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Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models

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***Abstract*—The introduction of information technology based on digital computers for the design of man–machine interface systems has led to a requirement for consistent models of human performance in routine task environments and during unfamiliar task conditions. A discussion is presented of the requirement for different types of models for representing performance at the skill-, rule-, and knowledge-based levels, together with a review of the different ways in which information is perceived at these different levels in terms of signals, signs, and symbols. Particular attention is paid to the different possible ways of representing system properties which underlie knowledge-based performance and which can be characterized at several levels of abstraction—from the representation of physical form, through functional representation, to representation in terms of intention or purpose. Furthermore, the role of qualitative and quantitative models in the design and evaluation of interface systems is mentioned, and the need to consider such distinctions carefully is discussed.**

Introduction

MANY technical systems in modern times are highly automated and do not rely on human intervention in the control of normally planned functions. Yet their existence depends on extensive support from a human staff to maintain the necessary conditions for satisfactory operation and to cope with all the badly structured and probably unforeseen states of affairs in the system. Due to the high risk involved in the potential for accidents in large centralized production units, concern with being able to predict human performance during complex rare events has increased. We therefore need systematic descriptions of human performance in total, from the observation of information to the physical actions on the process plant, and the descriptions should cover a wide range of work situations from daily routine to stressed encounters with accidental events.

We need tools for reliable prediction of human performance and of the various error modes for this purpose. A long tradition exists within vehicle control to use quantitative models for systems design and performance analysis, such as the models based on optimal control theory. During recent years, attempts have been made to extend these models to higher level human decisionmaking to conform with the increasing levels of automation in aviation, and to transfer such models for process control applications. Whether or not this approach is fruitful depends on the nature of the human task. The optimal control part of the model may not be needed if the manual acts are no longer an integral part of the control task but merely a general interface manipulation skill. In that case, independent development of a decision model may lead to a more direct approach. What we need is not a global quantitative model of human performance but a set of models which is reliable for defined categories of work conditions together with a qualitative framework describing and defining their coverage and relationships. In some areas, particularly in reliability engineering, several premature attempts have been made to quantify human performance due to the pressing need for prediction. This tendency to rush to measurement and quantification is, however, not only a modern trait of engineers. Indeed, the stranger in Plato's *Statesman* remarked:

> There are many accomplished men, Socrates, who say, believing themselves to speak wisely, that the art of measurement is universal, and has to do with all things.... But these persons, because they are not accustomed to distinguish classes according to real forms, jumble together two widely different things, relating to one another, and to a standard, under the idea that they are the same, and also fall into the converse error of dividing other things not according to their real parts.

The aim of the present paper is to discuss some basic distinctions which are useful in defining the categories of human performance for which separate development of models is feasible. In this effort we have to consider that humans are not simply deterministic input–output devices but goal-oriented creatures who actively select their goals and seek the relevant information. The behavior of humans is teleological by nature. In their classical paper Rosenbluth and Wiener [1] define teleological behavior as behavior which is modified *during its course* by signals from the goal. This restrictive definition seems, however, to be due to an inadequate distinction between two concepts: *causes* of physical events and *reasons* for physical functions, a distinction which has been discussed in detail by Polanyi [2]. Teleological behavior is not necessarily dependent on feedback during its course but on the experience from previous attempts, i.e., the reason for choosing the particular approach. *Reasons* act as the classical "final causes" and can control functions of behavior systems by selection,

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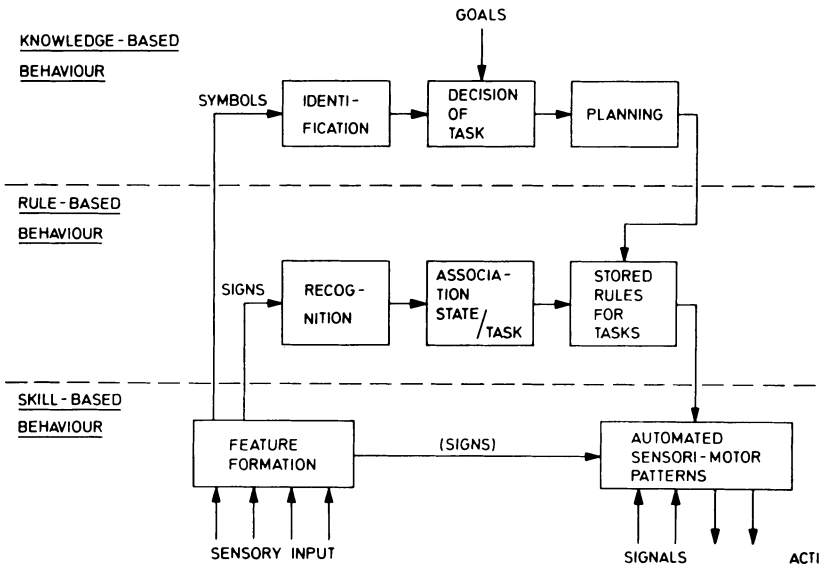

Fig. 1. Simplified illustration of three levels of performance of skilled human operators. Note that levels are not alternatives but interact in a way only rudimentarily represented in diagram.

be it natural selection in biological evolution or through human design choices for man-made systems. *Causes*, on the other hand, control functions through the physical structure of the system. Since all technical systems are designed for very definite reasons, it follows directly that teleological explanations—in the classical sense—of the functions of man-made systems derived from their ultimate purpose are as important as causal explanations based on engineering analysis. The same is the case for explanations of purposive human behavior.

Actually, even human position and movement in the physical environment are only occasionally directly controlled during the course of action by simple feedback. It may be the case in unfamiliar situations calling for accurate and slow time–space coordination, but in more complex rapid sequences, the sensory equipment is too slow for direct feedback correction, and adaptation is based on means for selection and regeneration of successful patterns of behavior for use in subsequent situations, i.e., on an internal dynamic world model.

