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Cognitive Control of Human Activities and Errors: Implications for Ecological Interface Design

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COGNITIVE CONTROL OF HUMAN ACTIVITIES
AND ERRORS: IMPLICATIONS
FOR ECOLOGICAL INTERFACE DESIGN

Jens Rasmussen and Kim J. Vicente

Abstract. Research during recent years has shown that human errors cannot be considered as stochastic events which can be removed by better training or by optimal interface design. Rather, errors tend to reflect either systematic interference between various models, rules, and schemata, or the effects of the adaptive mechanisms involved in training that lead to transfer of control from one cognitive level to another. Therefore, the approach to reliable human-system interaction will be to design interfaces which tend to minimize the potential for control interference and support the recovery from errors, i.e., to focus on control of the effects of errors rather than on the elimination of errors per se. In this paper, we suggest a theoretical framework for interface design that attempts to meet these objectives. The goal of ecological interface design (EID) is to develop a meaningful representation of the process which is not just optimised for one particular level of cognitive control, but that supports all three levels simultaneously. The paper discusses the necessary requirements for a mapping between the process and the combined action/observation surface, and analyses the influence on the interferences causing error and on the opportunity for error recovery left to the operator.

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1. INTRODUCTION

There has been a rapidly growing interest in the analysis of human error caused by technological development. On the one hand, the growing complexity of technical installations makes it increasingly difficult for operators to understand the system's internal functions. At the same time, the large scale of operations necessary for competitive production makes the effects of human errors increasingly unacceptable. Naturally enough, human error analysis has become an essential part of systems design. In order to conduct such an analysis, a taxonomy suited to describe human errors is essential. The structure and dimensions of the error taxonomy, however, will depend on the aim of the analysis. Therefore, different categorisations of human errors are useful during the various stages of systems design.

At least two different perspectives can be identified, each with its own unique set of requirements. One point of view is useful for predicting the effects of human error on system performance, i.e., a failure-mode-and-effect analysis. For this purpose, a taxonomy based on a model of human error mechanisms should be adopted. A second perspective for error analysis is required for identifying possible improvements in system design. In order to meet the requirements of such an analysis, an error taxonomy based on cognitive control mechanisms is more appropriate. Both types of analyses are essential to system design. The failure-mode-and-effect analysis allows the designer to identify plausible human errors and their effects on system performance. The second type of analysis provides a foundation for eliminating the error effects identified in the previous analysis through effective design. Together these analyses allow the designer to decide whether the effects of human errors can be removed, or whether they have to be compensated for instead.

This paper is concerned with the question of how to cope with human errors through system design. A complementary paper (Rasmussen, 1987) discusses the topic of error analysis from the point of view of predicting the effects of human error.

2. ERROR ANALYSIS FOR IDENTIFICATION OF DESIGN IMPROVEMENTS

As mentioned above, the goal of this type of error analysis is to minimize the effects of the errors identified in the error-mode-and-effect analysis. Different measures will be appropriate for different types of errors. Thus, it is useful to consider the following categories of errors (see Figure 1):

1. Errors related to learning and adaptation;
2. Interference among competing cognitive control structures;
3. Lack of resources;

4. Intrinsic human variability.

The types of human errors associated with each of these categories is discussed below.

2.1 Human Error and Learning

Some human error categories appear to be very closely related to a learning process (see Figure 2). The relationship between errors and learning is different for each of the three levels of cognitive control, and thus each will be discussed in turn.

COGNITIVE CONTROL AND SYSTEMIC ERROR MECHANISMS

EFFECTS OF LEARNING AND ADAPTATION:

Knowledge-based: search for information and test hypotheses in novel situations may lead to acts which are judged as errors after the fact;

Rule-based: the law of least effort may lead to underspecified cues.

Skill-based: optimisation of motor skill needs feedback from boundaries of acceptable performance (speed-accuracy trade-off);

INTERFERENCE AMONG COMPETING CONTROL STRUCTURES:

Knowledge-based: false analogies; interference in means-end hierarchy;

Rule-based: functional fixation; adherence to familiar rules;

Skill-based: capture by frequently used motor schemata;

LACK OF RESOURCES:

Knowledge-based: Limitations of linear reasoning in causal networks; insufficient knowledge, time, force, etc;

Rule-based: inadequate memory for rules;

Skill-based: Lack of speed, precision, force;

STOCHASTIC VARIABILITY:

Knowledge-based: slips of memory in mental models;

Rule-based: erroneous recall of data or parameters related to rules;

Skill-based: variability of attention; variability of motor parameters, motor noise (variation in force, precision of movements);

Figure 1. Different taxonomies of human error are useful for different purposes. A classification according to underlying psychological mechanisms is useful for failure-mode-and-effect analysis of the effect of errors in a particular design concept. A classification according to cognitive control mechanisms, as the one illustrated in the present figure, is useful for discussion of approaches to the design of reliable human-machine systems.

ADAPTATION AND LEVELS OF COGNITIVE CONTROL

KNOWLEDGE-BASED CONTROL:

In problem solving, experiments are typically necessary to update the mental model, to test hypotheses, etc.

RULE-BASED CONTROL:

Development of effective know-how and rules-of-thumb depends on replacement of prescribed or analytically derived cues for action with empirically found, informal cues sufficient to discriminate between the perceived alternatives for action in the given familiar context according to the Law of Least effort.

