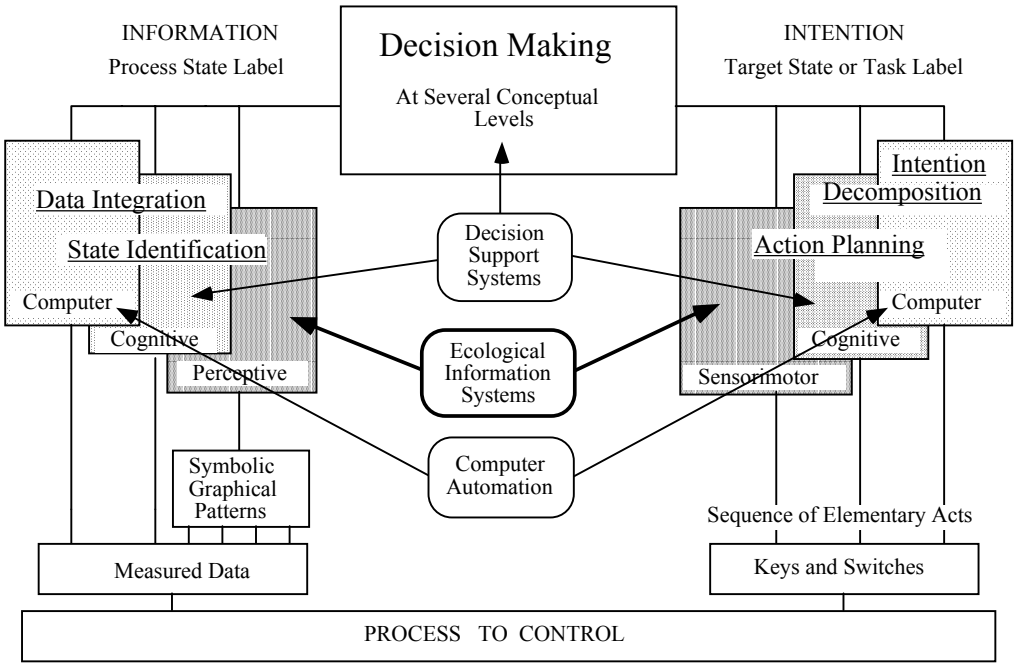


Figure 7. Modes of computer mediation of the cognitive coupling of a user to the work content.

MODES OF COMPUTER MEDIATION

In the following paragraphs, an overview is given of the different approaches to computer mediation of the cognitive coupling, with emphasis on the ecological approach.

1. Direct Manipulation Interfaces.

The *direct manipulation interface* (DMI) was originally described by Shneiderman (1983). Itself a product of the human-computer interaction (HCI) community, the concept deserves some mention here as a forerunner to the ecological approach. Many attempts have been made to describe the idea - e.g. "a representation of reality that can be manipulated" or "the user is able to apply intellect directly to the task - the tool itself seems to disappear" (both citations in Shneiderman's paper). There exist two theories of DMI. The first of these is the Syntactic-Semantic Model (SSM) of Shneiderman (1983), and the second is the description based on the Gulfs of Evaluation and Execution - Hutchins et al. (1986). Vicente and Rasmussen (1988a) discuss DMI and these underlying theories and their relation to the framework underlying this book. A brief overview of DMI will be useful in order to indicate its relevance to the ecological approach.

Norman (1986a) states that the general problem in human-computer interaction is that "the person's goals are expressed in terms relevant to the person - in psychological terms and the system's mechanisms and states are expressed in terms relative to it - in physical terms". Hutchins et al characterize this mismatch by two gulfs between person and machine (see figure 8). The Gulf of Execution refers to the gap between the person's goals and intentions, and the inputs that the computer recognizes. The Gulf of Evaluation, on the other hand, refers to the gap between the computer's output and the person's conceptual model of the task. Either of these gulfs can be bridged by the computer or by the person. Of course, placing the majority of the burden of bridging these gulfs on the person greatly increases the cognitive demands of the task, or the distance introduced by the interface. Each of the gulfs has two types of distance associated with it. Semantic distance refers to the disparity between the user's intentions and the meaning in the interface language, while articulatory distance refers to the distance between the physical form of the interface language and its meaning.

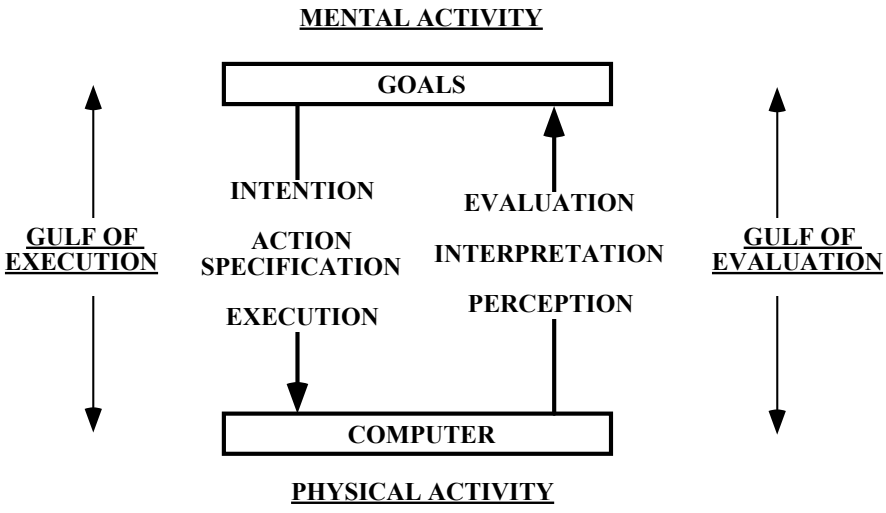


Figure 8. Norman's gulfs of execution and evaluation.

On the execution side, semantic distance of the interface is reduced if the user's intentions can be expressed in the command language in a concise manner. The goal should be to match the level of description required by the interface language to the level at which the person thinks of the

task. On the evaluation side, semantic distance is reduced if the displayed objects represent the higher level concepts that people naturally adopt when reasoning in the problem domain. In this case, the goal should be to provide a powerful, productive way of thinking about the domain.

The articulatory distance introduced by an interface is also an important factor. On the execution side, the articulatory distance is related to how closely the form of the action is to the meaning of the action. For instance, articulatory distance is reduced if the user can drag a mouse to move an object on the screen, rather than enter a command on the keyboard. On the evaluation side, articulatory distance refers to how closely the form of the displayed objects resembles their meaning. As an example, effective use of icons allows users to infer the meaning of an object from its visual appearance. See more on this in the readings on perceptual organization.

Hutchins et al. (1986) go on to say that the success of DMI is related to the feeling of direct engagement that they produce in the user. Thus, the person feels as if he/she is interacting with the concepts of the domain rather than an electronic intermediary. The shorter the semantic and articulatory distances, the greater the feeling of direct engagement. Therefore, the difference between DMI and conventional interfaces is that the gulfs are bridged by the computer, leaving the person to concentrate on the task at hand rather than the interaction process per se.

Vicente and Rasmussen (1988a) discuss the additional considerations required to achieve a truly ecological approach which caters both to the multifarious nature of human behavior with regard to levels of cognitive control and subjective preferences as well as the range of modern work systems with their multiple representations, conflicting goals and competing means-ends relationships.

2. Ecological Interface Systems

In a dynamic environment, appropriate support cannot be based on tools suitable for stable, pre-planned tasks. An exploration of the ends and means, opportunities and constraints present in a work situation is necessary for adapting to new requirements. Thus an information system which presents users with a complex, rich information context for direct perception as well as 'thought experiments' will be very effective for natural decision making. Decision makers can often be overloaded by the presentation of many separate data, whereas complexity in itself need not be a problem provided that meaningful information is presented in a coherent, structured way. Such users are not passively receptive to information input instead they actively ask questions of the environment, based on their perception of the context. Therefore, a rich support of this perception in context is a key design issue.

It is our experience that designers and consultants who are not thoroughly familiar with a work domain overestimate the amount of information required for action by a specialist who has effectively adapted to the work and is submerged in its context - while, at the same time, they underestimate the complexity of meaningful displays which are acceptable to such experts selectively seeking cues for action.

The design of ecological information systems attempts to exploit the large capacity of the human perceptual and sensory-motor system as encountered in natural environments by furnishing a complex yet transparent information environment. Through a suitable interface, the attempt is made to stimulate a user's direct perception of the invariants of the work environment,

that is, the constraints which determine purposeful behavior and, at the same time, to support the level of cognitive control at which the user chooses to perform. These interfaces should serve to couple all the means-ends levels of the work environment to the three levels of cognitive control and allow the users to dynamically switch their attentional focus and levels of control.

In Gibson's terms, the designer must create a virtual ecology which maps the relational invariants of the work system onto the interface in such a way that the user can read the relevant affordances for actions.

Ecological displays will often be complex because the user has to be able to generate a complex cue-action hierarchy at several levels below the currently viewed level of the work environment. In addition, in order to support analytical, functional reasoning, the displays have to present an effective, externalized mental model of the object of interest to the user. By recursion, a perception of this symbolic representation as accessible objects on the display surface will make the symbolic processing amenable to direct perception -> manipulative operations.

Natural decision making frequently involves rehearsals of previous scenarios and preparations for future encounters by mental simulations of expected situations. This kind of mental simulation can be effected through a recall of prior experience and 'simulation' of oncoming situations on the interface by presenting the scenery in which past and future events did/will occur.

While heuristics evolving in a stable work environment can be embedded in a work practice shared by the staff, it is reasonable to expect that the heuristics found in a dynamic work environment are different across members of a staff. In such a case, the adaptive features of advanced information systems could enable them to attempt to match work demands to the individual user and facilitate natural decision making based on personal experience. For example, they could store and replay prior cases, format information according to the user's subjective preferences and strategies and serve as a blackboard for cooperative work coordination within a group of highly proficient people.

The ecological system approach can be summarized in three principles:

1. Skilled routines: In order to support interaction via time-space signals, the user should be able to act directly on the display, and the structure of the displayed information should be isomorphic to the part-whole structure of movements.

2. Rule-based know-how: Provide a consistent one-to-one mapping between the work domain constraints and the cues or signs provided by the interface.

3. Knowledge-based problem solving: Represent the work domain in the form of a means-ends/part-whole relational network to serve as an externalized mental model that will support knowledge-based problem solving.

This approach will be expanded upon in a subsequent section.

3. Decision Support Systems

Ecological information systems effectively enhance the use of heuristic short-cuts in decision making while, at the same time, they present an effective mental model for functional reasoning without attempting to force the actor to apply a particular decision making process. Direct support of the mental processes connected with analytical decision making for situation analysis

or planning can be required in complex and stable tasks. Normally, this kind of support will be based on normative strategies derived from formal decision theories. The general aim of classic decision research is to prescribe how decision makers ought to behave considering some explicit optimal criteria. Such strategies are often tuned to particular domains and problems and generally applicable computer tools based on formal operations analysis are available for tasks such as, e.g., financial analysis, resource planning, accounting. This kind of work support falls outside the discussion in the present report. A recent review is found in Goodstein, 1991.

4.. Resource Management Support

Another group of work support systems are focused on the transformation of the intentions resulting from the decision making into concrete operations on the work content. Such systems help the user or operator in dealing with the resource management problem of selecting the proper means to carry out an intended task or act and to plan the proper sequence of acts in a work procedure. Also this kind of work support systems are developed for many common tasks.

In complex technical systems, dedicated automatic sequence controllers are provided for this very purpose and cover a wide variety of normal task sequences such as start-up of process plants, standard safety procedures, etc. For large-scale, stable systems such as power plants this kind of support system is designed for the individual plants.

For less structured work environments, these kinds of tools take on the form of separate, generally applicable computer programs which serve to replace well established manual work routines with more automated help functions these include word processors, spreadsheets, CAD programs, scheduling and planning tools, etc. Such programs can play an important role in the design of integrated ecological information systems to support many of the direct manipulative requirements. This kind of systems is the topic of the general HCI research and will not be discussed further here.

4. COGNITIVE COUPLING TO WORK

INTRODUCTION

The discussion in the introductory sections of the various envelopes of behavior shaping constraints around an actor defines the design problem we are facing. We are concerned with the very complex coupling of the cognitive processes of the user to the relational networks representing the sources of regularity of the work domain.

This complex and dynamic coupling is related to several levels of relational networks in the means-ends representation, to several modes of cognitive control and to different time horizons - each of which may change with the actual work situation, even within the same work domain. In order to relate the problem of user coupling to the domain characteristics, three categories of work environments will be briefly discussed with reference to Gibson's direct perception concepts.

GIBSON'S 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).

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.

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.

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 means-ends structure of the work taxonomy. This table emphasizes 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-ends relations. This has important implications for the design of 'ecological interfaces.' 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.

In Figure 9, 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.

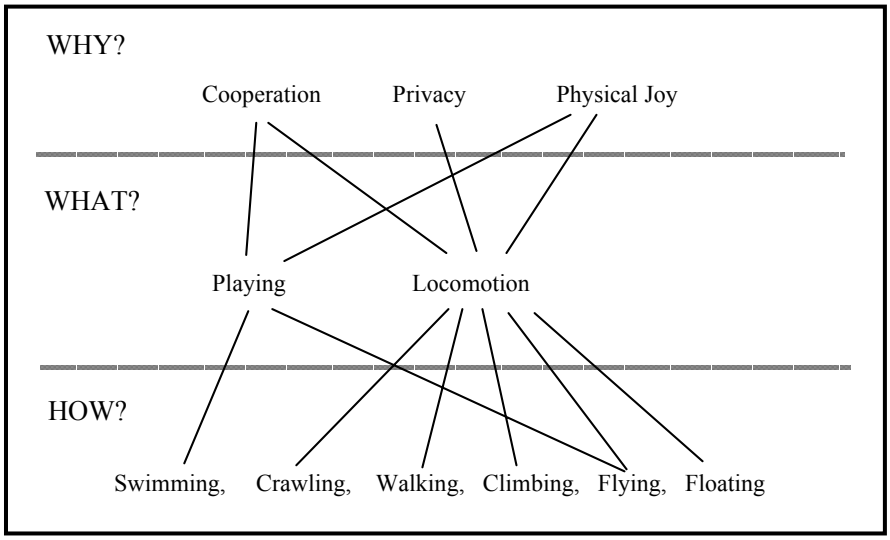


Figure 9 illustrates the many-to-many mapping between levels of abstraction in activities which will be related to environmental affordance at all levels. The three levels of abstraction in perception are relevant for control of goal setting, of activity control, and of movements respectively. Several 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.

While Gibson was concerned with the natural environment, the focus of the present discussion is modern work domains. Such domains can be viewed as a man-made ecology and it is argued that the theory of direct perception is applicable even to high-technology work domains as it is to the natural environment. The following brief discussion of different kinds of human environments will prepare for a subsequent discussion of distinctions between categories of work systems.

1. Natural Environments.

According to Gibson, the evolutionary process has resulted in the development of capabilities for reading off the functional properties and affordances of the environment at several levels of abstraction. Some of the characteristics of this perceptual-motor system are genetic while some depend on the individual's adaptation to the characteristics of the environment.

When considered as a 'display' of relational properties, the natural environment has some very characteristic features which are illustrated by figure 10. The intentions of the man in the bed can be directly perceived without any complicated analysis as can the functional structure of the overall arrangement. If interested, the viewer can also visually manipulate the physical processes involved at a local level. This means that shifts in abstraction as well as aggregation are immediately possible at the discretion of the spectator from this single representation of a 'complex' system .

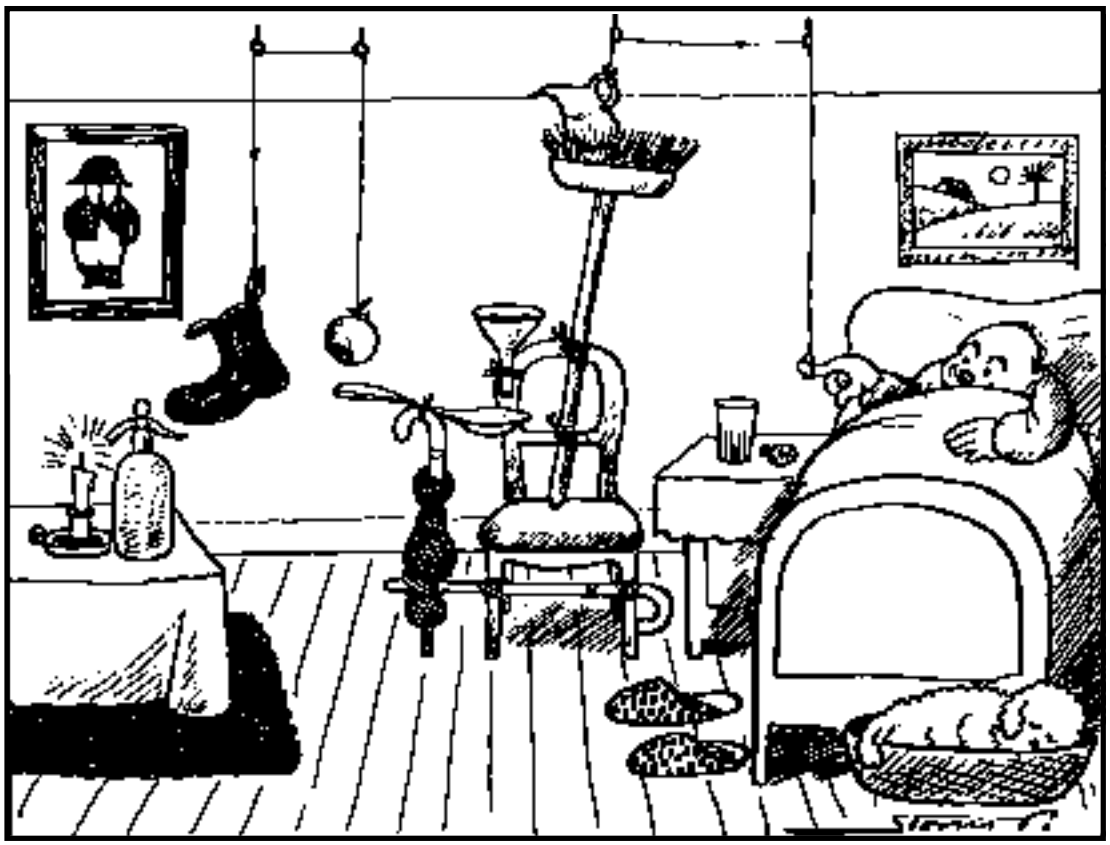


Figure 10. A natural environment. The cartoon illustrates how the human perceptive system is able to read off messages from a natural environment at several levels of abstraction. One can immediately perceive the intentions of persons, the functional relationships within the particular causal setting and the functional values of the individual objects, and all this without having to resort to analytical information processes. It is the aim of ecological system design to create user-work interfaces that support the same efficient use of the human input-output system.

2. Traditional Man-made Environments

In traditional man-made environments, humans will not be able to rely only on natural evolution. For instance, when new tools are introduced, an additional adaptation is necessary to supplement natural evolution. Learning to use new tools involves two phases. One is the 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 and the actor.

The first phase is a transient in stable work domains, and is eventually overcome with training and experience. The major part of work falls into the stable phase of unchanging stereotypical working patterns which are governed by surface features of the environment. That is, activity is guided by empirical cue-action correlation. As a result, for such work situations, users are not in general concerned with the system's internal physical functions - only the surface features. In case of difficulties, a trial-and-error exploration is acceptable because 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 knows how to operate one without knowing anything about its functional properties if success is not immediately achieved, a few trials will do, based on a perception of the features of a prototypical radio.

Normally, then, 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.

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.

In the present context, therefore, an important issue will be the interaction - in the different categories of work domains - between direct-perception and direct-manipulation features of an interface format which will support effective skill-rule based performance and the features which will be necessary for support of knowledge based reasoning.

3. Modern Work Systems

A number of complications confront an interface designer for many modern work domains. The automation of work processes moves workers from prescribed manual activities to situations of a discretionary nature involving decision making, conscious planning and choice. As a result, the exploration of opportunities and boundaries of acceptable performance form a part of the daily work activities. In other words, an ultimate stable phase of adaptation is never actually

reached. Instead, task demands are in a constant state of flux, requiring continual adaptive efforts on the part of the workers. A simple example from the consumer world. In contrast to radios, video cassette recorders - now a reasonably common household item - can vex ordinary users who have little or no experience with their broad repertoire of options and interface features.

In addition, for some systems, additional problems are encountered. Malfunctions in large-scale systems can have unacceptable consequences for people, property and/or the environment. Therefore, learning and adaptation based on trial and error explorations are not acceptable. In addition, unlike users of cars and radio receivers, operators in high-tech work domains are also responsible for safely controlling the system after it fails. Because the systems are so complex and are therefore often automated, there is still a very large number of possible malfunction modes. Many faults will be unique and cannot be anticipated. As a result, it will not be possible for operators to learn all appropriate response patterns in advance.

These factors combine to produce a new class of complex, flexible, changing work environments in which users and operators will not always be able to rely on patterns of performance derived from an 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. Unfortunately, in many cases, these are not visible. For instance, the internal mass and energy flows of a power plant cannot be observed directly and yet they are both the object of control of the operator and, at the same time, the basic sources of large accidents.

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

1. It is highly recommendable that the internal functions of the system be represented at the surface - i.e., the interface - so that they can be directly operated upon under unfamiliar as well as familiar conditions
2. In order to activate the normally very effective and reliable sensori-motor system, the representations used for the interface should support direct perception and manipulation of the internal control objects **as well as** analytical reasoning
3. The 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 derived by human factors experts. The interface design is an integrated part of the functional systems design and, like it, 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 to choose display formats which lead users to adopt effective mental models and to choose display elements which are not in conflict with the established stereotypes of the given professions or company.

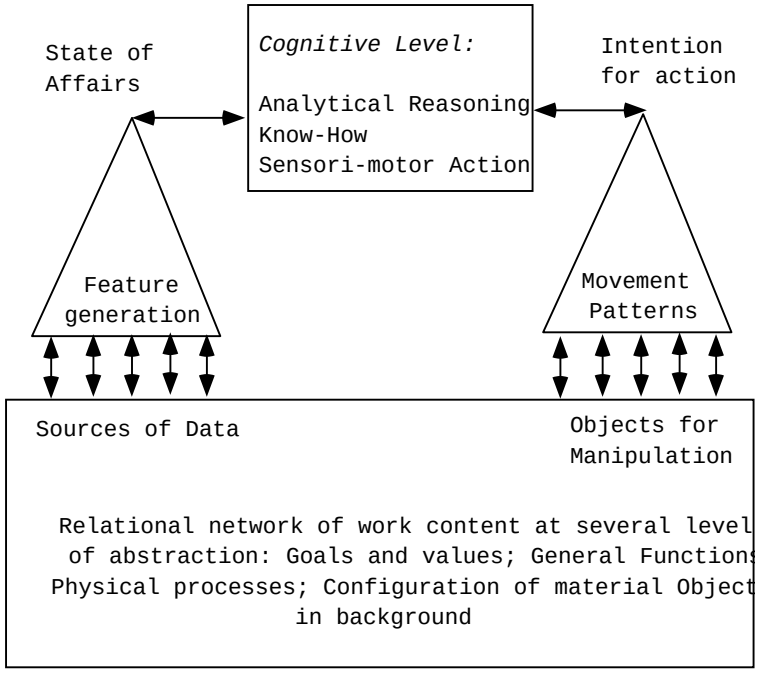


Figure 11. Cognitive user-work coupling in ecological information systems. Human actors in a natural environment plan and control activities at a high conceptual level. The information provided by the environment is not processed by scene analysis. Instead the features relevant for the occasion are directly and selectively perceived. Likewise, the movements necessary for an activity are not consciously controlled. When a decision has caused an intention to act, subconscious sensori-motor mechanisms will take over the control of movements.

SOURCES OF INVARIANTS IN WORK

Mediation by ecological support systems depends on a perceptually effective representation of the internal constraints shaping the behavior of the work environment in response to human activities. An important characteristic of the interface is the source of regularity which has been applied for its presentation of information. Three different sources of regularity are typically used for interface design:

1. *Laws of Nature***:** Some systems such as chemical process systems, production machinery, etc., are based on physical processes which are confined within a material configuration. The user has several different tasks: to *control the state* of the process, which implies representation of the relational network of the laws governing the process with an overlay of information about process state and target states; to *maintain boundary conditions* for the process as specified by the necessary and sufficient conditions of the laws applied; to *protect the confinement* during process control. This requires an overlay representing the boundaries of acceptable states as specified by the properties of the physical confinement. The content of the information environment necessary for these tasks can be derived from the *physical laws* on which the process and confinement is built.

2. *Intentions, Policy and Rules of Implementation***:** Another kind of systems is found when regularity of system behavior is related to human intentions, i.e., on the representation of policies, plans, and regulations. In such cases, the relational network to be respected can also be made directly visible for the user. Such a situation is, for instance, the production control in

manufacturing and planning of patient treatment and use of resources in a hospital. An important relational structure in this case is the event tree representing planning policies and regulatory rules and describing the possible paths of patients or products through a system. In this tree, the branching points reflect the decision points in which it is possible to change the course of events depending on the current diagnosis and resource situation. For each branching point, the possible alternatives together with the necessary and sufficient conditions can be made available. For planning, replay of previous cases can be made possible in each branching point, together with planning of future actions with alarm facilities to prompt future reviews. At each branching point, a world view or problem space should be defined for developing retrieval attributes to the relevant databases, both for planning, i.e., access to legal and regulatory files, and for retrieval of relevant prior cases.

3. *Metaphors.* For systems without structural invariants such as lexicographic data bases, general information systems for the public (when the user situation cannot be selectively defined), etc., a structure can be imposed on the interface which helps the user to navigate and to remember the location of previously consulted items. In general, a cover-story can be found which make it possible for a user to transfer intuition and skill from a familiar situation, i.e., a *metaphor* can be used, such as the desk-top metaphor for office systems, or the ware-house (the 'book-house') metaphor used by Pejtersen (1989) for library system and which is based on the mnemotechnic rule of Semonides: remembering information is a question of *where* to look. In the BOOK HOUSE, the metaphor is used for structuring the graphic *form* of the interface representation, whereas a careful analysis of user strategies is used for structuring the *content* of the interface formats. The metaphor approach is also the basis for the Japanese "Friend'21 Personalized Information Environment" program which is based on transfer of features of a familiar environmental to the computer-based medium in terms of two principles: the *multiple metaphor* and the *multiple agents* principles.

Coherence versus Correspondence. The distinction of cases when law based and metaphor based interface design is appropriate has been discussed by Vicente (1990) in terms of a *coherence* versus *correspondence* distinction. In some cases, when the designer has to respect the intrinsic invariants in the work domain, e.g., in process control, a correspondence principle should be applied; in other cases, when the designer is free to select the ‘structure of invariance’ himself, e.g. in information retrieval in libraries, to respect a coherence principle will guide a good interface design.

The different categories of invariants in system design are discussed in more detail in subsequent sections.

ADAPTATION IN WORK

One of the basic requirements for ecological information systems is that they support adaptation in the cognitive coupling between actors and their work environment. This takes on many forms which must be considered explicitly during system design. Adaptation to the work situation makes the interaction very dependent on subjective criteria - that is, a personal style of interaction emerges. Therefore, to accommodate these, either the interface must be "wide" enough to match the styles of all members of the intended user category or the system must

adapt to any user's preferred style. A summary of some of the aspects of user adaptation discussed in the previous sections will be useful here.

Evolution of expertise. Any modern information system must be able to support a novice without frustrating the expert. In this respect, it is very important to realize that expertise does **not** evolve because cognitive control becomes automatic through training but through an evolution of new control structures while the previous structures degrade. Consequently, to conform to the evolution of expertise, an interface must be able to support all the levels of cognitive control at the same time. The relationship between adaptation and errors is discussed elsewhere (Rasmussen, 1990c) and it is argued that an effective support of the evolution of expertise requires a design supporting error recovery by making the effects of errors immediately observable and reversible.

Shift of Mental Strategy. In most cognitive tasks, several different mental strategies can be used posing different resource demands for the user, who therefore will be able to shed work load and circumvent local difficulties by shifting strategy. As a result, user acceptance will depend on an information system's capabilities for supporting all relevant strategies or for following users' shifts among strategies.

Adaptive Division of Work. Shifts in the boundaries between roles taken up by different individuals can also take place in order to resolve resource-demand conflicts and to match performance to individual preferences. The subjective criteria active in this adaptation will be very situation dependent and directly related to the particular work process, such as perception of differences in work load among colleagues, the amount of communication necessary among actors for coordination, subjective preferences for certain activities, etc. This adaptation has a significant influence on the work conditions in computer supported cooperation and for the design of interfaces to shared work environments.

Adaptive Information Systems. As mentioned, when information systems cannot be made 'wide' enough to encompass a wide range of individual differences with respect to competence, level of expertise and subjective preferences with respect to work strategies and cooperative patterns, an alternate is to let the system adapt to the individual user's style. When the system's response changes with the behavior of the user - that is, does not demonstrate a stable and consistent response to user actions - the trust of the user and his/her acceptance of system support can very likely become a critical question. The control of adaptation between the system and the user and its effect on user trust has been studied within the supervisory control paradigm (Sheridan, 1984, Moray et al., 1990). Sheridan distinguishes between different modes of user control in the following way:

- The computer adapts itself to observed user characteristics without explicitly telling the user
- The computer adapts itself to observed user characteristics but tells the user so and accepts the user's possible rejection
- The computer adapts itself to observed user characteristics but asks the user for confirmation before implementation
- The computer proposes possible changes to the user, based on its observations. The user modifies the program according to recommendations
- The user identifies the potential for effective changes, but asks the program for advice with respect to implementation or, finally,

- The user introduces the necessary modifications on his own.

More work is required to extend the taxonomy by a more elaborate typology of features determining the level of trust in the response of users to adaptive mechanisms.

5. INFORMATION SYSTEM DESIGN

1 THE DESIGN PROCESS

Any attempt to formulate design guidelines should be based on a thorough understanding of the objectives and constraints faced by designers. For half a century, human factors specialists have complained that designers do not apply the guides which are available. This is probably due to two different factors. First, the human factors profession has not adequately studied the process of design for private (as opposed to military) dynamic, commercial environments. Secondly, it is only recently that the studies of natural decision making by substance matter experts have revealed its prevalence over the rational, utility oriented model of decision making. Decision making during work in a familiar work context will normally be a choice among perceived alternatives and, therefore, it is only to be expected that system designers will get through the design process without realizing the presence of human factors problems at the relevant steps in the process. It is often observed that designers may perfectly well know the conditions and constraints to respect, but they may not come to mind at the moment decisions are made. To have improvements of designs, we need to identify decision makers in the total system who *can* be made to change the basis of their decisions, i.e., who are in a rational, analytical mode of decision making and who therefore are evaluating goals and constraints, in stead of being in a routine mode responding stereotypically by choice among familiar alternatives.

Who are defining the constraints of an information systems designer? The customer, who thinks he knows what the supplier can deliver? The sales department requiring designers to follow the lead of the market? The hard ware technology and the opportunities for fancy new tricks?

Our studies of industrial design sessions have shown, that a normal design process is a very complex exploration of several different functional domains which cannot be represented as being an orderly progression from a functional specification to the final product (Rasmussen 1988).

The design process is by no means a well ordered progression from a problem formulation to the implementation of a solution. Nor is it a conscious, rationally planned process. Normally, a system designer is deeply embedded in his own context and very often he will treat his current requirement as an update or modification of prior designs. He will have many preconceived ideas and solutions at several levels in the goal-function-form hierarchy. In other words, he will not approach design as an orderly top-down synthesis but instead consider the process as a side-ways modification of prior solutions to similar problems. He will implicitly or explicitly have to conform with constraints from many different sources. These include the ultimate user needs, the company policy and product style, the financial policies of the company and its preferred part suppliers, the hot issues of his own profession and his subjective preferences, personal style and creative image. All of this influences his design choices and cannot be ignored from a rational 'guideline point of view'. Many degrees of freedom for choice are present within the space of acceptable product solutions.

As is the case with most activities in a modern, dynamic work environment, the design process is difficult to grasp and to formalize. It is therefore difficult to give advice from the outside *how* it should be approached. From this point of view, it is easier to understand why designers are not normally using the available human factors knowledge adequately *during the design process.* Design is a creative exercise which is constrained and inspired from many different directions. The guidelines approach that has traditionally been adopted for providing human factors advice to designers has several limitations which are severe enough to make it questionable as to whether such an approach alone can have a significant impact on the design process and lead to more effective information systems. Thus we can ask: what are these limitations and how can we assist designers of complex information systems? Several reasons for why the guidelines approach is inconsistent with the way design takes place will be identified. We will then propose an alternative form of providing recommendations to designers based on generalizations from prototypical work situations.

Limitations of Human Factors Guidelines

Modern technology is evolving at a very rapid pace. Thus, the "target" to which traditional design support is directed is constantly on the move. Seen in this light, a support in the form of design guidelines appears to be too rigid. A more flexible form of help is required, one that will allow designers to adapt to changes that are evolving in technology.

A second constraint on design is that designers tend to adopt a recognition-primed mode of decision making - in other words, they have "been there before". An important consequence of this fact is that if designers have not developed in the course of their career an intuition for human factors, then it is unlikely that they will ever specifically consider such aspects when decisions have to be made. Design guidelines do very little to foster such intuition and experience. On the contrary, guidelines can be viewed as an attempt at providing advice on how to deal with human factors issues to people who have little or no human factors expertise. As a result, designers will tend to ignore guidelines and base their design decisions on the factors that they are used to considering (Meister and Farr, 1967). This suggests that human factors will be put off until someone realizes that there is a problem, but by that time it is probably too late to remedy the situation in a cost-effective manner. A more productive form of guidance will have to instill a sense of intuition in designers so that human factors are naturally considered in the design process.

A third important constraint on design is that it is an inherently variable and opportunistic process. It is perhaps here that guidelines exhibit their greatest weakness. As mentioned earlier, the specific design solutions that are developed for any one application depend on a host of unpredictable factors which are unique to that particular problem. But since guidelines are intended to be generally applicable across a wide number and variety of design problems, they cannot possibly capture the rich sensitivity to context which is required for effective design. The point is well described by Gould (1988):

> "Guidelines cannot deal with choices that are highly dependent on context, as many choices in interface design are. Human performance adapts strongly to details of the task environment. There are simply so many details, and this adaptation is so little understood, that guidelines cannot hope to anticipate all of this" (p. 782).

In brief, design is heavily context-dependent whereas guidelines attempt to be context-free.

An excellent example of this point has been illustrated by Grudin (1989) who has pointed out the limitations of one the most frequently mentioned design guidelines, namely that interfaces should be designed to be **consistent**. Through the use of several detailed examples, Grudin demonstrates convincingly that

> "interface consistency is a largely unworkable concept the more closely one looks, the less substance one finds" (p. 1164).

The basic reason for this is that there are other considerations which may be more important and which should therefore over-ride consistency as a design criterion. Most of these other factors are contextual, depending upon the characteristics of the user and the work context. Thus, it is the users' work contexts which should be the primary constraint on design, not interface consistency. We would go one step further in hypothesizing that the difficulties identified by Grudin with consistency generalize to most, if not all, guidelines. Exceptions are always possible and design trade-off need to be made with a deep and clear understanding of the constraints imposed by the work context.

Other work leads to the same conclusion: Woods and Eastman (1989) found that

> "traditional human factors and human-computer interaction guidelines and handbooks were of extremely limited used during actual design projects" (p. 29).

