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HUMAN ERROR DATA. FACTS OR FICTION?

Jens Rasmussen

Abstract. The need for human error data for various purposes has been discussed for decades, yet no acceptable human error data bank has emerged. What is the problem? Are there events which can objectively be considered human errors and for which data can be collected from real-life work situations? What attributes are necessary to characterize the human involvement in accidental chains of events? In the paper, these questions are discussed, and it is argued that instead of focusing on human errors, data should be collected to represent situations of human-task mismatch and characterized accordingly. Furthermore, to support design of error-tolerant work situations, more emphasis should be put on analysis of error recovery features.

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INTRODUCTION

The need for human error data for various purposes has been discussed for decades, yet no acceptable human error data bank has emerged. What is the problem? Are there events which can objectively be considered human errors and for which data can be collected from real-life work situations? What attributes are necessary to characterize the human involvement in accidental chains of events? In the following sections, these questions are discussed, and it is argued that instead of focusing on human errors, data should be collected to represent situations of human-task mismatch and characterized accordingly. Furthermore, to support design of error-tolerant work situations, more emphasis should be put on analysis of error recovery features.

DEFINITION OF HUMAN ERROR

Analyses of incidents and accidents immediately make it evident that faults and errors cannot be defined objectively by considering the performance of humans or equipment in isolation. They can only be defined with reference to human intentions or expectations; they depend upon somebody's judgement of the specific situation. Faults and errors are not only caused by changes in performance with respect to the normal or accepted performance, but also by changes of the criteria of judgements, i.e. changes in requirements to system performance, in safety requirements, or in legal conventions, will be able to turn hitherto accepted performance into erroneous acts.

In other words, human error occurrences are defined by the behaviour of the total man-task system. Human intentions and the resulting actions may be correct from the performer's point of view, from the goal he selects - which may be inappropriate judged from system output.

Human Errors: Causes of Accidents?

In the present man-task context we can define faults and errors as causes of unfulfilled system purposes. If system performance is judged below the accepted standard, somebody will typically try to backtrack the causal chain to find the causes. How far back to seek is a rather open question; generally, the search will stop when one or more changes are found which are familiar and therefore acceptable as explanations, and to which something can be done for correction. In the case of a technical breakdown, a "component" failure is generally accepted as the cause at that component level where replacement is convenient. In some cases, however, component failure will not be found an acceptable cause; for example, if it occurs more frequently than expected. In such cases, the search will often continue to find the "root cause" of the component's malfunction. In summary, the characteristics of a fault are: It is the cause of deviation from a standard; it is found on the causal path back from this effect; it is accepted as a familiar and therefore reasonable explanation; and a cure is known.

This means that allocation of causes to people or technical parts in the system is a purely pragmatic question regarding the stop rule applied for analysis after the fact. There is no well defined "start" of the causal chain involved in accidents, and the link which is chosen to represent the "cause" for which "error data" are collected depend on the application of the data. This fact should, as will be discussed below, be reflected in the error data taxonomy.

Human Errors: Man-Machine Mismatch Situations?

For improvement of safety, a more fruitful point of view is to describe human errors as instances of man-machine or man-task misfits. In case of systematic or frequent misfits, the cause can then typically be considered a design error. Occasional misfits are either caused by variability on part of the system or the man and will typically be considered component failures or human errors, respectively.

The interaction can be seen as a complex, multidimensional demand/resource fit. To discuss the misfits and evaluate means for improvement, it is more important to find the nature or dimensions of the misfits than to identify their causes. In other words, it is necessary to find what went wrong rather than why, i.e. to identify potential conflicts, rather than their predecessors in the course of events. Again, this consideration should be reflected in the error data taxonomy.

With respect to man-system misfits, human variability can play a role in two different ways. First, mismatch may occur when human variability brings human actions on the system outside the boundary allowing continued acceptable system function. Second, adaptability and variability of human behaviour may not be large enough to maintain a match, following changes in system behaviour. To explain man-system mismatch we must therefore look at the control of human behaviour, to find mechanisms behind variability during normal, familiar situations and mechanisms limiting adaptability in unfamiliar situations when the system changes.

Human Errors: Experiments in an Unkind Environment?

Human variability is an important ingredient in adaptation and learning, and the ability to adapt to peculiarities in system performance and optimize interaction is the very reason for having people in a system. To optimize performance, to develop smooth and efficient skills, it is very important to have opportunities to "cut corners", to perform trial and error experiments, and human errors can in a way be considered as unsuccessful experiments with unacceptable consequences. When analysing incident reports, one rapidly gets the impression that human acts are only classified as human errors because they are performed in an "unkind" work environment. An unkind work environment is then defined by the fact that it is not possible for a man to correct the effects of inappropriate variations in performance before they lead to unacceptable consequences. Typically, because he either cannot immediately

observe the effects of his "errors", or because they are irreversible.