At a higher level of conscious planning, most human activity depends upon a rather complex sequence of activities, and feedback correction during the course of behavior from mismatch between goal and final outcome will therefore be too inefficient, since in many cases it would lead to a strategy of blind search. Human activity in a familiar environment will not be goal-controlled; rather, it will be oriented towards the goal and controlled by a set of rules which has proven successful previously. In unfamiliar situations when proven rules are not available, behavior may be goal-controlled in the sense that different attempts are made to reach the goal, and a successful sequence is then selected. Typically, however, the attempts to reach the goal are not performed in reality, but internally as a problem-solving exercise, i.e., the successful sequence is selected from experiments with an internal representation or model of the properties and behavior of the environment. The efficiency of humans in coping with complexity is largely due to the availability of a large repertoire of different mental representations of the environment from which rules to control behavior can be generated *ad hoc*. An analysis of the form of these mental models is important to the study of human interaction with complex man-made systems.

Basically, meaningful interaction with an environment depends upon the existence of a set of invariate constraints in the relationships among events in the environment and between human actions and their effects. The implications of the foregoing discussion is that purposive human behavior must be based on an internal representation of these constraints. The constraints can be defined and represented in various different ways which in turn can serve to characterize the different categories of human behavior.

Skills, Rules, and Knowledge

When we distinguish categories of human behavior according to basically different ways of representing the constraints in the behavior of a deterministic environment or system, three typical levels of performance emerge: skill-, rule-, and knowledge-based performance. These levels and a simplified illustration of their interrelation are shown in Fig. 1.

The *skill-based behavior* represents sensory–motor performance during acts or activities which, following a statement of an intention, take place without conscious control as smooth, automated, and highly integrated patterns of behavior. Only occasionally is performance based on simple feedback control, where motor output is a response to the observation of an error signal representing the difference between the actual state and the intended state in a time–space environment, and where the control signal is derived at a specific point in time. Typical examples are experimental tracking tasks. In real life this mode is used rarely and only for slow, very accurate movements such as assembly tasks or drawing. In most skilled sensory–motor tasks, the body acts as a multivariable continuous control system synchronizing movements with the behavior of the environment. Performance is based on feedforward control and depends upon a very flexible and efficient dynamic internal world model. Feedforward control is necessary to explain rapid coordinated movements, for instance, in handwriting, sports, etc. The role of feedforward control for industrial control tasks has been demonstrated experimentally by Crossman and Cooke [3]. Pew [4] found a shift from error correction mode to pattern generation mode between 0.5 and 1 Hz in sinus tracking.

The control of voluntary movements is even more complex. Since the success of rapid movements is independent of the initial positions of limbs, and since the topology of movements can be transferred to other metric proportions and limbs, the function must depend on schemata for generating complex movements with reference to a dynamic internal map of the environment. Sensory input is probably not used to control movements directly but to update and align this internal map (see Bernstein [5] and the excellent review by Pew [4]). The case in point is that the behavioral complexes necessary to perform an intention to "pick up a glass" or "place finger on nose" [6] are integrated wholes which cannot be decomposed into separate elements (without changing the level of description to neurophysiology). From this discussion the constraints in the behavior of the environment at the skill level appear to be represented only by prototypical temporal–spatial patterns.

Characteristically, skilled performance rolls along without conscious attention or control. The total performance is smooth and integrated, and sense input is not selected or observed: the senses are only directed towards the aspects of the environment needed subconsciously to update and orient the internal map. The man looks rather than sees.

In some cases, performance is one continuous integrated dynamic whole, such as bicycle riding or musical performance. In these cases the higher level control may take the form of conscious intentions to "modulate" the skill in general terms, such as "Be careful now, the road is slippery," or "Watch out, now comes a difficult passage." In other cases, performance is a sequence of rather isolated skilled routines which are sequences of a conscious "executive program." In general, human activities can be considered as a sequence of such skilled acts or activities composed for the actual occasion. The flexibility of skilled performance is due to the ability to compose, from a large repertoire of automated subroutines, the sets suited for specific purposes.

At the next level of *rule-based behavior*, the composition of such a sequence of subroutines in a familiar work situation is typically controlled by a *stored rule* or procedure which may have been derived empirically during previous occasions, communicated from other persons' know-how as instruction or a cookbook recipe, or it may be prepared on occasion by conscious problem solving and planning. The point here is that performance is goal-oriented but structured by "feedforward control" through a stored rule. Very often, the goal is not even explicitly formulated but is found implicitly in the situation releasing the stored rules. The control is teleological in the sense that the rule or control is selected from previous successful experiences. The control evolves by "survival of the fittest" rule. In effect, the rule will reflect the functional properties which constrain the behavior of the environment, but usually in properties found empirically in the past. Furthermore, in actual life, the goal will only be reached after a long sequence of acts, and direct feedback correction considering the goal may not be possible. Feedback correction during performance will require functional understanding and analysis of the current response of the environment, which may be considered an independent concurrent activity at the next higher level (knowledge-based).

The boundary between skill-based and rule-based performance is not quite distinct, and much depends on the level of training and on the attention of the person. In general, the skill-based performance rolls along without the person's conscious attention, and he will be unable to describe how he controls and on what information he bases the performance. The higher level rule-based coordination is generally based on explicit know-how, and the rules used can be reported by the person.