Similar negative evaluations of the role of guidelines on the design of human-computer systems have been expressed by others who are deeply involved and familiar with design (e.g., Gould, 1988, p. 782 Whiteside et al., 1988, p. 792). This is not to say that guidelines are useless only that they are extremely limited as a sole source of guidance.

An Alternative - Maps of the Design Territory

As an alternate to traditional guidelines, we propose an approach based on the taxonomy outline above, which is intended to help designers attain a more structured and hopefully a more generalizable view of their interface designs. As part of their continuing acquisition of experience and expertise, we wish to assist designers in gaining a better appreciation for the importance of understanding the relations between (a) user interfaces and (b) the work system properties and user characteristics. In this connection we propose the use of the WTU concept - an acronym for **W**ork domain, **T**ask situation and **U**ser profile - to denote a particular work system or, more importantly, to represent in the designer's eyes prototypical descriptors of classes of work systems to which, for example, interface solutions can be related. Therefore we prefer to use the concept of *maps* of the design *territory* within which designers will be able to navigate as an alternate to traditional route instructions or guidelines. These maps can hopefully help designers gain an awareness and intuition about the territory in somewhat the same way as skilled travelers develop a prototypical map of world capitals and their characteristic localities. This WTU triplet will be expanded upon in the later sections.

A Historical Perspective

During a review of the literature to find the origins of diagrammatic representations for use in interface designs, it turned out that the proposed approach to design guidance is not at all new. In a historical overview of the role of non-verbal thought in technology, Ferguson (1977) finds that "origins of the explosive expansion in the West" lie in a tradition of distributing heavily

illustrated machine books, such as those of Ramelli (1588) and Leupold (1724-1739), and other engineers' notebooks. The tradition started with Leonardo, who published numerous drawings of machines and machine elements - often in an original "exploded view" format in order to improve on traditional pictorial presentations. Early in the 18th century, Polheim constructed three dimensional models of a "mechanical alphabet" to assist designers. To cite Ferguson (op cit):

> "Just as the writer of words must know the letters, said Polheim, so must the designer of machines know the elements that are available to him. To Polheim, the 'five powers' - lever, wedge, screw, pulley and winch - were the vowels, while the rest of the elements were consonants."

Hindle (1981) found several attempts to map the world of available machine elements in the late 19th century. Bigelow (1840) published a classification of "Elements of Machinery" and Fulton (see Sutcliffe 1909) wrote:

> "The mechanic should sit down among levers, screws, wedges, wheels, etc. like a poet among the letters of the alphabet, considering them as the exhibition of his thoughts, in which a new arrangement transmits a new Idea to the world."

Hindle points out that many of the well known inventors of machinery used their spatial representational abilities in other contexts - as map makers, architects, artists, etc. Fulton and Morse were active artists before they became successful technological innovators. Hindle comments -

> "It became clearer how artists, used to filling their minds with the images they struggled to express on canvas, might understand the process of filling their minds with mechanisms in order to design machines."

Thus our approach seems to be a repetition of history, but at another level of abstraction.

6. DESIGN GUIDE FOR ECOLOGICAL INFORMATION SYSTEMS

INTRODUCTION

A complete cognitive work analysis following the taxonomy thoroughly is a time and resource consuming undertaking which cannot be undertaken for every design. Therefore it is important to derive aids which assist designers in generalizing from previous analyses when designing new ecological information systems. In a previous section, it was argued that displaying the invariant structure and the affordances of a work domain is a more effective way of supporting actors during discretionary tasks in a dynamic work environment than presenting procedural guides. In other words, the suggestion was that maps support navigation in a work space more effectively than do route instructions, that is, procedural advice. By recursion, this argument can be applied to a support of design itself which builds on a generalization in terms of descriptions of prototypical **W**ork domain/**T**ask situation/**U**ser profile (WTU) examples having different locations on a map of the general territory of system design. Making the relationships among different WTU sets evident can give designers an effective intuition about the design territory in the same way as a skilled traveler has developed a prototypical map of world capitals and their characteristic localities. Thus the hypothesis underlying the approach is that by giving a designer such a conceptual map, he or she will obtain an improved awareness of important similarities and differences between information system designs relevant for different WTU combinations and, at the same time, assimilate a working understanding of the influences of all of the dimensions of the framework - both system and human related.

Each prototype is intended to be a prime example of a class defined by a WTU-triplet. Classes are defined in a multi-dimensional WTU space describing the properties of the work domain, the task situation and the competency of the user according to the framework described in the previous chapters. Thus a prototypical interface will be characterizable by its location in this map in that it will be deemed most suitable for certain types of tasks in certain domains for certain user profiles. One possible application would be to abstract from a specific interface design and induce the class represented - i.e., define the boundary conditions of its applicability in terms of a prototypical WTU triplet. Identifying the general class of which the prototype is an instance thereby would allow one to generalize design results across work situations which, on the surface at least, might seem to be very different from each other.

Therefore the first goal in making this design approach realizable is to provide a number of varied examples that can serve as concrete instances to get designers thinking about the conceptual issues that need to be considered in the design of ecological information systems. Before these are presented, it will be necessary to discuss the design territory in a little more detail. The following maps of design territories will be considered: 1. a map of prototypical work situations, 2. a map of knowledge representations in design and 3. a map for guiding display composition.

1. A MAP OF PROTOTYPICAL WORK-TASK SITUATIONS

This map is based on the taxonomic dimensions representing the work domain and task characteristics and a projection of the three-dimensional WTU space onto a WT map is shown in figure 12.

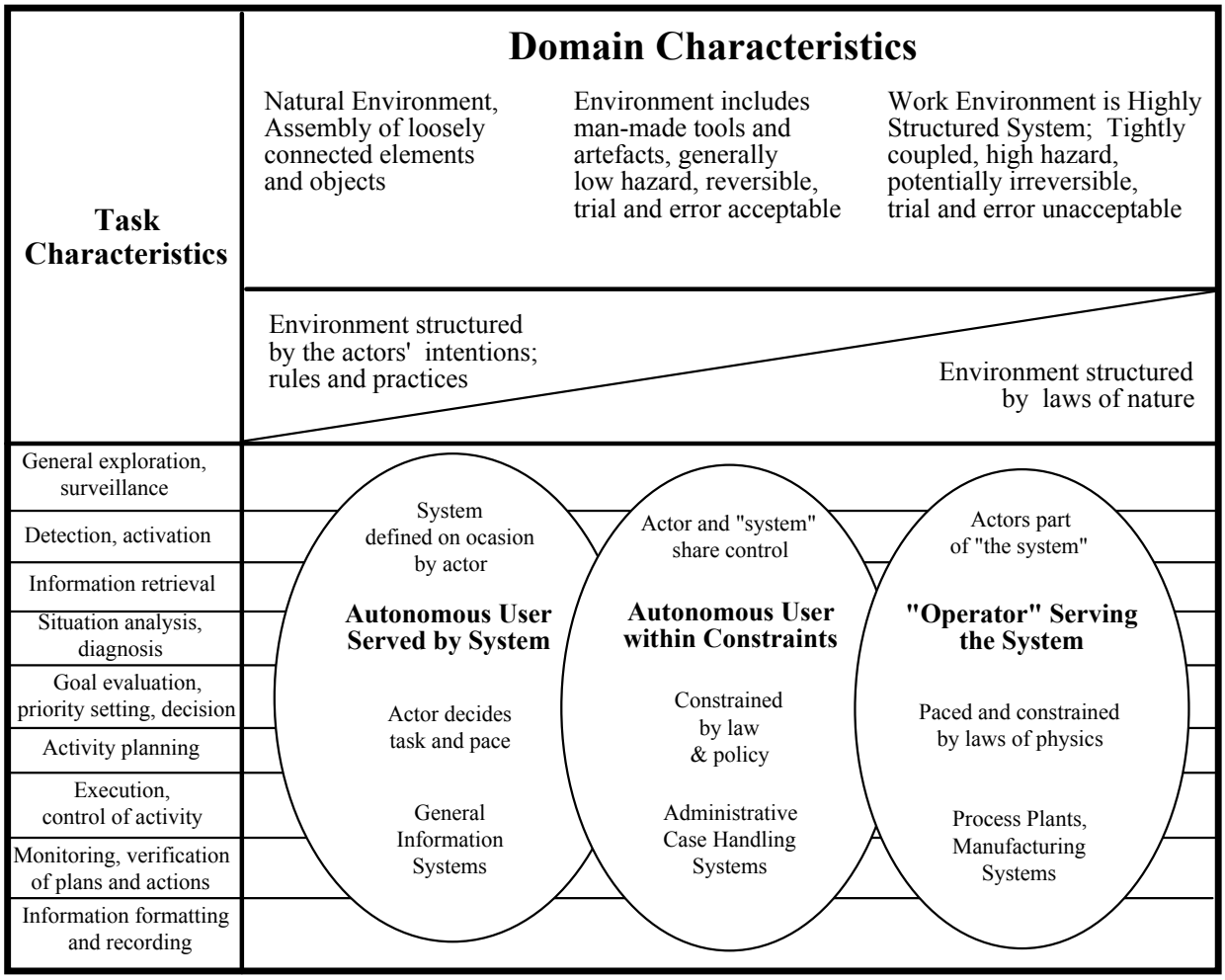


Figure 12. Some basic properties of different work domains. The properties of work domains and tasks vary along many dimensions which underlie the work framework. However some of the properties can be gathered together to generate typical cases. Thus the figure illustrates a continuum stretching from domains constituted by "natural environments" with loosely coupled assemblies of objects on the one hand to highly structured and tightly coupled technical systems at the other extreme. System design considerations at these two extremes will, of course, have to be very different. The general HCI (Human Computer Interaction) design guideline development is traditionally focused on the left part of the map, including activities such as Norman-Shneiderman approaches to "direct perception-direct manipulation" interfaces. Much CSCW (Computer Supported Cooperative Work) effort is focused at the center of the map, while the ecological interface approach typically has been focused on the right and left hand side of the map.

Different work domains are displayed along a horizontal continuum. At the left are found loosely coupled systems which comprise a selectable set of separate tools used by an autonomous user who defines the problem and composes or selects the necessary work environment on demand. To the extreme right are highly structured and tightly coupled technical systems, such as process plants, with dedicated operators who are paced by the system. Between these two extremes are found the more or less constrained autonomous users in environments

dictated by company goals and policies, legislation and/or other forms for regulation. The figure illustrates that these of course can overlap to some degree. The vertical dimension represents prototypical decision tasks which must be considered with respect to interface design. Not shown is a third orthogonal dimension coming out of the page representing user competence.

The map is intended to reflect the overall relationships among the different kinds of work domains and their sources of regularity and, from this, the information which will have to be considered for ecological system design after taking into account the characteristics of the expected users. The identity of a prototypical examples is determined by 1. the degree of internal coupling and of the autonomy of the user (which are often correlated) which determines the horizontal location in the map 2. the typical cognitive task of a work situation determines the vertical position in the map and 3. the cognitive characteristics of the users. In addition to these dimensions of the taxonomy which are used to distinguish prototypes, all the remaining categories of the taxonomy should be considered to characterize their similarity and differences so as to judge whether it is appropriate to transfer results of field studies or features of a design among available samples.

Such comparative analysis of particular work systems and successful system designs (if available) helps to make clear the invariants, constraints and affordances which will underlie the ecological interface design and to sharpen a designer's intuition. The map of figure 12 is used below in a further discussion of particular examples of WTU sets.

2. MAP OF KNOWLEDGE REPRESENTATIONS IN DESIGN

Another conceptual map of the various types of knowledge representations which have to be considered during information system design is useful for the comparative analysis mentioned as well as for guidance during design of new systems. The mental models of the ultimate user are different in content and form from the models developed by a work analysis. In turn, these are different from the models used for interface design as well as the formal models necessary for software development see figure 13. The paths of transformation connecting these different kinds models depend on the characteristics of the work domain, and a map representing these paths can be useful for making generalizations.

The figure is organized in three vertical columns. The center column shows the representations of the properties of the work system as described within the different dimensions of the work analysis framework this include the means-ends structure of the work domain, the task situation in work terms, the decision task and the cognitive strategies which ***can*** be used. In addition, there is indicated that the work analysis will include several levels of abstraction, representing the physical anatomy and topography, the processes and tools in the various activities, general functions and, finally, the goals and value structures - all of which define the ***content*** of the knowledge-base of the information system which must be accessible through the interface.

The right hand column of the figure indicates the representation of the work domain which is found in textbooks, manuals, training material and in the professional literature. This kind of material will influence the mental representations of system users. The figure also hints at eventual influences from general information sources such as radio, TV, newspapers and other

media on user representations - especially in work domains with casual, perhaps non-professional, users and in work systems for the general population. Such representations will often include established general population stereotypes which can be utilized in the interface. However, while these can be exploited as metaphorical representations, they can also cause interferences in situations where their interpretation is misleading.

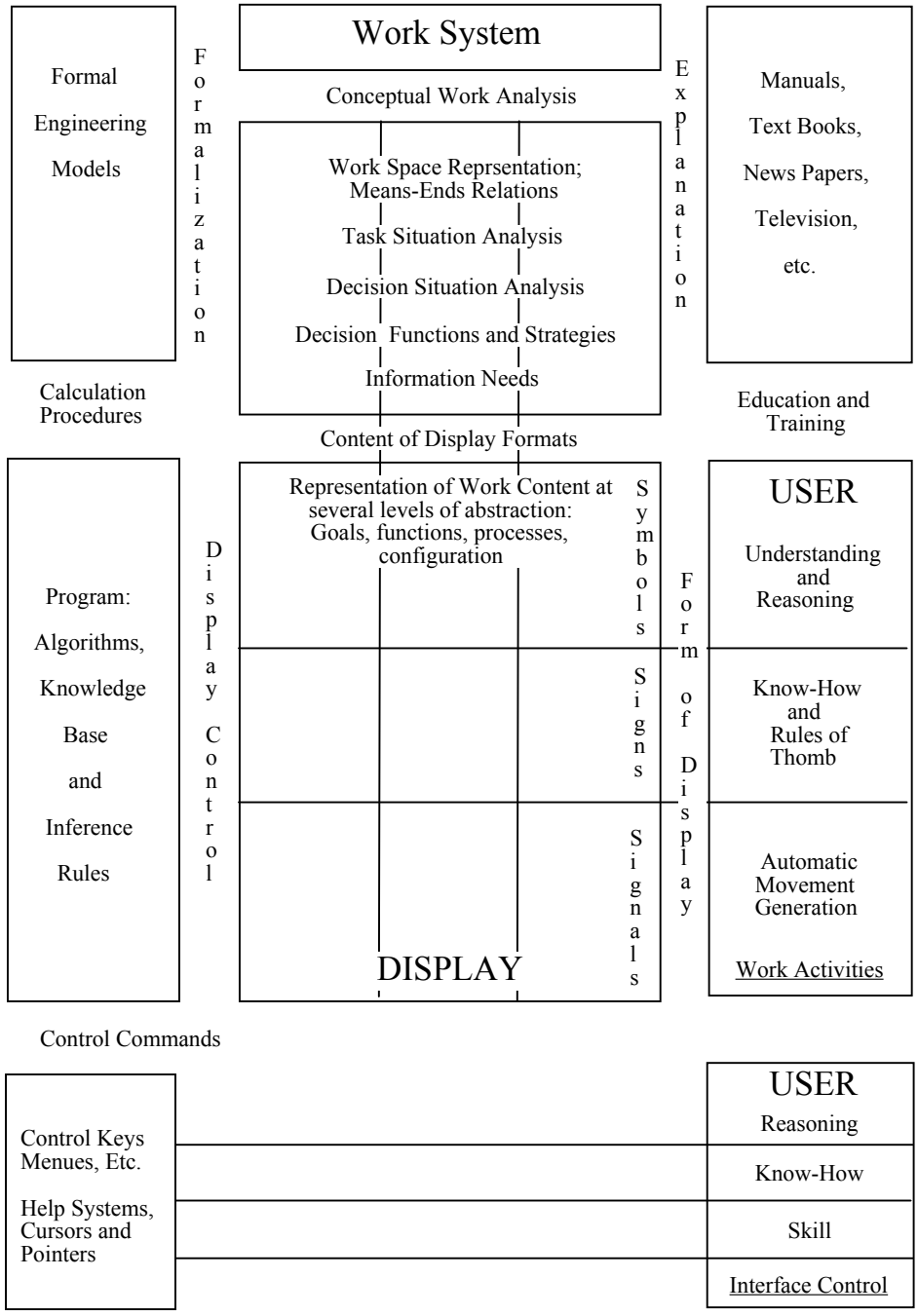


Figure 13. is a map illustrating the various representations of the work content which are used for information system design. The upper part of center column indicates the conceptual analysis of the work content along the dimensions specified by the work framework. This analysis specifies the information content of display formats. The right hand column indicates (a) the representations which a user will encounter in textbooks and manuals and (b) reflects the fact that different forms of representation will be useful for different levels of cognitive control. The left hand column indicates that different representations are necessary for the formal processing by computers controlling the dynamic display presentation. At the bottom is indicated the representations to be considered when a user is involved in a direct interaction with the computer functions.

The figure illustrates that the choice of the ***form*** of display representation is to some degree independent of its ***content*** and therefore different representational forms can be chosen to match the interpretations involved in skill, rule and knowledge based operations. As the examples later will demonstrate, WTU differences will be reflected in the relationships between ***users*** and

content. The matrix in the center of the figure pin-points the complex matching problem in interface design where the information content has to match a user's discretionary choices of means-ends levels to work at and, at the same time, the form of the display has to match the needs of users with varying levels of expertise.

The left hand column sketches the formalized, computational representations which are necessary for driving the information systems. Normally, a design will aim at a direct communication between user and work through the center matrix. However, occasionally some control of parameters or functions of the program system is required and the relevant information must be available at the interface; see the bottom row of the figure. This communication path is useful in systems serving professional users who will have the system adapt to their own particular needs. Thus the importance and the functions involved in the computer-program-user interaction depend on the degree and mode intended for the adaptation of the system to user characteristics as discussed above on p.25.

Also this map is used in the examples discussed in subsequent sections to illustrate the path of design.

3. MAP OF DISPLAY COMPOSITION AND INTERPRETATION

The various modes of interpretation of information applied by users depend on their level of expertise and cognitive style and on the particular task situation. This interpretation will change with work domains, professions and cultures and a conceptual map can assist in guiding the design of graphic interfaces, icons and metaphors.

The aim of an ecological display is to present a rich information environment that leaves the choices of level of interpretation and cognitive control to the discretion of the user. For generalization, it will be advantageous to identify some regularities in the relationships between the composition of complex displays and the structure of the work requirements. Some preliminary observations will now be discussed.

In most activities, the work sequence will involve shifts in levels of abstraction and in aggregation of perceptual/conceptual units together with concurrent changes in levels of intentional/activity-related complexity. In natural environments, all observable information is available all of the time. Thus, the level of abstraction at which the environment is perceived can be varied at will by the actor. The degree of perceptual chunking is discretionary and is related closely to the level at which the actor expresses an intention to act. This, in turn, is determined by the complexity of the automated patterns of movements available to the actor for the particular activity.

A good example which will help to make these ideas more concrete is that of musical skill. Skilled sensorimotor performance with an instrument is characterized by integrated patterns of movements resulting in 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.

Decomposition-Chunking of Information Content

This suggests that in order to facilitate skilled sensorimotor performance in complex work domains, a similar mapping should be facilitated by the interface. 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 task activities.* This can be accomplished by revealing higher level information as aggregations of lower level information (e.g. through appropriate perceptual organization principles). In this way, multiple levels are visible at the same time and the user is free to guide his attention to his current 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.

Therefore low level display elements should map closely to actions on physical items or components. Since such items will no doubt be found in a wide context, the form should match population or professional stereotypes. At a somewhat higher configural level, activity is related to functional relations for which stereotype representations (in some cases standards) for drawings and manuals can be found for the given profession. At the global level, activity is related to the constraint structure of the global task situation. Flach and Vicente (1989) advocate the use of the abstraction hierarchy as a framework for parsing the functional structure of work domains together with Gibson's concept of nested invariants as a framework for parsing the display composition in a way that will map naturally onto the abstraction hierarchy.

Visual Coding and Form

While these considerations are focused mainly on the structuring of the *content* of a composite display, the *visual form* to choose for display coding depends on the level of cognitive control for which the support is intended. Figure 14 clarifies further earlier remarks made in connection with figure 13 concerning relevant sources and transformation paths.

For knowledge based reasoning, the visual form serves as a symbolic representation - that is, an externalized mental model of the relational network representing the work content at the appropriate means-ends level(s). The form of the displays should not be chosen to match the mental models of actors found from analyses of an existing work setting. Instead they should induce the mental models which are effective for the tasks at hand in the new work ecology. If they exist, established graphical designs which have been used for decades in textbooks and for teaching are probably the best sources for these representations.

In addition to the graphical representations which relate symbolically to the contents of the work domain, special consideration needs to be given to those elements of the display formats which basically serve as signs - that is, cues for action at the rule based level of performance. Symbolic graphical representations used for knowledge based reasoning can be helpful in this regard. As symbolic representatives of system state, they can provide action cues based on

defining attributes and thus serve to prevent errors due to the use of under-specifying cues for actions.

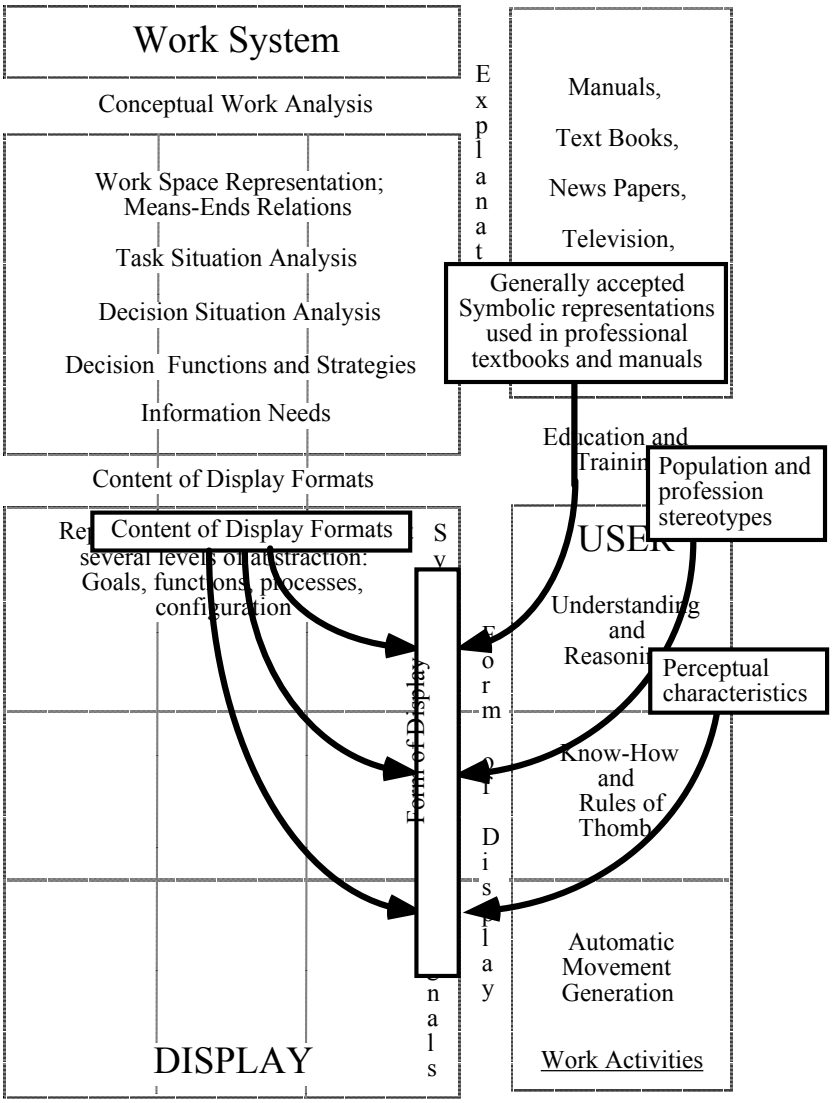


Figure 14. Different sources of content and form of display formats. The information content of displays is derived from the work analysis. The form or shape chosen for representation is subject to different requirements depending on the level of cognitive control for which the displays are intended. Seen in isolation for a particular application, many degrees of freedom confront a designer. However, an important consideration will be to match mental models which are induced in a user by textbooks, manuals and/or population stereotypes coming from general information media, etc.

For supporting skill-based operation, the visual composition should be based on visual patterns which can be easily separated from the background and perceptively aggregated/decomposed in a way which matches the formation of patterns of movements at different levels of manual skill.

More concrete remarks can be made in the matter of display composition and interpretation. For example, there exist several generic ways of mapping information onto displays Pepler and Wohl (1964) describe four such types. With some modifications, these comprise:

- *scalar* - the basic coding is *geometric* i.e., magnitude-length, angle, area.. The underlying data is quantitative and can be discontinuous (discrete) or continuous in nature. Reference infor-

mation identifying coordinates, scales and units is alphanumeric. There are many variations on this theme. The time dimension can be explicit or implicit.

- *matrix* - the basic coding is *positional* i.e., data-cell in a 2D row-column array-like arrangement. Cell coding can consist of any of the other types.

- *diagram* - the basic coding is *representational* and/or *relational*. Diagrams comprise connected elements coded as lines, symbols, text., etc. to reflect structure, function etc..

- the basic coding is *symbolic* , i.e. everything from narrative-like formats employing words and numbers to pictorial, analogical or abstract entities (*icons*) serving as symbols or signs relating to domain or task.

- *composite* - a format which combines one or more of the above.

The general applicability of the basic types should be obvious. Scalar displays are an indispensable tool where the data is (can be made) quantitative. However certain variations will be domain-dependent. Likewise matrix-type arrays are widely employed for depicting spatially organized information (e.g. spreadsheets) moreover they form the basis for menu arrangements, groupings of command icons and the like. Where relevant, diagrams play an indispensable role in supporting mental models of structure and function, while symbolic representations are of course commonplace. One of the important differences across applications for a particular display type will quite naturally lie in the differences in the semantic content and relations in the underlying information base and, consequently, the resultant depiction, behavior and significance of the perceived entities.

Representation of invariants and affordances:

For direct perception interfaces, some guidance can be drawn from the concepts of invariants and affordances. To sum up: The aim of ecological information systems is to present to the user relevant information about the state of affairs in the work environment structured according to its invariant properties. The regularity of behavior of a work domain comes from a combination of functional and intentional factors and consequently the invariants and constraints to be depicted in an interface depend on the type of system considered.

"The constraints forming (the system's) invariant structures" have been discussed by Hansen (1992). These constraints should strongly shape the displayed representations of the system in order to deal with important features of persistence and change - i.e., "the visualization of persisting constraints and the invariants in the changes which occur" (both citations from Hansen 1992). A preliminary overview of invariant types would include items such as:

- relations (causal, intentional, empirical, organizational,...)
- boundaries (physical, intentional, formal, legal, resource,..)
- sequences (time and order)
- behavioral paths (system performance trajectories, footprints of a strategy,..).

The second ecologically relevant parameter to consider has to do with the object's, system's and/or event's affordances - i.e. the possibilities offered for the user to exert control in some sense within the limits of his/her capabilities. This of course is of prime importance - i.e., 'no affordances, no possibilities for response'. Thus designers will have to identify what it is their users are supposed to "pick up and gain a possibility to act on" and thereafter ensure that these facilities "appear" on the displays . It is also possible to list general classes of affordances:

- maintain "something",
- adjust, modify "something",
- reconfigure "something".

The list and their connotations will of course have to be expanded depending on the domain application. However, some general guides can be given for their display.

Information about invariants:

1) Actual vs. goal state:

- map as a configural "goodness": use linearity, symmetry, balance, alignment ; take advantage of persistence with the onset of deviations to enhance the detection and identification of (invariant) "non-good" configurations .

- map as graphical (scalar) figure from established repertoire of candidates include comparative coding of "is/should be", "is/was" and/or "is/will be" where possible and relevant. The time dimension can also be coded.

- map as graphical symbol, e.g. as mimic or analog: use position, size, area, outlining, texture with/without text to (discretely or dynamically) depict state, result or outcome.

-map connections between entities as geometric lines, intersections, coincidences use width, texture, direction to code connective attributes.

2) Constraints, limits:

- map as background containment, boundaries, areas.

- map as text message use size, framing, texture etc. to denote type, urgency,... .

As Hansen points out, a useful display will probably consist of an appropriate integration (or overlapping) of these items.

Information on affordances (potentials for action):

- map as a track, pattern or other geometric entity which "affords" adjustment, i.e. straightening, turning, lifting, moving, connecting, etc. via some kind of direct manipulation.

- map as a set of alternatives which "afford" selection (= operation, manipulation,...). These alternates can utilize iconic, textual or geometric representations and they can also be conditionally visible (available).

In connection with human-created environments, Michaels and Carello (1981) point out that it is important that there also exists an invariant relation between the distal object, system, place or event and *detectable information* about it. To this one must add the obvious need for an invariant relation between this information and its visual representation on the display screen.

Icons in the interface

An important feature of an information system for the casual user is to support the novice and infrequent user without frustrating the frequent expert user. An element of the interface design therefore relates to the requirements of the various levels of cognitive control. In this respect, an iconic interface can be advantageous. It is well known that icons are faster to "read" compared to text since one icon can communicate complex messages. They are easier to learn than text, easier to remember and to recognize once learned which is advantageous since recognition is easier than recall. Visually we can process a far larger amount of information than with any other form. We can, for instance, recognize a well known face in a big crowd, and it is easier to use a topographic map of a town than a verbal instruction.

In any single situation, any particular user will choose a given way of responding which will depend on a host of factors - need, available time, training, and in particular in our case, the repertoire of heuristics and skills. How a user interprets an icon in a given situation depends on his/her intentions/experience at the given moment. The challenge for the designer is to provide a match between the context of the information retrieval task, displayed as icons, and the context of the intentions and needs of users' problem space, so that the user perceives the icons in the intended fashion.

Icons as Symbols

Analytical interpretation of icons depends on a figural mapping of information onto symbols with reference to the user's problem space. This mapping turns out to be very complex because the symbolic reference can be concerned with several different conceptual levels of the invariant structure of the user's domain and thus can relate to value/goal related concepts, tasks and functions and physical processes depending on the actual circumstances. In addition to serving as cues for action, a properly chosen icon can also be interpreted in several ways as a symbol for reasoning and a novice can identify its meaning through an inference related to the underlying conceptual relations. See section on library displays for example.

Command Icons

Special command icons, which are separate from the ecological work content representation, can also be necessary to give access for the user to manipulate elements of the work system or the information system in some way. Such icons are smaller pictorial entities on the display screen serving as signs which are related to actions by convention. They are chosen so as to be easily understood and remembered by expressing an idea, concept, thing or action by their resemblance and/or suggestiveness regarding the related action.

A command icon is a graphical object on the display screen which, if selected, will result in the execution of a given operation connected with the information retrieval process itself. In designing command icons, there are various representational problems to be dealt with. What are important to consider are (a) the features of the command to be "iconized" and (b) how these features will be represented. The goals of course are to enhance the user's initial linking of the icon with its command and thereafter his/her recognition of the icon followed by a quick retrieval of its command link from memory. It is important to realize that the interpretation of the content of the icon will be dependent on the current context from which it is viewed, and the comprehension of their form will be dependent on user characteristics and level of expertise. One way of achieving meaningfulness and suggestiveness would be to study the conventional use and repertoire of icons for directing action in the context of potential users' work environment and everyday life. To ensure a consistent, systematic design of icons based on such an analysis, a frame of reference containing the identified scenarios together with a selection of examples of related icons should be developed. Such a study in relation to the design of command icons for the library programme called the Book House (described later), indicated that the design/interpretation of the links between action intentions/formulations and icons can be structured in a systematic way referring to the action scenarios:

1. If State - 2. Then Actor - 3. Does Act - 4. With Object - 5. to reach goal State (Pejtersen and Rasmussen ,1987) . See figure 15

In addition to the referent in the action scenario, the pictorial *form* of a sign is chosen to enhance fast learning and recognition. This pictorial form can be based on a pictogram (a realistic reproduction), an analogy or an arbitrary representation (Lodding 1983). The possibilities are enormous and there are no rules or guidelines for making the best (or avoiding the worst) selection. See section on library displays for examples.

1. State of affairs needing attention Everyday context: Traffic signs, a "steam engine" informs about crossing trains. Be careful. Book House context: Books put aside as interesting candidates for later perusal: "Pile of books" icon
2. The actors who should care Everyday context: Icon: Lady's and gents on restroom doors Book House context: Adults and children in search of books matching their age. Icon: Adults and children searching the book shelves
3. Action to perform Everyday context: Icon: Man walking on stairs. Book House context: Put aside interesting candidates of books for later perusal. Icon: Hand putting a book aside on a table
4. Object to use Everyday context: Garbage can icon. Book House context: Delete a search term. Rubber icon
5. Target State to reach Everyday context: "Light on" icon. Book House context: Get more books. Icon: Book case full of books
6. State to avoid Everyday context: "Flame" icon informs about open fire to be avoided. Book House context: None
7. Symbolic reference Everyday context: "Hammer and Sickle " icon informs about Socialism. Book House context: Books dealing with religion. Icon: The bible
8. Pure Convention Everyday context: Red light at street crossing. Book House context: Keywords displayed in red, black text

Figure 15. Design of icons as signs can be based on different reference to items in an action scenario.

4. NAVIGATION IN THE INFORMATION SYSTEMS.

In general, there will exist a set, often a hierarchy, of display formats comprising the necessary combination and integration of the above types to cover WTU requirements. Therefore special means are necessary to support users' navigation in the representation system in order to maintain their "cognitive momentum" throughout the accession process without their "getting lost" (Woods, 1984). The problem is to create in the users a cognitive *map of the display system* including their present location, without constraining any possibility for them to develop and choose their own preferred work trajectories. Different approaches to this guidance have been discussed for process plant and library systems in subsequent sections.

5. SYMBOLIC, VISUAL REPRESENTATION IN RESEARCH

It is argued in the previous sections that the symbolic representations found in text books can be an important source of ideas for configural representations, and we have made a tentative effort to identify good sources. More work should, however, be done in this direction.

Research on the visual representation of scientific concepts seems to be focused on imagery with reference to perceptual structures in the physical world (for a recent review of imagery in science, see A Miller, 1989). Examples are the planetary model of the atom and Bolzman's mechanical model of electromagnetic coupling (see figure 16).