COGNITIVE CONTROL OF HUMAN BEHAVIOUR

To discuss the interaction between an occasionally changing task environment and a varying and adaptable human, we have to consider the different ways in which human behaviour can be controlled, depending upon the degree of familiarity with the environment. For this purpose we consider three different levels of control, as shown on Figure 1, the levels of skill-, rule-, and knowledge-based behaviour.

The skill-based behaviour represents sensori-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 behaviour.

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 behaviour 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. Performance is based upon a very flexible and efficient dynamic internal world model.

At the next level of rule-based behaviour, the composition of a sequence of subroutines in a familiar work situation is

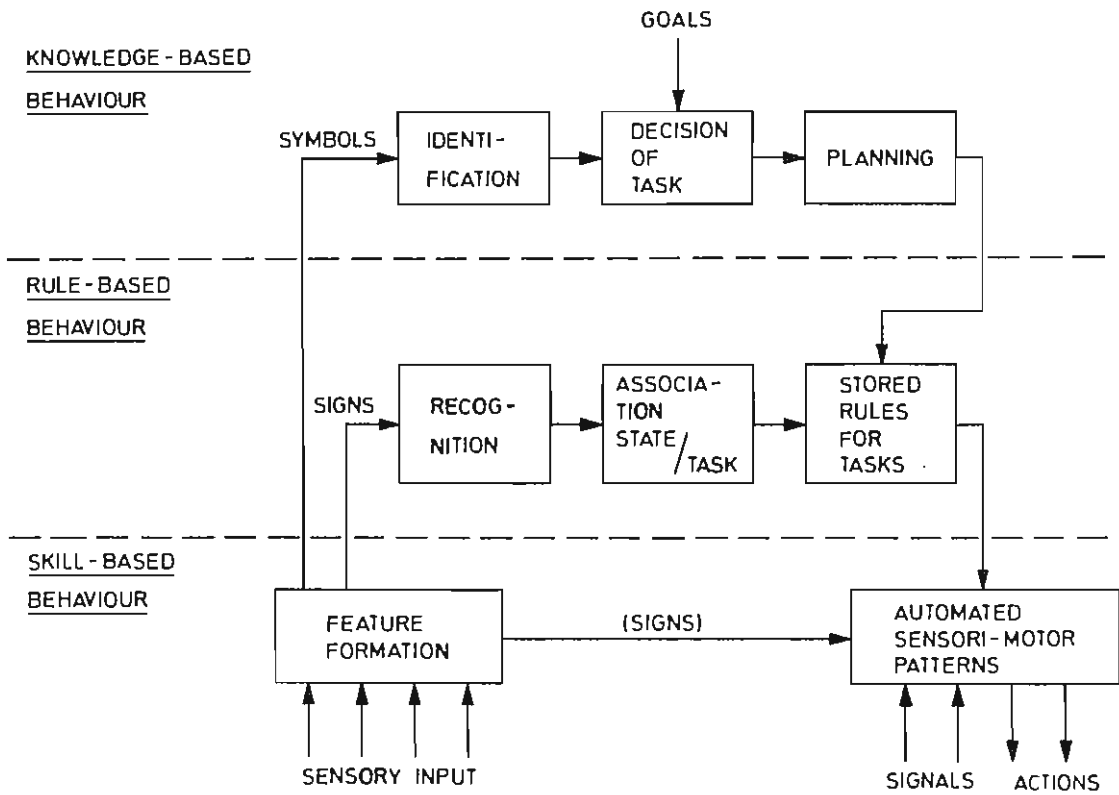


Figure 1. The diagram illustrates how different cognitive functions and interpretations of information are used in control of human behaviour.

typically controlled by a stored rule or procedure which may have been derived empirically during previous occasions, communicated from other persons' know-how as an instruction or cookbook recipe, or it may be prepared on occasion by conscious problem solving and planning. The point is here 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. 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.

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 behaviour by convention or prior experience; they do not refer to concepts or represent functional properties of the environment. Signs are generally labelled by names which may refer to states or situations in the environment or to goals and tasks of a person. 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.

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

of 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. To be useful for causal functional reasoning in order to predict or explain unfamiliar behaviour 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.