SKILL-BASED CONTROL:

During training, the necessary sensorimotor patterns develop, while the activity is controlled by the higher levels. The subsequent fine-tuning of behaviour depends upon a continuous updating of the sensorimotor schemata to the time-space features of the task environment under influence of a speed-accuracy trade-off.

Figure 2. An important point is that it is not the behavioural patterns of the higher levels that are becoming automated skills. Automated time-space behavioural patterns are developing while they are controlled and supervised by the higher level activities - which will eventually deteriorate - and their basis in terms of knowledge and rules may degenerate. Adaptation is a continuous process to keep performance aligned with the changes in the work environment. Adaptation controlled by optimisation of speed, smoothness, and required effort implies the need to identify empirically the boundaries of acceptable performance, i.e., errors have a function in terms of feedback control signals.

In a manual skill, fine-tuning depends upon a continuous updating of the sensorimotor schemata to the temporal and spatial features of the task environment. If the optimisation criteria are speed and smoothness, the boundary of acceptable adaptation can only be identified by the experience gained when, once-in-a-while, crossing the tolerance limits, i.e. by the experience of errors or near-errors (speed-accuracy trade-off). Some errors, therefore, have a function in maintaining a skill at its proper level, and they neither can nor should be removed.

At the rule-based level, development of know-how and rules-of-thumb depends upon the opportunity for experiments to find shortcuts and to identify convenient and reliable signs which make it possible to recognise recurrent conditions without analytical diagnosis. In this way, effective, rule-based performance depends on empirical correlation of cues with successful acts. Humans typically seek the path of least effort. Therefore, it can be expected that no more cues will be used than are necessary for discrimination among the perceived alternatives for action in the 'Particular situation'. This implies that the choice is 'under-specified' (Reason, 1986) outside this situation. Thus, when situations change, reliance on the cue subset which is no longer valid will lead to errors due to inappropriate "expectations". Another heuristic may be related to the principle of "the point of no return". When information is observed sequentially, empirical evidence (Rasmussen and Jensen, 1974) suggests that operators show a strong tendency to make a decision to act as

soon as information is pointing to a familiar routine. Even when subsequent observations indicate that the routine will be inefficient, the decision will not be reconsidered.

In genuine problem solving at the knowledge-based level during unusual task conditions, the ability to test hypotheses becomes important. Typically, operators are expected to check their diagnostic hypotheses conceptually by thought experiments before acting on the plant. This appears, however, to be an unrealistic assumption, since it will be tempting to test a hypothesis on the physical work environment itself, in order to avoid the strain and unreliability related to unsupported reasoning in a complex causal network. Designers have available to them a variety of effective tools to test their hypotheses, such as experimental set-ups, simulation programs and computational aids, whereas the operator has only his head and the plant itself. In the actual situation, no clear-cut stop rule exists to help the operator decide when to terminate the conceptual analysis and when to start acting. This means that the definition of error, as seen from the situation of a decision maker, is very arbitrary. Acts which are rational and important during the search of information and test of hypotheses may, in hindsight without access to the details of the situation, appear to be unacceptable mistakes.

2.2 Interference among Control Structures

In actual, real-life work conditions, the requirements from several different tasks will be considered by the operator on a time-sharing basis (see Figure 3). Consequently, performance will be sensitive to interference between control mechanisms belonging to otherwise unrelated activities. This factor is typically not considered in the usual studies of separate task procedures.

Work implies a very complex interaction between the different levels of cognitive control. At any particular moment, each level of cognitive control may be concerned with different aspects of the job. Tasks are frequently analysed in terms of sequences of separate acts. Typically, however, several activities are going on at the same time. At the skilled level for example, Activity is more like a continuous, dynamic interaction with the work environment. Attention, on the other hand, is scanning across time and activities for analysis of previous performance, monitoring the current activity, and planning for foreseen future requirements. In this way, the dynamic world model is prepared for oncoming demands; rules are rehearsed and modified to fit predicted demands, and symbolic reasoning is used to understand responses from the environment and to prepare rules for foreseen but unfamiliar situations. Attention may not always be focused on current activities, and different levels of control may be involved in different tasks, related to different time slots, in a time sharing or a parallel mode of processing. This, of course, makes the unattended activity vulnerable to interference. A conscious statement at the rule-based level can activate a complex sequence of skilled actions where-after

the attention may be directed to other matters. Since it will not be monitored, the current schema will be sensitive to interference from other, more frequently used schemata, which can take over control, in particular if the action sequences involved have similar parts. other sources of interference at the higher cognitive levels can be the intrusion of familiar rule sets, or interference in the means-ends hierarchy of functional reasoning in terms of, for instance, false analogies. This category of errors has similarity with Reason's (1986) similarity matching' bias.