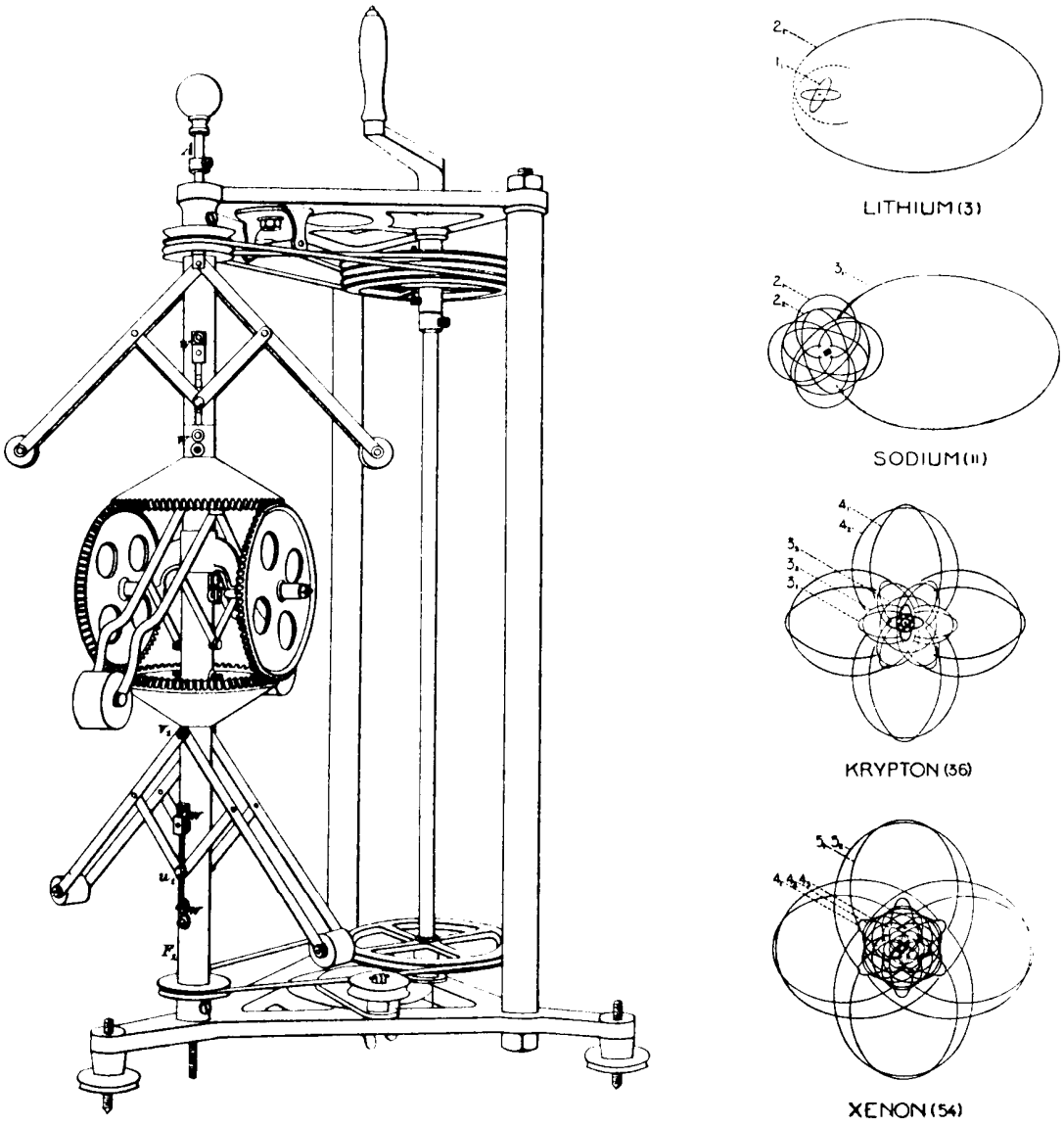


Figure 16. Visualization in terms of physical analogies which are discussed in publications on imagery and conceptual visualization used in science. To the left is shown Bolzmann's analog representation of electro-magnetic coupling and, to the right, planetary models of atoms after Bohr (reproduced from A.I. Miller, 1989). Physicists have long had problems with their object oriented representations of the nature of matter. Very little is written on their visualization and imagining in terms of abstract diagrams.

Discussion of the use of diagrammatic representations in science and technology is sparse and yet many diagrammatic representations have been used as "externalized mental models" for visualizing the effects of manipulations. That is, a mathematical, relational representation is reinterpreted in terms of causally related objects responding to 'events' such as design decisions and changes of scientific hypotheses.

A classical example is the volume-pressure diagram for adjustment and maintenance of steam engines - used for over a century (figure 17). With this "integrated display", a large repertoire of heuristic rules evolved for diagnosing deficiencies and identifying maintenance needs from the shape of the curve. Another example well known to control engineers is the pole-zero root locus representation of the mathematical representation of the dynamic properties of a feedback loop. For this representation, rules for changing system properties in an intended direction have also evolved which are directly related to the visual shape of the representation (see figure 18).

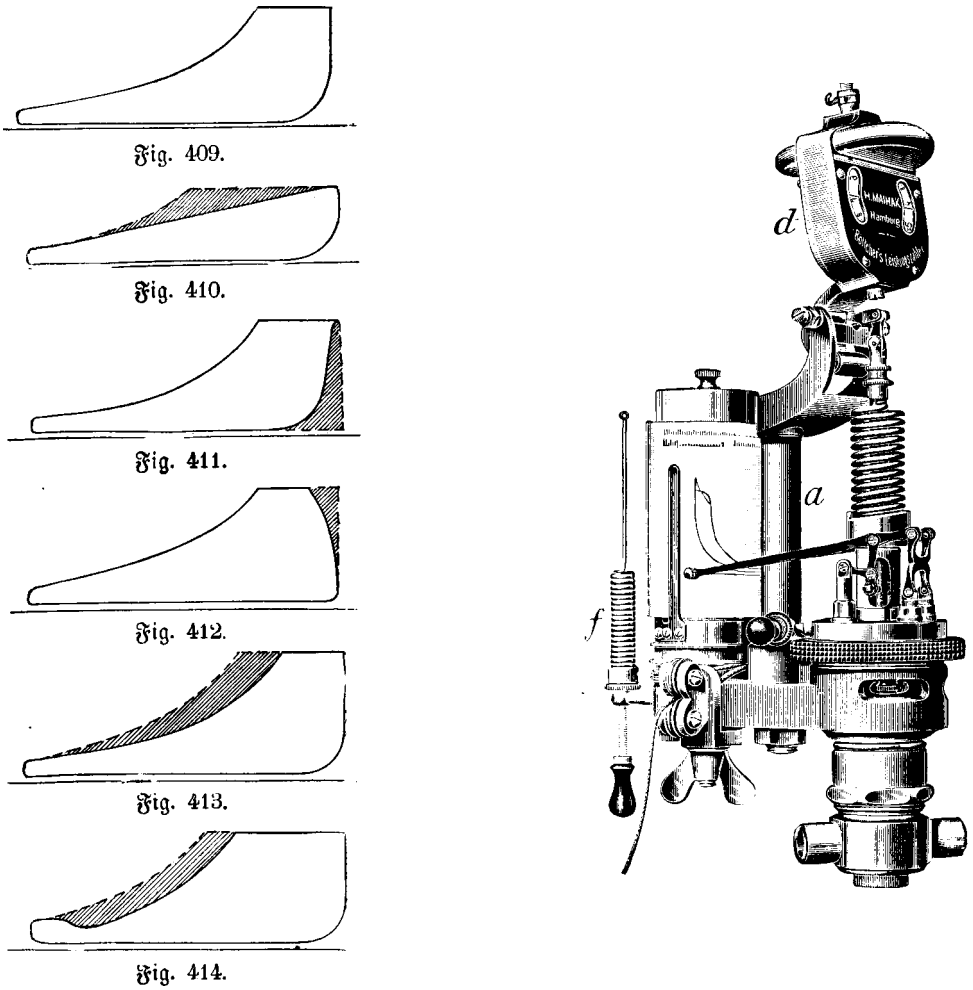
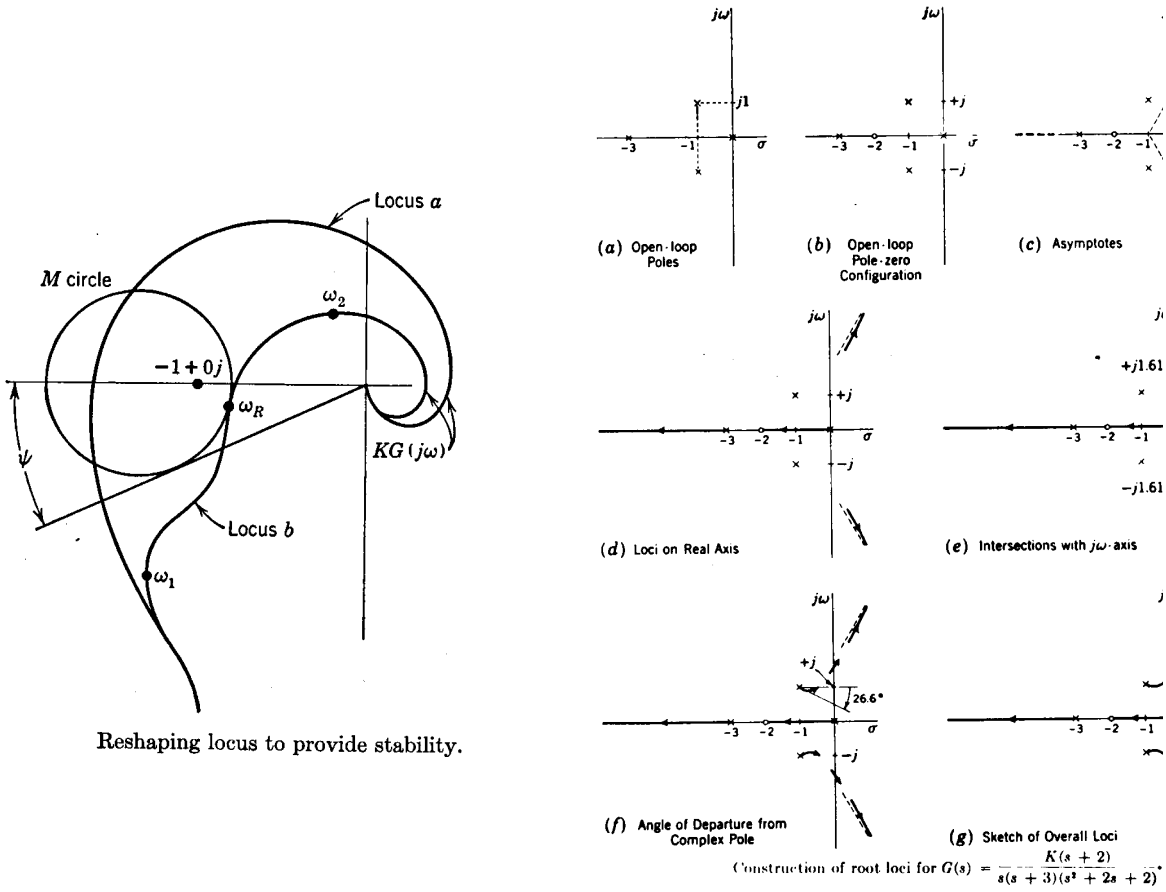


Figure 17. A graphic display of the volume-pressure relationship in the steam engine cylinders has been a common tool for operating steam engines efficiently for nearly a century. This "integrated" display was generated mechanically by combining the cylinder pressure and the piston movement by mechanical means. Heuristic rules relating shapes of the curve to necessary adjustments were well developed. The left hand figure illustrates the cues to observe from the shape of the pattern (Reproduced from Häntzschel-Clairmont, 1912).



Reshaping locus to provide stability.

Figure 18 The potential for direct perception-direct manipulation emerging from good visual mapping of abstract relationships derived mathematically from a quantitative, relational model of a "practically isolated" problem, that is, the dynamic stability of a feedback loop. To the left is shown the root locus trajectory with increasing frequency (ω) and the re-shaping necessary to obtain stability without having to solve the complex mathematics just by making sure the locus does not encircle the point -1,0. Heuristic rules for shaping such loci are shown to the right (Reproduced from Truxal (1955) with permission from McGraw-Hill International Book Co.).

The causal representation of objects and their interaction in events and the mathematical, relational representation each seem to have a distinct and different significance for design and for optimization and operation. The causal representation has played a major role in the intuition of inventors. Hindle (1981) discusses the imagination of the steam boat designers in terms of 'steam boat images':

> "The mental images of the steam boat builders have to be the historian's most important quest. He can never reach them directly, but illustrations known to have been used are basic sources, original drawings come very close to the mental conceptions, and machinery components embody the concepts."

The illustrations presented by Hindle are all drawings of the physical anatomy and the mechanical linkages of components of the machinery discussed that is, the figures are visualizations of perceptual images. Inventions apparently emerge by imaging familiar elements in new roles and combinations. A steam engine, for instance, in the early period has been described as being a backward running pump, and the first steam boats were based on engine-driven paddles. Hindle mentions that many early inventors of machinery had spatial representational abilities from other activities - as map makers, architects, artists, etc. During a voyage to the United States, a shipboard discussion of Ampere's experiments with the effect of

electromagnets on needles and a question of whether the speed of response of the needle depends on the length of the wire prompted the visualization of telegraphy by Morse. Hindle notes that Morse's sketches

> "reveal no input of analytical science or projected circuit parameters and quantitative performance. Indeed, they resemble remarkably the spatial images recorded in his travel notebooks of the scenes, costumes, and technology he encountered."

Even when inventions are based on a creative imagination concerning the interaction among objects in a new constellation, the derivation of optimal operation of the involved processes and the limits of acceptable operation will be linked to mathematical analyses of the relationships among quantitative variables which can be measured. The limits to efficiency and conditions of optimal operation of steam engines were derived by the science of thermodynamics. Therefore, abstract diagrams representing theoretical relationships are developed when mathematical, relational representations enter the scene. Diagrammatic representations to guide causal, functional reasoning were suggested by Babbage (1826) who pointed out the necessity for an abstract, functional representation in addition to the visual illustration of the machinery itself. Also Gibbs (1873) explicitly stressed the need for diagrammatic representations of phase relationships in thermodynamics. A careful review of the history of scientific, diagrammatic representations with respect to the relationships between subject matter characteristics and configural form and their role in causal reasoning could be fruitful to guide the design of ecological interfaces in the same way as catalogues of machine elements were used to guide designers of mechanical machinery during the period of industrialization.

7. WTU-EXAMPLES

1. INTRODUCTION

In line with the presentation at the beginning of this section of the use of maps of the design territory as a design aid, some examples characteristic of different locations on the map of figure 12 will now be presented. Hopefully these can serve as an incitement to designers to investigate the potential benefits of organizing their own bank of prototypes. The examples of WTU sets are drawn from field studies in process control, manufacturing, hospitals and libraries and the design of prototype interfaces for libraries and control rooms. Displays based on ecological principles are only available for process control, aircraft piloting and libraries. The discussion of manufacturing systems is based on needs identified during field studies and should be construed as a contribution for further work. The Friend'21 public information service system is included to illustrate the use of purely metaphorical systems (Friend'21, 89).

2. WTU EXAMPLES

The discussion will be introduced by examples from process plant control, which is typical for WTUs at the tightly coupled system border to the right on the map of figure 12. This will be followed by an example of a WTU set at the loosely coupled system side of the map using information retrieval in public libraries as represented by displays from the Book House system.

In the process control case, the functionality and intentionality for all task situations are well defined and give a good foundation for creating ecological interfaces. In the library case, the user needs and intentional structure, which can be explicitly formulated for a specific, well bounded and known task situation. In this situation, there exists a basis for the design of an information environment which matches user needs explicitly and an ecological interface can be proposed. In a way, process control and the library system can be viewed as prototypes of border cases encompassing many other important WTU sets located between these two on the map. These include case handling in offices, production management in manufacturing systems and maintenance activities in process systems. In discussing these intermediate examples, reference can be made to the two border cases, so we will begin with them.

1. System Driven WTUs- Process Plants.

The presentation of examples will begin from the tightly coupled system side of the map shown in figure 12, because the domain properties on this side of the map can be explicitly formulated and because ecological displays, for that reason, have been designed. The discussion will be structured as an overview according to the taxonomy.

Domain characteristics. In a WTU comprising a tightly coupled technical system located at the extreme right side of the spectrum in figure 12, such as power plants and chemical process plants, laws of nature dictate to a great extent the regularity of system functionality and behavior at all levels of the means-ends representation. That is, the functional invariants derived from

laws of nature as materially manifested in the physical process system are active upwards through the means-ends network because the entire system is functionally integrated and tightly coupled at all levels. This functional structure and coupling is also sensitive to intentional influences from production and safety goals and constraints which propagate top down through the means-ends structure as a combination of automatic control functions and procedural specifications.

Due to this functional implementation of the intentional structure, invariants can be explicitly defined at all levels of the means-ends structure and used to structure ecological displays. At the physical level, functionality depends on the boundary conditions imparted to the physical processes by the material topography and anatomy. At the process level, functionality is governed by laws of nature constraining the particular electrical, mechanical or chemical processes. At the level of general functions, invariant functional relations are governed by general laws of control theory, thermodynamics, information theory, etc. The abstract functions relating priority measures are governed by functional invariants defined by laws of conservation of values, matter and energy.

Decision making of the operating staff in their control task will be to monitor and control the state of the process systems with reference to design intentions at each level. For this task, reasoning to explain the behavior of the process system will usually be based on this causal, functional structure. On the other hand, the intentional structure defining the normal operational states of technical systems and the necessary protection against disturbances is planned by the designer and embedded in some sort of control and protection system. The higher level goals with respect to production and safety are decomposed and implemented in terms of target states and boundaries of acceptable operation downward through the levels of a hierarchically organized control system and thus impose bounds and constraints on the quantitative relationships among the functional variables. The task of the operational staff is to ensure that the functioning of the control and protection systems actually represents the intentionality of the original design. This means that they have to explain its functioning through intentional and not functional inferences, even when the behavior of the automatic system is governed by the laws underlying the physical processes of its implementation. (Its own physical structure and functioning serve only as a medium for processing this intentional information and, consequently, will only be of interest to maintenance teams.) Thus it is important to make these design intentions accessible to the operating staff. In general, great effort is spent to supply the operating staff with factual data, whereas little is done to include design base information on the displays. This is a topic well suited for expert system technology. The subjective intentionality of operators will only become relevant in boundary cases - e.g., between whether to trust instructions or to rely on one's own judgment. Figure 19 reflects this functionality - intentionality trade-off.

The *complexity* of the work environment is high, due to the large number of different, interconnected parts. The *transparency* is low at all levels because the control task is related to the thermodynamic, chemical and/or electrical processes within a closed confinement. Therefore this category of systems has been considered ripe for 'transparent' ecological displays at an early point in time. *Stability and predictability* are generally high because of the relatively long lifetimes of these types of (often large and complex) plants. Consequently there is a basis for

designing information and display systems to match specific task requirements. In the following paragraphs, a couple of display examples are discussed to outline the WTU approach.

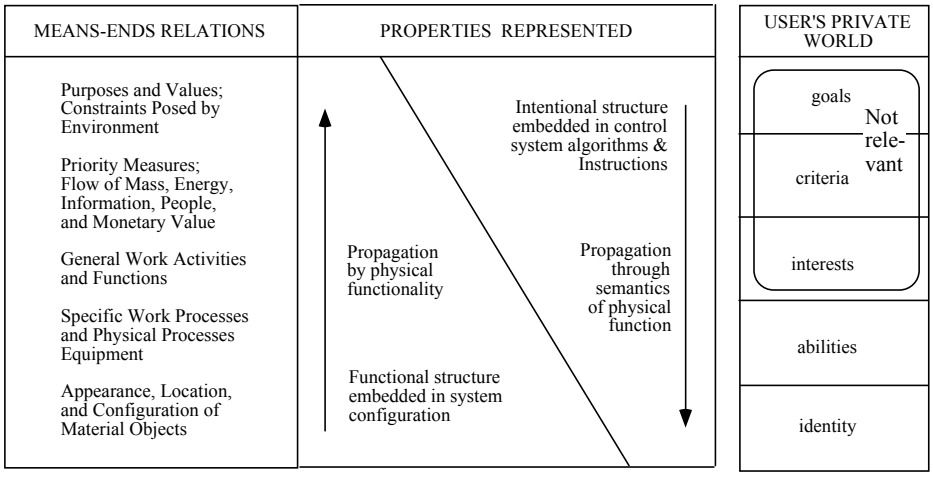


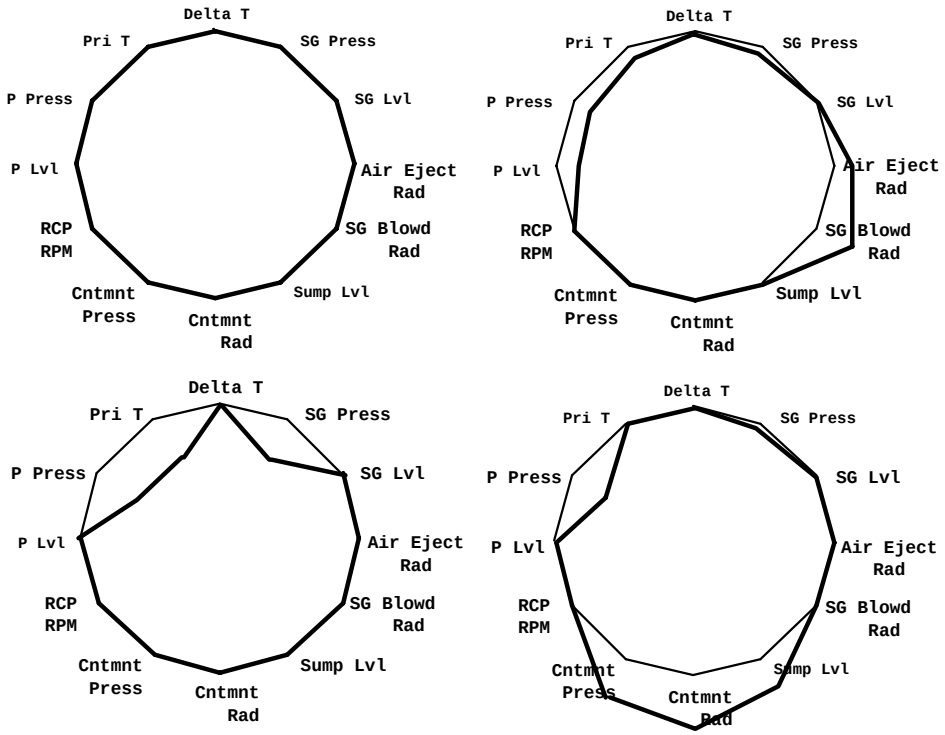
Figure 19. Functional and intentional structures. In a tightly coupled, technical system, both the functional and the intentional structures are embedded in the physical configuration and its functions

1. Process Monitoring

The display shown in figure 19 is a display aimed at **W**: a tightly coupled technical system for **T:** monitoring normal operation by **U:** a dedicated, professional operator.

During normal, automatic operation of industrial process plants, the operating staff is, more or less consciously, *monitoring* operation to detect whether plant operation needs intervention by the operator. This is done by scanning the information presented to test it for indications of possible violation of the defined operations constraints. Th2 *polar display* shown in figure 20 is based on the fact, that in a tightly coupled technical system, the magnitude of variables within a sub-system are very tightly correlated during normal operation and, therefore, the magnitude of only one variable will signal normal operation. Consequently, the selection of one representative variable from each sub-system and presentation in an integrated polar diagram for the entire system will very clearly show, when deviation from normal signal need intervention. Since *no mapping of the functional work system structure* is present, only empirically derived references to the task to enter can be derived (the display is a sign, not a symbol) and, therefore, this kind of display can be used for any system which is composed of a loosely coupled set of tightly coupled sub-systems. The 'expression of the face' of this display can give the highly skilled operator clues about the underlying cause of a disturbance by recognition. However, due to the lack of symbolic, functional connotation, it will not support analytical reasoning and, consequently, an operator will normally turn to other information sources for the diagnostic inference. The display is optimized for a very selective task situation for a well defined class of systems, see item 1 in figure 55 .

This display does not qualify as an ecological display according to our definition, because it does not make visible the internal constraints of the work domain, that is, it does not allow the user to ask questions which were not anticipated by the designer. It is aimed at a pre-defined cognitive function.



Content: Mutual Relationship within a set of the normalized magnitudes of n variables.

Sources: Intentional, normal state of system.

Form: Regular polygonon aimed at immediate perception of distortions.

Source: Human perception characteristics.

Domain characteristics:

Pacing: System paces operator

Stability: A stable system for which variables can be normalized;

Predictability: High, "normal" operational states can be defined;

Source of regularity: Laws of nature, technical system.

Complexity: Moderate to high

Structure: Can be decomposed into a set of functional units for which one variable under normal condition is correlated to and will be an indicator of the magnitude of all other relevant variables. The normal coordination among the state of these systems is stable and represented by the shape of the polygonon.

Intrinsic coupling: Only systems highly coupled at the physical process level have highly correlated variables.

Task situation: Surveillence of need to act. During monitoring the state of affairs, an actor will easily, by fringe consciousness detect the need for intervention. To the trained user, the shape of the distortion will tend to indicate the identity of the abnormal variable(s) and, thus, where to look for further information for diagnosis.

User profile:

Dedicated operator: familiar with the system configuration (he knows where to look in case of distortion).

Cognitive level: skill-based attention allocation; detection; for the expert user, pattern recognition based diagnosis.

Figure 20. A prototypical display for **W**: a tightly coupled technical system for **T:** monitoring normal operation by **U:** a dedicated, professional operator. See item no. 1 in figure 55

2. Monitoring and Disturbance Control

Information systems for monitoring and disturbance control in process plant operation present some particular problems. In this case, performance in the individual, rare but hazardous situations is as important as average good performance during normal operation. Therefore, support of an effective mental model of the functional structure of the technical system is important and a truly "ecological" representation is advantageous to re-enforce a proper model for the reasoning process.

Task Characteristics. For most industrial process systems, which normally have high hazard potentials, the task situation serving as the design basis for the control interface is the task of operations monitoring and resource management for disturbance control. Design priorities are then assigned to performance during rare situations punctuating periods of automatic operation. In these cases, the ecological approach to interface design aims at displays which aid skill and rule-based performance during normal operation and, at the same time, stimulate and support knowledge-based analysis during disturbances. Disturbance control involves diagnosis which, in a well structured system, can be done effectively through the use of strategies comparing the actual state of the system with the normal, intended state. One important characteristic of process systems is that the means-ends level at which the diagnostic problem should be considered varies with the phase of the disturbance control task and the related diagnostic perspective (Rasmussen, 1991).

User characteristics. In industrial process systems, 'users' are dedicated system operators, thoroughly familiar with the system. Their key operational role is to monitor the functioning of the automatic control and safety systems and to control operations during planned changes as well as disturbances. The intentionality of these actors is dictated by the system. It is only when an operator actually has to take on the role of a designer - e.g., in situations requiring an ad-hoc, goal directed reconfiguration of the system - that some of the intentional structure becomes operator-dependent.

Content of Ecological Displays. For highly structured technical systems, the work system itself is the exclusive source of the behavior-shaping constraints to be represented in the display formats. In figure 21, the map of knowledge representations is used to illustrate this via the emphasized path of the work analysis used for identifying the ***content*** of the display information for this class of WTU.

A visual support of diagnosis in a system which has a stable and well defined functional structure can be given by displays which overlay actual and intended states at different levels of representation useful for different objectives and perspectives which may govern the diagnostic task (see Rasmussen, op. cit.). In an ecological display, configural representations should be found which support direct perception of the relationship between the actual, functional state (the relationship among measured variables) and the intentional target and limit states. To enhance this direct perception of discrepancies between the *actual* and the *intended* states of operation, it is necessary to represent the actual, functional state (the relationships among measured variables) and the intentional target and limit states in a compatible fashion. Consequently, the intentional structure - as reflected in the target operating states and boundaries to unacceptable operation - should be represented by an overlay on the representation of the actual functional structure and states. Therefore, for this class of WTUs,

the representation of invariants will normally be in terms of diagrammatic and scalar representations of relationships among quantitative variables.

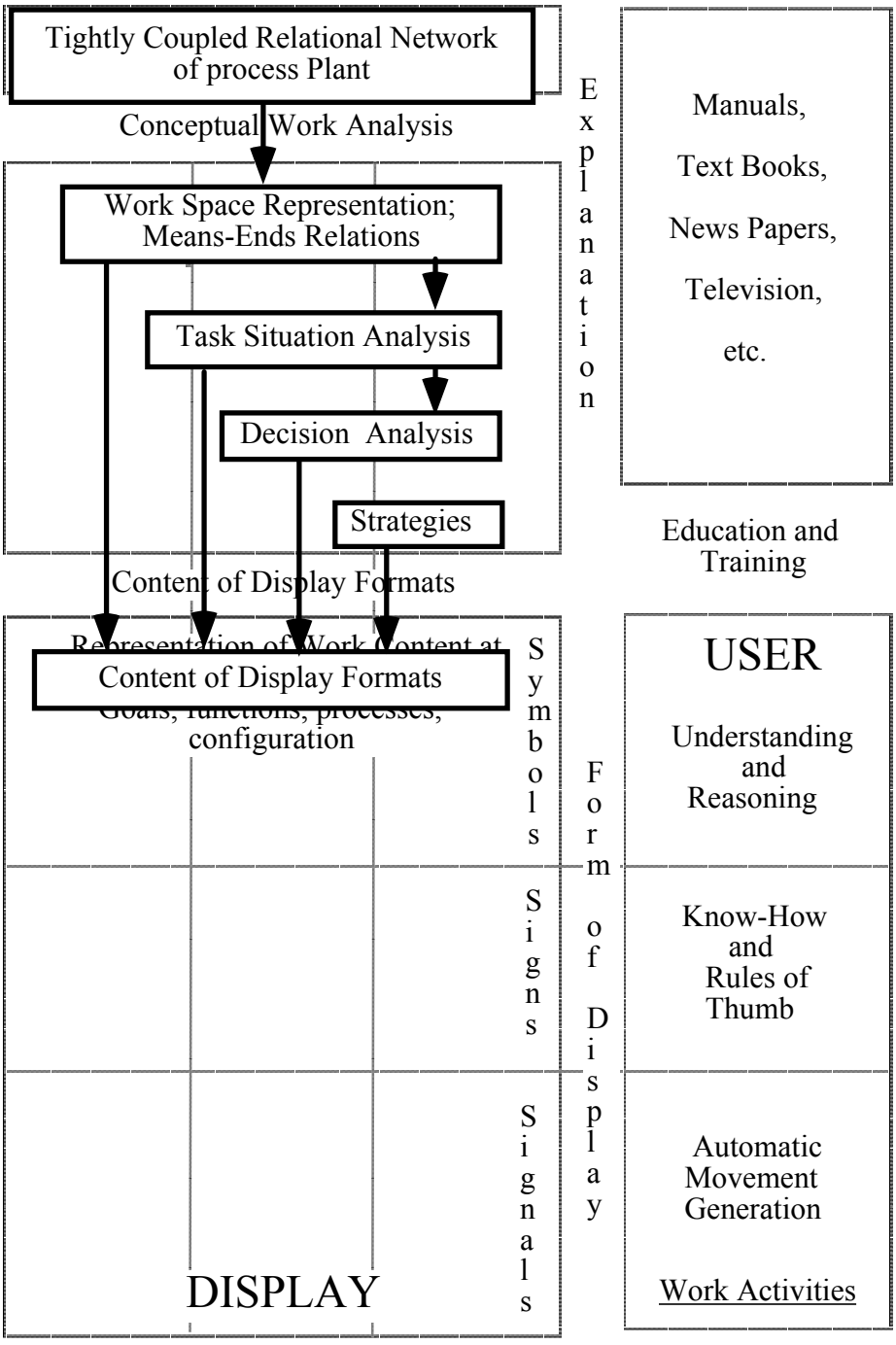


Figure 20. Identification of display content for tightly coupled systems.In highly structured and tightly coupled technical systems, the elements as well as the structure of the domain representation are defined by the work system, and the source of relational structures of the display formats is solely the work system. The users are operators serving the needs of the system according to its design intentions.

Form of Ecological Displays. The basic idea behind an ecological interface design is that the relationships characterizing the internal functioning of the work system should be made available to the kind of reasoning that is natural to the human agent. Therefore for directly

perceptive displays in tightly-coupled domains, the symbolic relationships among the quantitative variables which underlie any adjustments of the conditions for optimal or satisfying operation within acceptable limits should be represented so as to be useful for functional reasoning. This requires that diagrammatic representations be used to support this reasoning in terms of causal relationships among virtual objects. As a result, the quantitative relationships among variables and their acceptable limit values should be represented by virtual objects changing their shape and/or moving in a symbolic topography which matches the characteristics of direct human perception.

In open ended, diagnostic situations, an exploration of the state of the work space is important and will require the opportunity for flexible shifts in level of abstraction simultaneously with degrees of system decomposition so that a "narrowing-in" on the source of the problem and the resources for action can take place. Thus the trajectory of exploratory searches in the abstraction-decomposition work space will primarily be along the top-left/bottom-right diagonal. The design of ecological displays can thus build on this by ensuring that span of attention and shifts in abstraction are correlated. See figure 22.

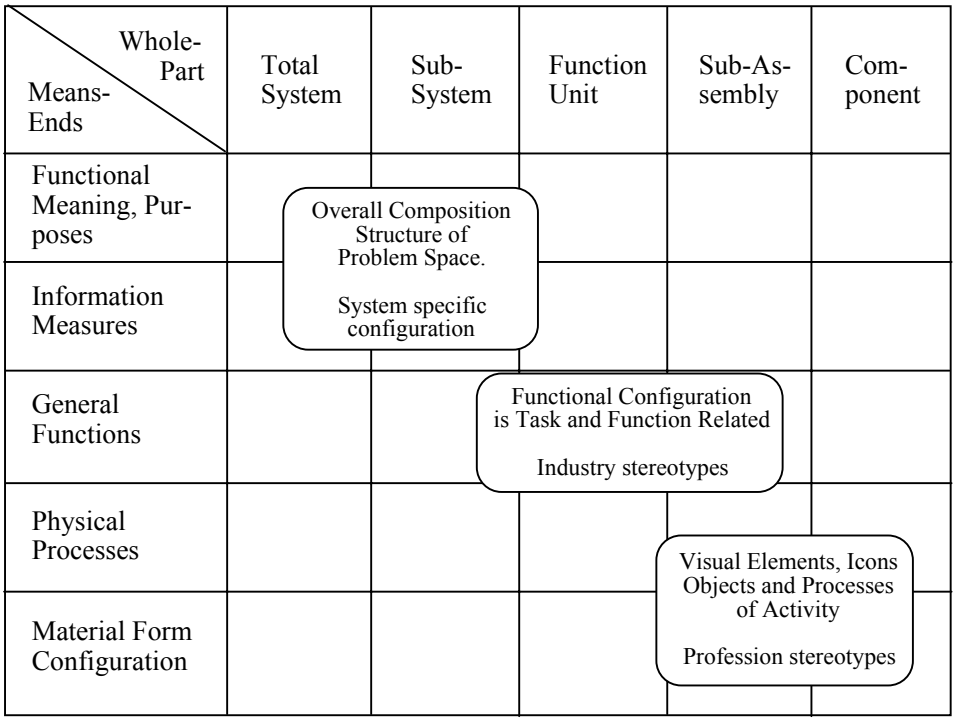


Figure 22. Mapping of the sources of display forms onto work domain. In the design of composite displays, the source of regularity or the inspiration for design will have to be related to different sources of visual codes, depending on the level of aggregation. For a similar mapping of display composition, see Vicente, 1991.

At the global level, display composition should reflect the plant structure and will be specific for the kind of system. On the other hand, low level display elements should map closely to actions on physical items or components. Since these no doubt will be utilized in a wide context, the form should match population or professional stereotypes. At the intermediary and more "black-box" level, activity is related to functional relations for which stereotype representations (in some cases standards) from drawings and manuals can be found within the involved profession (Figure 23).

A Display Coding Example

A more detailed discussion of the coding of the qualitative variables and constraints used in figure 23 will be illustrative to show the dynamic features of the ecological displays.