During unfamiliar situations, faced with an environment for which no know-how or rules for control are available from previous encounters, the control of performance must move to a higher conceptual level, in which performance is goal-controlled and *knowledge-based*. In this situation, the goal is explicitly formulated, based on an analysis of the environment and the overall aims of the person. Then a useful plan is developed—by selection—such that different plans are considered, and their effect tested against the goal, physically by trial and error, or conceptually by means of understanding the functional properties of the environment and prediction of the effects of the plan considered. At this level of functional reasoning, the internal structure of the system is explicitly represented by a "mental model" which may take several different forms. We will return to this point in discussion of reasons and causes later.

Similar distinctions between different categories of human behavior have been proposed elsewhere. Fitts [7] distinguishes between three phases of learning a skill: the early or cognitive phase, the intermediate or associative phase, and the final or autonomous phase. If we consider that in real life a person will have a varying degree of training when performing his task depending on variations and disturbances, the correspondence with the three levels in the present context is clear.

Whitehead [8, pp. 92–98], discussing symbolism, operates with three categories of human performance: instinctive action, reflex action, and symbolically conditioned action, which are also related to the present discussion:

> Pure instinct is the most primitive response which is yielded by organisms to the stimulus of their environment.... Reflex action is a relapse towards a more complex type of

> instinct on the part of an organism which enjoys, or has enjoyed, symbolically conditioned action.... Reflex action arises when, by the operation of symbolism, the organism has acquired the habit of action in response to immediate sense-perception, and has discarded the symbolic enhancement of causal efficacy.... [In symbolic conditioned action] the causal efficacy is thereby perceived as analyzed into components with the locations in space primarily belonging to the sense-perceptions.... Finally mankind also uses a more artificial symbolism, obtained chiefly by concentrating on a certain selection of sense-perceptions, such as words for example. In this case there is a chain of derivations of symbol from symbol whereby finally the local relations between the final symbol and the ultimate meaning are entirely lost. Thus these derivative symbols, obtained as they were by arbitrary association, are really the result of reflex action suppressing the intermediate portions of the chain.

Whitehead's discussion of symbols and derived symbols, the meaning of which is lost, leads to the distinction between signals, signs, and symbols.

Signals / Signs / Symbols

One aspect of the categorization of human performance in skill/rule/knowledge-based behavior is the role of the information observed from the environment, which is basically different in the different categories. The fact that information or indications from the environment can be perceived in basically different ways by a human observer is no new discovery, but curiously enough it has so far not been considered explicitly by man-machine interface designers. This is the case even though major problems during unfamiliar situations may be caused by the fact that the same indication may be perceived in various different roles and that it is a well-known psychological phenomenon that shift between different modes of perception is difficult.

At the *skill-based* level the perceptual motor system acts as a multivariable continuous control system synchronizing the physical activity such as navigating the body through the environment and manipulating external objects in a time-space domain. For this control the sensed information is perceived as time-space *signals*, continuous quantitative indicators of the time-space behavior of the environment. These signals have no "meaning" or significance except as direct physical time-space data. The performance at the skill-based level may be released or guided by value features attached by prior experience to certain patterns in the information not taking part in the time-space control but acting as cues or *signs* activating the organism.

At the *rule-based* level, the information is typically perceived as *signs*. The information perceived is defined as a sign when it serves to activate or modify predetermined actions or manipulations. Signs refer to situations or proper behavior by convention or prior experience; they do not refer to concepts or represent functional properties of the environment. Signs are generally labeled by names which may refer to states or situations in the environment or to a person's goals and tasks. Signs can only be used to select or modify the rules controlling the sequencing of skilled subroutines; they cannot be used for functional reasoning, to generate new rules, or to predict the response of an environment to unfamiliar disturbances.

To be useful for causal functional reasoning in predicting or explaining unfamiliar behavior of the environment, information must be perceived as *symbols*. While signs refer to percepts and rules for action, symbols refer to concepts tied to functional properties and can be used for reasoning and computation by means of a suitable representation of such properties. Signs have external reference to states of and actions upon the environment, but symbols are defined by and refer to the internal conceptual representation which is the basis for reasoning and planning. Cassirer notes [9]:

> Symbols—in the proper sense of the term—cannot be reduced to mere signs. Signs and symbols belong to two different universes of discourse: a sign is part of the physical world of being, a symbol is part of the human world of meaning.

The difference between signs and symbols, and the difficulty in the shift from rule-based reliance on signs to knowledge-based use of symbols, is clearly illustrated in the testimony of the Three Mile Island operators to the Congress [10, p. 138].

> Mr. Frederick: "Let me make a statement about the indications. All you can say about them is that they are designed to provide indications for whatever anticipated casualties you might have. If you go out of the bounds of an anticipated casualty, if you go beyond what the designers think might happen, then the indications are insufficient and they may lead you to make wrong inferences. In other words, what you are seeing on the gage, like what I saw on the high pressurizer level, I thought it was due to excess inventory. In other words, I was interpreting the gage based on the emergency procedure, where the emergency procedure is based on the design casualties. So the indications then are based upon my interpretation. Hardly any of the measurements that we have are direct indications of what is going on in the system. They are all implied measurements."

If to this is added the difficulty in abandoning a search for a rule which is not there, the point becomes clear [10, p. 139].

> Mr. Faust: "What maybe you should try to understand here is that we are trying to gain the proper procedure to go at it. We were into possibilities of several procedures, not just one, to cover what was happening. It has not been written, in fact. So we were still trying to determine which procedure to go by."