INTERACTION BETWEEN THE DIFFERENT LEVELS OF COGNITIVE CONTROL

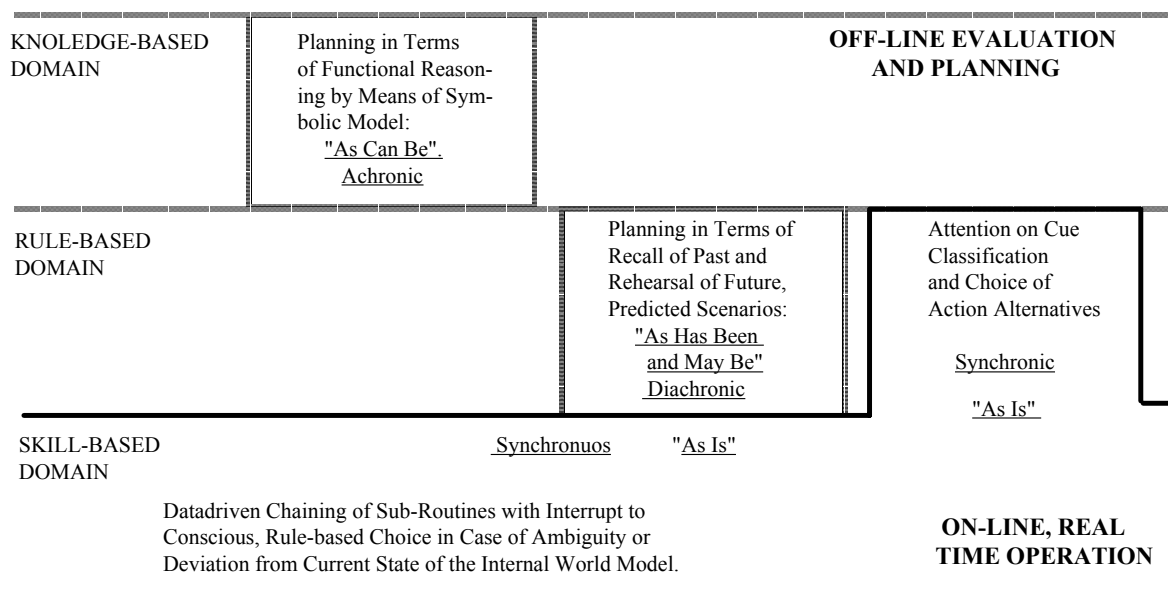


Figure 3. The figure illustrates the complex interaction between the different levels of cognitive control. Tasks are frequently analysed in terms of sequences of separate acts. Typically, however, several activities are going on at the same time, and at the skilled level, activity is more like a continuous, dynamic interaction with the work environment. Attention, on the other hand, is scanning across time and activities for analysis of the past performance, monitoring the current activity, and planning for foreseen future requirements. In this way, the dynamic world model is prepared f or upcoming demands, rules are rehearsed and modified to fit predicted demands, and symbolic reasoning is used to understand responses from the environment and to prepare rules for foreseen but unfamiliar situations. Attention may not always be focused on current activities, and different levels of control may be involved in different tasks related to different time slots in a time sharing or a parallel mode of processing

2.3 Lack of Resources

This category is typically a problem at the knowledge-based reasoning level. It can be caused either by insufficient knowledge of the basic functional principles behind system design, or by a lack of mental capacity for coping with causal reasoning in a complex causal network. As a result, reasoning in complex, disturbed work situations frequently fails because of lack of consideration of proper preconditions or likely side effects of the decision.

By definition, lack of resources at the skill-, and rule-based levels should not be a serious problem in familiar, planned work conditions. However, in different branches of sport, the joy of the actors appears to be tightly connected to performance at the borderline to inadequate resources; a performance criterion which may also be used for getting excitement into a boring job. In the present context, however, the related error mechanisms belong to the category of learning and adaptation.

2.4 Stochastic Variability

The categories discussed so far are related to systemic errors changing the structure of task performance. In addition to these, errors which reflect stochastic variations in behaviour are also observed. Examples include variability in recall of data used in reasoning and in rules for work, and also variability, or noise', in the control of movements. As discussed earlier, at the sensorimotor level, at least, this variability can be a precondition for optimising performance. However, at the higher levels of cognitive control, the role of noisy performance in learning is more doubtful even if errors made at the rule-based level occasionally can lead to discovery of effective tricks-of-the-trade.

3. COPING WITH HUMAN ERRORS BY SYSTEM DESIGN: WHAT TO DO?

In system design, the errors associated with these four categories will require different measures in order to achieve reliable system performance in spite of the human error opportunities. In the present context, the focus is on the design of interfaces that will lead to increased reliability. Rather than attempting to remove the basic 'human error', this approach attempts to increase the system's tolerance to errors by providing the operator with improved means of controlling their effects on system performance. In this section, the appropriate means for dealing with the errors associated with each of the four categories outlined above will be discussed. In addition, guidelines for system design are proposed.

3.1 Errors Related to Learning Processes

The opportunity to perform errors in this category neither can nor should be removed. As mentioned previously, occasional errors play an important role in the speed-accuracy trade off at the skill-based level. This feature is reflected in the current discussion of traffic safety. A general conclusion of this discussion has been that social control of risk perception may be the only factor which is capable of a long term reduction in the frequency and severity

of accidents, while changes in other factors such as perceptual, decisional, and control skills, will have only temporary influence (see Rasmussen, 1987).

This point of view has been stressed by Taylor who observed that drivers tend to try to keep their arousal at a desired, constant level, and consequently, if conditions become too lax, will go faster to generate more arousing incidents (Taylor, 1980). The conclusion drawn by Taylor (1981) is that traffic safety is hard to improve beyond a certain limit. Wilde's (1976) theory of traffic behaviour depends on risk homeostasis, i.e., actors in traffic tend to keep the level of perceived risk at a constant level. However, if errors are considered as consequences of adaptive processes, the reason for a particular behaviour may be to detect boundaries to loss of control, which may not be correlated with perceived risk of accidents in a simple way.