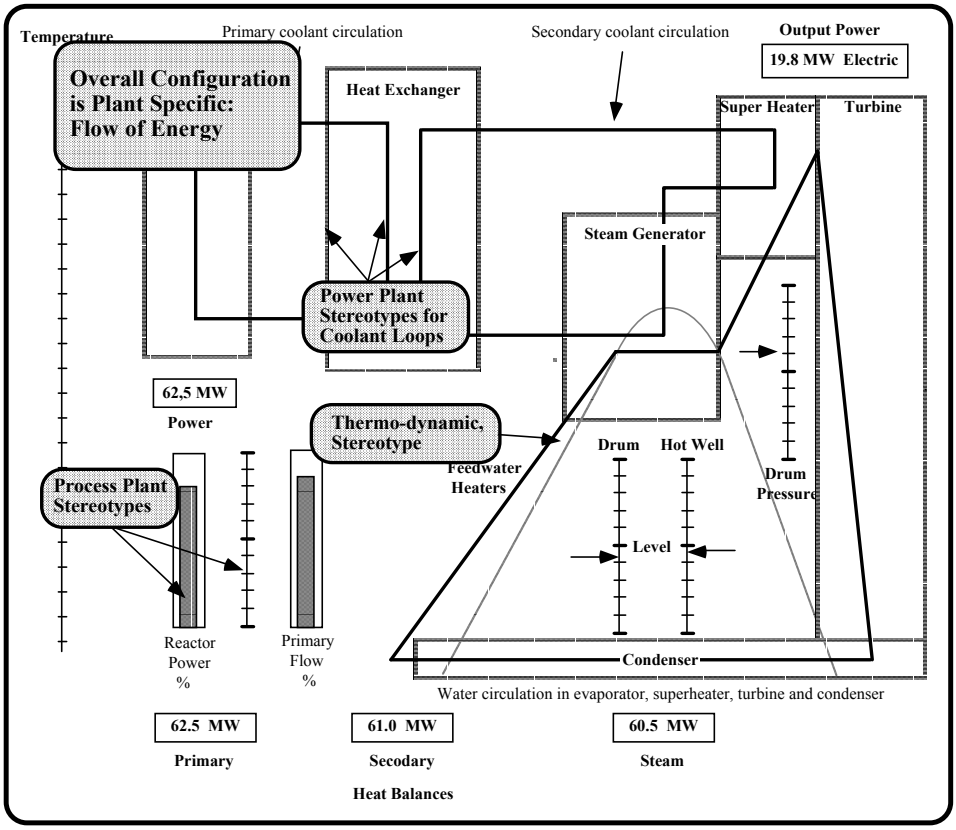
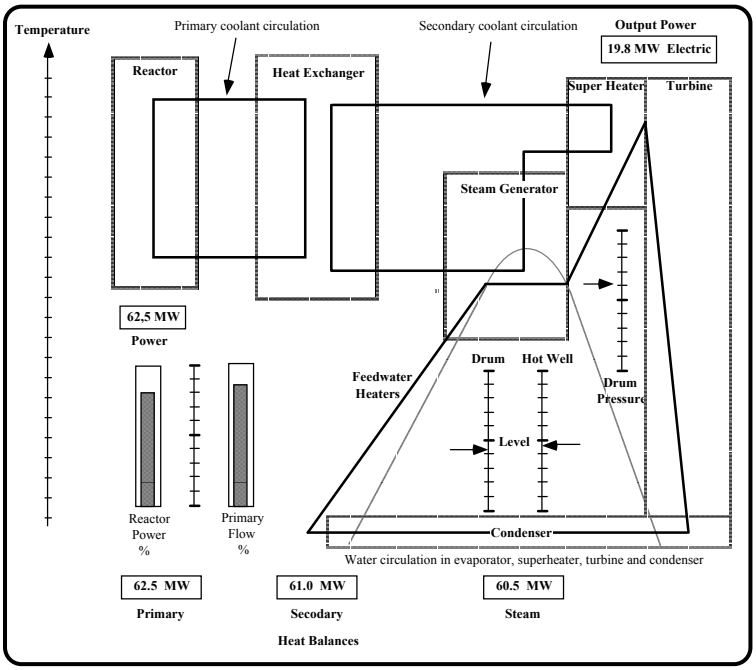


Figure 23. An experimental overall display for a nuclear power reactor. The display is based on measured plant data used to modulate the shape of graphical patterns which support perception of higher level functional features. Graphical patterns show the circulation paths of coolant and water. The temperature at different points of the paths can be read on the common scale. The patterns, therefore, directly show the temperature rise and fall in core, heat exchanger, etc., at the same time as the temperature differences across heat exchangers can be read. Experiments with the dynamic display show that the propagation of a disturbance in the energy flow through the system can be directly perceived from the overall pattern. 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. (Reproduced from Lindsay and Staffon 1988).

The symbols used in the display are expanded in figures 25 to 29. Figure 25 explains the display of the coolant circuit displays, while figures 26 and 27 illustrate the complex pressure-temperature relationships in a boiler, in this case a steam generator. Note that even when the primary, measured data are shown directly, the functional status of the system can be read directly from the *interrelationships* between the data.

The phase diagram of a water-steam mixture existing in a boiler is shown on figure 26 To the left is water, to the right steam and within the curve is found a boiling water-steam mixture. This relationship is the basis of safe boiler control. Figure 27 shows the Rankine cycle overlay on the phase diagram. This underlies the thermodynamic performance of the steam-water system. Water boils along the horizontal line and the operating point of the steam generator should be kept safely along this line. At the right side of the curve, the boiler becomes dry, at the left side it will be full of water - i.e., it "goes solid", in the terminology of operators. Both cases are

dangerous because control of temperature/pressure/inventory is difficult and an accident can threaten. 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 'super-heater' before it goes to the turbine where it 'cools down' by delivering its energy content to the turbo-generator. Thereafter the steam is condensed and the pre-heat cycle is re-entered.



Content: Representation of the relationship of state variables of a physical process and the boundary conditions of acceptable relationships.

Form: Developed from the graphical representation of the relationships adopted for research and teaching of professionals and as defined by the laws of nature underlying intended function.

Task situation:

Situation assessment (detection, diagnosis, hazard priority judgment, and resource management during disturbance). Selection of tools for action will require shift to other display.

Domain characteristics required:

Pacing: by system
Complexity: high;
Source of regularity: Stable laws (of nature);
Coupling: tightly coupled system for which relationships among variables can be controlled;
Level of coupling: physical processes;
Predictability: high.

User profile:

Dedicated operator. Experts can develop direct manipulation skills, and know-how rules working at the face expression at the same time as novices and experts in unfamiliar situation can use the configuration as an externalized mental model for reasoning.

Figure 24. An ecological display for monitoring, diagnosis, and disturbance control in process plants.

Figure 28 and 29 illustrate how the graphic patterns can support an overview of the propagation of changes through the system in case of disturbances. Figure 26 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 23. 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.

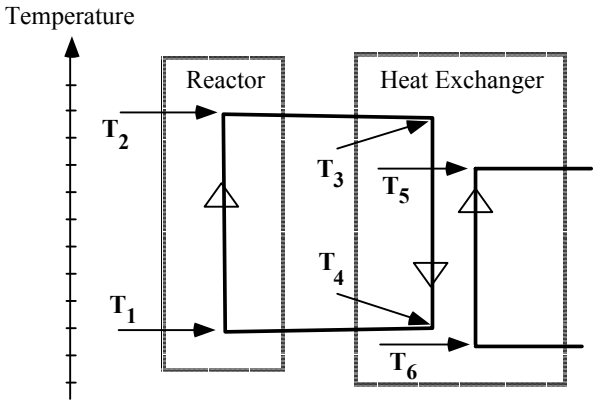


Figure 25 shows the basic graphic symbol for a cooling circuit. The background boxes represent the heat producing reactor core and the primary heat exchanger. The rectangular overlays represent the cooling circuits with arrows indicating the coolant flow direction. The sides of the rectangles indicate 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.

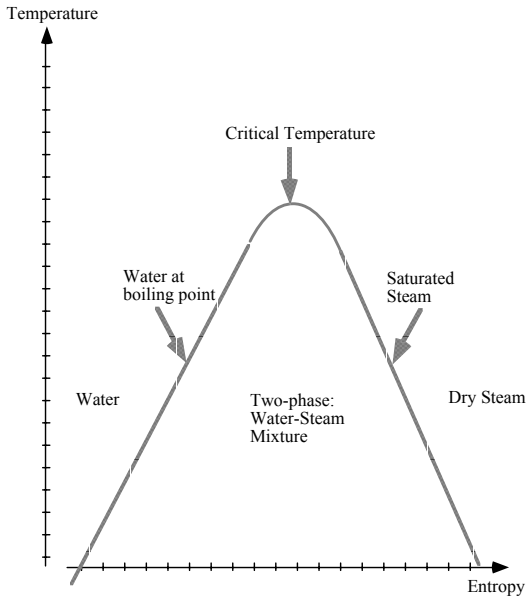


Figure 26 shows the two-phase diagram of a water boiler

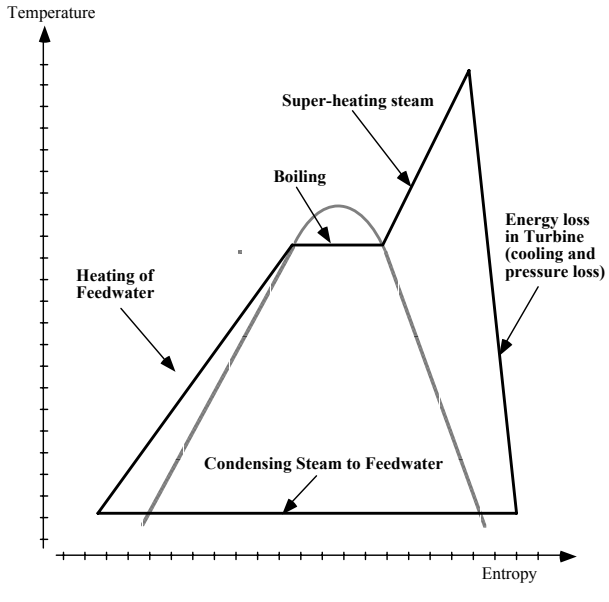


Figure 27 shows the Rankine-cycle of a power plant.

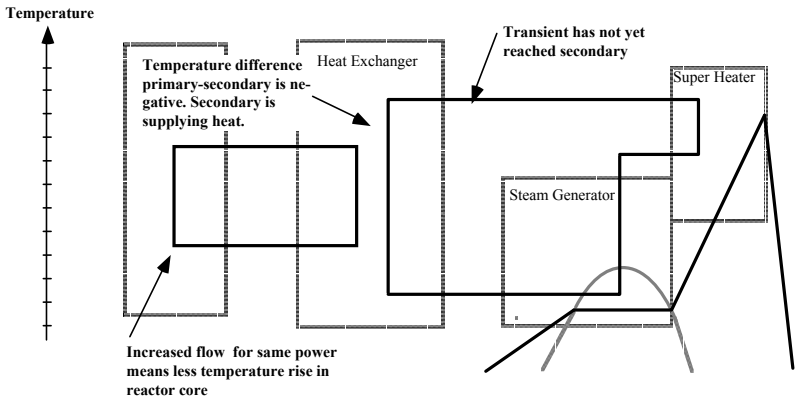


Figure 28 illustrates the change in the coolant flow/temperature pattern when the primary coolant flow is suddenly increased. The power production can now be transported by the coolant with a lower temperature rise and the temperature profile of the primary collapses. The secondary circuit is not yet 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.

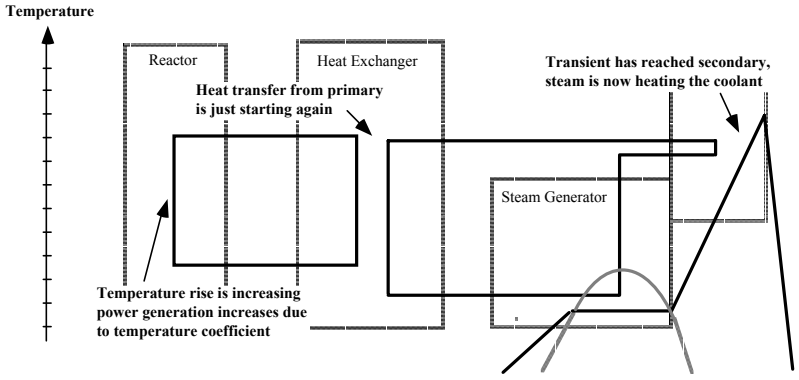


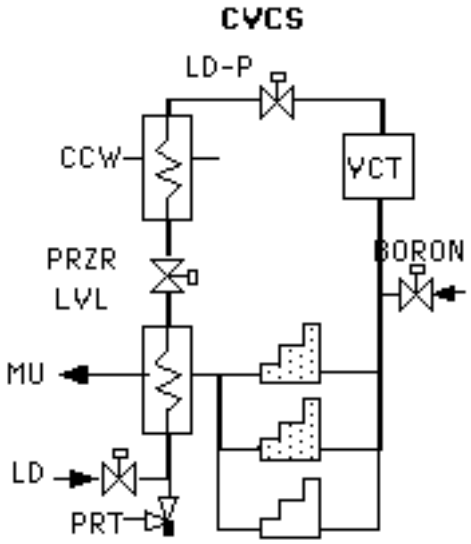
Figure 29 presents the state a little later. The transient has now reached the secondary circuit while the primary circuit is restoring due to an increase in power production caused by the decreased temperature and a negative power-temperature coefficient. Note that the individual temperature representations of the display, such as for instance, output temperature from the core and input temperature in the heat exchanger, are based on separate sensors. Inconsistencies from a sensor failure can therefore be seen directly if a slope appears on the horizontal lines representing a pure coolant transport in pipes.

Figure 29 presents the state of the system a little later. The transient has now reached the secondary circuit while the primary circuit is recovering 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, the output temperature from the core and the input temperature in the heat exchanger, are based on separate sensors. Therefore, an inconsistency because of a sensor failure can be seen directly if an unexpected slope appears on the horizontal lines representing a pure coolant transport in pipes.

The important point to gather from this example is that in this Rankine cycle display there is the opportunity for the operator to choose the level of decomposition in the perception of the state of affairs which matches the task at hand. The display can be perceived at the level of flow of energy, of the 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 has long been 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 become correlated to familiar action sequences are likely to be defining patterns rather than convenient

signs and, therefore, can effectively prevent 'under-specified' action mistakes. Finally, the faithful representation of the control objects embedded in their structural context is likely to invite the evolution of reliable 'direct manipulation' skills. Direct manipulation directly from an abstract, functional display at the level of the Rankine example requires computer based generation of the detailed manipulation sequence at the level of the physical components. In general, this is a very complex task, if the number of action alternatives is high and the criteria for choice are ambiguous and situation dependent. In a highly regulated environment such as a nuclear power plant, the alternatives are limited and the acceptable control sequences bounded by the safety philosophy and, in that case, automatic generation of control procedures is not impossible. An approach to this kind of ad hoc procedure generation for giving advice to the operating staff has been proposed (see e.g., Monta, 1991).

3. Resource Management



Content: Representation of the physical anatomy of a technical system including objects (means for actions) and their operational availability.
Source: Anatomy of Process Plant
Form: Professional conventions for representation of equipment.
Source: Text books, engineering blueprints.

Task situation:
Planning of system reconfiguration operations.

Domain Characteristics:
Pacing: By user
Complexity: Typically high, by number and connectivity of objects
Source of regularity: Physical laws
Coupling: tight
Level of coupling: physical anatomy and function
Predictability: high

User profile:
Semi autonomous, professional user.

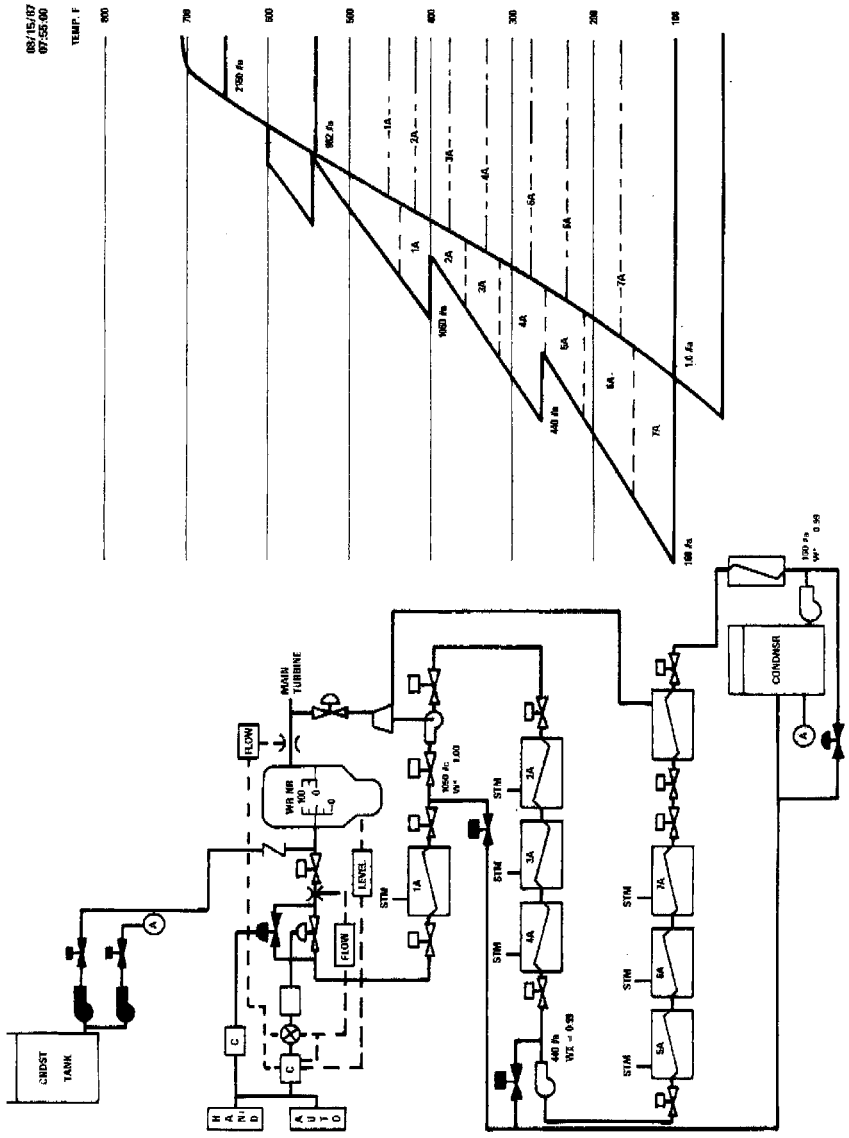


Figure 31. Beltracchi's display for the pre-heat function.The display integrates the configural display of actual and intended system state and the physical configuration representation for resource management.

When direct manipulation of material resources is not possible from the functional level, access to the physical configuration and the operational status of the components is necessary. Resource management in disturbance control involves the exploration of resources for re-configuring the system to prepare for maintenance or to compensate for disturbances or for component malfunctions. In such a situation, it is important to check the operational availability of stand-by facilities because the equipment to be used for control actions may or may not be available depending on maintenance, use for other functions, etc. The domain of search is the population of physical parts relevant to the task and the criterion of choice is their location in the physical functional anatomy. Therefore, a suitable presentation is a "mimic diagram" showing

Figure 30. Analog ("mimic" in process plant terms) representation of the physical anatomy of a technical system including objects (means for actions) and their operational availability.

the possible, alternative physical functional units together with an indication of their availability and the operational states of the parts. See figure 28 for a simple example and figure 31 for an integrated diagnostic and resource management display. Here the form is an analog representation of the connectivity (not the topography) of the system using icons which are more or less industry standards for the components used.

Compare the representation used in figure 29 and 30. For many decision tasks, even in process control, a representation based on *causal relations* among objects, states, and events is used, as is the case in resource management. In contrast, the ecological interface representation relevant for operations monitoring and disturbance control depends on a *quantitative, relational* representation of operating states and constraints modulating the shape of a configural display format. The two types of representation can be combined, as suggested by Beltracchi (1987) in figure 31

4. Navigation in the Information System.

The examples in the previous paragraphs concern a single composite display for selected task situations. A total set of displays would encompass all of these and many more - covering the functionality at all relevant levels of means-ends and decomposition as well as (hopefully) intentional information about the automatic systems, relevant instructions, etc. Thus an ecological information system in an actual control room will include a large number of displays. Since, for tightly coupled systems, the structure of the associated control tasks will closely match the structure of the means-ends/part-whole work space, it would be reasonable to use the same approach in structuring the set of necessary display formats . Thus a suitable navigational support can be based on this structure, as suggested by Goodstein for the GNP experimental display system (Goodstein, 1985). See figure 32.

5. Flying Aircraft

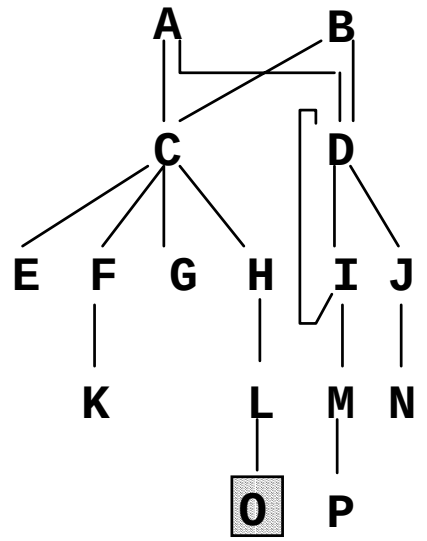
Displays for of aircraft piloting is another area for which the development of ecological displays has been explicitly considered at an early stage. In addition, this represents a WTU which is located close to the process plant example in the map of figure 12. The reader's attention is directed toward this application area because a significant effort has been spent on the development of displays based on Gibson's direct perception theories (see Stokes and Wickens, 1988).

Domain characteristics. In this case, the work environment is characterized by the interaction of an aircraft possessing well defined dynamic properties with an environment which is constituted by a continuously changing topography. However the latter can be characterized by a stable set of anatomical and configural elements which can be quantitatively represented.

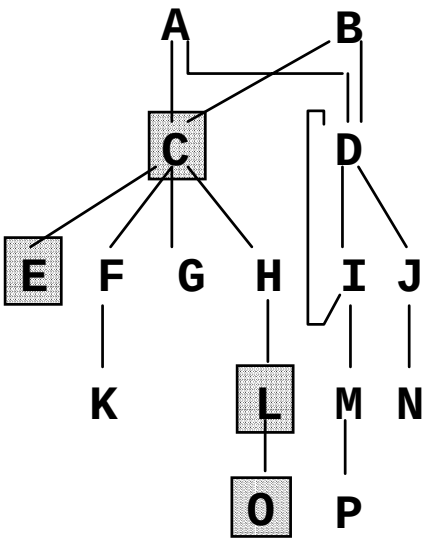
Task characteristics. Aircraft piloting depends heavily on skill and rule-based competences, and maintaining optimal performance during normal as well as infrequent situations is important. Knowledge-based performance is found typically during rehearsals of critical scenarios in advance of actual missions in order to generate proper skill/rule based responses (Amalberti and Deblon, 1989).

Ecological display. Research on display design has been focused on representing those features of Gibson's 'optical array' in a normal flight environment which support perception of

speed, height and flight direction. Most 'head-up' displays serve to integrate measured flight variables into a dynamic analog representation of the behaviour-shaping features of the topography of the environment modulated by the movements of the aircraft. This requires a representation of the quantitative relationships of the environment and the flight dynamics. It has recently been proposed to present to pilots an envelope around the flight path which is recommended by the computerized fight management system based on measured data and a model of the aircraft's flight dynamics and limiting properties. An example from Stokes and Wickens (1988) is shown in figure 33. A comparison with figure 34 will show that this kind of display can be perceived as an adaptation of Gibson's concept of 'the field of safe travel' for car-driving from the 1930's.



Single alarm



More complex alarm pattern

Figure 32 A navigational aid in the form of a functional alarm/display presentation. When an alarm calls for the attention of the operator, the relevant display formats are highlighted in a tree showing the available formats and their location in a network representing the levels of the means-ends hierarchy.

Since both the functional invariants and the dynamic constraints can be represented by quantitative, configural displays, considerable similarities can be seen with the thermodynamic displays for power plants. In a way, these latter displays are analog to navigation displays, in process plant in fig. 32 and in the library system in fig. 37, but at a higher level of abstraction.

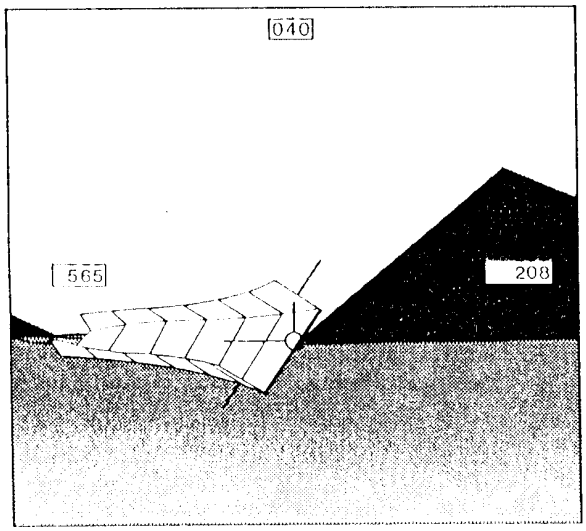


Figure 33. A 'highway-in-the-sky' display showing the constraints around the flight path as defined by the flight-management system. It shows the recommended path which can be overruled by the pilot. (Reproduced from rom Stokes and Wickens, 1988)

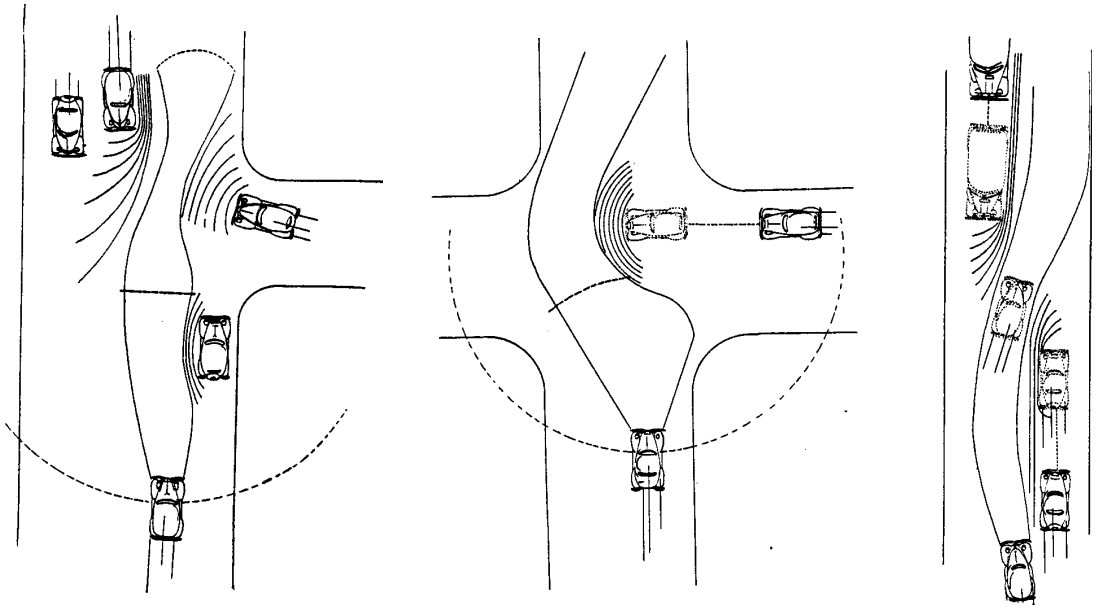


Figure 34. Field analysis of car driving. An early approach to modelling a work environment in terms of the behaviour-shaping constraints defining an envelope within which the actors can freely navigate is found in Gibson and Crooks (1938) field analysis of car driving. For explaining skilled car driving, they identify the "field of safe travel and minimum stopping zone of a driver in traffic." Gibson's account is only dealing with locomotion in a physical environment but similar constraint-based descriptions can be used at higher levels of abstraction with respect to descriptions of the environment and higher levels of cognitive control.

2. User Defined WTU - Libraries

As mentioned above, the WTU related to information retrieval in public libraries is typical of the other border line case between WTU sets for which the user intentions can be explicitly

formulated and for which ecological displays are useful - while the unstructured situations further to the left in the map represent those for which metaphor based systems normally are required. The presentation of WTUs from process control and library work will subsequently serve to illustrate how analogies from these two borderline cases can be used for the design of information systems in the middle region of figure 12.

Domain Characteristics. The work domain in libraries is very loosely coupled, constituted by a large collection of similar items, books and documents and a set of separate tools, such as card catalogues and printed materials. Invariants originating in causal laws, therefore, are only to be found at the lower means-ends levels - in the anatomy and processes of the separate items of equipment and tools and their related work processes. The functionality at the higher levels depends on human activities and the predominant sources of regularity - the invariants - related to the coordination of the work processes can only be found in an intentional structure derived from institutional policies, legislation, socially established rules of conduct, etc. In the library, the institutional intentionality is derived from financial constraints and legislation concerning the role of libraries in public education and their mediation of cultural values, etc. In the work situation to be considered, i.e.information retrieval for the reader of fiction both as an educational activity as well as a leisure activity, - this intentionality is reflected only in the selection of books for the shelves and in the objective and subjective contents of the instructions from the librarians to the users on the basis of their training, instructions and personal experience.

Task Situation Characteristics. In the present example, the task situation considered deals with a user in a public library looking for fiction to read. Thus the 'work space' activated within the domain is basically a collection of books with no natural functional structure. In work systems designed for meeting the personal (recreational and educational) needs of a user, the intentionality governing the use of the system (within the envelope defined by institutional policies and constraints) is exercised entirely by the user. Many alternatives underlie the choice 'what, when and how to do', and these are left to the discretion of the users, see figure 35.

User characteristics. Library systems must cater to a wide range of casual and professional users - often children and adults - with varying backgrounds, experience, needs and temperaments - e.g. the amount of time they are willing to spend, their 'fear' of technology, etc..

Design of an ecological support system. The basic conditions for designing retrieval support systems for this WTU example comprise a large collection of items and a set of separate tools - in all a work environment essentially without any inherent structure. Therefore, to support exploration and search, the functionality of the work system must be designed to match as well as possible the work processes, that is, search strategies, relevant to the task and preferred by the users. As the basis for the design of the *functionality* of such an integrated information system, it is necessary to know the search strategies which are effective for retrieval and which match the resource profiles and preferences of the user. The representation of the field in which the search is done, that is, the semantics of the functionality in terms of the content of the documents must also match user values and needs. Therefore as the basis for system design, the users' educational and recreational *reading needs* must be identified. In addition, *preferred strategies* for searching through a book stock must be formulated from analyses of users' retrieval behavior in libraries. (Pejtersen, 1979, 1980).

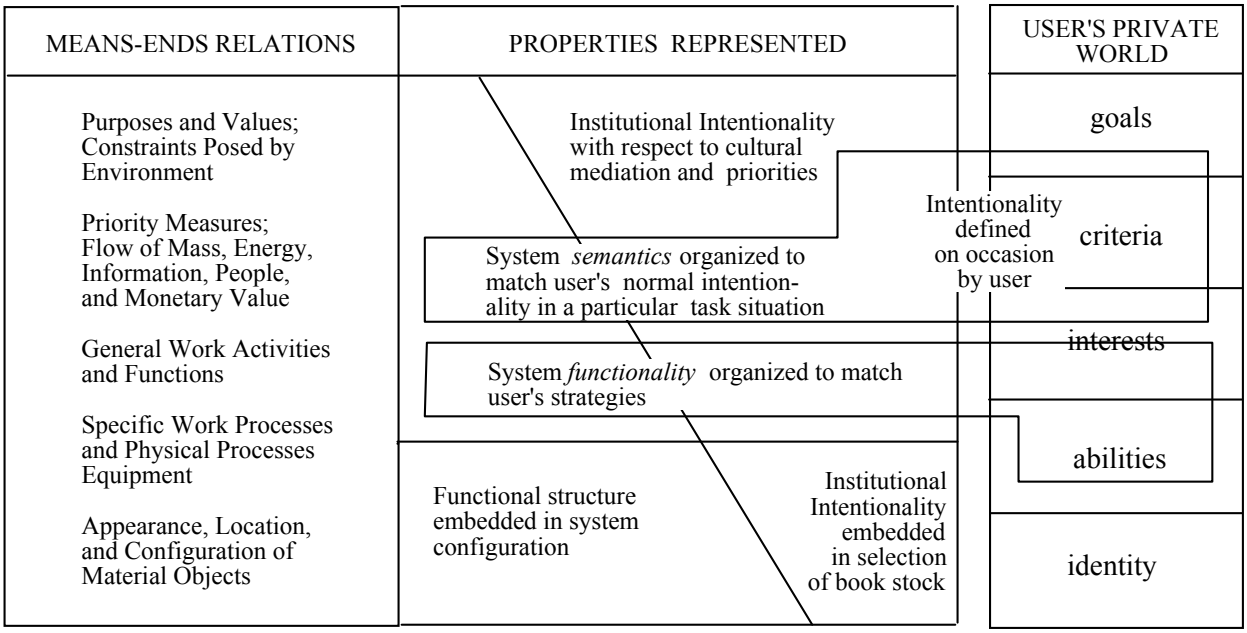


Figure 35. Sources of intentionality in a library system.An ecological information system is organized so as to match intentionality and functionality (search strategies) in a way which is natural for the user in his/her given problem situation.

The content of the display system. It follows that the functionality of the support system, its syntax, is derived from these analyses of users' preferred work processes, their strategies, while the semantics of the system is based on users' formulation of their subjective values and reading intentions. The semantics defines essentially the *content* of the necessary display formats. The transformation of representations involved is illustrated in figure 36.

Display structure and form. The overall *structure* of such an information system which can provide the user with navigational support as well as the *form* of the required displays cannot be derived solely from the functionality derivable from the individual search strategies. The users in a library represent a wide selection of the general public and therefore an overall organizing principle cannot be related to a particular problem space and its related knowledge structure as is the case for systems such as process plants and manufacturing systems. Unlike with a power plant, there is no object system in the background to structure the context of the search and its pictorialization. Therefore, one must seek a more universal means and a higher level organizing principle must be found which is familiar to users from another context - that is, a suitable metaphor has to be found.

Since the functionality necessary for supporting search strategies does not in principle constrain the context in which a search is performed, a metaphor utilizing a "storehouse" was chosen to exploit the general observation that information is a question of "where" (Semonides, 500 bC, Miller, 1968). Several of the display formats will be discussed here to illustrate this approach.