The distinction between the perception of information as signals/signs/symbols is generally not dependent on the form in which the information is presented but rather on the context in which it is perceived, i.e., upon the intentions and expectations of the perceiver. Whorf expresses

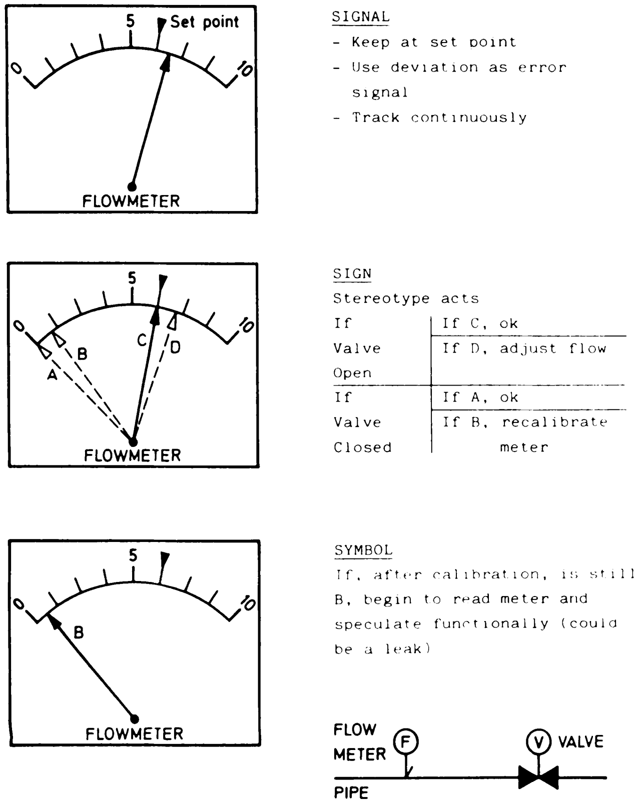

Fig. 2. Same physical indication on control panel can serve to communicate to operator in form of signal, sign, and symbol.

this well-known fact in the following way [11]:

> The categories and types that we isolate from the world of phenomena we do not find because they stare every observer in the face; on the contrary, the world is presented to us in a kaleidoscopic flux of impressions which has to be organized by our minds....

Fig. 2 illustrates how the same instrument can serve to transmit all three kinds of message.

The discussion of the different perception of information is a classical topic within biology and philosophy, and similar distinctions have been drawn. Dewey and Bentley [12] apply the same definition for sign and symbol as discussed but use the term signal in a different way which is more related to its use in classical discussions of reflexive behavior such as that of Pavlov's dogs. They

> have employed the word "sign" to name this technically characteristic 'indirectness' as it is found across the entire behavioural field... Within the range of sign, the word "signal" was chosen to name the underlying sensory-perceptive level; the word "designation" for the next higher evolutionary level—namely, that of linguistic sign operation; and the word "symboling" for a still higher range in the evolutionary sense....

In the present man–machine context, it seems to be important to keep the role of information as time–space signals, which are processed directly in a dynamic control of the motor performance, separate from the role as signs which serve to modify actions at a higher level.

The distinction between signs and symbols is also treated by von Foerster [13]. However, he focuses upon the difference between humans and animals.

> Communication among social insects is carried out through unalterable signs which are linked to the genetic make-up of the species... To communicate acquired knowledge by passing through generations, it must be communicated in symbols and not signs. This separates man from beasts.

This may be the case sometimes, but operating from signs may also be the normal way to be efficient for humans.

To sum up, the three levels of behavior in the present context are characterized by different uses of the information available, and the distinction is very clear from an information processing point of view.

Signals are sensory data representing time–space variables from a dynamical spatial configuration in the environment, and they can be processed by the organism as continuous variables.

Signs indicate a state in the environment with reference to certain conventions for acts. Signs are related to certain features in the environment and the connected conditions for action. Signs cannot be processed directly, they serve to activate stored patterns of behavior.

Symbols represent other information, variables, relations, and properties and can be formally processed. Symbols are abstract constructs related to and defined by a formal structure of relations and processes—which by conventions can be related to features of the external world.

Reasons / Causes

As previously mentioned, in the knowledge-based domain the functional or causal properties of the environment can be represented in different ways. Several problems meet the human data processor at this level in the interaction with a complex physical environment. Only a few elements of a problem can be within the span of attention simultaneously. This means that the complex net of causal relations of an environment must be treated in a chain of mental operations, often leading to effects like the law of least resistance and the point of no return. That is, strategies which depend on sequences of simple operations are intuitively preferred, and little tendency will exist to pause in a line of reasoning to backtrack and develop alternative or parallel paths [14].

An effective way to counteract limitations of attention seems to be to modify the basis of mental data processing —the mental model of the causal structure—to fit it to the specific task in a way which optimizes the transfer of previous results and minimizes the need for new information. The efficiency of human cognitive processes seems to depend upon an extensive use of model transformations together with a simultaneous updating of the mental models in all categories with new input information, an updating which may be performed below the level of conscious attention and control.

From the analysis of verbal protocols, it appears that several strategies for model transformation are generally

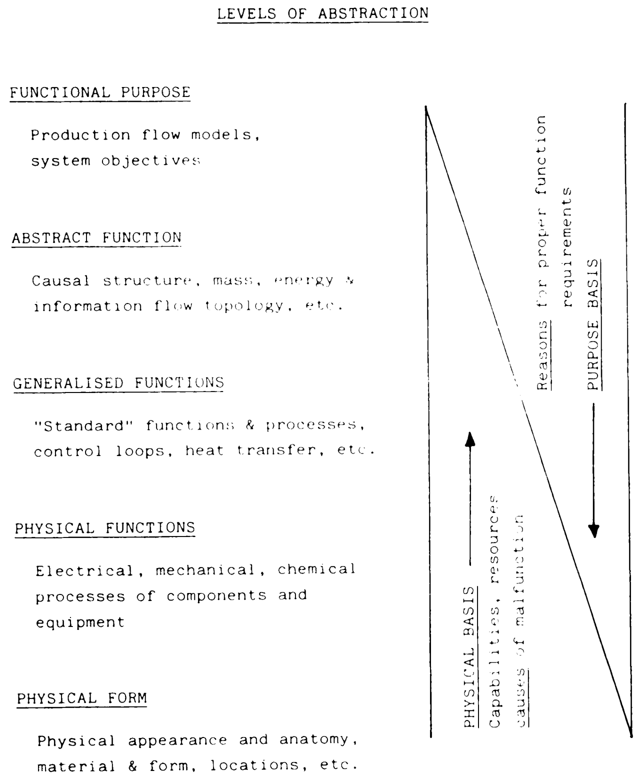

Fig. 3. Properties of system will be used in operators' decisionmaking in terms of concepts at several levels of abstraction; frequently even during single decision sequence.

used to facilitate mental data processing, such as the following.