Guideline 1:

The basic guideline for system design to draw from this discussion is to accept that experiments are necessary for system users in order to be able to optimise skill. Thus, interface design should aim at making the limits of acceptable performance visible to the users, while the effects are still observable and reversible.

Such a design strategy is, in general, only possible for the direct dynamic interaction at the sensorimotor level, and even so, only if perceptual monitoring can be maintained. At the higher level of rule-based control, error observability and recovery can be much more difficult to arrange for two reasons. First, the unacceptable consequences of an erroneous act in a work procedure may be substantially delayed, and direct observation will be too late for correction. Error recovery in this case cannot be based on monitoring the product of a rule-based task sequence. Instead, a knowledge-based understanding and monitoring of the functional process is necessary. Second, the defence in depth philosophy of large scale systems requires that critical functions be unaffected by certain categories of component faults and human errors committed by other actors (e.g. , maintenance personnel) . This implies that work procedures frequently include actions and precautions which normally are without effect and only serve to decrease sensitivity to possible latent conditions. Recovery from violation of such precautions by feedback, therefore, can be difficult to arrange because it will not turn out as an error in immediate task performance.

This problem exists in the direct control interaction and maintenance of a technical system but it is also very important in organisational decision making. Management of an industrial installation involves operating in a competitive environment and continuous experiments are necessary for operational and economic optimisation. A major problem in the design of deci-

sion support systems is to be able to make visible the many safety related constraints upon management's decisions concerning operations and maintenance planning, modification of equipments, etc. A typical feature of this problem is that constraints and conditional rules for critical work can be, and typically are, planned by another person with a different professional background than the actor who is likely to violate the rules, at a later point in time.

Guideline 2:

A design guideline to consider in this context is to provide the actor with feedback on the effects of actions so as to allow her to cope with the time delay between the execution of an intention and the observation of its effect. This should facilitate error recovery by supporting functional understanding and knowledge-based monitoring during rule-based performance. In addition, it will be important to make latent, conditional constraints on actions visible, in particular if such constraints are prepared by another decision maker or by the designer.

Another aspect of adaptation at the rule-based level to consider is the evolution of signs to control choices. The cues adapted to choose between the perceived action alternatives should not only be convenient signs, but also reflect the preconditions for their validity. This leads us to an additional guideline at the rule-based level.

Guideline 3:

A display should be designed so as to make cues for action not only convenient signs, but also representing the necessary preconditions for their validity. This implies that signs should also have symbolic content.

At the knowledge-based level, efforts to explore system characteristics and to test hypotheses during problem solving will very likely turn out to be judged as errors if the system is in an irreversible functional state. As Mach (1905) said: "Knowledge and error flow of the same source, only success can tell one from the other". The only design remedy is either to make the system reversible, or to supply tools for decision makers for simulation of system response for action.

Guideline 4:

When designers assign the task to complete the design of control strategies during unforeseen situations to plant operators, they should supply them with the tools to make experiments and test hypotheses without having to do this on a high risk and possibly irreversible plant.

3.2 Errors Related to Interference among Control Structures

As mentioned previously, attention will be scanning through tasks and time. In order to decrease the likelihood of capture errors, appropriate measures must be taken. At the skill-based level, the following measure is appropriate.

Guideline 5:

Make available overview displays by which 'free-running' routines can be monitored by fringe consciousness.

In rule-based tasks, the inadvertent activation of familiar tasks (i. e., procedural traps) should be avoided. This leads to the following recommendation.

Guideline 6:

Make the cues for action integrated patterns based on defining attributes and serving, at the same time, a symbolic representation necessary for functional monitoring of performance.

At the knowledge-based level, interference between mental models is to be avoided. This is an important requirement since the operator is likely to have various mental models of the process at various levels of abstraction.

Guideline 7:

Support memory with externalisation of the effective mental models (see also guideline 9 below).

3.3 Errors Related to Lack of Resources

Support of human mental resources for knowledge-based, functional reasoning can be given in different ways. One way is to take over some of the information processing tasks more or less completely. For instance, the designer could let the interface system take care of the lower level data integration and

action coordination tasks. Another way to support knowledge-based reasoning is to support the human resources by, for instance, externalising the mental model required for analysis and prognosis. Both of these support strategies are discussed below.

Any decision process involves the identification of the state of affairs, i.e., interpretation and reformulation of the primary data at the level of concern; prognosis and decision making; and, finally, planning of actions. Basically, the subjective complexity of a task is significantly increased when the actor has to operate at several levels of abstraction.

Guideline 8:

Use the available data to develop consistent information transformation concepts for data integration. This will enable the interface to present information at the level which is most appropriate for decision making.

Prognosis and planning implies causal reasoning in a complex functional network, which is very demanding upon mental resources. Thus, it is imperative that this activity be supported.

Guideline 9:

Present information imbedded in a structure that can serve as an externalised mental model, effective for the kind of reasoning required by the task. Since the mental process adopted for problem solving in a unique situation cannot be predicted, support should not aim at a particular process, but at an effective strategy, i.e., a category of processes.