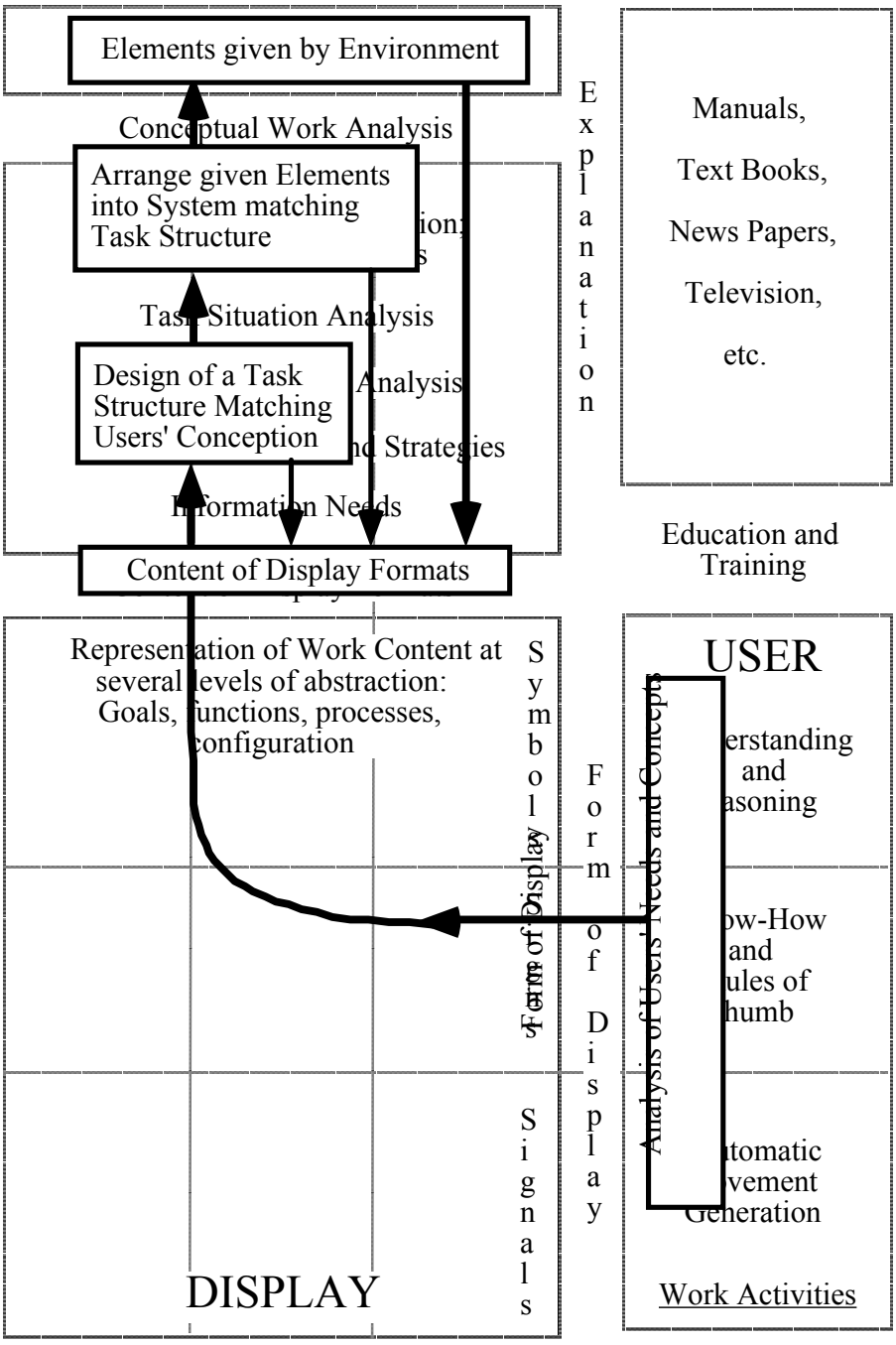
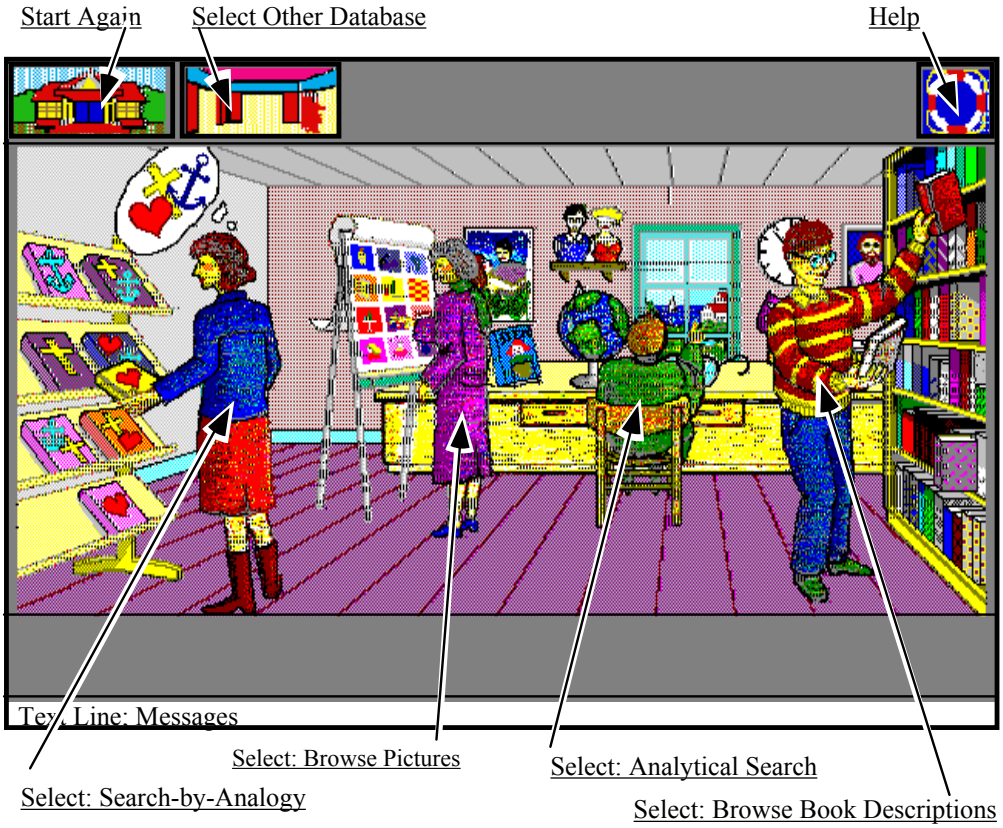


Figure 37. Identification of the content of displays for user-driven system.For systems in which users are autonomous and determine the goals, task and approach to their work, the sources of regularity to embed in the information system design and to represent in the content of interface formats reside in the problem space defined by the users' own needs. This does not imply that an information system cannot be highly structured by a formal concept, but only that it should be based on an analysis of the relational structure of the users' needs folded onto the means for support given. Thus, in contrast to figure 21, this WTU support design utilizes the user as the source of the transformational process leading to the contents of the displays.

Bookhouse "Strategy Selection" Room



Content: Representation of the separate search strategy options for searching books in the database and the action possibilities for navigation in the system
Source: Analysis of functions and information content in strategies applied in information retrieval in libraries
Form: Pictorial representations of end users as actors performing different search activities and interacting with various forms of objects, events and concepts involved in a search strategy
Source: Analysis of pictorial conventions in the population and common knowledge about libraries

Task situation:
Planning or selection of actions and search activities, selection among resources available to user

Domain characteristics:
Pacing: by user
Complexity: low to moderate number of alternatives
Source of regularity: Derived by design from intentional structures of users' problem space involved in various search patterns in libraries
Intrinsic Coupling: low
Predictability: Low, high by design

User profile:
Autonomous, casual and professional user. Typically autonomous user belonging to a defined group (defined by age, sex, profession, nationality. etc.) sharing cultural prototypes

Display for Choice of Search Strategy

Figure 37. The 'room' for choice of search strategy in library system. From the left: Search by analogy, browsing through pictures, analytical searches, browsing through book descriptions. When the user selects a strategy, the system supports the further processing of the search, including automated retrieval functions. See item 11 in figure 55.

In this metaphor, separate 'rooms' are available to support the various decisions which have to be made during a retrieval. For example, a particular *search strategy* can be activated by selecting one of four work places in the "strategy room" of the storehouse - see figure 37 which illustrates the matrix approach to all the BookHouse displays. Here a user can decide to *browse* in two ways - via 1) intuitive matching of random book contents with one's current reading need or via 2) comparisons of one's own semantic interpretations of pictorial icons with current reading inclinations, 3) *search by analogy* by asking for a book similar to a known title, and 4) *search analytically* by an explicit specification of needs. See item 11 in figure 55.

Analytical Search

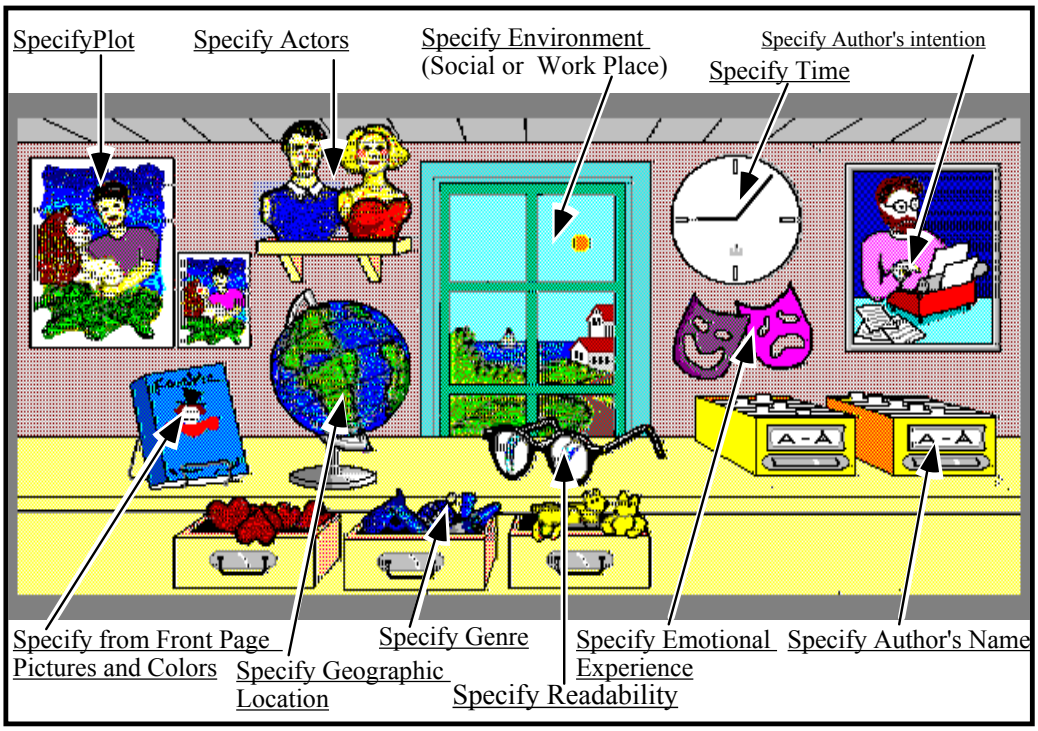
In connection with the analytical atrategy, a further support of the user's explicit *formulation of reading needs* is given through the display of a work desk with icons which identify the various dimensions of need found from field studies - see figure 38. The work room display in figure 38 supports analytical search in a work space with attributes of the book collection at several levels of abstraction as identified in a work analysis, including the user's overall goal with the search and the user's reading capability. The work room makes the invariant structure of the data base immediately transparent to the user, and supports the analytical situation analysis, domain exploration, planning and execution of a search. By making these dimensions explicit, the display probes the user's memory for aspects to consider. At the same time, the icons function as command icons which allow the specific dimensions to be used for search to be specified by direct manipulation. The abstract attributes of items in the data base are consistently recoded as physical objects to positions in various spatial arrangements as tools on the desk and posters on the wall to reinforce the development of manual skills in the spatial-temporal working space

On and around the table are icons representing the different dimensions of the invariant structure used to classify books in the system. They give a pictorial link to the semantics of the dimension they represent and are also signs for action in order to proceed further. see item 10 in figure 55.

The Browsing Strategy

To support domain exploration and intuitive searches as identified in the work study, a picture association thesaurus with icons can be selected to provide a quick birds eye view of the semantic content of the data base and subsequent recognition of need situation and goal setting.(see figure 39). When a picture is selected, books are retrieved and book descriptions displayed. This delimits the search space to a partial selection of the semantic network, which can then be searched with keywords. To serve this purpose, each icon represents a semantic, associatively related network with a large number of keywords. Each network represented by an icon can then be combined with another network rpresented by another icon as the user browses, associates and recognizes more icons of relevance to the need. However, apart from being an effective representation of an associatively related semantic network, the rich connotations of icons can provide an unexpected aesthetic and emotional experience, and give rise to potentially new perspectives and associations on vaguely perceived needs. Figure 40 illustrates a display supposed to support the strategy of browsing book description to support a textual recognition of need, which is a more complex form of browsing. See item 9 in figure 55 for the position of picture browsing displays .

Bookhouse "work" room



Content: Representation of the dimensions of the search space characterizing multidimensional items in a database collection of books.
Source: Analysis of the aspects of book descriptions derived from user quiries during searches in libraries
Form: Pictorial representation of objects illustrating the concepts defining the dimensions of the search space.
Source: Population stereotypes from association tests and questionaires.

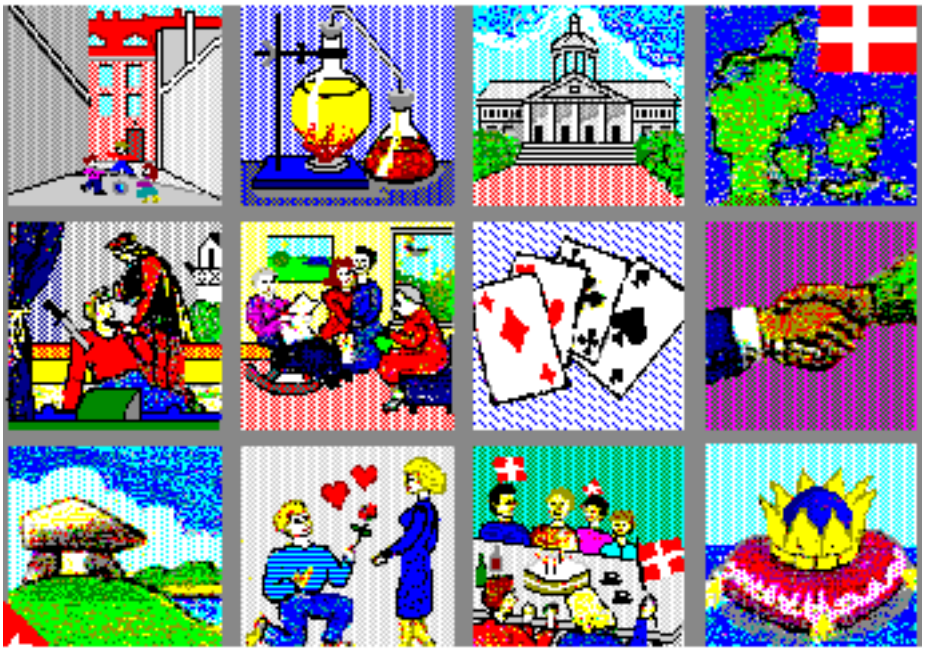
Task situation:
Formulation of search questions for retrieval of items from large database collection of books during analytical searches.

Domain Charateristics
Pacing: by user
Source of regularity: Intentional, structured by design according to dimensions of users' concepts and information needs.
Stability and predictability: High within culturally uniform groups.
Intrinsic coupling: Collection of separate items with very loosely coupled objects, concepts and events
Complexity: Large number of multidimensional items, made moderate by design

User profile:
Autonomous, casual and professional user. Typically autonomous user belonging to a defined group (defined by age, sex, profession, nationality. etc.) sharing cultural prototypes

Figure 38. Display of 'work place' for analytical retrieval in libraries. Shows the iconic display of the means/ends hierarchy of the work domain in terms of a multi- facetted classification scheme based on an empirical analysis of users' search queries in libraries. When the user selects an icon, keywords are displayed, and the user can specify his need by clicking on one or more keywords and a subsequent search is performed. See item 10 in figure 55.

Bookhouse "Browsing Icons" Display



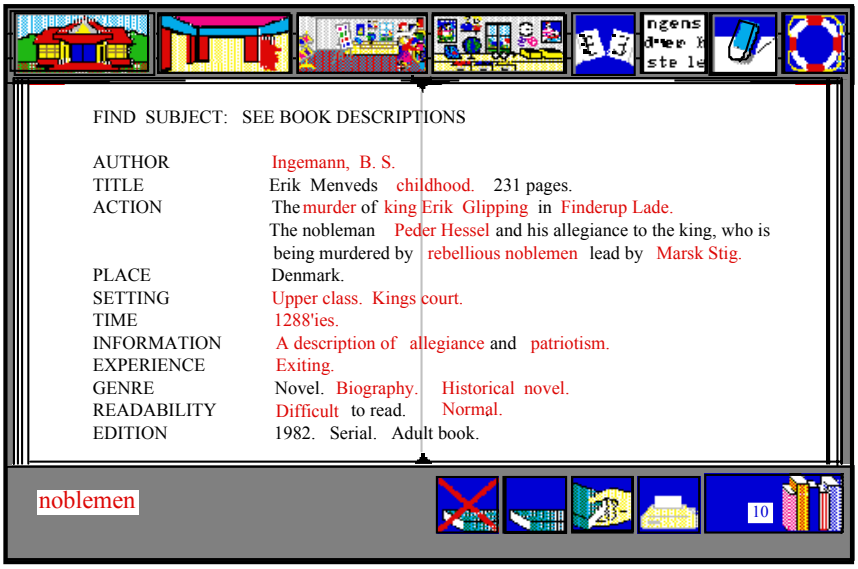
Content: Pictorial representation of objects, concepts and events representative for the categories within the multi-dimensional structure of the user's problem space, which is relevant for the browsing strategy.
Source: Keywords expressing the set of concepts, events, and objects necessary to map the domain of book content to be covered.
Form: Pictorial representation of prototypical concepts with reference to population stereotypes
Source: Analysis of the intuitive classification in a multiple choice association test of the target group of end users.

Task Situation: Exploration of potentially useful sources of information for recognition of vaguely specified needs during browsing.

Domain characteristics:
Pacing: by user
Source of regularity: Culturally common knowledge and conventions, and stereotypical concepts valid for the general population
Stability and predictability: High within culturally uniform groups
Complexity: Very large; high number of items and relationships. Exhaustive identification and description of elements impossible.
Intrinsic coupling: Combination of a very loosely coupled collection of objects, concepts and events as well as a very tightly coupled collection.

User profile
Autonomous, casual and professional user. Typically autonomous user belonging to a defined group (defined by age, sex, profession, nationality. etc.) sharing cultural prototypes

Figure 39 The display for browsing icons; designed for exploration and situation analysis, and intended to probe the user's tacit knowledge and support intuitive recognition of invariants of relevance to the user's current need situations. Six pages of icons in the metaphor of a photo album represent the book content of the data base. These icons are symbols that represent a semantic network of associatively related keywords belonging to several different dimensions of the invariant structure in the user domain. The red corners of the picture album is an analogy used to page forward and backwards. See item 9 in figure 55.



Content: Textual representation of objects,concepts and events in books represented within the multidimensional structure of the user's problem space. Keywords are displayed as textual objects in the text.
In the upper and lower parts pictorial representation of objects with reference to action possibilities and decision tasks during a search performance.
Source: The domain of book content from a library stock covered as indexed abstracts in the data base.
Decision taks during performance of retrieval sessions
Form: Textual reference to common terminology and vocabulary of the population of end users.
Pictorial reference to common knowledge about objects and their functionality in the population of end users
Source: Analysis of the language and quiries in intuitive classifications by the target cultural group of end users.
Analysis of population stereotypes from observations and quistionaires

Task Situation:
Comparison of match between users information needs and retrieved books.
Planning the continuation of the search

Domain characteristics:
Pacing: by user
Source of regularity: Intentional, structured by design according to dimensions of users' concepts and information needs.
Culturally common vocabulary, conventions and knowledge valid for the general population
Stability and predictability: High within culturally uniform groups
Complexity: Very large; high number of items and conceptual relationships within and across items. Exhaustive identification and description of elements impossible.
Intrinsic coupling: Very tightly coupled collection.of objects,concepts and events in books

User profile
Autonomous, casual and professional user. Typically autonomous user belonging to a defined group (defined by age, sex, profession, nationality. etc.) sharing cultural prototypes

Figure 40. An open book with a description of a retrieved document;.It illustrates the multidimensional information contents of a novel analyzed, represented and made accessible according to the invariant structure identified in the users' domain. The book meataphor display enables the user to perform an efficient evaluation of the degree of precision and match of the retrieved books with the user's need. The user can then step through other book descriptions and continue verification and check of the result. This display will be presented as the final output after browsing books, browsing icons, analytical keyword searches and search by analogy. Controlled, selectable keywords are displayed in red in the context of the book description.

Command Icons for a Library System

Special command icons, were necessary to give access for the user to manipulate elements of the work system or the information system in some way. Such icons are smaller pictorial entities on the display screen serving as signs which are related to actions by convention. They are chosen so as to be easily understood and remembered by expressing an idea, concept, thing or action by their resemblance and/or suggestiveness regarding the related action. The design of command icons as signs was based on the items in the action scenario described previously on p. 35 in the section on maps of display composition and interpretation. The use of this action scenario is illustrated in figure 15.

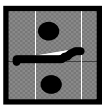
	Delete search terms from the current search profile. The metaphor refers to object to use.
	Print book description for later use in finding books on the shelves. The pictogram refers to object to use.
	Help is a metaphor that refers to object to use.
	Select new search terms from the book description and modify the need by adding to the current search profile. The metaphor refers to the state to reach. When the icon is selected, a key word will appear.
	Modify the current search profile by removing red search terms in the current book description and a Boolean NOT is automatically performed. The metaphor efers to state to reach.
	Find books similar to any current book on the screen. The metaphor refers to state to reach.

Figure 41. A selective repertoire of command icons; to be perceived as signs for action. They are selectable for execution and control of the search, whenever a book description is on the screen. The user can repetitively select among these options including shift of strategy without entering a previous room. The metaphor, and pictogram are cues for action referring to *objects* to use and *states* to reach and supports rule based activity.

Form of Command Icons

The form of icons designed to ease novice users' ability to understand, learn, and distinguish among the numerous possibilities for control actions at the lowest level of a search, refers to *objects* to use and *states* to reach. With respect to objects to use, *metaphors* are chosen to support *analogical* reasoning, determined by a familiar context for the general, public novice user (eraser, life belt). The printer is a pictogram, which is actually the tool used to make a print, but a picture on the screen is clicked instead of the actual device. The strength of similarity of the picture with the real device rather than with an analogy is in focus here. States to reach refers to the *target state* in the relevant part of the system once, the action is executed (a keyword with a minus, a text with red keywords inserted). The command icon to be used for search by analogy is a sign that shows a mirror reflecting the content of two books and indicates that choice of this icon will lead to a state of similarity between books.

Icons as Symbols in Library System

Special symbolic icons were used for the BookHouse, see figure 39. Novice and casual users of the Book House are likely to interpret information as symbols when trying to build a mental model of their problem space and its representation in the system. Embedded in the metaphor of a house, the semantics of the fiction retrieval domain are displayed in a work room as iconic tools and objects to be perceived as symbols used to classify books in the data base in a way which reflect users' needs and intentions . Pictures in the Picture Association Thesaurus are designed as symbols with reference to users' conceptual levels of prototypical concepts and needs. The effectiveness of these icons in supporting prediction and symbolic reasoning depends on the user's familiarity with their content and form.

Icons as Signs and Cues for Action in a Library System

Signs govern the user's choice among the action possibilities within the information retrieval procedures. The display provides the user with signs or command icons that he/she uses as cues for the selection of an appropriate action. Typically, the action alternatives consist of a set of familiar alternatives (select keywords, display retrieved set, print etc.). The problem with conventional interfaces is that the cues they provide the users are not unique with respect to the current operational state. This difficulty is overcome in the Book House by developing a unique and consistent mapping between the symbols that represent the semantic contents of a database and the signs, or cues, provided by the interface. This will reduce the frequency of errors due to procedural traps because the cues for action, based as they are on retrieval process properties and visualized as analogies, pictograms, etc., will uniquely define the related action. In addition, if the signs can also be interpreted as symbols, they can support functional reasoning while looking for action cues.

The BOOKHOUSE make extensive use of menus which essentially are displayed "lists" of the command options in standardized positions on the screen. Only those which are 'legal' at a given stage in the user-system dialogue are visible. Each icon has an associated short textual explanation which appears at the bottom of the screen whenever the mouse passes over the sensitive area on the screen "owned" by the particular icon. This was felt to be necessary - especially to help first-time users, since the meaning of an icon can be multiple and even ambiguous to a user. Thus the top and bottom rows of figure 40 illustrates some of these icons and their fixed locations on the screen; the dedicated text area is at the lower left. Figure 41 depict some of these command icons in more detail.

Navigation in the information system.

Overall navigation in this information system is supported via indications of the rooms which have been previously visited and which can be revisited by direct manipulations on the room icons displayed at the top and buttom of the screen.

Thus the library example illustrates the combined use of a representation of the invariant dimensions of the intentional structure attributed to users of an information system for a known task situation, and a metaphorical principle for the overall organization of the information system. As stated, this approach will be relevant for work support in WTU's lying in the left-to-middle range of the domain map of figure 12. In addition, experience indicates that such an

approach can be rendered flexible enough to cope with a wide range of users - casual, professional, children and adults - with more or less analyzable needs and intentions. This can be contrasted with the public information system to be described below, which is an attempt to "metaphorize" a set of everyday activities without any detailed knowledge of users' goals, information needs, strategies, criteria, etc.

3. User Driven, System Constrained WTUs

Covering the right-center of figure 12 are the less tightly coupled WTU's involving an autonomous but (possibly severely) constrained staff. This region of the map includes the large majority of work systems and system design is often considered under the heading of office systems or administrative data processing. Typically, such systems have been considered to be rule-based transaction systems, controlled by procedures and paper forms. Recently, however, the more unstructured and adaptive features of office work have received considerable attention.

To our knowledge, no actual ecological displays have so far been developed for this class of systems. A discussion of the display requirements emerging during the field studies in manufacturing is included to facilitate a comparison with the process and the library domains discussed above. During field studies and analyses of accidents, we have found several critical work situations in which ecological displays can furnish an effective work support. A brief review is included to indicate topics for further work, even though actual display examples are not included. For illustrative purposes, also some generally used display formats are discussed with respect to their location within the map of figure 12.

Domain Characteristics. In these environments, separate tools and equipment are often used together in loosely coupled functional assemblages. Examples are manual assembling tasks in workshops, work on construction sites, hospital operating wings. Others include all kinds of information processing in office work, banking, government, etc. - i.e. what often has been traditionally termed "paper pushing". The office environment is typically very loosely coupled, constituted by an aggregation of separate work places, tools, case inventories, data bases, etc. In addition, many aspects of the manufacturing domain apply here. Indeed all WTU's encompass situations which are analogous to those of the two borderline cases.

Office work has often been called "open-ended" - i.e., "the complete set of actions relevant to the organizational world is unknown and unknowable. The set of possible states is unknowable as are all possible alternatives for achieving a goal. The result is that unforeseen situations are a common occurrence" - (Barber et al 1983). Office functions have been defined as rule-based state transitions, transforming one set of information into another. However the related procedures must be interpreted very cautiously - not in the usual operational sense but in terms of "practical action" (Suchman, 1982, 83) having to do more with "what things should come to, and not necessarily how they should arrive there". Office work is structured around goals and "office workers are able to handle unexpected contingencies in their daily work because they know the goals of the office work. These goals and action are often implicit in the office workers' knowledge of their work" (also Barber et al).

Parameters of office functions include:

1- degree of structuredness depends on several factors:

- size of problem space = number of sub-goals computability cannot be assured within a reasonable time.

- volume of information involved in each transformation - its decomposability into intermediate operations,..

- degree of routinization of the process = f(frequency of repetition).

- frequency of exceptions from rules - frequency of errors in input data, deficiencies,..

2- control structure of the function - sequential, concurrent or iterative.

3- mode of employment of rules - event/data-driven or goal-driven.

Simplifying these leads to a scale ranging *from* simple transformations (organization and reorganization of information involving creating, editing, sorting, merging, arithmetic operations, filing/retrieving..) *to* decision making on the basis of pattern recognition *to* unstructured problem solving involving extensive information searching. These functions can be algorithmically or heuristically controlled - e.g. decision making can be discretionary or procedural.

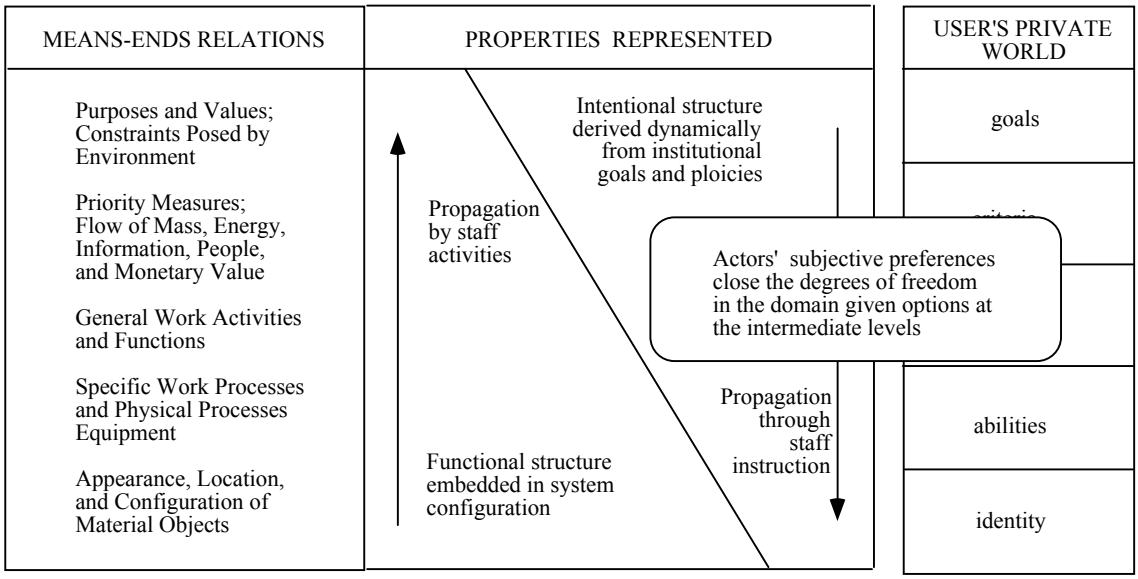


Figure 42. Source of intentionality in less tightly coupled work systems. In such systems, many degrees of freedom will be left to the discretion of the actors with respect to when and how to meet work requirements. That is, the intentionality faced by the individual actor depends on the subjective preferences of cooperators.

As stated, in discussing the present conceptual framework, it has been argued that administrative office activities should be considered to be the control function of the work content at the lower levels in the means-ends framework. From this point of view, different sources of behavior-shaping invariants and constraints will be found in different kinds of office work which should be considered in the design of ecological interfaces - especially in dynamic environments for which stable procedures cannot be found.

The main *source of regularity* of behaviour of this category of systems is the intentionality of management and the staff as implemented in policies and work practices. Laws of nature only supply regularity to the behaviour of equipment and tools at the lower process and functional levels. Propagation upwards depends on coordinating efforts by the staff, see figure 42.

The intentionality originating from the interpretation of environmental conditions and constraints by management propagates downward and becomes implemented in more detailed policies and practices. Making intentions operational and explicit during this process requires instantiations by a multitude of local details. Therefore at the intermediate levels of the means-ends structure, many degrees of freedom remain to be resolved by situational and subjective criteria. This in turn implies that the individual actor faces a work environment in which the regularity to a considerable degree depends on the intentionality brought to bear by colleagues. In a stable work environment, the odds are that intentionality can be embedded in a common work practice. However in a modern, flexible work system, the exchange of intentional information among cooperating actors becomes an important function of an information system.

A couple of selected examples will be discussed to illustrate different sources of behaviour-shaping constraints.

MEANS-ENDS RELATIONS	ACTORS	DECISION TASK
Goals and Purposes, Constraints.	Chairman of board; president.	Value analysis; goal setting; policy making.
Priority Measures; Flow and Accumulation of Mass, Energy, Information, People, and Money.	Vice presidents; department heads.	Strategical planning; priority judgments
General Functions and Activities	Department heads; office and group leaders.	Resource allocation and function coordination.
Physical Processes in Work and Equipment.	Skilled staff; workers.	Control and execute work procedures; control and monitor equipment operation.
Physical Processes in Work and Equipment.	Skilled and unskilled staff.	Find and identify work items; move things; plan navigation and transport.

Figure 43. Typical actors and their decision tasks in a loosely coupled work system.

1. Management Activities.

In the more loosely coupled, administrative work systems, different task situations are found at various means-ends levels. They relate to different invariant structures and depend on different actors - see figure 43 . Consequently, different display structures are relevant at the various levels. At the top level, ***policy making*** involves the exploration of values and intentions, opportunities and constraints in the environment and, as Minzberg observes (Minzberg, 1979), this involves live interactions rather than studies of factual information. Thus computerized information systems are at present not realistic. At the abstract functional ***priority setting*** level, the invariants depend on the conservation principle and the intended flow structure connecting sources and sinks of monetary values and products (commercial perspective), energy and substances (environmental perspective) and manpower (social perspective). Values are represented by quantitative variables and displays can be based on dynamic, diagrammatic representation of relationships among measured variables and intentions (budgets, plans) related to process and units, see the discussion of.Kaplan's (1990) strategy for introduction of a new

accounting system in flexible organizations with the need to respond quickly to a dynamic, competitive environment.

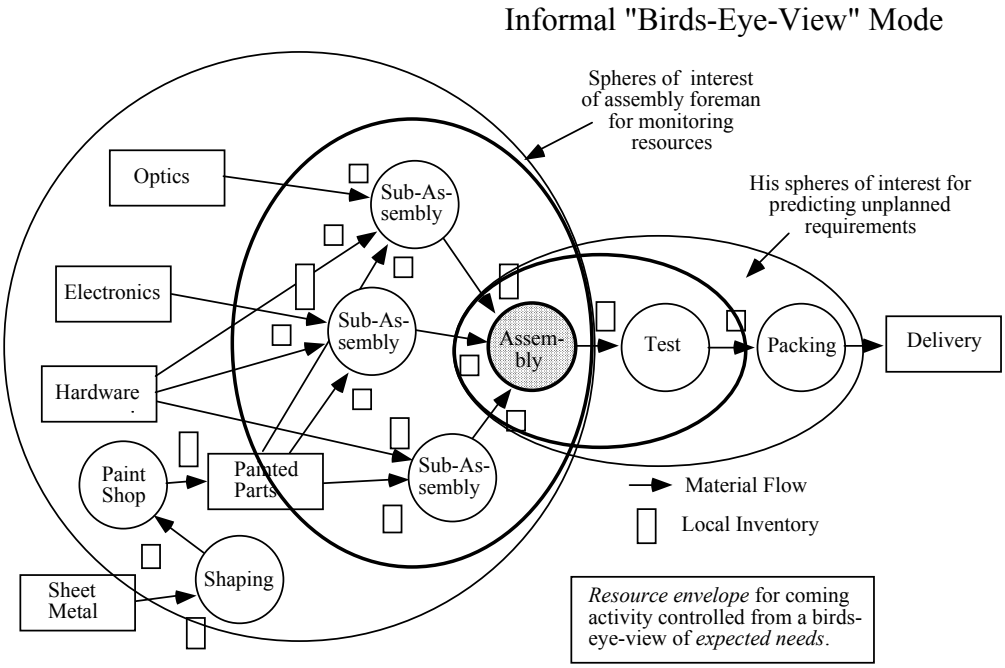


Figure 44. The varying attention horizons of a shop foreman's informal information network which has been established to monitor the adequacy of his resource envelope for oncoming requests. In the kanban system, production control depends on a feedback control of the flow of resources to a work place. However, requests for supply propagates along the flow lines in the form of cards and consequently delays are found. The foremen's informal network serves to give a birds-eye view and a prediction of the likelihood of inadequate resources. This makes the system much more responsive to rapid disturbances. The figure indicates the kind of structural invariants and of both state and intentional information that should be considered for an ecological display for fast response production control.

2. Production Control in Just-in-time Manufacturing

For process systems, regularity could be represented by quantitative relationships among measured or specified variables. In looser coupled work domains such as manufacturing systems, functionality depends on a flow of discrete parts and products through a number of work stations performing discrete, rule-based acts (object transformations) and, consequently, functionality is normally represented by causal connections of decisions, events and acts. This will influence the composition of suitable displays. Instead of diagrammatic representations of relations among variables, the prevalent form will be figurative indications of products and their locations with respect to the different work stations of the production system, together with exchange of verbal information about decisions and intentions (i.e., negotiation).