- *Aggregation*: Elements of a representation are aggregated into larger units, chunks, within the same model category as familiarity with the context increases.
- *Abstraction*: The representation of the properties of a system or an environment is transferred to a model category at a higher level of abstraction.
- *Analogies and Use of Ready-Made Solutions*: The representation is transferred to a category of model for which a solution is already known or rules are available to generate the solution.

In the *abstraction hierarchy*, which has been identified from analysis of verbal protocols from computer maintenance and process plant control, the system's functional properties are represented by concepts which belong to several levels of abstraction (see Fig. 3). The lowest level of abstraction represents only the system's physical form, its material configuration. The next higher level represents the physical processes or functions of the various components and systems in a language related to their specific electrical, chemical, or mechanical properties. Above this, the functional properties are represented in more general concepts without reference to the physical process or equipment by which the functions are implemented, and so forth.

At the lower levels, elements in the description match the component configuration of the physical implementation. When moving from one level of abstraction to the next higher level, the change in system properties represented is *not* merely removal of details of information on the physical or material properties. More fundamentally, information is added on higher level principles governing the cofunction of the various elements at the lower level. In man-made systems, these higher level principles are naturally derived from the purpose of the system, i.e., from the *reasons* for the configurations at the level considered. Change of level of abstraction involves a shift in concepts and structure for representation as well as a change in the information suitable to characterize the state of the function or operation at the various levels of abstraction. Thus an observer will ask different questions regarding the state of the environment depending on the nature of the currently active internal representation.

In other words, models at low levels of abstraction are related to a specific physical world which can serve several purposes. Models at higher levels of abstraction are closely related to a specific purpose which can be met by several physical arrangements. Therefore, shifts in the level of abstraction can be used to change the direction of paths which are suitable for transfer of knowledge from previous cases and problems. At the two extreme levels of models, the directions of the paths available for transfer are in a way orthogonal, since transfer at one level follows physical, material properties, while at the other it follows purpose.

Important human functions in man–machine systems are related to correction of the effects of errors and faults. Events can only be defined as errors or faults with reference to intended state, normal function, or other variants of system purpose or functional meaning. The functional models at the different levels of abstraction play different roles in coping with error struck systems. *Causes of improper functions* depend upon changes in the physical or material world. Thus they are explained "bottom-up" in the levels of abstraction, whereas *reasons for proper function* are derived "top-down" from the functional purpose (see Fig. 3). The clear difference between the propagation of causes of faults and reasons for function in the hierarchy has been discussed in detail by Polanyi [2]. This role of the abstraction hierarchy can be seen clearly in verbal protocols recorded during diagnostic search in information processing systems. The diagnostician will frequently be forced to consider the functions of the system at several levels. He will typically have to identify information flow paths and proper functional states by arguing top-down from the level of symbolic information, while he will utilize bottom-up considerations to analyze and explain the actual functional state from physical causes.

Another human task for which the use of representations at several levels of abstraction is of obvious value is the *design of technical systems*. Basically, system design is a process of iteration between considerations at the various levels rather than an orderly transformation from a description of purpose to a description in terms of physical form. A many-to-many mapping exists between the two levels; a purpose can be served by many physical configurations, and a physical system can serve many purposes or have a variety of effects. The use of different categories of representation in a design strategy has been explicitly discussed by Alexander [15, p. 89, 90]:

> Every form can be described in two ways: from the point of view of what it is, and from the point of view of what it does. What it is, is sometimes called the formal description. What it does, when put in contact with other things, is sometimes called the functional description.... The solution of a design problem is really only another effort to find a unified description. The search for realization through constructive diagrams is an effort to understand the required form so fully that there is no longer a rift between its functional specification and the shape it takes.

If we accept the complex of strata between physical form and functional meaning of technical systems, an "invention" is related to a jump of insight which happens when one mental structure upward from physical form and another downward from functional meaning, which have previously been totally unconnected, suddenly merge to "a unified description."

Each level of abstraction or category of representation depends upon a special set of concepts and relationships. Shifting the level of modeling can be very effective in a problem situation since data processing at another level can be more convenient, the process rules can be simpler or better known, or results can be available from previous cases. A special instance of this strategy is the solution of a problem by simple analogy which depends upon the condition that different physical systems have the same description at higher levels of abstraction.

In some cases, efficient strategies can be found where symbols are transferred to another level of abstraction and reinterpreted. A simple example will be the subconscious manipulation of symbols which are reinterpreted as artificial objects, e.g., Smith's [16] solution of scheduling problems by manipulation of rectangles; or the reinterpretation of numbers in terms of actions for calculations by means of an abacus. This recursive use of the categories of functional models adds another dimension to the variety of tricks to cope with complexity. The most general is, of course, the use of natural language which can be used to make statements about models and operations at all levels of abstraction. However, this generality is frequently offset by the difficulty of keeping track of the context, i.e., the category of model behind the symbols.