3.4 Stochastic Errors

Since intrinsic variability and learning are closely connected, the precautions that should be taken for the present category are covered in the previous section. However, the following recommendation is also relevant.

Guideline 10:

Support of memory of items, acts, and data which are not part of an integrated 'gestalt' can be useful,

4. COPING WITH HUMAN ERRORS BY SYSTEM DESIGN: HOW TO Do IT?

The guidelines proposed above imply that an interface should be designed so as to explicitly represent the abstract properties of the process (i.e., symbols in semiotic terms, or deep knowledge in artificial intelligence terms). This is equivalent to externalizing the relational structures, or mental model, that is required for functional reasoning. In this way, the interface will provide the support the operator needs to carry out knowledge-based activities. However, the fact that these symbols are explicitly represented in the interface means that they may also be interpreted as signs for rule-based behavior, and signals for skill-based behavior. Such a configuration allows the operator to effectively rely on the perceptual cues provided by the interface to control the system, since there is a consistent mapping between these signs and the symbols that unambiguously define the process' state, i.e., he will be able to manipulate the invisible relationships directly (Rasmussen, 1986, p.138).

4.1 Direct Manipulation Interfaces

This idea of externalizing the abstract system properties is also the concept behind the direct manipulation interfaces (DMI) discussed by Shneiderman (1983) and, later, by Hutchins, Hollan, and Norman (1986). In this section, we will briefly review these two approaches to direct manipulation in order to compare them with the approach being proposed in this paper.

Shneiderman's (1983) discussion is centered around a Syntactic Semantic Model of DMI. He begins with the distinction between syntax and semantics. syntax is viewed as being an arbitrary convention, and therefore may be difficult to learn and remember. In contrast, semantic knowledge represents the user's understanding of the domain.. Usually, semantic knowledge is hierarchically organized with general knowledge being decomposed into more specific concepts. Because it is meaningful, semantic knowledge is viewed as being system independent and relatively stable in long-term memory. Given this distinction, Shneiderman states that, when interacting with computers, users decompose higher level semantic concepts into lower level concepts that come closer to the syntax domain. The advantage of DMI is that they display the objects of interest to the user, so that actions are directly in the high-level problem domain. As a consequence, the degree of decomposition required before selecting a command is reduced.

Shneiderman's model was the first discussion of DMI, and therefore it is not surprising that the concepts need some refinement. First, the term semantics is used loosely to include the user's goals, his knowledge about how to carry out those goals (independent of syntax) , and his domain knowledge. It is important to distinguish between these for they are not the same. A second limitation of the model is that it only describes the process of forming a com-

mand (the output side of the interaction process). An equally important aspect of DMI is the processes involved in the input side, i.e., in the perception and interpretation of the displayed information. This aspect is relatively ignored, the only mention being that the objects that are displayed represent high-level semantic concepts. Finally, the most complicated issue is exactly how the semantics should map onto the syntax. This problem is not dealt with in the model.

Hutchins et al. (1986) also provide a theory of DMI. They begin their discussion with the premise 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" (Norman, 1986, p. 38). The mismatch can be characterized by two gulfs between person and machine. 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 the gulfs on the person greatly increases the cognitive demands of the task, or the distance introduced by the interface (Hutchins et al., 1986).

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 she is interacting with the concepts of the domain rather than an electronic intermediary. The shorter the distances associated with each of the two gulfs, the greater the feeling of direct engagement.

The aim of the later developments of direct manipulation interfaces as presented by Hutchins et al. (1986) is similar to that of the guidelines presented in the previous section. For process control, however, there are some complications and special features which need to be carefully considered. First of all, it is necessary to take into account the fact that multiple representations of a process system at different levels of abstraction are used by operators for problem solving. Also, as mentioned before, it is important to realize that there are multiple levels of cognitive control, each with its own particular requirements in terms of information support. Neither of the models describe above takes these considerations into account. On the other hand, a process system possesses a well defined structure which is rather stable through time. As a result, the direct manipulation interface can be designed for a specific system, and the generality required for general purpose tools discussed by Hutchins et al. (1986) is not required.

4.2 Summary

To summarize, theories of DMI are similar to the approach being proposed here in the sense that both attempt to display the domain objects of interest and allow the operator to act directly on those objects. However, there are certain limitations of existing theories with respect to complex systems. The general problem is that, with complex domains, it is necessary to define the complex mappings that exist between the internal process being controlled, the interface surface, and the operator's mental model. While this is Relatively simple in domains such as text editing, in systems such as process control, the necessary requirements for these mappings are not at all obvious. The reason for this is that a complex work environment like process plants can be represented at several levels of abstraction, depending upon the actual control task, at the same time as different cognitive control levels can be applied, depending on an operator's expertise in the particular task. In the next section, we will discuss the structure of this mapping problem for systems which should conform with the guidelines proposed above.

5. ECOLOGICAL INTERFACE DESIGN

Ecological interface design (EID) is a theory that attempts to minimise the potential for control interference, as well as supporting recovery from errors. In effect, it attempts to conform with the guidelines for coping with errors through system design, as outlined above. In this section, the fundamentals of EID are discussed and then illustrated by considering the activities associated with cognitive control of a thermodynamic process. For a more comprehensive account of EID, see Vicente and Rasmussen (1987).