Current trends toward *integrated* and more *tightly coupled* manufacturing systems are being widely discussed. Actually the coupling is only at the lower levels via an integrated physical structure. In general, the integration depends on human actors who strive to coordinate the interaction among the various production process so as to keep the inventory (parts-in-process) low while responding to customer needs ('just-in-time' systems). In other words, the integration is based on functions *connected through communication* horizontally among members of a team.

An important functional invariant to consider as a basis for an ecological display is the intended *functional structure* of the production system. In manufacturing systems, the functional structure will normally be a river-like structure like the one illustrated by figures 44 (based on field studies by Kaavé (1990).

User Characteristics. In manufacturing, system users are actors who have the opportunity for becoming thoroughly familiar with the work environment and the information system. Their professional background is known and can give a basis for the design of display form.

Task characteristics and Ecological Interfaces. At the level of general functions, two prototypical work situations are of interest in the present context. One is the *control of product flow* through the production system. The river-like structure of a production system is based on the (often hierachical) organization of parts in the product and the related sequential assembly processes. This means that the structure is stable for the same kind of product, whereas the sequencing of products through the structure changes with customer requests for product variants. Thus the coordination function of the staff is to schedule the product flow according to the customer requests and the constraints in the production equipment, supplemented by local, subjective criteria. The *complexity* of this scheduling task is considerable, but a professional team will undoubtedly develop effective heuristics. The support required in such a turbulent environment is more likely to be related to presentations of the production flow and the intentions of cooperators than to normative scheduling strategies.

The WTU set related to production control in the previous paragraph involving an informal network for negotiation among foremen (figure 44) is very similar to the concepts for computer supported cooperative work in offices presented by Flores et al. (1983). Therefore, a comparison between production control and case handling in offices can be useful. The example considered here is compensation management following a work accident. This example has been chosen because efforts have recently been spent on formulating explicitly the internal constraints in a legal system for social care (ref. xyz, the Alvy project). It was suggested that the structure of the British legislation could be represented in first order propositional calculus, which implies that the intentional invariants and constraints for case handling can be formulated and used for ecological displays. This is a case for further work.

3. Office Case Handling

A typical office system task, as in manufacturing, involves the transformation of a product, the 'case', and the control of the sequencing of cases through a network of information sources, probably mediated through integrated workstations. As an example to compare with the manufacturing case, we will consider *compensation management following a work accident*.

The invariant structure underlying product transformation in the manufacturing case is a river structure reflecting the intended hierarchical production and assembly structure. This structure is identified by an analysis of the composition of the final product in the light of the manufacturing processes available. In case handling for accident compensation, the invariant structure governing the sequencing of product (case) transformations is a decision tree reflecting the structure of the relevant legislation. In this tree, the branching nodes reflect the decision points at which it is possible to change the course of events by remedies, medical care, financial

support, retraining efforts, etc. For each branching point, the possible alternatives together with the conditions for choice are defined by legal rules.

Content of Ecological Displays. Many degrees of freedom in interpretation are left to the intentionality brought to bear by the actors and this will be implicitly represented by the decisions made. Since, in this case, the evolution of a common, accepted practice will be the aim, having access to the intentionality embedded in earlier decisions will be advantageous. For the development of an appropriate information retrieval system, a world view or problem space should be defined at each branching point for identifying the invariant dimensions in client attributes, work places, type of accidents, type of compensations, laws and legal intentions, local union policies etc., and action alternatives. An equivalent approach was described above for libraries. For each work station in the case flow system, an ecological interface system could be suggested to give an overview of the inventory of cases and their characteristics to assist in making priority judgment and controlling the sequence (cf. the manufacturing case in figure 44).

Form of ecological Displays. Unfortunately, no examples of ecological displays for this task situation are available at present. However, from the principles discussed here, effective overview displays could be based on analysis of the intentional and functional constraint structure illustrated by figure 44. One basic problem, however, remains for more research, that is, the replacement of the communication of subjective values and intentions which, in present 'natural environments' largely depend on non-verbal and informal communication.

4. Metaphorical Displays in Office Work

Metaphorical displays are well known in office environments, in particular from the desk-top metaphor system developed by Xerox for the Xerox Star system and made a market standard through Apple's applications. In most cases, these metaphors are intended for "resource management" during separate, common place office activities and the source of their form is the work environment found under the past technology, hence 'desk top.' To have an overview of the sources of content and form of some generally used displays, the annotated figures 45-51 are added. This kind of metaphorical displays are directed towards a narrow task, that is, selection and control of manual or computer driven tools. They are, however, due to this lack of reference to particular work contents for which the tools are used, useful across a variety of work domains (see the overview in figure 45-51).

More focused metaphorical displays similar to the BookHouse work room metaphors have, however, been proposed for office work in particular domains, such as the work accident compensation case mentioned above (See Carstensen et al., 1990).

Work Space for Word Processing

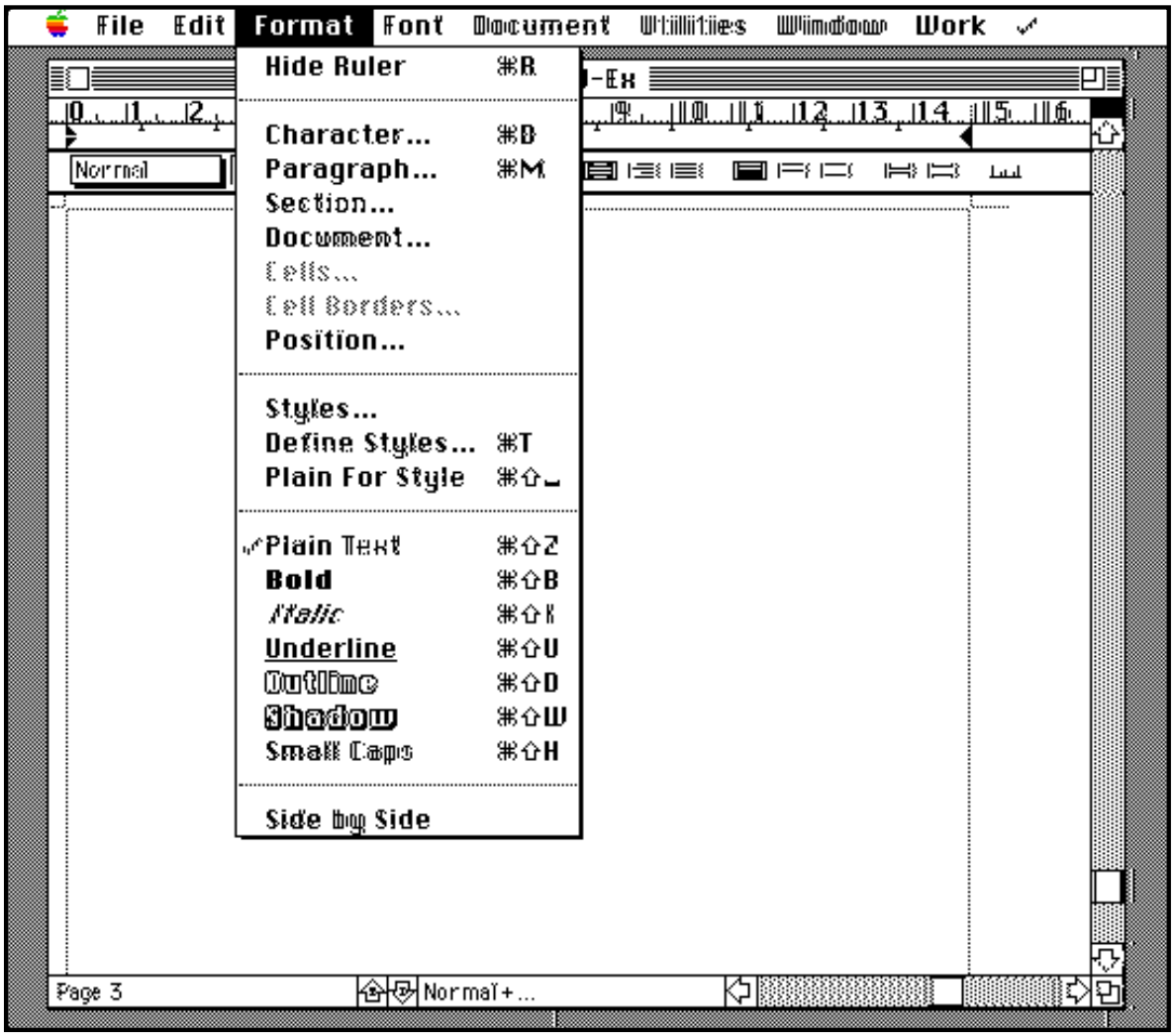
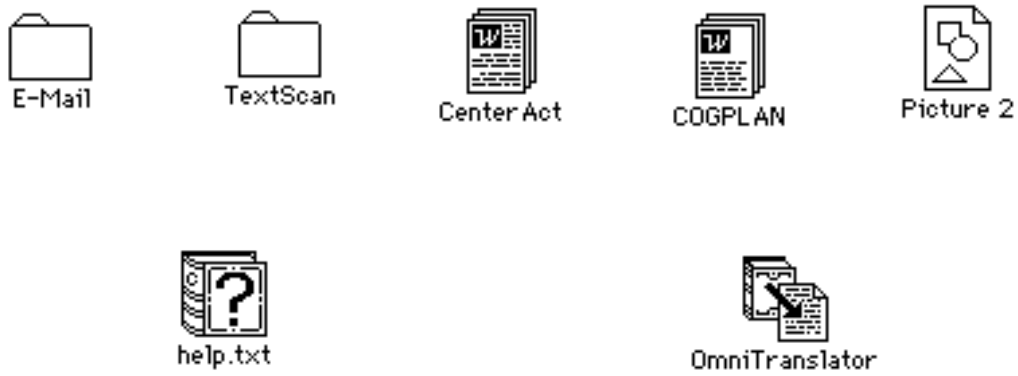


Figure 45. A composite, metaphorical display representing a desk top work space for word processing. Within this system, several different sources of content and form of work objects and tools are used, see the subsequent examples.

Mac Desk Top Metaphors: Work Objects



Content: Reference to individual work items in typical set.
Source: Identification of the usual set of work items in a task.
Form: Picture of work items in the previous technology.
Source: Work items

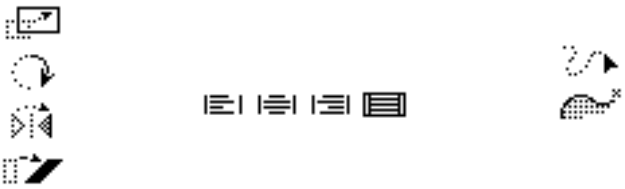
Work situation:
Choice of item to work on.

Domain Characteristics:
Pacing: user
Reversibility: trial and error acceptable
Complexity: low to moderate number of separate items.
Source of regularity: intentional, by work plan,
Coupling: irrelevant, separate items.
Predictability: deterministic, good.

User profile:
Professional user familiar with the work content in the traditional technology.

Figure 46. Source of content and form of metaphorical desk-top icons.

Mac Desk Top Metaphor: Tools 1



Content: Separate reference to individual tools.
Source: Identification of the set of tools.
Form: Schematic representation of the function of the tool.
Source: Common knowledge in profession baseed on work experience.

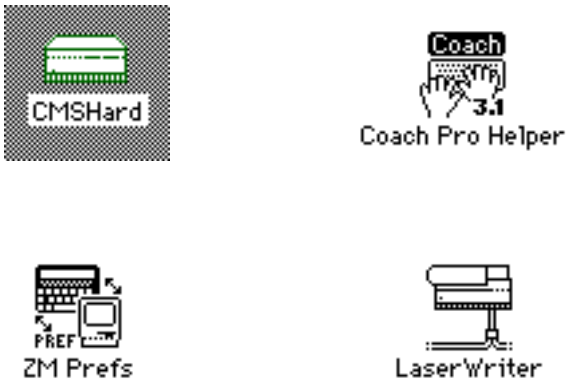
Task situation:
Choice of resources for a familiar activity.

Domain Characteristics:
Pacing: user
Reversibility: trial and error acceptable
Complexity: low to moderate number of separate tools.
Source of regularity: intentional, by design,
Coupling: irrelevant, separate tools.
Predictability: deterministic, good.

User profile:
Professional user familiar with the function of tools of the trade.

Figure 47. Source of content and form of metaphorical desk-top icons.

Mac Desk Top Metaphors: Tools 2



Content: Separate reference to individual tools.
Source: Identification of the set of tools.
Form: Picture of the tool.
Source: The tool.

Task situation:
Choice of resources for a familiar activity.

Domain Characteristics:
Pacing: user
Reversibility: trial and error acceptable
Complexity: low to moderate number of separate tools.
Source of regularity: intentional, by design,
Coupling: irrelevant, separate tools.
Predictability: deterministic, good.

User profile:
Professional user familiar with the particular models of tools.

Figure 48. Source of content and form of metaphorical desk-top icons.

Mac Desk Top Metaphors: Tools 3

Content: Separate reference to individual tools.
Source: Identification of the set of tools.
Form: Picture of similar tools in previous technology.
Source: The tool.

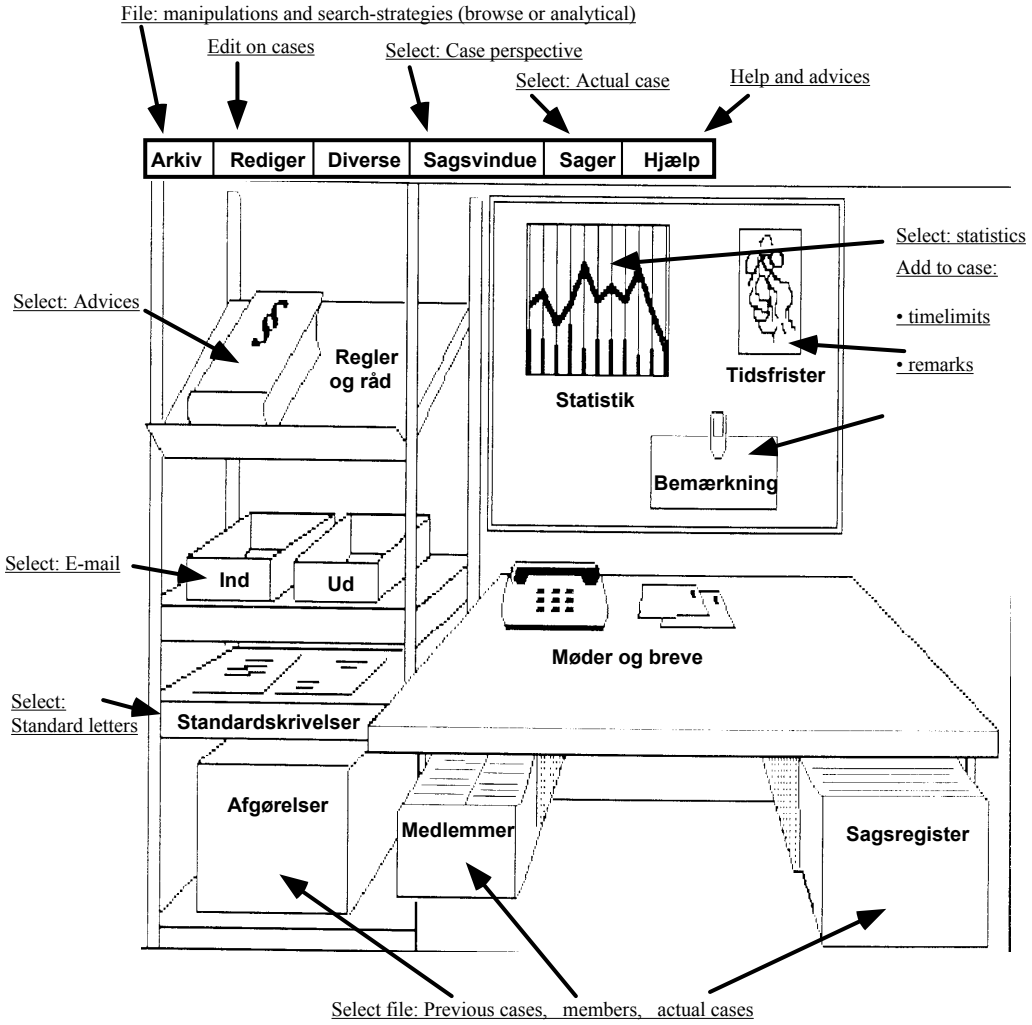
Task situation:
Choice of resources for a familiar activity.

Domain Characteristics:
Pacing: user
Reversibility: trial and error acceptable
Complexity: low to moderate number of separate tools.
Source of regularity: intentional, by design,
Coupling: irrelevant, separate tools.
Predictability: deterministic, good.

User profile:
Professional user familiar with the tools available in the traditional technology.

Figure 49 Command icons from Apple Mac tools with reference to tools from the "desk top" technology.

Case Handling Work Place



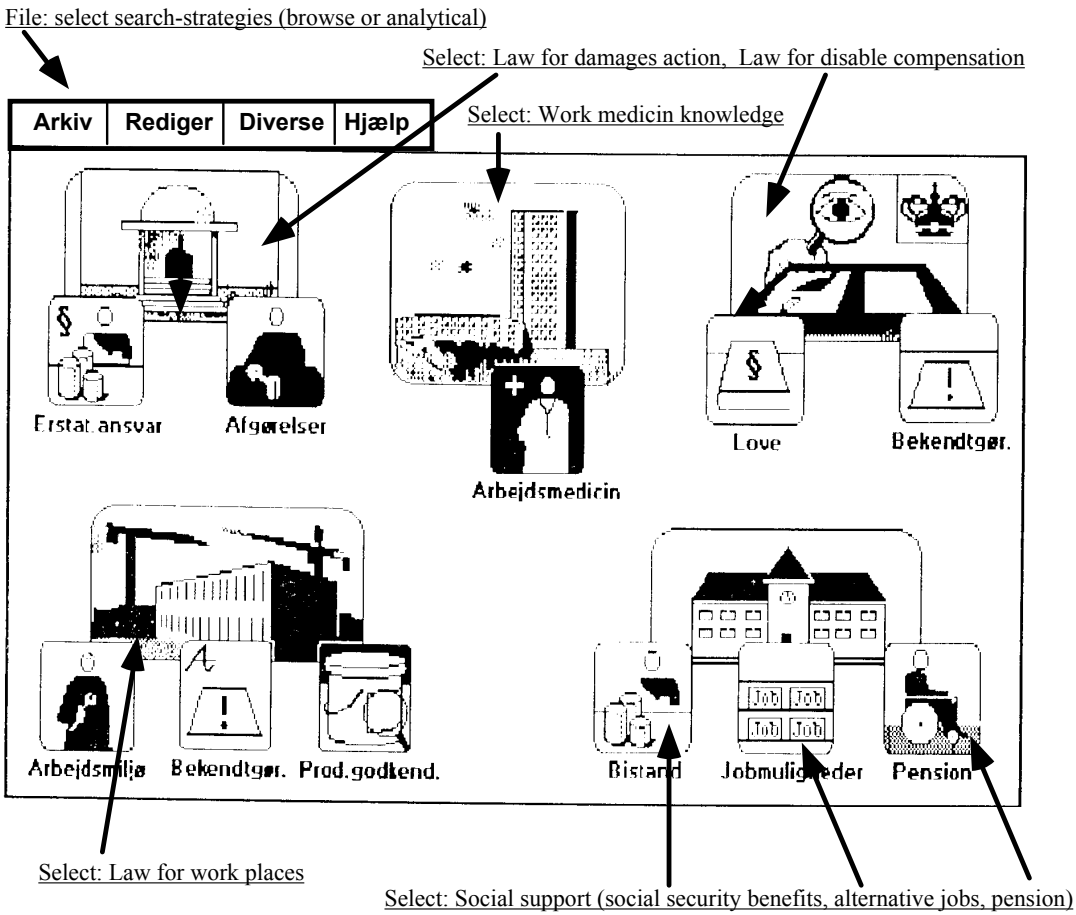
Content: Information sources, files with current and previous cases, standard formula for registration of new cases, mail and meeting agenda, and statistical data etc. representing integrated information items to be used in case handling in work accidents.
Source: Analysis of client characteristics and legal claims to information content in case treatment
Form: Pictoral representations illustrating the basic tools based on an office metaphor.
Source: Manual tools from previous technology familiar to user group.

Work situation: Case handling, analyzing a specific case, probing client for inforamtion about accident, planning registration, editing and further actions, retrieval of case relavant legal and medical information, reporting cases to network of domain experts in the central office.

Domain characteristics: Pacing: by user
Reversabillity: possible to some extent
Complexity: high, made moderate by design
Source of regularity: Intentional laws, instructions, policies
Coupling: loose, individual cases
Predictability and stability: high within uniform group of clients/workers and job category

User profile: Trained users with some domain knowledge, but not experts in the three involved domains of laws for work accidents and for acceptance of work diseases , social securaty laws and medical knowledge about diagnosis and causes for work diseases.

Legal Desk Top Work Place



Content: Information about the relevant domains of laws and medical knowledge pertinent to 1) Work accidents (The law of damages, the law of work places) 2) Diseases due to work (Law fo work diseases, work medicin knowledge) 3) Social support (Social security benefits, alternative jobs, pension)
Source: Analysis of information needs of domain experts (laywers, social workers, case workers) in relation to laws and policies for case handling of work accident

Form: Icons representing the semantic content of different information sources familiar to case workers from existing pictorial representations in the domains (logo) and textbooks.
Source: Well known symbols for public institutions and work places familiar to users from every day life experience

Work situation: Information retrieval of background information for specific cases. Education and training.

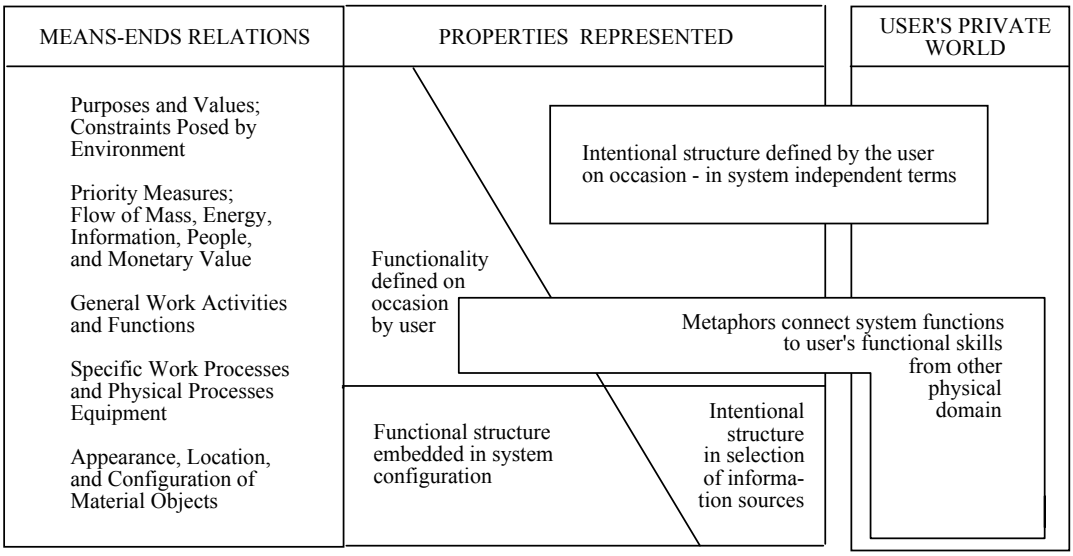
Domain characteristics: Reversabillity:high
Complexity: high, made moderate by design
Source of regularity: Intentional, laws, instructions, policies
Coupling: loose
Predictability and stability: High

User profile: Trained users with some domain knowledge, but not experts in the three involved domains of 1) laws for work accidents and for acceptance of work diseases , 2) social securaty laws and 3) medical knowledge about diagnosis and causes for work diseases.

4. Autonomous User-driven WTU's - Public Information Services

To the left of the library example in the map of figure 12 the are found the WTUs for which neither the user nor the user's problems and needs can/have been formulated in advance of the information system design. As an example is used the Japanese personalized information environment of the Friend'21 project to illustrate a design approach based on an extension of the desk-top metaphor.

Domain characteristics. In the region to the extreme left end of the spectrum of figure 12 are found the autonomous user-defined WTU's. In this class are found public information systems. Typical examples include lexicographic data bases and information services for the general public where the task situation and needs and intentions of (primarily) casual users are essentially unknown. These systems usually include a set of generally useful information sources and data bases issuing from many different public services, institutions and commercial companies. No generally relevant intentional structure and/or expected task situations are formulated or considered as part of the design basis underlying system functions or interface design. Thus the higher level means-ends structure of such systems are only formulated in very general terms - such as making information available to the public. The intentionality of the task situation is dictated entirely on-line by the actual user using the available system facilities. See figure 52.



.c.Figure 52. Functionality in metaphor-based information systems, such as the Friend'21 personalized information environment, is organized to match user intentionality in the user's normal environment. No influence from the users' intentional structure can be included since typical task situations are not assumed as a design basis.

Task situation. Thus the basic activity is information retrieval on an ad-hoc basis where the user makes his/her wishes known through a dialogue with the system. In this situation, the functionality of the system cannot be based on user's preferred search strategies because the context and semantics of the user problem is undetermined.

User characteristics. Briefly stated, anyone requiring information.

Interface characteristics. A structure must be imposed on the interface to help the user to navigate, find and manipulate information as well as remember where to find previously

consulted items. In general, a cover-story of some kind is required which makes it possible for any user to transfer intuition, habits and skills from other situations, perhaps in other contexts.

The *content* portion which depends on the data base information to be integrated and the *form* portion established by the particular cover story selected - which itself will be a product of the culture, what others have tried or simply good ideas. Usually a *metaphor* is resorted to. A recent, ambitious approach is the multiple metaphor/multiple agent approach in the Japanese Friend'21 personalized information environment (Friend'21, 1989). "Agents" provide various services, while multiple metaphors are used to diminish semantic distance in that they can be switched dynamically to suit user and situation demands. A TV-metaphor presents information in a TV-news context both pictorially and with a robot providing comments and explanations. A newspaper metaphor permits retrieval of information via a "turning pages" facility while an album metaphor assists the user in filing, sorting and retrieving pictures. Figures 53 and 54 illustrate this.

It is a basic problem in this kind of general information services that the various institutions and companies which supply the source material and data bases structured according to their individual professional needs and traditions thereby determine the information indexing and the display contents while the information service tries to integrate it all by cover story chosen on the basis of accepted practice, cultural preferences and/or good ideas determines the packaging of the information content and the associated retrieval dialogue. The content and form sources are independent of each other and it is up to each user to fit his/her intentions and needs to the capabilities of the system (or vice-versa).

Thus metaphors, as 'cover stories', couple the functionality built into a system to an intentional structure relevant to another domain. Metaphors are discussed by Clanton (1983). He classifies them as functional (to reveal the relations between the system's functionality and the user's task perception - e.g., a spreadsheet), operational (these refer to actions in such a way that the user's natural expectations of the meaning and the results are confirmed - e.g., object manipulation), organizational (they show how notions on location and structure of information can be used for planning and application) and integrating (as described, these represent the integration of system components and sub-systems in relation to the accomplishment of complex tasks). See also Mihram and Mihram (1974) and Mihram (1972). The subject is also treated by Hollan (1989) who deals with three concepts or dimensions and their interrelationships - model world based metaphors (based on what we know about the world), language based metaphors (based on what we know about language) and agency which has to do with whether the intermediary (computer) contributes as an active partner to the interaction.

Navigation in the information system. The functionality underlying the metaphoric representation is intended to make it possible for users to transfer familiar needs and habits from traditional settings to the new environment.

Figure 55 attempts to summarize the range of WTU coverage of a sample of well known display types by using the same framework as figure 12. Many of the types have been utilized in the previous WTU examples. The others are hopefully familiar enough to be recognizable from their name. We feel that this kind of information - with further extensions - would be a natural result of using the design map approach over time - as experience leads the designer to an

intuitive understanding of the links between WTU requirements and relevant interface solutions as well as across WTU's.

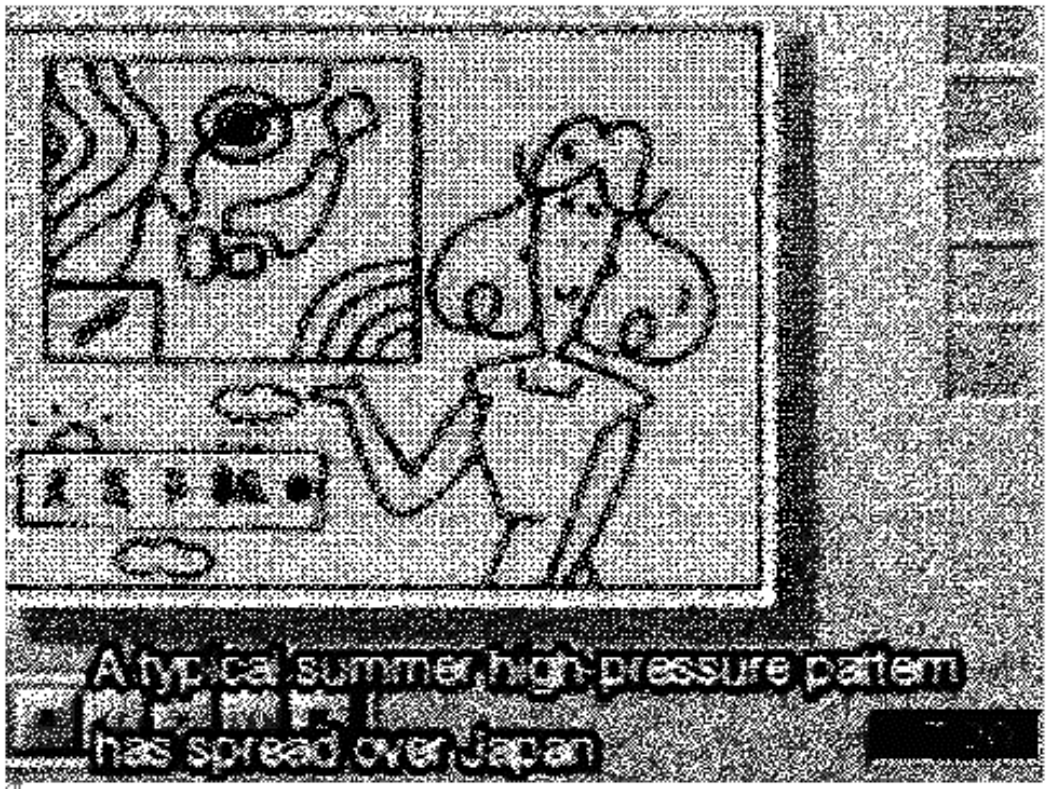


Figure 53 The Friend'21 Personalized Information EnvironmentComposite display based on multiple metaphors for the information search: Tv newsreel, album, newspaper metaphors, etc.

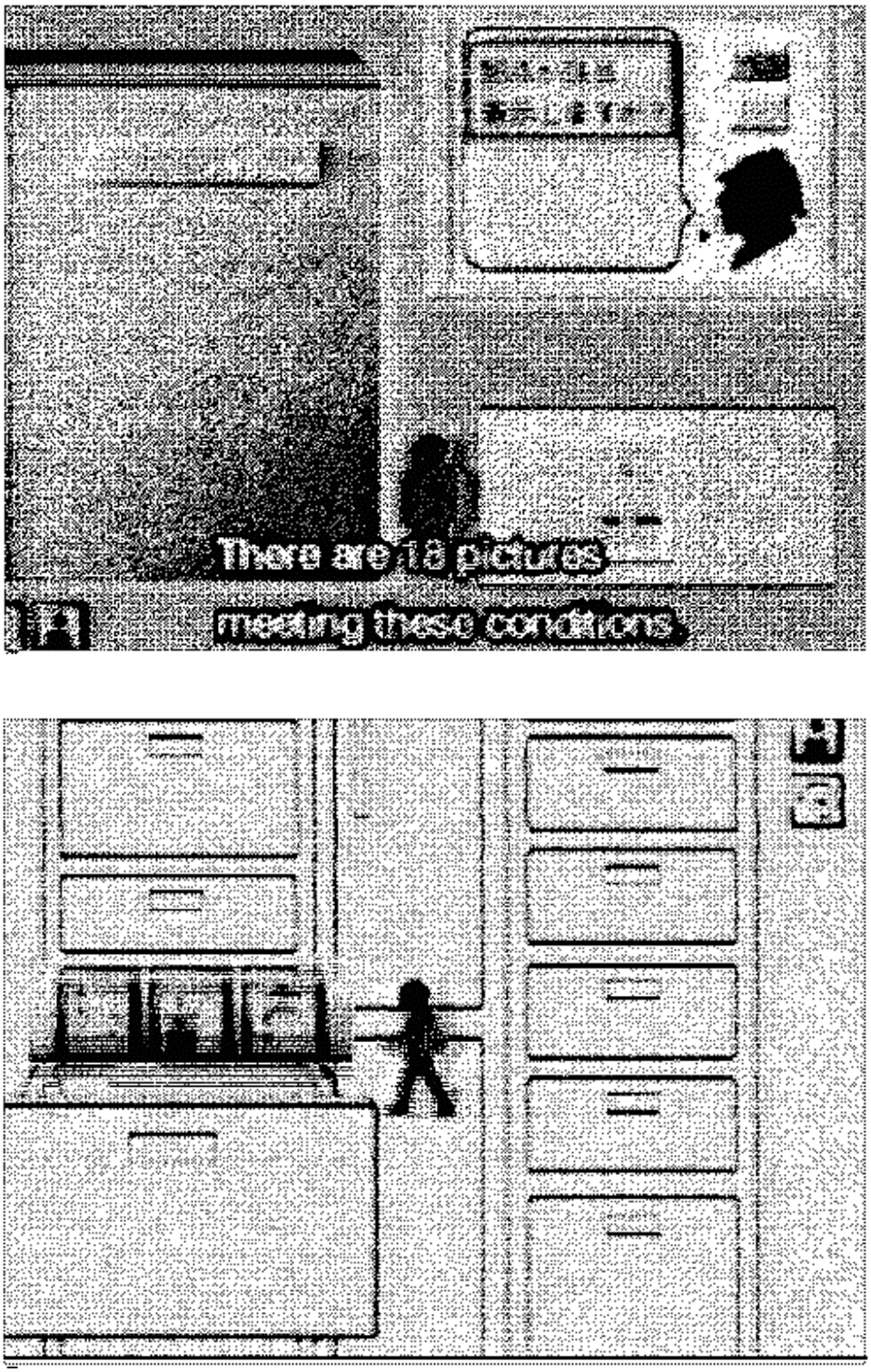


Figure 54 . The Friend'21 Personalized Information Environment. Composite display based on metaphor: Information is retrieved from a chosen data base by means of an agent.