Another consideration should be added to this discussion. Frequently, other persons will be part of the environment with which a particular person interacts and for which he has to use mental models in order to cope with unfamiliar situations. As for technical systems, various levels of abstraction can be used to model human functional properties, and an analogy of the levels discussed in Fig. 3 is drawn for "models of man" in Fig. 4. All the levels are used in various professional contexts, but what is of particular interest here is that, in ordinary working life, human interaction is based on a top-down prediction drawn from perceptions of other persons' intentions, motives, and on common sense representations of human capabilities, together with knowledge of accepted practice. Causal bottom-up arguments play literally no role, and the most important information to use for planning human interactions for unfamiliar occasions is therefore knowledge of the value structures and myths of the work environment. The obvious reason for this is the complexity and flexibility of the human organism. However, it should be emphasized that due to the growing complexity of information and control systems, the role of such intentional models [17] is rapidly increasing, and for interaction with such technical systems as well.

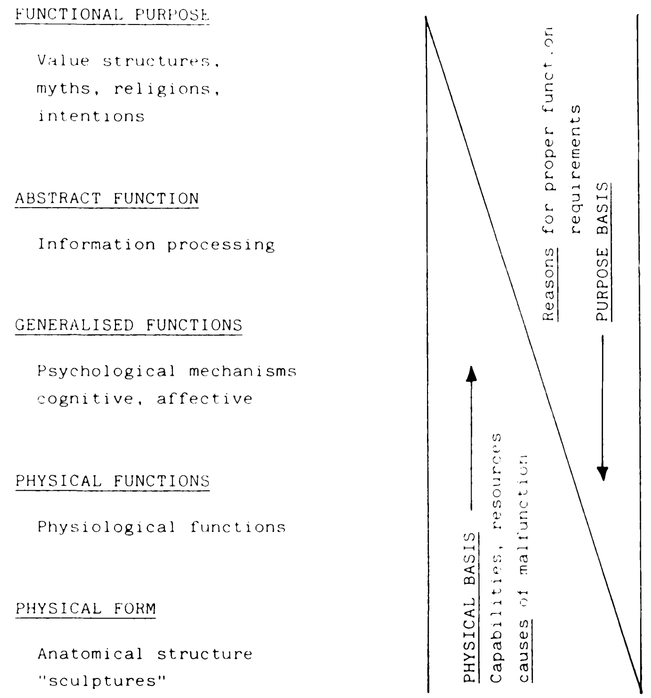

Fig. 4. Models of man also exist at several levels of abstraction. Note that interaction with work environment will require consideration of all levels from physical injuries at bottom to perception of goals and policies at top.

Qualitative Versus Quantitative Models of Human Performance

A discussion of models of human behavior raises immediately the distinction between qualitative and quantitative models. Frequently, qualitative models are considered to be merely premature descriptive models which, after further work, will develop into or be replaced by proper quantitative models. However, this is not necessarily the case. The two kinds of models have in several respects different and equally important roles for analysis and prediction of performance. This difference in significance is related to the distinction between categories of behavior and the members of such categories, i.e., the specific behavior in particular situations. Bateson [18, p. 46] discusses this distinction in detail with reference to Whitehead and Russells' logical types:

> ... there is a deep gulf between statements about an identified individual and statements about a class. Such statements are of *different logical types*, and prediction from one to the other is always unsure.

The fact that "the generic we can know, but the specific eludes us" [18, p. 45] has different implications depending upon the purpose of the modeling effort. For systems design, qualitative models will serve important purposes if they are able to predict the category of behavior which will be activated by different possible interface configurations and display formats. The model will then support the choice of an interface design which will activate a category of behavior having limiting properties compatible with the functions allocated the human operator. In a way, research on human performance in order to support system design should not focus on modeling actual performance in existing environments but on *possible* performance in optimal future systems, as has been discussed by Sloman [19] in a philosophical context. Qualitative models identifying categories of behavior and the limiting properties of the related human resources will serve designers a long way in the design of systems which allow humans to optimize their behavior within a proper category [20]. Compare this with Norman's arguments [21] for the importance of considering the proper mental image for design of "friendly" systems and the need for a profession he calls "cognitive engineering." The distinctions between models of categories and of particulars have different implications depending also on the cognitive level of behavior considered. At the skill-based level we are considering highly trained people, similar to experimental psychologists' "well trained subjects" who have adapted to the particular environment. In this domain, models of optimal human performance are mainly models of the behavior of the *environment*, as seen through the man. Therefore, generic quantitative models of human performance in well structured tasks can be—and have been—developed at this level of performance. At the level of knowledge-based behavior, we are dealing with individual reactions to unfamiliar situations, and models will be more a question of qualitative matching of categories of system requirements with human resources. For unfamiliar tasks, these resources depend on a specific person's subjective preferences, experience, and state of training. In this context, training means supplying people with a proper repertoire of possible behaviors for unexpected situations, and qualitative models matching categories will be highly effective. Until recently, the training of industrial operators has not been based on models of human performance compatible with those used for systems design. However, the explicit use of qualitative models for matching categories of system requirements and human resources for planning of training programs by Rouse and his coworkers [22] has turned out successfully and proves the value of qualitative models.

To be useful, qualitative as well as quantitative models must reflect the structure underlying the mental processes, i.e., the internal or mental *models*; the kind of *data* dealt with by the processes; and the *rules* or *strategies* used to control the processes. In addition, the models must reflect the limits of human capabilities so that human "errors" are also modeled properly.