During training in a particular task, control moves from the knowledge- or rule-based levels towards the skill-based control, as familiarity with the work scenarios is developed. An important point is that it is not the control processes of the higher levels that are automated. Automated manual skills are developing while they are controlled and supervised at the higher levels. When explicit knowledge or rules are no longer needed for behavioural control during normal work, they may eventually deteriorate. With respect to error observability, it is a problem at the skill- and rule-based levels that the goals are not explicitly controlling the activity. This means that errors during performance may only be evident at a very late stage - an error in the use of a recipe may not manifest itself until you taste the cake, i.e. when the product is present. Early detection of the effect of one's own variability (or of changes in system conditions) depends on an ability to monitor the process, i.e. on knowledge-based monitoring based on understanding of the underlying processes. For error detection it may therefore be important to maintain knowledge, even though high skill is developed.

Skill-, rule- and knowledge-based behaviour are not alternative human processes; they are categories of behavioural control which are probably all active at all times. During familiar work situations, when immediate activity is controlled by

know-how and automated subroutines, the conscious mind has time left for other business, which may be to plan the future, to monitor the effects of past activities, or to speculate on private troubles. The degree to which people tend to use knowledge-based functional reasoning to monitor their activities during familiar work situations probably depends very much on one's individual disposition, but the opportunity to do so certainly also depends on the man-task interface design.

The variation in human behaviour when control moves downwards during training and adaptation probably has important implications for human-task mismatches, which may ultimately be judged human error if not corrected in due time. In general, the only information available to the person to judge the proper limits of adaptation will be occasional mismatches of behaviour and environment. In this way conscious as well as subconscious experiments are part of the adaptation mechanisms at all levels of cognitive control.

The efficiency of human interaction with the environment at the skill-based level is due to a high degree of fine-tuning of the sensori-motor schemas to the time-space features in the environment. Changes in the environment will often be met by an updating of the current schema by a subconscious reaction to cues or a consciously expressed intention: "Now look, be careful, the road is icy".

However, frequently the updating of the current schema will not take place until a mismatch has occurred, for instance when walking onto more uneven ground, adaptation of the current motor schema to the actual features of the environment may first happen after the feet have detected the mismatch by stumbling. The point here is that adaptation and fine-tuning of sensori-motor schemas basically depend upon mismatch occurrences for optimal adjustments. The proper limits for fine-tuning can only be found if surpassed once in a while.

If the optimization criteria for manual skill development are speed and smoothness of movements, optimization can only be

constrained by the experience of the precision tolerance limits. This means that the shape of the distribution curve representing variability in time-space coordination is not a characteristic of the person's motor control, but reflects tolerance limits of the environment, and the "risk sensitivity" of the individual. This feature of human behaviour has also been identified and discussed by researchers in traffic safety which is related to a high skill manual control task. It appears (Taylor, 1981) that beyond a certain limit, efforts to decrease accident frequency may influence the accident patterns, but not the general risk level.

Also the development of efficient rules-of-thumb and know-how at the rule-based level depends on a basic variability and experimentation to develop and adjust the proper rules and to identify the information patterns which are suitable signs to control the rule application. The initial conditions for this adaptation by a novice are either knowledge-based rational planning or a set of simplified stereotype procedures supplied by an instructor. In both cases the process of adaptation will lead to experiments, some of which are bound to end up as human errors in unfriendly work environments.

The rational process of analysis, evaluation and planning of an informed novice will not be maintained during a familiar work situation. The use of symbolic information for rational inference will gradually be replaced by use of convenient signs which are empirically correlated with the conditions necessary for the steps in a work procedure. This information may very well be informal information, like relay clicks and mechanical noise. Such signs are, however, not reliable guides if the internal structure of the task environment changes, as it may in case of component faults. In that situation the convenient signs may lead the person into a trap in terms of acts on wrong premises. Again, occasional experience of unacceptable adaptation may serve basic control functions in the learning mechanism.

Formal work procedures will normally be based on signs and readings which are functionally defining the required initial

states, and the planning of the steps and their mutual relationships in the work sequence will be made under consideration of likely variations in the work context. During adaptation, not only the formal sign will be replaced by more convenient, informal signs, but the sequence of work elements may - consciously or subconsciously - be rearranged to have a more natural and smooth sequence, judged from the immediate, normal experience with the task. This deviation from "working according to rules" is the hallmark of experienced people, but is bound to give experiences which, depending on the consequences, gives rise to human error and the related blame after the fact.

It should be considered here that the adaptation to informal signs and rules-of-thumb is not generally the result of conscious decisions, but found as a result of the general variability of human behaviour. Adaptation can be an evolutionary process, where effective variations survive and are integrated in behaviour, whereas the unsuccessful are experienced as lapses and later avoided.

At the knowledge-based level where people are trying to cope with unfamiliar situations and therefore have to base behaviour on functional analysis, evaluation, and planning, we will consider two major groups of human-task mismatches.