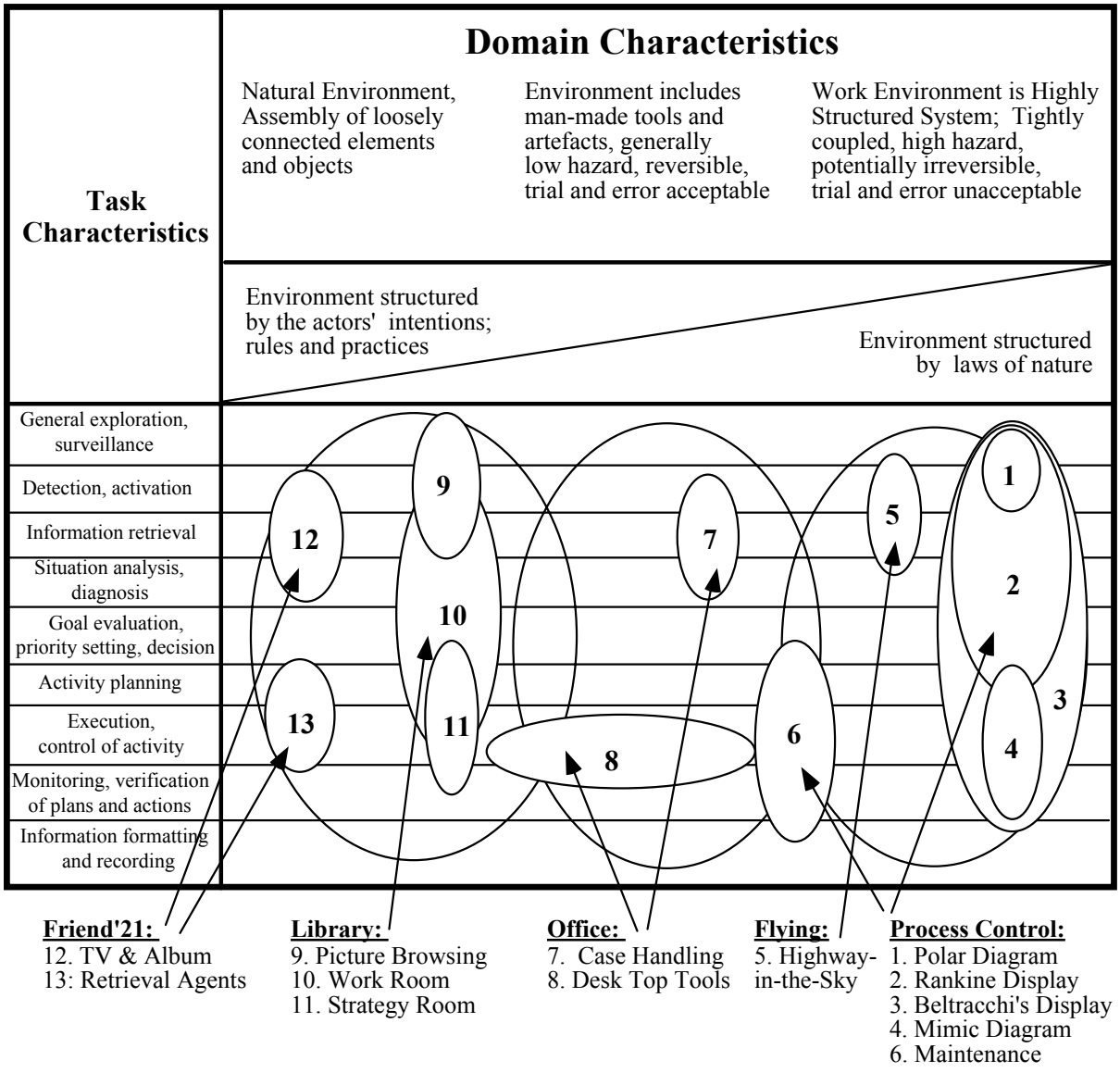


Figure 55. Overview of WTU examples, that is, relationships between the domain, the task situation and a set of typical display examples

8. SYSTEM EVALUATION

Since the creative phase of design cannot be formalized, we face the need for systematic methods for the evaluation of advanced human-machine systems. This is not the place to discuss evaluation methodology in detail, the aim is only to demonstrate the implications of the taxonomy for system evaluation and to prepare for a brief discussion of the use of the taxonomy for specification of the boundary conditions of design and evaluation experiments .

The evaluation of the quality of a new system can be done analytically and/or empirically. The role of the two approaches has been discussed by Rouse (1984, Rouse et al., 1984) for evaluation of DASS systems (Disturbance Analysis and Surveillance Systems). In this context Rouse considers several levels of human-system interaction for separate evaluations:

- *Compatibility* with human sensory and homomorphic characteristics - that is, can the displays be read and the controls operated?

- *Understandability* - can the user understand the text and graphics of the interface; does the user understand the provided functions?

- *Effectiveness* - do the functions provided meet the task requirements of the end user? Can the system be used?

To these categories, we can add:

- *Acceptability* - does the design approach and the assumed work organization match the performance criteria and preferences of the users. Will the system be used?

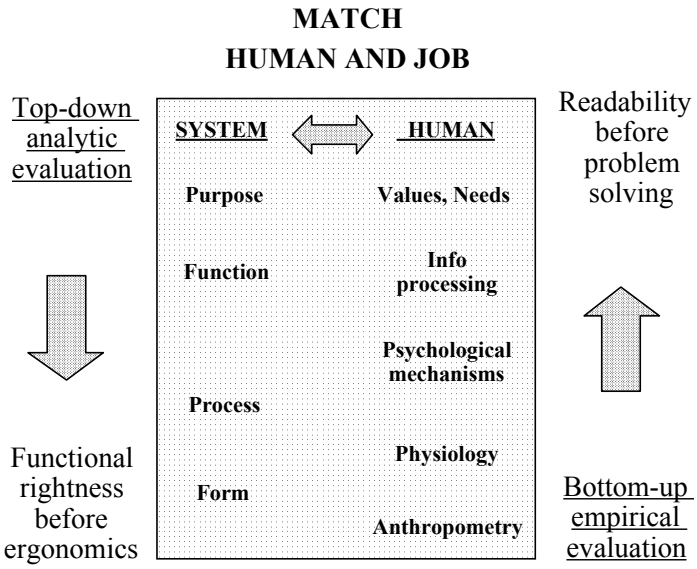


Figure 56. The complementary nature of analytic and empirical evaluation.

Analytical vs. Empirical Evaluation

In an evaluation exercise, Rouse's categories will be considered in a different order depending on whether an analytical or an empirical evaluation is being made, see figure 56.

An orderly, top down progression from purpose and goals to physical implementation cannot be requested for the design process itself when it depends on opportunistic trade-off between

creativity and constraints such as company practice, prior solutions, and market trends. It is therefore essential that the design is rationalized after the fact and its consistency evaluated *analytically* with reference to a consistent framework. In this process, evaluation will not concerned with ergonomic aspects of displays, letter sizes, digital vs analog information presentations and the like before the functionality of the proposed system has been considered. This evaluation depends on a reasonably thorough top-down mapping process following the levels of the taxonomy, starting (a) with defining system requirements for the meeting of critical goals, continuing (b) with a consideration of the decision-making necessary for carrying out the associated tasks, then (c) looking at the information necessary for making these decisions, (d) checking assignments of decision making part tasks to computer and user based on their respective abilities and limitations. Considering the dimensions of the work analysis as a specification of the basic features of the behavior-shaping factors infringing on the user, an orderly evaluation can be planned as shown in figure 57. A natural approach will be to perform the analytical evaluation more or less concurrently with the design and, in the case that prior experience or analyses of work in the existing systems do not support the necessary design decisions, to test design concepts empirically during design.

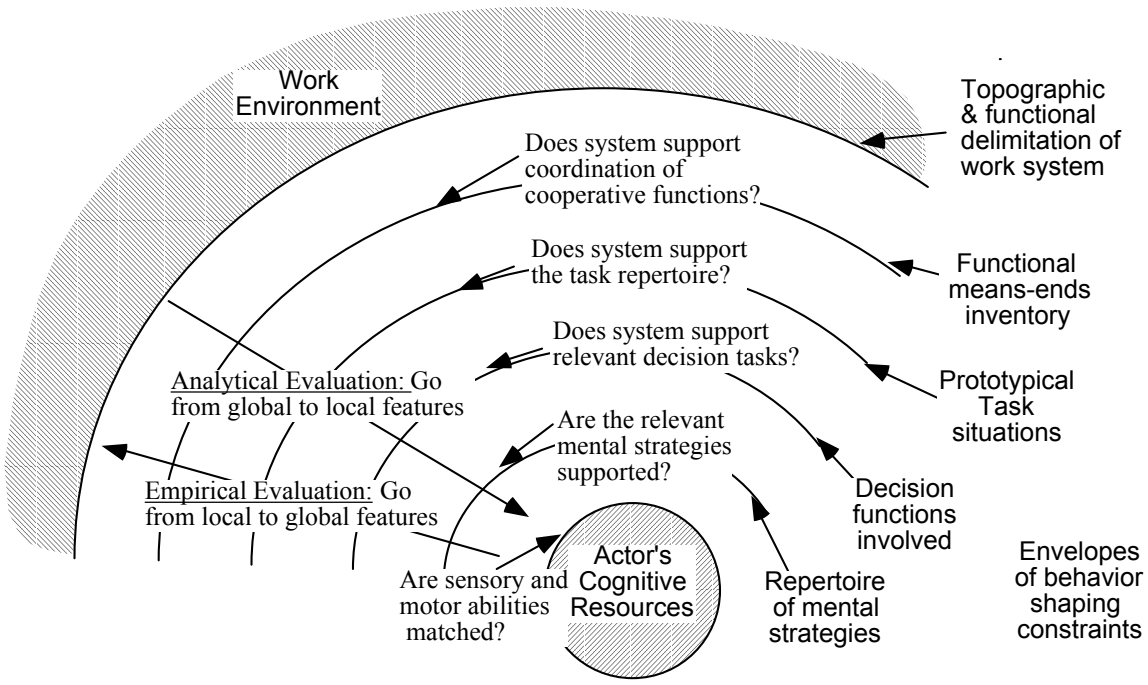


Figure 57 The relationship between modes of evaluation and the constraint envelopes identified defined with reference to the taxonomy for work analysis described in Rasmussen et al., 1991. In the figure, the level of analysis at the various constraint boundaries is shown by annotations. In addition, an evaluation question is suggested for each of the behavior shaping constraint envelopes.

In contrast, an *empirical* evaluation of a new system - e.g., a new display - will start from the bottom in order to ensure 'compatibility' of the displays before testing 'understandability', which is then done before checking whether the new system actually improves 'effectiveness'. It has no purpose to plan and carry out the complex task of testing effectiveness if the individual messages cannot be read or understood.

Empirical evaluation of new systems is often required by potential customers who want proof by hard data that an expensive system meets their expectations or by regulators for acceptance tests. The present taxonomy represents behavior-shaping constraints by a nested set of constraint envelopes around the individual actor and thus suggests the definition of a matching set of nested boundary conditions for experimental scenarios which can serve empirical evaluation in its various shades. Many complex experiments for evaluating advanced information systems have been wasted because trivial violations of well known human factors principles existed which could have been identified by check lists or simple experiments with elements of the system.

For empirical evaluations, it is necessary to establish an experimental work situation creating a defined constraint envelope around the subject and to study whether subjects' responses to this envelope leads to the mode of behavior which was assumed as the design basis. For a comprehensive experimental evaluation of a prototype system, it is necessary to define a set of boundary conditions with increasing distances from the subject in order to be able to evaluate features of the system at various levels of detail. This experimental evaluation should be compatible with the analytical evaluation which is made concurrently with the design and, therefore, a common taxonomic framework should be used for the two approaches, see figure 57.

It seems clear that the analytical and the empirical approaches to evaluation are compatible and, in most cases, can both be used in different phases of a design process. However, in some cases, it can be advantageous or necessary to integrate the two approaches for the same evaluation problem.

Certification and Hybrid Evaluation

The use of the taxonomy to coordinate an analytic and an empirical evaluation is useful for some complex certification problems.

"Hard data" from a comprehensive, empirical evaluation of new systems are often required by regulatory bodies before a new conceptual design can be approved. Evaluation of a new decision support system with respect to its performance during rare, critical events which punctuate the routine operations of e.g., power plants, is a good example of an application for which direct, empirical evaluation is difficult, if not impossible. Even when reliable performance under such conditions is the raison d'etre for advanced support systems, it is difficult to recreate experimentally the situation where highly skilled personnel are caught unawares by an unfamiliar, high risk situation. Under such conditions, an indirect test can be advantageous - i.e., a hybrid evaluation based on an analytical identification of the preconditions for successful performance followed by an experimental test of the match of the relevant functional elements of the system to such preconditions.

In terms of figure 57 this implies a replacement of an empirical test of performance during the *prototypical task situation* of "disturbance control" by an analytic breakdown of this problem to the elements at the next lower envelope of the *decision functions involved.* This breakdown must be based on a cognitive performance model and the test of the match of the support system with the requirements of the involved decision functions will require several separate empirical tests. The reliability of the cognitive model of the requirements of the task situation should of

course be tested by analysis of a representative set of disturbance scenarios. Readers familiar with nuclear safety analysis will realize the analogy with safety evaluation based on predictive risk analysis: By an analytical model, the preconditions of the acceptable risk is calculated, and these preconditions are then (hopefully) controlled empirically during operation (Rasmussen, 1991).

A first approach to a hybrid evaluation test along such lines was used for a test of the Rankine cycle display by Moray et al., 1991, for development of performance indicators for human-machine interfaces.

Experimental Psychology as a Database

When a task situation has been decomposed into a number of more elementary and generally applied cognitive processes, performance data from the database offered by psychological experiments in general become useful for evaluation if and when an explicit boundary conditions of the experiments can be identified in terms compatible with the model used for decomposition of the task situation.

For psychological experiments, a sector of a natural human work environment is separated to serve as an experimental vehicle. In consequence, an experimental design implies the choice of constraint envelopes around the subject. The dimensions of the framework for the analysis of cognitive work mentioned above, which is based on a representation of behavior-shaping constraints, appear to be well suited to identify experimental designs in the general psychological literature and to transfer data for use in a hybrid evaluation exercise, see figure 58 The figure illustrates the relationships among the different constraint envelopes of the taxonomy and different approaches to experimental design. In order to establish a reliable connection between the existing experimental database and a framework for hybrid evaluation, a taxonomy such as the one developed within the MOHAWC project, will be necessary.

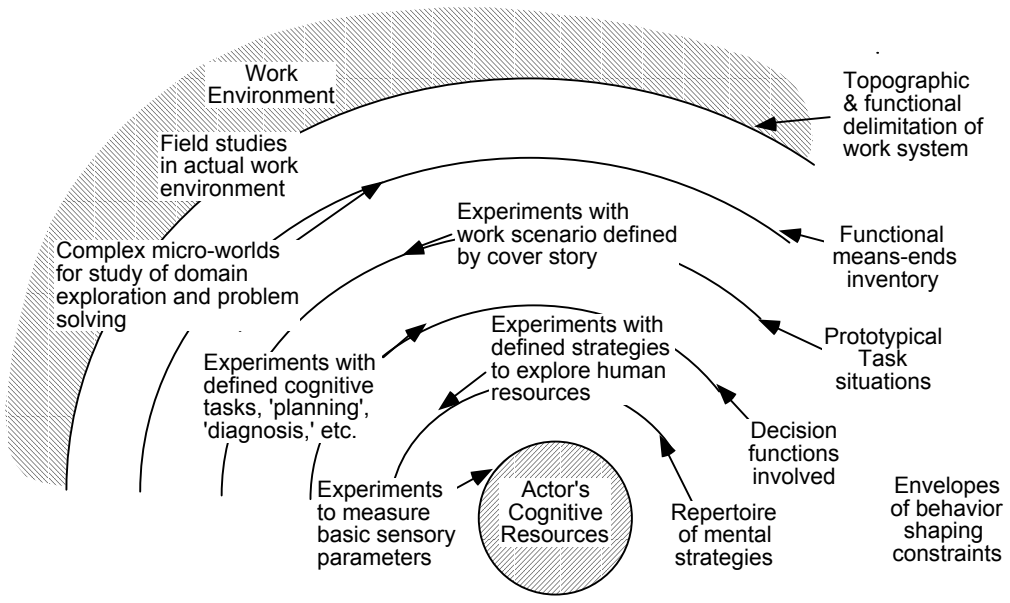


Figure 58 Boundary conditions of experiments. The figure illustrates the relationships among the different conceptual layers of constraints of the framework and different approaches to the design of psychological experiments.

9. REPRESENTING BOUNDARY CONDITIONS OF DESIGN AND EVALUATION EXPERIMENTS

INTRODUCTION

An important issue in the Mohawc project has been the interaction between field studies and experiments in simulated task environments, "micro-worlds." A taxonomy of micro-worlds was proposed by Brehmer (1990) concurrently with the development of the taxonomy for cooperative work. In the present section, the use of this work taxonomy to characterize also experimental designs is discussed. In this way, Brehmer's development of a micro-world taxonomy and the present application of the work taxonomy are approaching the issue of experimental design from two opposite points of view and further work for integration of the results can be fruitful.

In laboratory experiments, as it is the case in actual work, humans serve as controllers of the state of affairs in a local sector of the environment. Consequently, a taxonomy for analysis of cognitive work in the field should be well suited also to characterize the structure and content of an experimental task and the functions and mechanisms brought to work by the subject. There is no basic difference between the nature of an actual work situation and that of an experimental task and, consequently, there is no essential need for a separate taxonomy of experimental "mikro-worlds." (A note in passing: The classical, psychological label "subject" should be revised. They are the passive *subjects* of manipulation by the experimenter? They are *objects* of our interest and in many complex experimental programs they are more like *"experimental workers"* or *participants* in research? In the following sections, we have chosen the shorter term "actor").

The difference between experimental and actual tasks is largely related to the fact that an experimental task can be more isolated from the natural context and objectives of the individual than is the case in most tasks of a work environment. Traditionally, a psychological experimenter will do his best to 'decouple' the situation from the contextual influence of the private world of the subject. In simple, well structured experiments this is done by an explicit instruction in more complex experiments, by matching conditions to a well formulated cover story.

To be useful for characterizing the conditions of an experimental scenario, a taxonomy should not only be suited to specify the experimental task as specified by the experimenter, but also to make explicit the boundary conditions of the experiments within the total social context as seen from the point of view of the actor. Therefore, a taxonomy for describing an actual work situation will, by nature, also be useful for describing an experiment in its social context.

BOUNDARY CONDITIONS OF PSYCHOLOGICAL EXPERIMENTS

The point of view taken to be the basic perspective of the taxonomy is that evolution of a particular behavioural trajectory results from a goal driven adaptation to the constraints of the

environment in which an actor finds herself. From this perspective there is no basic difference between the nature of an actual work situation and that of an experimental task with respect to the dimensions and categories which must be considered for a taxonomic framework. The difference is largely related to the salience of features, to the spectrum of features relevant, and to the fraction of the real world considered.

Generalization within the framework established by the present taxonomy implies a definition and specification of the boundary conditions of an experiment with reference to the levels, dimensions, and categories specified by the taxonomy. The defined boundary conditions of an experiment will then serve to characterize the experiment as a well bounded region which can exist in many possible global environments. Generalization then means to "fold back" the mechanisms identifyed in an experiment onto one of the possible global contexts which can match the boundary conditions as shown in figure 3. The significance of experimental studies depends on this ability to define boundaries around a particular phenomena in the world, to disconnect at the boundaries and move it to a controlled experimental setting and, to insert it (together with the model of the phenomena found in the experiment) into various new (work) contexts of interest.

The form of generalization to choose depends very much on the research strategy adopted, and generalization will, therefore, be discussed in more detail in the sections discussing the different kinds of experimental settings in terms of the taxonomy. One more general distinction between form of generalization should be mentioned. This is the basic distinction between representation of research problems in terms of properties of "practically isolated relations among variables" (as is normally done in mathematically based natural sciences) and representation in causal terms as "behavioural sequences" (as is the normal way in most human sciences). In the first case, generalization is related to objectively described relational structures and objectively defined variables, and an exhaustive list of defining attributes of the concepts used can be given. In the second case, generalization is made in terms of events and objects defined as prototypes (in the sense of Rosch, 1975) and, consequently, generalization deals with relationship between categories and classes, not particulars. It has, therefore, no meaning to look for "same behaviour" in actual work and in experiments in terms of *particular trajectories*. Validity of generalization depends on demonstration of "prototypical significance" of experimental results (see Brehmer et al, (1991) for a detailed discussion of this problem related to simulation studies).

In psychological experiments, a sector of a natural human work environment is separated to serve as an experimental vehicle. Proper experimental control implies an explicit definition of the boundary of the particular cut and the "decoupling" used to separate it from the influence from the rest of the environment, typically by keeping factors and variables constant or, at least, tightly controlled by the experimenter.

To be useful for the explicitation of experimental condition, a taxonomy should not only cover a conceptual framework for representation of the "micro-world" used for experiments, but it should also be able to represent, in an exhaustive way, the boundary conditions of the experimental scenario and the competence of the actor with reference to the natural environment. The boundary of the experimental "world" vary considerably dependent on the aim of an experiment and, therefore, frameworks suited for identification of the boundary conditions

of different experiments will, in fact, have to be embedded in a framework for analysis of cognitive work in general. The taxonomy for analysis of cognitive work is based on the view that work performance evolves within a set of constraints which can be described at different conceptual envelopes around the agent. Since experimental design implies the choice of constraints envelopes around the actor, this taxonomy appears to be well suited to represent the conceptual design of experimental "micro-worlds."

Figure xyz illustrates the relationship between the different conceptual layers of constraints of the taxonomy and different experimental approaches. The point being that the present diversity in the complexity of experimental setttings in fact correspond to the choice of different controlled, conceptual boundaries around the actor which closely match the constraint boundaries used in the taxonomy.

In the following sections, different examples of psychological experiments, in particular as performed within the MOHAWC project, are discussed in the terms of the taxonomy to illustrate the use of the taxonomy for specification of the experimental conditions and the boundary conditions of the cognitive task situation.

EXPERIMENTAL DESIGNS

Psychological experiments have different purposes, and the experimental domain chosen will reflect these differences. The following sections present a preliminary discussion of the use of the taxonomy to characterize different types of psychological laboratory experiments.

MEANS-ENDS RELATIONS	PROPERTIES OF EXPERIMENTER'S DOMAIN	SUBJECT'S DOMAIN	SUBJECT'S NORMAL DOMAIN
GOALS & OBJECTIVES, CONSTRAINTS	*Experimental Objectives and Constraints*	*Subject's Goals*	*Goals and Constraints of Work and Leisure*
PRIORITY MEASURES, MONETARY VALUES, PERSONNEL, MATERIAL	*Experimental Evaluation Measures*	*subject's Priorities*	*Subjective Priorities and Performance Criteria*
GENERAL FUNCTIONS AND ACTIVITIES	Experiment ***Functions involved in Experiment***		*Functions Of Work and Private Life*
PHYSICAL ACTIVITIES AND PROCESSES OF EQUIPMENT	***Physical Processes of Experimenal Equipment***		*Processes known from Work and Private Life*
APPEARANCE, LOCATION & CONFIGURATION OF MATERIAL OBJECTS	***Configuration of Lab. and Equipment***		*Familiar Objects , Configurations and Topography*

Figure 59 The means ends structure of experiments. The figure illustrates the interaction between the means-ends structure of the experimenter, of the subject-in-experiment and of the subject in a normal context..

Its a trivial fact that a psychological experiment is embedded in the total work domain of the experimenter and in that of the actor and that severe interference can be found even in carefully designed experiments. To prepare the ground for the use of the taxonomy, however, figure 59 is presented to illustrate the interaction between the means-ends structure of the experimenter, of

the actor-in-experiment, and of the actor's normal, personal context. The specification and the control of the experimental boundary conditions will define different boundaries in this map, and different means, varying from metaphorical cover-stories to explicit instructions, can be used to specify the boundaries to the actor, as discussed for different typical kinds of psychological experiments in the subsequent sections.

Classical Psychological Experiments

Classic psychological experiments are designed to identify and describe separate psychological phenomena. Influenced by the natural sciences, experiments are based on counting and measuring observable phenomena and a well developed methodology has evolved shaping scientific accounts in a standard format of hypothesis, method, findings and discussion and with a strong emphasis on statistical significance of the quantitative findings. Examples from the human factors domain include controlled experiments to selectively measure human performance parameters and capacity limits, such as speed, accuracy and signal-to-noise ratios in motor control (for a review, see Pew, 1974) capacity of working memory span speed of response, etc. Experiments for this purpose are based on carefully chosen and well controlled experimental tasks which selectively stress the application of particular psychological mechanisms - the 'isolated relationship'. For such purposes, experimental tasks are normally very artificial and have been given special research-related labels - e.g., tracking task, dual choice task, etc.

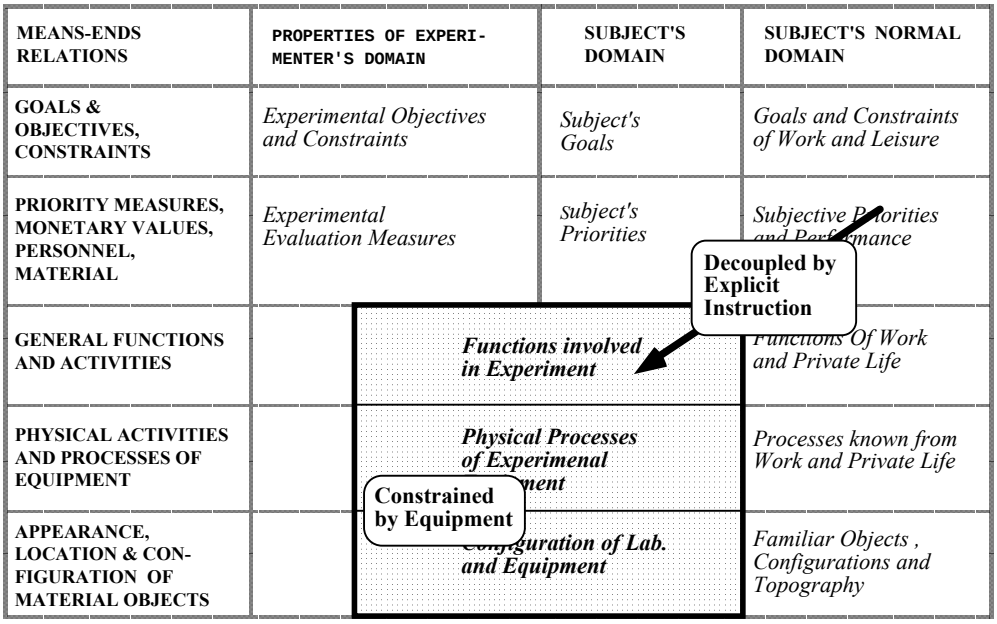


Figure 60. Classical experimental psychology. The instruction of task procedures is very explicit; i.e., the particular process to be applied in the experiment is clearly specified together with a process-related criterion, e.g., related to speed or accuracy. In effect, the experimental work space is effectively decoupled and any consideration of all higher level functions, goals and priorities is excluded by the instruction since only the lowest levels of the means-ends hierarchy are relevant for the subject. A particular feature is the close relationship between the processes of the experimental equipment and the experimental task, which is not found in more complex simulation scenarios.

The instruction of the task procedure is very explicit - see figure 60. and its connected text. This explicit formulation of the instruction at the procedural level defines the constraint boundary

around the situation and thereby isolates the situation from the general, personal knowledge background and performance criteria of the subject. A particular feature is often the close relationship between the processes of the experimental equipment and the experimental task, which is not found in more complex simulation scenarios.

An example of this category within the MOHAWC context is the memory retrieval experiments by Reason (1991) which are aimed at an identification of basic psychological primitives such as "similarity matching" and "frequency gambling" and an investigation of the relationship between such mechanisms and the reliability of memory access. Generalization of the findings are not based on reference to statements about the actor's general background or profession, but to a detailed analysis of their individual knowledge base.

Studies of Particular Cognitive Tasks.

This category includes experiments with a focus on the study of separate decision functions, such as diagnosis, goal evaluation, planning or the execution of planned acts.

Within the human factors areas, the methodology of experimental psychology has been extended to more complex studies in terms of manual control. These have typically been focused on practically isolated relationships based on control theoretic concepts and were pioneered by McRuer et al. (1957) and Crossman et al. (1962). In these investigations, the boundary conditions of the experiments are rather well defined because the behaviour-shaping constraints to a large degree are given by the simulated properties of a well structured process system.

Another extension of the traditional psychological paradigm-driven experiments is focused on studies of problem solving and decision situations. Here, the cognitive processes are more complex and less constrained by the environment. An illustrative example of this category and the involved problems in generalization and transfer to actual work conditions has to do with experiments on diagnostic reasoning.

In this category, the boundary condition of the experimental scenario is defined by the cognitive task given the subjects. In general the strategy is specified only implicitly by the particular presentation of the problem. When considering this category within the present context, a frequent problem appears to be that experiments often are initiated from problems identified in actual work performance. A 'cover story' is then used for instructing the subject which refers to the work context without a rigourous analysis of the differences in behaviour-shaping constraints with respect to criteria for the choice of mental strategy. If the differences in constraints cannot be explicitly formulated, other means of identifying the different mental strategies in work and in experiments must be used (verbal protocols, discriminant analysis, cluster analysis, etc.).

An example of this problem arises in connection with experiments on diagnostic behaviour studied within the social judgement paradigm. The approach has been based on regression analyses of the influences of available cues on judgments made by subjects in laboratory tasks. Studies have been made with reference to several professional activities such as stockbrokers, clinical psychologists and physicians (see e.g., Brehmer, 1981). In these experiments, cues identified as diagnostically relevant by expert judges are used to present subjects with trial cases, generally in the form of verbal descriptions on cards. From the experimental sessions, a statistical model describing diagnostic behaviour is identified. The general result has been that

linear statistical models, such as a multiple regression analysis, have been adequate to describe performance. Conclusions from these experiments are typically as follows. The judgment process tends to be very simple. Even though experts identify up to 10 cues as relevant to a diagnosis, they actually use very few - usually only two or three, and the process tends to be purely additive. Furthermore, the process tends to be inconsistent. Subjects do not use the same rule from case to case and judgment in a second presentation of a case may differ considerably from what it was the first time. There are wide individual differences even among subjects with years of experience. They differ with respect to the cues used and the weights they apply. Finally, people are not very good at describing how they make judgments (Brehmer, op. cit.).

In the present perspective, the constraint envelope around the subject for these experiments is defined at the decision task level, see figure 58. Professional subjects are normally used - e.g., medical doctors - and the task is well specified in terms of a diagnostic problem stated in professional domain terms. However the experimental setting is removed from the natural context and therefore an important question relates to the extent to which this condition forces the professional subjects to chose a different mental strategy for diagnosis. Another illustration of the importance of defining the experimental boundary conditions can be found in the experiments of Wason and Johnson-Laird (1972). They indicate that a logical inference task which proves to be difficult for subjects when presented in abstract logical terms becomes very easy when embedded in a familiar context - e.g., a shopping account approval task.

Thus the problem for this category of experiments is normally not connected with the validity of the results, but instead the generalizations made. Generalization is frequently made in terms of the behaviour of professionals in a nominal task, e.g., 'diagnosis' under actual work conditions a generalization which is unreliable. After comparing the results of laboratory studies with our analyses of diagnostic tasks in hospitals and repair shops, we can identify some important differences which signal great caution concerning any transfer of the laboratory results to the actual professional work context. This does not imply that the results of the diagnostic laboratory experiments are invalid for multiple attribute judgement tasks, but instead that isolated multiple attribute judgement is not always a characteristic of a diagnostic judgement in actual work (Rasmussen, 1991). Reliable generalization at this level of constraint specification requires the identification of the relationship between the experimental situation, the possible mental strategies and the performance criteria governing the actual choice. In the present case, any generalization should probably be stated in terms of the ability for intuitive, multiple attribute judgments rather than for professional diagnostics.

Many laboratory studies have been designed for the study of diagnosis and fault management (see e.g., Rouse, 1981, Sanderson, 1990). They are often referred to as experiments on 'fault-finding', or 'trouble-shooting'. However, the diagnostic conditions during work are different from those in an investigation requiring a subject to locate a fault in a logic network. The experimental design presents to a subject a symbolic representation of the system in which the problem is found and therefore a particular 'diagnostic field' is forced upon the subject. Thus this turns the experiment into an evaluation of the subjects' ability to operate in this particular diagnostic field and to use the related diagnostic strategy. This does not make the experiment invalid, but a careful explication is required of the boundary conditions of the experiment and the kind of mental strategy the experimental conditions impose on the subject. That is, a generalization

should not be made with reference to the domain which is the source of the cover story, but only with reference to the applied strategy.

An interesting approach to an experimental design of a series of simulation experiments to train diagnostic skills and, at the same time, train the ability to generalize has been taken by Rouse (1982). In this 'mixed fidelity simulation' training, the trainees are subjected to diagnostic tasks moving through levels similar to those of figure 58 from the simulation of faults in logic networks to simulated task situations.

We find that the framework suggested here can serve to resolve much of the standing controversy about the value of laboratory experiments for understanding 'real life' work. This discussion is caused by designers' frustrations with the lack of explicit descriptions of the boundary conditions of experiments in terms which could facilitate the transfer of results to a work context.

The structure of the experimental work domain faced by the subject in this category is somewhere between the situations illustrated by figures 60 and 61. The functions required by the subjects are to a lesser degree related to the configuration and processes of the experimental set-up while the explicit task instruction is to some degree replaced by a 'cover story' referring to work context (trouble shooting, scheduling, etc.).

Experimental Task Scenarios

The development of advanced information technology and the need for models of cognitive processes in work performance have brought about a significant interest in more complex experiments focused on actual task situations. Consequently, the simulation of complex task situations as represented by the next envelope in figure 58 has become popular.

Also in this category, two approaches are found. Studies based on a separation of relational networks have been made - in particular for modelling human performance in aircraft and vehicle control in terms of an extension of the manual control paradigm to include complex optimal and adaptive control models (for review see Sheridan and Ferrell, 1974). Due to a rigourous representation in terms of sets of differential equations (possibly due to the well known dynamics of aircraft) and of the parameters involved in planning and decision making, the boundary conditions of the experiments are explicitly known and the basis for generalization is well documented.

A problem is that the transfer of the mathematically based modelling methodology to less constrained environments is difficult if not impossible. Another line of experiments has therefore emerged, based on more qualitative causal task scenarios, (for a review of activities in Europe, see e.g., Funke, 1988). In this category, we find studies of decision making and diagnostic behaviour using simulators of high functional fidelity for aviation, chemical process plants, power plants, etc. (Woods, 1984). Also the optimal control models have recently been extended by adding decision and planning modules based on a causal, object oriented modelling approach (Baron et al, 1986).

In other cases, special experimental simulators have been used. The line of experiments with manual control of Crossman has been continued using simulated industrial process systems by Moray et al. (1986, 1989), Sanderson et al. (1989), Vicente (1991). Also Rouse and his group have been doing experiments in problem solving in simulated industrial process tasks (Rouse,

1982, Knaeuper and Rouse, 1985, Morris et al., 1985). Other examples are GNP, a simulator of a generic nuclear power plant (Goodstein, 1985), and the simulation of nuclear reactor feed-water systems (Cacciabue, Codazzi and Decortis, 1990).

Since such simulations are designed as replicas of actual work scenarios, the expectation often is that the behaviour observed in these experiments will mimic the actual behaviour of people in the 'real situation' provided that the subjects have had some experience with the real system. However an important factor to consider is that attention with this kind of simulation normally is focused on a particular task, such as 'diagnosis' or 'scheduling', and, at the same time, on a particular part of the system. This will change the constraint set at the boundaries around the experiment. For example, when the simulation is concerned with some work process, the laboratory situation will differ from the real work situation in that the subject may work alone, rather than as a member of a shift team the motivational structure may be different the person may work for a shorter time, and so on. Whether these differences are important must be carefully assessed. The only possible way to generalize from such experiments is to seek an identification of the behaviour-shaping features at the boundaries of the experimental situation in order to be able to compare them to other situations and systems.