5.1 Making Visible the Invisible

The principle goal behind EID is to design an interface that will not force cognitive control to a level higher than that required by the demands of the task, and yet that provides the appropriate support for each of the three levels. In order to design such an 'ecological interface', the following factors must be taken into consideration. First, it is necessary to merge the observation and action surfaces so that the time-space loop is maintained, thereby taking advantage of the efficiency of the human sensorimotor system. In addition, it is also necessary to develop a consistent one-to-one mapping between the abstract properties of the internal process to be controlled and the cues provided by the manipulation/observation surface. As already mentioned, the goal is to make the invisible, abstract properties of the process (those that should be taken into account for deep control of the process) visible to the operator. In semiotic terms, this means that the cues provided by the interface have a consistent mapping onto the symbolic process properties. In this way, the

same conceptual model may act as a symbolic representation when considered in relation to the elements of the environment and the laws controlling their relationships, and as a system of prescriptive signs when considered in relation to the rules for model actions on the system.

5.2 Cognitive Control of a Thermodynamic Process

Figure 4 illustrates the mappings between the process, the interface, and the operator's mental model for a typical process system. The activities associated with each of the three levels of cognitive control are described below.

Skill-based level. Because the operator cannot directly observe or act on the process, the sensorimotor control patterns at the skill-based behavior level will only be concerned with the manipulation of items on the interface surface. The use of a mouse or a tracker ball is preferred to command languages for this task because it maintains the communication of spatial-temporal aspects of the perception-action loop intact. To allow the development of a high degree of manual skill, the interface must 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. Thus, the display of information should be isomorphic to the part-whole structure of movements rather than being based on an abstract, combinatorial code like that of command languages.

Rule-based level. The rule-based level governs the choice of control alternatives. The display provides the operator with signs that he uses as cues for the selection of an appropriate action. Typically, the action alternatives consist of a set comprised of operating procedures and routine control strategies. As discussed before, the problem with conventional interfaces is that the cues they provide the operators with are not uniquely defining with respect to the current process state. The result is that the cues that operators rely on are optimized for frequently encountered situations, but they can lead to 'procedural traps' in novel situations. EID attempts to overcome this difficulty by developing a unique and consistent mapping between the symbols that govern the behavior of the thermodynamic process, and the signs, or cues, that the interface displays. This will reduce the frequency of errors due to procedural traps because the cues for action,, being based on abstract process properties, will be uniquely defining.