This question of also modeling errors properly leads directly to the issue of analog parallel processing models versus the sequential digital models of human information processes of the artificial intelligence (AI) community. Can holistic human perception, for instance, be properly modeled by the sequential "production rule" systems? In the present context of models for system design and evaluation, the fundamental question appears to be not whether a model is implemented for experimental evaluation by means of one or another physical information processing system but whether or not a theoretical framework exists formulated independently of the tools for experimental implementation. This framework must have a one-to-one correspondence to human psychological mechanisms, their processing limitations, and error characteristics. If such a separation between model and implementation were maintained, many of the arguments between psychologists and AI researchers [23] could be circumvented. An implication of this point is that computer programs based, for instance, on the production systems of Newell and Simon [24] cannot in general be accepted as theories unless they adequately represent limiting properties and error characteristics of the human processes. Proper representation of the failure properties of human information processes will be difficult, for instance, if holistic perception is modeled by sequential scene analysis. Therefore, proper evaluation of a model requires analysis of instances when the model breaks down rather than a search for correspondence with human performance in successful instances. This is the essence of Simon's statement [25]:

> A thinking human being is an adaptive system;... To the extent he is effectively adaptive, his behaviour will reflect characteristics largely of the outer environment... and will reveal only a few limiting properties of his inner environment....

Successful performance does not validate a model, only tests of its limits and error properties can do this.

Conclusion: Implications for Design

In our work, concern is with the timely development of models of human performance which can be useful for the design and evaluation of new interface systems. For this purpose, we do not need a single integrated quantitative model of human performance but rather an overall qualitative model which allows us to match categories of performance to types of situations. In addition, we need a number of more detailed and preferably quantitative models which represent selected human functions and limiting properties within the categories. The role of the qualitative model will generally be to guide overall design of the structure of the system including, for example, a set of display formats, while selective, quantitative models can be used to optimize the detailed designs.

In many cases, the use of quantitative models for optimizing a design can be replaced by experimental evaluation. Unfortunately, however, it is the categories of performance for which experimental evaluation is most feasible—i.e., skill- and rule-based performances—which are also most readily modeled quantitatively. A major difficulty is the modeling of the knowledge-based control of performance during unfamiliar situations as well as the interaction among the different levels of performance depending upon the state of training. In particular, experimentally as well as analytically, studying the interference from overlearned routines during situations calling for knowledge-based responses is very difficult. Several problem areas for research can be identified for which we find it important to separate the categories of performance while keeping in mind the distinctions discussed previously. The first problem we meet in design of interface systems based on modern information technology is the tradition from the one-sensor–one-indicator technology that the operator task is expressed in terms of actions on the system, the state of which the operator is supposed to "figure out for himself" from readings of a number of physical variables and his training in system fundamentals. However, if computer technology is to be used to optimize man–machine communication, information presentation must be structured according to the nature of the control tasks the operator is supposed to perform. To do this properly, it is necessary to design the hierarchy of functions called for in the control of complex systems as one consistent whole —regardless of whether the individual functions are automated or allocated to operators. In a supervisory control task, the operator will have to face tasks at several levels in the hierarchy of control functions; i.e., the concepts used in a proper description of the various tasks will vary in the level of abstraction between physical implementation and overall system purpose, as discussed in relation to causes and reasons [26], [27]. In order to plan the formats of data presentation and the integration of measured data needed to derive the related variables, a *formalized description of the categories of control tasks* at the various levels of abstraction is necessary. An attempt to develop such a description is given by Lind [28].

A further requisite to structuring the man–computer interaction will be a description of these various categories of control tasks in information processing terms, together with a description of the strategies the operator is supposed to use; i.e., the *control task must be described in terms referring to human mental functions* rather than system requirements. This is particularly important, since several strategies which have very different requirements for human information processing capacity and data formats may be used for a specific external control task. As an example, consider the identification of the actual state of the system to be controlled: should identification be based on recognition of a specific symptom, on a decision table look-up, or on genuine diagnosis based on functional reasoning? However, as stated earlier, to match the interface to human capabilities in a specific task, we do not need a model of the detailed data process which will be performed but rather of the characteristics of different possible categories of performance in terms of the strategy and the related representation of system structure and state variables, together with requirements for processing capacity. In addition, information on the subjective human preferences or performance criteria which will control the selection of strategy in a given environment is necessary for design.

This situation leads to the need for human *performance analyses in real-life situations* to identify mental strategies and subjective performance criteria. From the analysis of task performance by observation, interviews, verbal protocols, error reports, etc., leading to descriptions of actual performance in a number of situations, generalization across instances can lead to descriptions of prototypical performance [29] from which a repertoire of formal strategies can be identified and described with reference to the distinctions described in the present paper. For instance, see [30] for a discussion of diagnostic strategies.

Evaluation of a specific interface design will require different types of experiments for which the distinctions discussed in the present paper have proved useful in our research [31]. For *evaluation of the system design concepts*, experiments involving the total set of display formats to be used in a work scenario are necessary to validate the design; i.e., to see whether the data presentations in actual work situations activate the strategies on which the display formats are based. In most cases, this validation is more readily based on a qualitative evaluation of the match between the predicted strategy and the strategy that was actually used than upon a quantitative performance measure. An effective tool in the qualitative evaluation is analysis of verbal reports and interviews. Although it may be doubtful whether verbal reports reveal mental data processes, they can be very valuable in identifying categories of performance by means of the distinction discussed previously on the basis of the concepts used to name tasks, models, and variables for the different categories of behavior.

Other kinds of experiments are required to *verify the internal consistency* in models. For this purpose, computer simulations related, for instance, to optimal control models or production rules for intelligent artifacts can be used. In addition, selective laboratory experiments with human subjects using quantitative performance measurements can be useful. See, for instance, the diagnostic experiments of Rouse and his coworkers [32]. Such experiments may also be used to optimize the ergonomic design of a display or set of displays for a specific selected task. However, even when quantitative performance measures are used, verbal statements are valuable in verifying that the performance trials analyzed in an experiment belong to the same category.