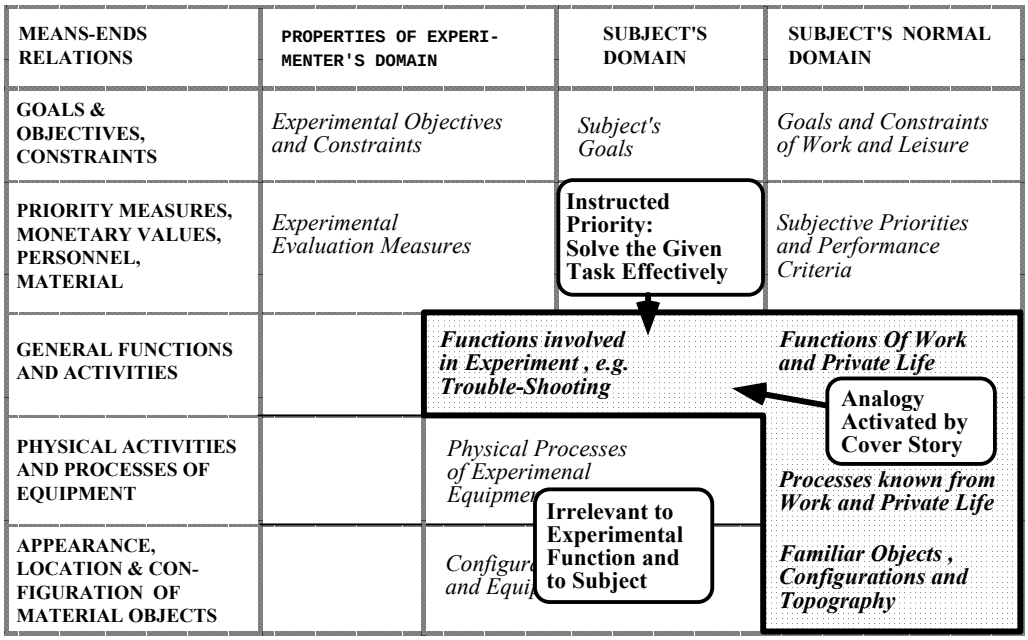


Figure 61. Complex experimental settings serving to study hypotheses about the relationships between particular task parameters and task performance are frequently designed to mimic the actual work situation in process control, forest fire fighting, hospital diagnosis, etc. In such experiments, specification of the boundary conditions is made with reference to the subjects' experience with or general understanding of the work scenario which is mimic'ed.

In experiments striving to constrain the actor only by specifying the task situation, the boundary of the experimental domain is less well defined because a 'cover-story' is used to invoke the subject's 'private' context. That is, the specification of the boundary conditions is made with reference to the subjects' experience with or general understanding of the work scenario which is being mimic'ed. See figure 61. Therefore it is necessary that the functional structure of the experiment match the context alluded to by the cover story. This match can only be demonstrated by an explicit identification of the behaviour-shaping constraints of the

experiment and intimate knowledge about the constraints of the actual substance matter domain. In efforts to cope with the difficulties of mapping the transformations across the boundaries shown in figure 58, Moray (Moray et al, 1992) has designed a sequence of experiments in a psychological laboratory and in a model workshop of an industrial engineering laboratory

Several experimental programs within the MOHAWC project fall in this category. One example is the experiments with *Forest Fire Fighting.* This experimental task situation is used in two different series of experiments. One is the DESSY (Brehmer & Allard, 1989) program which is focus on analysis of separate, quantitative relationships across the set of experimental actors. One series of experiments was focused on investigation of the effects of various factors such as magnitude of information delays and the location of the delays in the information feedback loop on average performance measured by the amount of forest lost. In the DESSY experiments, the subjects are given very precise goals. They are asked to assume the role of a fire chief and charged with the task of fighting forest fires. They are told that their task is to put out the fires as quickly as possible. In this case, then, there is no uncertainty with respect to when the end state of no fire has been reached. Another experimental program, "NewFire," with simulated forest fires has been presented in the MOHAWC context by Løvborg (1990). In contrast to Brehmer's experiments which were focussed on the influence of certain factors on quantitative performance measures, a central aim in the NewFire series has been identification of the strategies applied in fire-fighting by the individual actors and the evolution of effective strategies through a learning sequence.

Complex Work System Simulations

Another kind of experiments have recently become popular, that is, experiments aimed at a study of the performance of actors in exploration of a complex problem domain, their formulation of the problem they face, the goal they adopt, and the solution they generate. In this case, the instruction of the actors cannot make explicit the goal of the experimental task, neither the experimental task procedure since the study of the formulation by the actor is the central experimental objective. Consequently, the instruction necessarily is very open and given by a description of a 'cover story,' i.e., a description of an actual work situation which has been the source of the simulated relational, functional network, see figure 62.

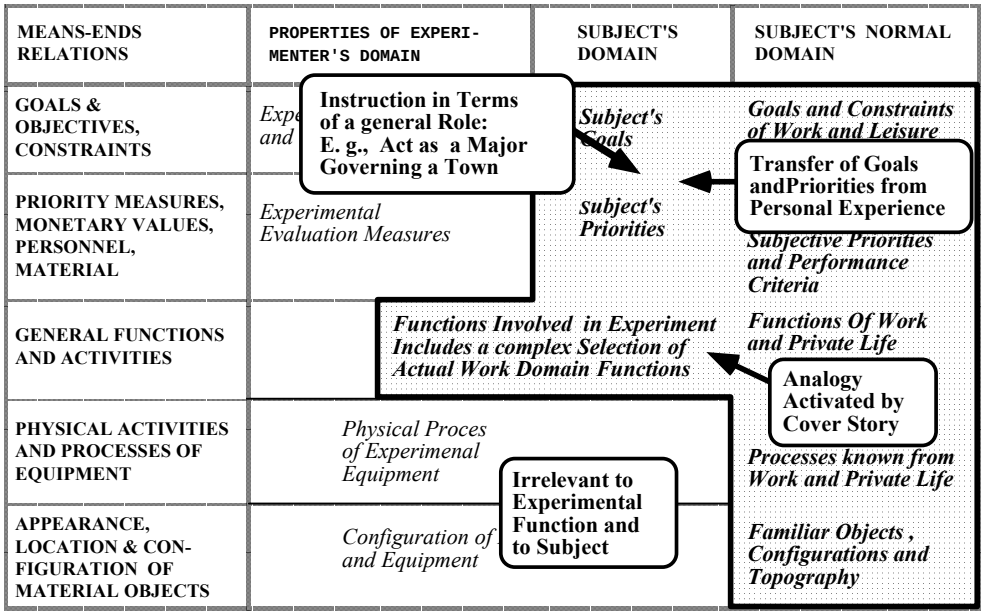


Figure 62. Micro-world experiments.Recently, several experiments were aimed at the performance of subjects in complex problem domains, their formulation of the problem they face and the goal they adopt. In such experiments, instruction of subjects can not make explicit the goal of the experimental task or the experimental task procedure since the study of the formulation by the subject is the central experimental objective. Consequently, the instruction necessarily is very open and is given by a 'cover story' which relates the experiment to the general experience of the subject.

When computers are used to simulate complex scenarios from real-life work context, naive actors (e.g., psychology department students) or professional agents from the particular work domain are asked to cope with tasks in this environment. In this case it is very difficult to control reliably the actual goals and performance criteria adopted by the actors. It is, of course, the intention to keep the higher functional properties of the task, the working goals and actor priorities as undisturbed as possible but it should be realized that the physical process and anatomy of the real work domain are replaced by the processes and anatomy of the computer installation, see figure 62. Typically, an actor will be well aware of this fact, in particular when "in trouble". It is often found, that a actor will explain unexpected simulator performance by program inadequacies or bugs. In an actual work environment, there is a very subtle, many-to-many relationship between the goals, the functional level and the possible implementations at the physical process level and it will be very difficult for a actor to judge what is and what is not included in the simulation. The actor will, therefore, have to infer a number of goals, constraints, and functions from more or less intuitive assumptions about the task as conceived by the designer of the experiment.

In this situation, it is important to be able to analyze and describe explicitly the actual source domain of the research hypothesis as well as the research domain selected under the assumption that human agents in any work domain are basically goal directed, adaptive organisms having several mental strategies at their disposal in each situation and choosing the actual strategy from context and situation dependent performance criteria. If we accept this basic assumption, we can only draw conclusions from selective experiments and simulations, if we explicitly can describe the similarities and differences between the actual behavior shaping constraints of the actual work conditions and of the experimental conditions.

The studies of Dörner (see Dörner, 1989) are very good examples to discuss this category of experiments from a taxonomy point of view. In a simulation of a town, "Lohhausen" actors were asked to act as the major of the town and to look after the well being of the inhabitants ("fur das 'Wohlergehen der Einwohner' zu sorgen." Op. cit. p. 87). The formulation of operational goals and the identification of means for action were left to the actor who, not being professional majors, only had the choice to rely on trial and error or, more likely, to import intuition from their private life. In this case, performance is highly influenced by the particular background of the individual actor. Dörner presents very clear examples of this situation:

In this way it is very difficult to control reliably the actual goals and performance criteria adopted by the actors, when naive actors (e.g., psychology department students) or even professional agents from the particular work domain are asked to cope with tasks in this environment.

When instruction in a complex experimental task is given by a cover story, the personal experience and knowledge-aboute-the-world is activated for control of the task with very idiosyncratic effects. Dörner gives some beautiful examples of this influence: In the Lohhausen experiment, a actor who is a school teacher, focus activities on particular teaching problems in the school system and leaves rest of the society at its own (p.90) a left wing actor decided to introduce extensive socialistic measures and explained difficulties by reactionary sabotage (p.105) a student actor without any experience in production planning used a simple analogy, that is her personal experience from rolling her own cigarettes, for her decision making (p.113). Similar experience has been reported by Sanderson (1989) who found that different assumptions about the use of cars and busses in the USA and in England were likely to influence her results when she duplicated experiments on implicit and explicit learning originally done in Oxford by Broadbent et al (1986). In Sanderson's experiments, it seemed (Sanderson, private communication) that the USA subjects did not believe that "citizens" would continue to accumulate at a bus stop until a bus came. Instead they assumed that the longer the time periods between busses, the fewer people would elect to take the bus. The assumption was that everyone had cars. This is probably less likely in the Oxford subject pool which is composed typically of women with sufficient time on their hands and/or a financial need who desired to take part in psychological experiments at the university.

INSTRUCTIONS, METAPHORS AND COVER-STORIES.

In experiments, actors are supposed to control an experimental set-up, a micro-world, according to an instruction. The content of the instruction changes with the experimental strategy. In classical, well controlled experiments, the instruction can be explicit and unambiguous. In complex experiments with "micro-worlds" such explicit unambiguous instructions are impractical and "metaphorical" instructions are used. A case in point is the forest-fire experiment discussed above. The phenomenon of forest-fire is common knowledge and the instruction to deal with it is an effective short hand instruction. An attempt to formulate an instruction without retreating to a metaphor, i.e., expressing it in terms only relating to the features of the simulation display, and actions upon it, turns out to be complicated, lengthy, and incomprehensible. Because the phenomenon of forest fire is common knowledge, the instruction is rather well bounded to a specific task. In the Lohhausen, the instruction has the form of a

cover-story, which is raising a much more complex inner world which varies widely among actors controls behaviour.

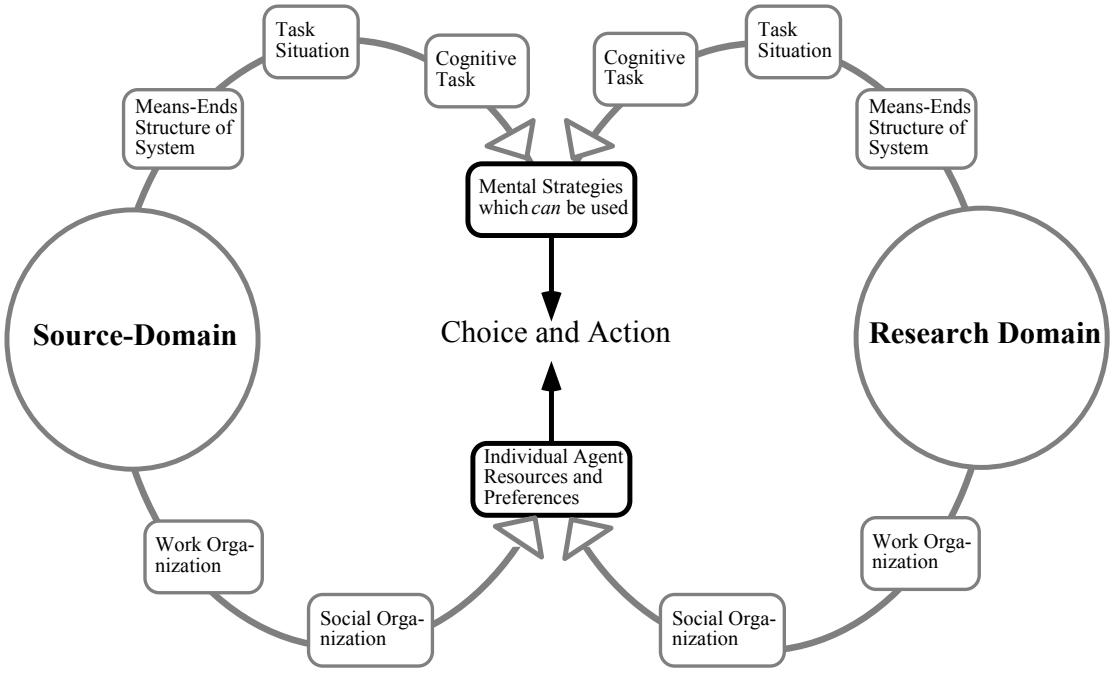


Figure 63. Propagation of constraints in experimental design.The propagation and resulting transformation of behaviour-shaping constraints will very likely be very different between the work context and the actor and between the experimental scenario and the subject. Therefore, care should be taken in the formulation of the 'cover story' used to instruct the subjects. It is likely that a reference to the actual work situation should be avoided. Instead a matching cover story should be *designed*, based on an analysis of the background of the subjects.

REFERENCES

Alexander, C. (1964): Notes on the Synthesis of Form. Cambridge, MA: Harvard University Press.

Amalberti, R. and Deblon, F. (1989): Cognitive Modelling of Fighter Aircraft's Process Control: A Step towards an Intelligent On-board Assistance System. Int. Journ. of Man-Machine Studies, Vol. 36, No. 5, pp. 639-671.

Ashby, W. R. (1962): "Principles of the Self-Organizing System," in von Foerster, H. and Zopf, G.W. (Eds.): Principles of Self-Organization, New York: Pergamon Press.

Babbage, C., (1826): On a Method of Expressing by Signs the Action of Machinery. Philosophical. Transactions of Royal. Society of London for the Year MDCCCXXVI. Part III.

Barber, G., DeJong, P. & Hewitt, C. (1983): Semantic Support for Work in Organizations. in R. E. A. Mason (ed) Information Processing 83. New York: Elsevier Science Publishing.

Baron, S., Fehrer, R., Pew, R. and Horwitz, P. (1986): Approach to Modelling Supervisory Control of a Nuclear Power Plant. NUREG/CR-2988. ORNL/Sub/81-70523/1.

Beltracchi, L. (1984): A Process/Engineering Safeguards Iconic Display, Symposium on New Technologies in Nuclear Power Plant Instrumentation and Control, Washington, D. C. 28-30 Nov.

Beltracchi, L. (1987): A Direct Manipulation Interface for Water-based Rankine Cycle Heat Engines. IEEE Transactions on Systems, Man, and Cybernetics, Vol. 17, pp. 478-487.

Beltracchi, L. (1989): Energy, Mass, Model-Based Displays and Memory Recall. IEEE Transaction on Nuclear Science, Vol. 36, pp. 1367-1382

Bigelow (1840): see Hindle

Brehmer, B. , Leplat, J. and Rasmussen, J., (1991): Use of Simulation in the Study of Complex Decision Making. In: Rasmussen, J., Brehmer, B. and Leplat, J. (Eds.): Distributed Decision Making: Cognitive Models for Cooperative Work. London: John Wiley and Sons.

Brehmer, B. (1981): Models of Diagnostic Judgments, in J. Rasmussen and W. B. Rouse, eds. Human Detection and Diagnosis of System Failures. New York: Plenum Press, pp. 231-241.

Brehmer, B. (1990): Towards a Taxonomy for Microworlds. In: J. Rasmussen, B. Brehmer, M. de Montmollin and J. Leplat (Eds.): Taxonomy for Analysis of Work Domains. Proceedings of first Mohawc workshop. Roskilde: Risø National Laboratory

Brehmer, B.and Allard, R. (1991): Dynamic Decision Making: The Effect of Task Complexity and Feedback Delays. In: Rasmussen, J., Brehmer, B. and Leplat, J. (Eds.): Distributed Decision Making: Cognitive Models for Cooperative Work. London: John Wiley and Sons.

Broadbent, D., Fitzgerald, P. and Broadbent, M. H. P. (1986): Implicit and Explicit Knowledge in the Control of Complex Systems. British Journal of Psychology, 77, pp. 33-50.

Cacciabue, P. C., Codazzi, A. and Decortis, F. (1990): The Analysis of the Functional Role of Man and Machine in the Control of a Notional Auxiliary Feedwater System. In: J. Rasmussen, B. Brehmer, M. deMontmollin and J. Leplat (eds), Proceedings of the First MOHAWC Workshop on Taxonomy for Analysis of Work Domains, Liège, 15-16 May.

Peter Carstensen, Henrik Jensen and Gordon McAlpine(1990):Arbejdsskadesagsbehandling og Behov for Edb Støtte. Administration of Work Damage Cases and Requirement for Decision Making Support. Internal Report from LO, Landsorganistionen i Danmark. (In Danish)

Clanton, C. (1983): The Future of Metaphor in Man-Computer Systems. Byte, No. 12, pp. 263-270.

Crossman, E. R. F. W., and Cook, J. E. (1962): Manual Control of Slow Response Systems. In: Edwards, W. and Lees, F. P. (Eds.): The Human Operator in Process Control. London: Taylor and Francis.

Dörner, D. (1989): Die Logik des Misslingen. Reinbek bei Hamburg: Rowohlt.

Ferguson, E. S. (1977) The Mind's Eye: Nonverbal Thought in Technology, Science, vol. 197, no. 4306, pp. 827-836.

Flach, J. M. & Vicente, K. J. (1989): Complexity, Difficulty, Direct Manipulation and Direct Perception. Report EPRL-89-03. Urbana-Champaign. Ill.: Engineering Psychology Research Laboratory, University of Illinois at Urbana-Champaign.

Flores F., Graves, M., Hartfield, B. and Winograd T. (1988): Computer Systems and the Design of Organizational Interaction. ACM Transactions on Office Systems, Vol. 6, No. 2, April 1988, Pages 153-172

Friend'21 (1991): Proceedings of the International Symposium on Next Generation Human Interface Technologies, September November 1991, Tokyo: Institute for Personalized Information Environment.

Funke, J., (1988): Using Simulation to Study Complex Problem Solving. Simulation and Games, Vol. 19, No. 3, September 1988, 277-303

Gibbs, J. W. (1873): Graphical Methods in the Thermodynamics of Fluids. Trans. Connecticut Acad. Vol. 2, pp. 309-343.

Gibson, J. J. (1950): The Perception of the Visual World. Boston: Houghton-Mifflin.
Gibson, J. J. (1966): The Senses Considered as Perceptual Systems. Boston: Houghton-Mifflin.
Gibson, J. J. (1979): The Ecological Approach to Visual Perception. Boston: Houghton-Mifflin.
Gibson, J. J. and Crooks, L. E. (1938): A Theoretical Field-Analysis of Automobile Driving. The American Journal of Psychology, Vol. 51, No. 3. pp 453-471.
Goodstein, L. P. (1985a): Studies of Operator-Computer Cooperation on a Small-scale Nuclear Power Plant Simulator. Risø-M-2522. Roskilde: Risø National Laboratory, .
Goodstein, L. P. (1985b): Functional Alarming and Information Retrieval. Risø-M-2511. Roskilde: Risø National Laboratory, .
Goodstein, L.P., and Rasmussen, J., (1988): Presentation of Process State, Structure and Control. Travail Humain, Vol. 51, No. 1, .
Gould, J. D. (1988): How to design usable systems. In M. Helander (Ed.), Handbook of Human-Computer Interaction (pp. 757-789). Amsterdam: North-Holland.
Grudin, J. (1989): The Case Against User Interface Consistency. Communications of the ACM, Vol. 32, pp. 1164-1173.
Hansen, J. P., (1992): Representation of System Invariants by Optical Invariants in Configural Displays. In: Flach, J., Hancock, P., Caird, J. and Vicente, K. (Eds.) (1992): The Ecology of Man-Machine Systems: A Global View. Hillsdale, NJ: Lawrence Erlbaum. In Press.
Hindle, B. (1981): Emulation and Invention. New York: New York University Press.
Hollan, J. (1989: Metaphors for Interface Design. presented at U. S. Nuclear Regulatory Commission's Man-Machine Interface Workshop. 10-12 January, 1989. Washington, DC: U. S. Nuclear Regulatory Commission.
Hutchins, E. L., Hollan, J. D., and Norman, D. A. (1986): Direct Manipulation Interfaces. In D. A. Norman and S. W. Draper (Eds.), User Centered System Design: New Perspectives on Human-Computer Interaction (pp. 87-124). Hillsdale, NJ: Lawrence Erlbaum.
Hutchins, W.J. (1978): The Concept of 'Aboutness' in Subject Indexing. Aslib Proceedings, Vol. 30, No. 5, pp. 172-181.
Häntzschel-Clairmont, W. (1912): Die Praxis des Modernen Maschinenbaues. Berlin: Verlag von C.A. Weller.
Kaavé, B. (1990): Exploration of the User-System Interaction in Production Control (In Danish). Unpublished MSc diss., Copenhagen: Technical University.
Kaplan, R. S. (1990): The Four-Stage Model of Cost System Design. Management Accounting, February 1990, pp. 22- 26.
Knaeuper, A., and Rouse, W. B. (1985): A Rule-based Model of Human Problem-Solving Behavior in Dynamic Environments. IEEE Transactions on Systems, Man, and Cybernetics, Vol. 15, pp. 708-719.
Lindsay, R. W., and Staffon, J. D. (1988): A Model Based Display System for the Experimental Breeder Reactor-II. Paper presented at the Joint Meeting of the American Nuclear Society and the European Nuclear Society, Washington, DC.
Lee J. and Morray, N. (1991): Trust and the Allocation of Function in the Control of Automatic Systems. To be published in Ergonomics.
Lodding, K. N. (1983): Iconic Interfacing; IEEE Computer Graphics and Applications, Vol. 3 pp 11-20.
Løvborg, L. (1990): New Fire. Proceedings of CEC Esprit Basic Research Action Project: MOHAWC. Vol.2. Roskilde: Risø National Laboratory.
McRuer, D. t. and Krendel, E. S. (1957): Dynamic Responses of Human Operators. W-DC-TR-56-524. US-Air Force.
Meister, D., and Farr, D. E. (1967): The Utilization of Human Factors Information by Designers. Human Factors, Vol. 9, pp. 71-87.
Michaels, C. F. & Carello, C. (1981): Direct Perception, Prentice-Hall, Englewood Cliffs, NJ.
Michalski, R. S., Carbonell, J. G. & Mitchell, T. M. 1986): Machine Learning: An Artificial Approach, Vol. 2: Los Altos, CA. : Morgan Kaufman.
Mihram, D. & Mihram, G. A. (1974): Human Knowledge, the Role of Models, Metaphors and Analogy, International. Journal of General Systems, Vol. 1, pp. 41-60.
Mihram, G. A. (1972): The Modeling Process, IEEE Transactions on Systems, Man and Cybernetics, Vol. 2, No. 5, pp. 621-629.
Miller, A. I. (1989): Imagery in Scientific Thought Creating 20th-Century Physics. Boston: Birkhauser.
Miller, G.A., (1968): Psychology and Information. **A. Docum.**, Vol. 19, 286-289.
Mintzberg, H. (1979): The Structuring of Organizations. Englewood Cliffs, NJ: Prentice-Hall.
Monta, K., Takizawa, Y., Hattori, Y. Hayashi, T. Sato, N., Itoh, J. Sakuma, A. & Yoshikawa, E. (1991): An Intelligent Man-Machine System for BWR Nuclear Power Plants. AI'91 Frontiers in Innovative Computing for the Nuclear Industry. Jackson, Wyoming, USA, Sept. 15-18.

Moray, N. and Dessouky, M. I. (1992): Taxonomy of Scheduling Systems as a Basis for the Study of Strategic Behavior. Technical Report to be published. Champagne-Urbana, Ill.: Engineering Psychology Research Laboratory, University of Illinois at Champagne-Urbana.

Moray, N., and Rotenberg, I. (1989): Fault Management in Process Control: Eye Movements and Action. Ergonomics, Vol. 32, pp. 1319-1342.

Moray, N., Lootsteen, P., and Pajak, J. (1986): Acquisition of Process Control Skills. IEEE Transactions on Systems, Man, and Cybernetics, Vol. 16, pp. 497-504.

Morris, N. M., Rouse, W. B., and Fath, J. L. (1985): PLANT: An Experimental Task for the Study of Human Problem Solving in Process Control. IEEE Transactions on Systems, Man, and Cybernetics, Vol. 15, pp. 792-798.

Norman, D. A. (1986a): Cognitive Engineering. In D. A. Norman and S. W. Draper (Eds.), User Centered System Design: New Perspectives on Human-Computer Interaction (pp. 31-61). Hillsdale, NJ: Lawrence Erlbaum.

Norman, D. A. (1988): The Psychology of Everyday Things. New York: Basic Books.

Pejtersen, A. M. and Rasmussen, J. (1988): Information Retrieval in Integrated Work Stations. Proceedings of the International Conference on Information and Knowledge; Yokohama, 1988. Yokohama: Kanagawa University.

Pejtersen, A. M. (1989): A Library System for Information Retrieval based on a Cognitive Task Analysis and Supported by an Icon Based Interface. In: ACM, SIGIR Conference Proceedings. Boston: ACM.

Pejtersen, A.M., (1979): Investigation of Search Strategies Based on an Analysis of 134 User-Librarian Conversations. In: T.Henriksen (ed): IRFIS 3. Third International Research Forum in Information Research, pp. 107-132. Oslo: University of Oslo

Pejtersen, A.M. (1980): Design of a Classification System for Fiction Based on an Analysis of Actual User-Librarian Communications and Use of the Scheme for Control of Librarians' Search Strategies. In: O.Harbo and L.Kajberg (eds): Theory and Application of Information Research, pp.146-159. London: Mansell, .

Pejtersen, A.M. (1989): The Book House. Modelling Users' Needs and Search Strategies as a Basis for System Design. Risø-M-2794. Roskilde: Risø National Laboratory.

Pejtersen, A.M. and Goodstein, L.P. (1990): Beyond the Desk Top Metaphor: Information Retrieval with an Icon-based Interface. In M.J.Tauber and P.Gorny (eds): Visualisation in Human-Computer Interaction, Lecture Notes in Computer Science, Berlin: Springer Verlag.

Pew, R. W. (1974): Human Perceptual-Motor Performance. In: Kantowitz, B. H. (Ed.): Human Information Processing: Tutorials in Performance and Cognition. Hillsdale, NJ.: Lawrence Erlbaum

Polanyi, M., (1958): Personal Knowledge. London: Routledge& Kegan Paul.

Ramelli (1588): See Ferguson.

Rasmussen, J. (1988): Models for Design of Computer Integrated Manufacturing Systems: The Human Perspective. Invited Conference Address, 1'st International Conference on Ergonomics of Advanced Manufacturing and Hybrid Automated Systems. Louisville, Kentucky, USA. August 1988. In: International Journal of Industrial Ergonomics, Vol. 5, No. 1, pp. 5-16, January, 1990.

Rasmussen, J. (1990c): Human Error and the Problem of Causality in Analysis of Accidents. Philosophical. Transactions of Royal. Society. Vol. B 327, pp. 449-462.

Rasmussen, J., (1985): The Role of Hierarchical Knowledge Representation in Decision Making and System Management. IEEE Transactions on Systems, Man and Cybernetics. Vol. 15, No. 2, pp. 234-243.

Rasmussen, J., (1986): Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering. Amsterdam: North Holland, .

Rasmussen, J., (1991): Diagnostic Reasoning in Action. Risø-M- 2952. Roskilde: Risø National Laboratory

Rasmussen, J., (1992): Deciding and Doing: Decision Making in Natural Context. In: Klein, G. and Calderwood, C. (Eds.): Decision Making in Action: Models and Methods. Ablex Publishing. In Press.

Rasmussen, J., and Vicente, K. J. (1989): Coping with human errors through system design: Implications for ecological interface design. International Journal of Man-Machine Studies, 31, 517-534.

Rasmussen, J., and Vicente, K., (1990): Ecological Interfaces A Technological Imperative in High tech systems? International Journal of Human Computer Interaction Vol. 2, No. 2, pp. 93-111

Rasmussen, J., (1991): Human Sources of Work Complications, Invited position paper for the Conference on Human Error in Anesthesia. 26 Feb.- 1 March '91. Stanford: University School of Medicine.

Rasmussen, J., Pejtersen, A.M. and Schmidt, K. (1990): A taxonomy for Analysis of Cognitive, Cooperative Work. Risø-M-2871. Roskilde: Risø National Laboratory.

Reason, J.Marsden, Cacciabue,C., (1991): Modelling Fallible Human Cognition in a Variety of Context. In: Rasmussen et al.: Taxonomy for Analysis of Work Domains. Proceedings of The First MOHAWC Workshop, Liege, 1990.

Rosch, E. (1975): Human Categorization. In: N. Warren (Ed.): Advances in Cross-Cultural Psychology. New York: Halsted Press.

Rouse, W. B. (1981): Experimental Studies and Mathematical Models of Human Problem Solving Performance in Fault Diagnosis Tasks. In: Rasmussen, J. and Rouse, W. B. (Eds.): Human Detection and Diagnosis of System Failures. New York: Plenum.

Rouse, W. B. (1982): A Mixed Fidelity Approach to Technical Training, Journal on Education in Technological Systems, Vol. 11. No. 2, pp. 103-115.

Rouse, W. B. (1984a): Developing an Evaluation Plan: Computer-generated Display System Guidelines, Tech. Report EPRI-NP-3701 Vol. 2. Norcross, GA. : Search Technology Inc.

Rouse, W. B., Frey, P. R. & Rouse, S. H. (1984b). Classification and Evaluation of Decision Aids for Nuclear Power Plant Operators. Report 8303-1. Norcross, GA. : Search Technology Inc.

Sanderson, P. M. (1990): Knowledge Acquisition and Fault Diagnosis: Experiments with PLAULT. IEEE Transactions on System, Man, and Cybernetics, Vol. 20, pp. 225-242.

Sanderson, P. M., Flach, J. M., Buttigieg, M. A. & Casey, E. J. (1989): Object Displays Do Not Always Support Better Integrated Task Performance, Human Factors, Vol. 31, No. 2, pp. 183-198.

Sanderson, P. M., Haskell, I. & Flach, J. (1990): The Complex Role of Perceptual Organization in Visual Display Design. Report EPRL-90-08. Urbana-Champaign, Ill.: Engineering Psychology Research Laboratory, University of Illinois at Urbana-Champaign.

Sheridan, T. B. (1984): Interaction of Human Cognitive Models and Computer-based Models in Supervisory Control. Tech. Report: ONR Project NR-196-179. Cambridge, MA.: MIT, Department of Mechanical Engineering.

Sheridan, T. B. and Ferrell, W. R. (1974): Man-Machine Systems: Information, Control, and Decision Models of Human Performance. Cambridge, MA: MIT Press.

Shneiderman, B. (1983): Direct Manipulation: A Step Beyond Programming Languages. IEEE Computer, Vol. 16, No. 8, pp. 57-69.

Stokes, A.E., and C. Wickens (1988): Aviation Displays. In: Wickens, C. (ed): Human Factors in Aviation, London: Academic Press.

Storrs, Graham: "Group Working in the DHSS Large Demonstrator Project," EC-CSCW '89. Proceedings og the first European Conference on Computer Supported Cooperartive Work, Gatwick, London, 13-15 September, 1989.pp. 102-119.

Suchman, L. A. (1983): Office Procedures as Practical Action: Models of Work and Systems Design. ACM Transactions on Office Information Systems, Vol. 1 No. 4, pp. 320-328.

Sutcliffe, A. C. (1909): Robert Fulton and the "Clermont". New York.

Truxal, J.G. (1955): Automatic Feedback Control System Synthesis. New York: McGraw-Hill.

Vicente, K. (1991): Supporting Knowledge-Based Behavior through Ecological Interfaces. (Unpublished Dissertation). Urbana, Il: University of Illinois at Urbana-Champaign.

Vicente, K. J. (1989): Mediating direct perception in complex work domains. In Proceedings of Fifth International Conference on Event Perception and Action. Oxford: OH.

Vicente, K. J., (1990): A few implications of an ecological approach to human factors. Human Factors Society Bulletin, Vol. 33, No. 11, pp. 1-4.

Vicente, K. J., and Rasmussen, J. (1988): A Theoretical Framework for Ecological Interface Design. Risø-M-2736. Roskilde: Risø National Laboratory.

Wason, P. C. and Johnson-Laird, P. N. (1972): Psychology of Reasoning. Cambridge, MA: Harvard, .

Whiteside, J., Bennett, J., and Holtzblatt (1988): Usability engineering: Our experience and evolution. In M. Helander (Ed.), Handbook of human-computer interaction (pp. 791-817). Amsterdam: North-Holland.

Woods, D. D. (1984): Visual Momentum: A Concept to Improve the Cognitive Coupling of Person and Computer. International Journal of Man-Mchine Studies, Vol. 21, pp. 229-244.

Woods, D. D., and Eastman, M. C. (1989): Integrating principles for human-computer interaction into the design process: Heterarchically organized HCI principles. In Proceedings of the 1989 International Conference on Systems, Man, and Cybernetics (pp. 29-34). New York: IEEE.

Woods,D.D. & Roth, E.M. (1988): Cognitive Systems Engineering. in M.Herlander (ed): Handbook of Human-Computer Interaction, pp.3-43. Amsterdam: North-Holland.

Woods,D.D. (1986): Paradigms for Intelligent Decision Support. in E.Hollnagel, G.Mancini & D.D.Woods (eds). Intelligent Decision Support in Process Environments, pp.153-173. Berlin: Springer-Verlag.

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Abstract (Max. 2000 Char.)

The report presents a discussion of the implications of the taxonomy for work analysis developed for the CEC project MOHAWC (Models of Human Activities in Work Context) by the Risø group. The discussion is introduced by a brief overview of the taxonomy to set the stage for new readers. Following this, different approaches to the support of performance in actual work context are discussed and it is argued that ecological information systems making visible the 'deep' structure of a work space is particularly effective for discretionary tasks in modern work systems: a map of the domain is a better guide than route instructions, that is, work procedures. The complex cognitive coupling found in such work systems is analyzed and the importance is stressed of being able to support different levels of cognitive control and perception of the work domain at several levels of abstraction.
Next, the nature of design is discussed together with the traditional lack of success of human factors guidelines. It is suggested, that rather than to try to guide the design process by guidelines and checklists, it should again be accepted that 'maps are better guides than route instructions.' That is, an attempt is made to support information system and interface designers by maps of the various design territories in stead of the usual guidelines. For this purpose, maps are suggested of 1. prototypical work-situations, of 2. knowledge representations used during design and of 3. display composition and interpretation. Further support of designers is suggested by the use of a catalogue of annotated interface formats and samples of annotated designs are presented.
Finally, the use of the taxonomy for empirical as well as analytical evaluation of prototype systems is discussed in some detail, as is the use of the taxonomy to specify the boundary conditions for psychological experiments in order to facilitate the transfer of results of such experiments to design and evaluation of information systems.

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