COGNITIVE CONTROL IN PROCESS SYSTEMS

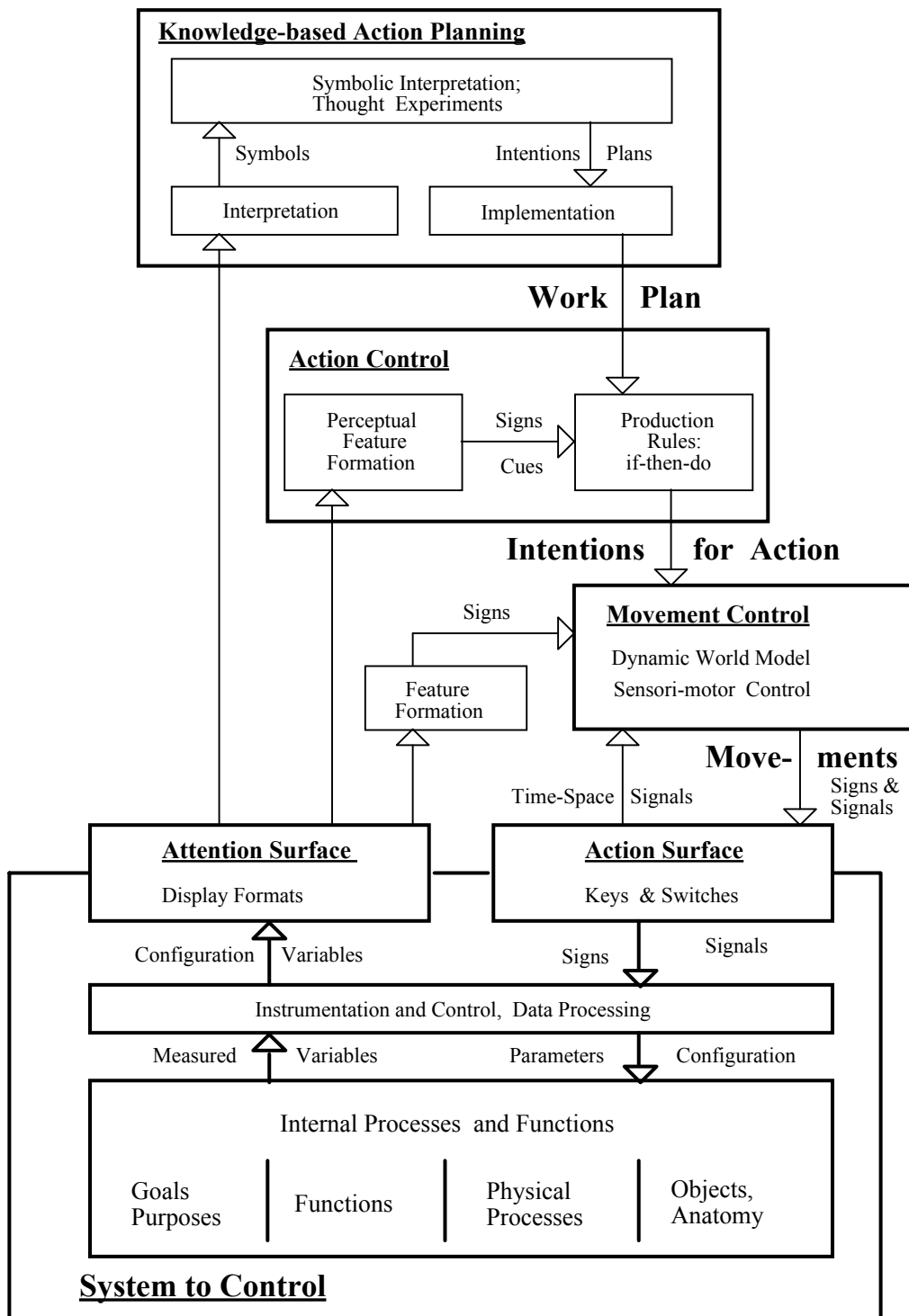


Figure 4. The figure illustrates the complex mapping between the different levels of representation of the invisible process and the different levels of cognitive control of operator action.

Knowledge-based level '. Knowledge-based behavior consists of abstract reasoning based on a mental model of the process. EID supports this level of cognitive control through the mapping of signs onto symbols. This mapping turns out to be very complex because the symbolic reference can be to several different conceptual levels representing general functions, physical processes, or equipment anatomy, depending on the actual circumstances (Rasmussen and Goodstein, 1987, in press). This means that, in addition to serving as cues for action, the same display configuration can also be interpreted in several ways as symbols for reasoning. Thus, if the display configuration is interpreted symbolically, it presents the operator with a visible model of the process that can support thought experiments and other planning activities. In addition, it is suggested that such a mapping will also support functional understanding necessary for error recovery. If signs can also be interpreted as symbols, then this may force the user to consider informative aspects when looking for action cues.

Display formats having these features can, in some cases, readily be developed from the 'lexternalised mental models' which are normally being used as a support of functional reasoning in the form of graphic representation of relational structures such as technical drawings, graphs, and diagrams. Semi-otic analyses of the use of such professional representations in actual work (Cuny and Boyd, 1981) have shown that they are actually interpreted as prescriptive signs or descriptive symbols, depending on the requirements of the task. Such an interface based on the engineering representation of two-phase thermodynamic systems in terms of a Rankine cycle diagram has been proposed by Beltracchi (1987).

5.3 Summary

The EID approach to interface design can be summarized as follows:

1. Synthesize the control and the observation surfaces so that interaction can take place via time-space signals;
2. Have the computer perform the translation task by developing a consistent, one-to-one mapping between the invisible, abstract properties of the process and the cues or signs provided by the interface.
3. Display the process' relational structure directly to serve as an externalised mental model that will support knowledge-based processing.

The theory has the advantage that it is based on fundamental properties of human cognition (the SRK model) , which in turn means that its generalisability is greatly enhanced.

6. WHAT'S IN A NAME?

The name ecological interface design alludes to a philosophy that is a very important part of our framework. We are referring to the ecological approach to psychology first advocated by Brunswik, and later, albeit in a different form, by Gibson (see Brunswik, 1957 and Gibson, 1966). In this section, we will try to relate EID to each of these approaches.

6.1 Probabilistic Functionalism

The basic premise of Brunswik's theory of probabilistic functionalism is that psychology should be concerned, not just with the organism, but more importantly, with the interrelationships between the organism and its environment (Brunswik, 1957). Thus, Brunswik distinguished between two types of stimulation: distal variables represent objective descriptions of the state of the organism's ecology, whereas proximal variables represent the sensory input that the organism receives from its ecology. Brunswik believed that the organism is not able to perceive the distal variables directly, but instead must infer what is going on in the ecology from the imperfect (i.e., probabilistic) cues provided by the proximal variables. This leads to another important distinction, that between a cue's validity and its utilization. cue validity is given by the correlation between the proximal and the distal variables. However, utilization of the sensory input, may or may not be appropriate. Therefore, the concept of cue utilization is needed to describe how the organism makes use of the cues available to her.

Given this framework, it follows that an appropriate goal for interface design would be to provide the operator with cues that have perfect ecological validity. In fact, this is the goal behind EID: by mapping symbols onto signals, we are in fact mapping distal variables onto proximal variables. Ideally, this would lead to a completely transparent system; the interface should completely and unambiguously define the current system state. Note that this does not necessarily guarantee that the organism's utilization of the cues will be optimal.

6.2 Direct Perception

Gibson's approach differed from Brunswik's in that he believed that perception was direct, i.e., that people directly perceived the higher order variables that the ecology had to offer them, without any mediating information processing. These higher order variables are combinations of the simple variables that Brunswik dealt with, and according to the theory of direct perception, they completely specify the distal objects, thereby eliminating the need for inference and probabilism (Brehmer, 1984).