A general conclusion from our research has been that, in order to switch from the traditional one-sensor–one-indication technology to effective use of modern information technology for interface design, we have to consider in an integrated way human performance which is normally studied by separate paradigms. In addition, it is evident that we, like Eddington's ichthyologist [33], will be able to obtain some of the results needed more readily by conceptual analysis before experiments than by data analysis afterwards.

References

[1] A. Rosenbluth, N. Wiener, and J. Bigelow, "Behaviour, purpose and teleology," *Phil. Sci.*, vol. 10, pp. 18–24, 1943.

[2] M. Polanyi, *Personal Knowledge*. London: Routledge & Kegan Paul, 1958.

[3] E. R. F. W. Crossman and J. E. Cooke, "Manual control of slow-response systems," presented at the Int. Cong. Human Factors in Electronics, Long Beach, CA, 1962. Also in E. Edwards and F. Lees, *The Human Operator in Process Control*. London: Taylor & Francis, 1974.

[4] R. W. Pew, "Human perceptual-motor performance," in *Human Information Processing: Tutorials in Performance and Cognition*, B. H. Kantowitz, Ed. New York: Erlbaum, 1974.

[5] N. Bernstein, *The Coordination and Regulation of Movement*. New York: Pergamon, 1967.

[6] J. C. Eccles, *The Understanding of the Brain*. New York: McGraw-Hill, 1972.

[7] P. M. Fitts and M. I. Posner, *Human Performance*. Brooks/Cole, 1962.

[8] A. N. Whitehead, *Symbolism, Its Meaning and Effect*. New York: Macmillan, 1927.

[9] E. Cassirer, *Essay on Man*. New Haven, CT: Yale Univ. Press, 1944.

[10] Oversight Hearings, "Accident at the Three Mile Island nuclear power plant," U.S. Gov. Printing Office, Washington, DC, 1979.

[11] B. Whorf, "Science and linguistics," *Technol. Rev.*, vol. XLII, 1940. Also in *Language, Thought and Reality. Selected Writings of Whorf*, J. B. Carroll, Ed. Cambridge, MA: MIT Press, 1956.

[12] A. F. Bentley, "Kennetic inquiry," *Sci.*, vol. 112, pp. 775–783, 1950.

[13] H. von Foerster, "From stimulus to symbol: The ecology of biological computation," in *Sign, Image and Symbol*, G. Kepes, Ed. London: Studio Vista, 1966.

[14] J. Rasmussen and A. Jensen, "Mental procedures in real life tasks: A case study of electronic trouble shooting," *Ergonomics*, vol. 17, pp. 293–307, 1974.

[15] C. Alexander, *Notes on the Synthesis of Form*. Cambridge, MA: Harvard Univ. Press, 1964.

[16] H. T. Smith, "Perceptual organization and the design of the man-computer interface in process control," in *Monitoring Behaviour and Supervisory Control*, Sheridan and Johannsen, Eds. New York: Plenum, 1976.

[17] D. C. Dennett, "Intentional systems," *J. Phil.*, vol. LXVIII, Feb. 25, 1971.

[18] G. Bateson, *Mind and Nature*. New York: Elsevier-Dutton, 1979.

[19] A. Sloman, *The Computer Revolution in Philosophy: Philosophy, Science, and Models of Mind*. Sussex, England: Harwester, 1978.

[20] J. Rasmussen and M. Lind, "Coping with complexity," presented at European Ann. Conf. Human Decision and Manual Control, Delft, 1981, Risø-M-2293.

[21] D. A. Norman, "Steps toward a cognitive engineering: Systems images, system friendliness, mental models," presented at the Symp. Models of Human Performance, ONR Contractor's Meeting, La Jolla, CA, June 19, 1981.

[22] W. B. Rouse, "Panel on human performance theories and models," presented at the IEEE Standards Workshop on Human Factors in Nuclear Safety, Proceedings to be published. 1982.

[23] H. L. Dreyfus, *What Computers Can't Do*. New York: Harper and Row, 1972.

[24] A. Newell and H. A. Simon, *Human Problem Solving*. Englewood Cliffs, NJ: Prentice-Hall, 1972.

[25] H. A. Simon, *The Sciences of the Artificial*. Cambridge, MA: MIT Press, 1969.

[26] L. P. Goodstein and J. Rasmussen, "Man/machine system design criteria in computerized control rooms," abbreviated version in *Proc. ASSOPO 80—an IFIP/IFAC Symp.*, Trondheim, Norway, June 16–18, 1980.

[27] L. P. Goodstein, "Computer-based operating aids," presented at Design 82, Birmingham, UK, Sept. 22–23, 1982.

[28] M. Lind, "Generic control tasks in process plant operation," to be published, 1982.

[29] E. Hollnagel, O. M. Pedersen, and J. Rasmussen, "Notes on human performance analysis," Risø-M-2285, 1981.

[30] J. Rasmussen, "Models of mental strategies in process plant diagnosis," in *Human Detection and Diagnosis of System Failures*, J. Rasmussen and W. B. Rouse, Eds. New York: Plenum, 1981.

[31] E. Hollnagel, "The methodology of man–machine systems: problems of verification and validation," Risø-M-2313, 1981.

[32] W. B. Rouse, "Experimental studies and mathematical models of human problem solving performance in fault diagnosis tasks," in *Human Detection and Diagnosis of System Failures*, J. Rasmussen and W. B. Rouse, Eds. New York: Plenum, 1981.

[33] A. Eddington, *The Philosophy of Physical Science*. New York: Cambridge Univ. Press, 1939 (also Ann Arbor, MI: Univ. of Michigan Press, 1958).