Gibson (1979) introduced a new vocabulary to explain his theory of direct perception. The basis for perception is said to be the invariant relationships in the ecology that are made available to the observer via invariants in the optical array. The notion of an affordance, an invariant combination of variables that demands or invites appropriate behaviors, was introduced to account for goal-oriented behavior. Basically, an affordance represents attributes of the environment that are relevant to the organism's purposes; it specifies a possibility for action. An object's affordances are perceived via the invariants in the optical array through a process of direct---.attunement which is closely related to the conditioning of the neural system as represented by the internal dynamic world model underlying skill-based performance (Rasmussen, 1986, p. 79). Thus, perception is viewed as a means of selecting the appropriate action to attain a goal, and the concept of an affordance relates perception to action. The result is goal-oriented behavior.

In our case, the ecology is the process being controlled, and its invariants are described by a set of mathematical equations. Because the process is invisible, the information intrinsic in these invariants is normally not available to the operator. EID attempts to map the invariants in the process onto invariants in the interface. Again, the idea is to make visible the invisible. According to Gibsonian theory, these invariants in the interface should allow operators to directly perceive the system's affordances. Thus, EID can be viewed as building into the interface the affordances that the operator needs to effectively control the system. Because the system is best described in terms of an abstraction hierarchy, the process will actually be described in terms of a hierarchy of higher-order invariants at various levels of abstraction.

This description of EID within the framework of direct perception implies that the system could be controlled without any mediating decision making; the information in the invariants would be perceived as affordances that would specify what action to take. This is only true if we are rigorous in our extension of Gibson's concept of affordance to the domain of complex systems. While in certain cases, it is possible to design an interface that will offer an affordance in the classical sense of a possibility for action, we will argue that there will be other cases where this will not be possible.

Using Rasmussen's (1986) decision ladder as a framework, we see that there are three general states of knowledge that an interface can provide an operator with. These are:

1. Current system state;
2. Target state to be achieved;
3. Action to carry out.

Each successive category requires more information in order to remove the degrees of freedom that the operator is left with. The third category is the case of direct perception. But one of the fundamental assumptions of the theory of direct perception is that there is usually enough information available in the optical array to make the basic affordances of the terrestrial environment directly perceivable (Gibson, 1977). If this assumption does not hold, direct, veridical perception is impossible. We believe that, in fact, this assumption does not always hold in process systems. The natural environment is more rich in information than a thermodynamic process.

The complexity of process systems 'means that sometimes, it is only possible to provide information at the first or second level. In these cases, the operator is required to reason in order to deal with the degrees of freedom he has available to him. For instance, because of the many-to-many mapping between levels in the abstraction hierarchy, there are various ways to attain a given target state. This creates a need for planning since the appropriate path to take cannot be determined from the available information. In addition, the fact that each fault is unique means that, even if the current system state is completely specified, the target state to be achieved is not obvious. Again there are degrees of freedom, this time in determining, for instance, whether it is better to keep the system on-line and try to compensate for the fault, or whether to suspend production. Thus, there is a need to evaluate conflicting criteria before deciding what the goal state should be. It should also be noted that, due to uncertainty in the data obtained from sensors, it is even sometimes difficult to accurately determine what the current system state is. To summarize, depending upon the circumstances, control of the system will be more or less mediated by inferencing.

Reinterpreting Gibson's theory in terms of the SRK framework will show how EID is related to direct perception. In the natural environment, there is enough intrinsic information in the optical array for interaction to take place at the skill-based level. This represents the case of affordances in terms of actions (category 3 above). However, the complex nature of process systems implies that the operator will have to resort to higher levels of cognitive control at certain times. This will occur when he is only afforded the target state to achieve (category 2 above), or the current system state (category 1 above). During these times, rule- or even knowledge-based behavior will be necessary to successfully cope with task demands. In order to deal with these situations, EID attempts to make the most of the information that is available in order to afford the operator as much as possible. It is only because of the comparative complexity of process systems that control via direct perception is not possible as it is in the natural ecology.

7. CONCLUSION

In dealing with the topic of how to cope with errors through system design, we began by describing the different types of errors associated with learning, interference between cognitive control structures, lack of resources, and stochastic variability. A variety of design guidelines for dealing with these different classes of errors were proposed. It was argued that these guidelines should result in reliable system performance. Subsequently, a theory of interface design that incorporates these guidelines was described. The theory, called ecological interface design (EID), attempts to provide recommendations for designing interfaces that take into account and support the properties of human cognition. EID represents a novel theoretical framework for interface design that presents the ecology of the problem solving domain in a manner that is consonant with the properties of the human organism.

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Abstract (Max. 2000 char.) Research during recent years has shown that human errors cannot be considered as stochastic events which can be removed by better training or by optimal interface design. Rather, errors tend to reflect either systematic interference between various models, rules, and schemata, or the effects of the adaptive mechanisms involved in training that lead to transfer of control from one cognitive level to another. Therefore, the approach to reliable human-system interaction will be to design interfaces which tend to minimize the potential for control interference and support the recovery from errors, i.e., to focus on control of the effects of errors rather than on the elimination of errors per se. In this paper, we suggest a theoretical framework for interface design that attempts to meet these objectives. The goal of ecological interface design (EID) is to develop a meaningful representation of the process which is not just optimised for one particular level of cognitive control, but that supports all three levels simultaneously. The paper discusses the necessary requirements for a mapping between the process and the combined action/observation surface, and analyses the influence on the interferences causing error and on the opportunity for error recovery left to the operator.				
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