One group includes those cases when people have proper intentions, but fail to implement them. In such cases people may commit errors during reasoning due for instance to slips of memory, lack of knowledge, or to high workload - it may be difficult by unsupported, linear reasoning to deal with the complex causal net of the real world. It is not, however, possible to establish a complete set of preconditions to consider in practical work situations, and logically to make sure your considerations are reliable. The only reliable test will be to judge the response from the environment - and to correct yourself when unsuccessful. With the risk that you commit what later may be judged an error. Not even scientists are reliable - measurement of the atomic weights did first

converge on whole numbers when theoretical considerations asked for that - and supplied the stop rule for the necessary efforts (Kuhn, 1962).

The other major category includes cases when the humans' acts are in good correspondence with their intention, which however serves a subgoal not acceptable from an ultimate task or system performance point of view. An illustrating example may be the situation when an operator in a disturbed process plant has several alternative hypotheses on the failed state which he has to test. The classical research on problem solving (Duncker, 1945) shows that it is a normal feature to develop several branches in a "solution tree" (see Figure 31) before one settles down for detailed consideration of one of the solutions. Theoretically, the test of hypotheses could be done conceptually, but faced with the system itself, test by means of manipulations on the system will be a tempting solution. In case the hypothesis is incorrect this act may add another disturbance to a system in an unknown state, and the result after the fact may be accusation of serious decision error.

The conclusion of this discussion is that "errors" are basically the effect of human variability in an unfriendly environment, and that this variability is an inherent element in human adaptation. In the following section these aspects will be discussed in more detail in order to identify the most important classes of "human error".

ERROR RECOVERY

If variation of human behaviour is an important ingredient of development of smooth skills and professional know-how, and experiments on the environment are necessary for problem solving, definition of error should be related to a lack of recovery from unacceptable effects of exploratory behaviour.

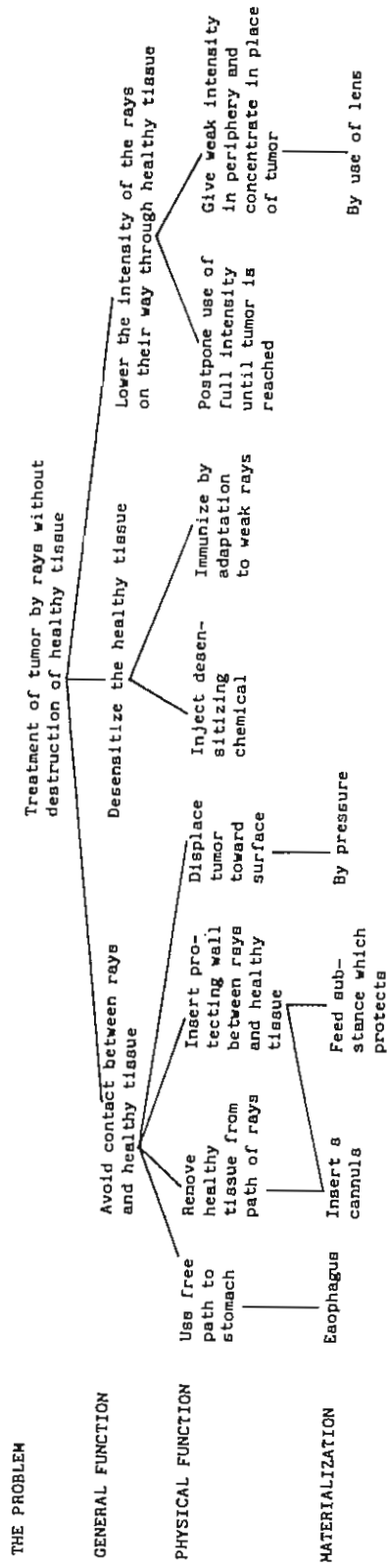


Figure 2. The generic solution tree found by Duncker in a problem solving task.

Error recovery depends on observability and reversibility of the emerging unacceptable effects. Reversibility depends largely on dynamics and linearity of system properties, whereas observability depends on the properties of the human-environment interface which will be greatly influenced for many tasks by the use of advanced information technology.

Error observability depends on the perception of a mismatch between the expected and the actual system response to human actions. At the level of skilled behaviour, the patterns of behaviour are continuously adapted to the changes in the environment to absorb variations in coordination. Only when variations exceed the limits of adaptability in the current regime and cues call for modification, is it usually referred to as an error (for instance when stumbling). Error corrections then depend on the availability of alternative control patterns, and on the activation of these patterns by proper cues before control is lost irreversibly. This means that error recovery is tightly related to specific dynamic properties of the actual interface configuration.

Related to the rule-based coordination of a sequence of skilled routines, error recovery may be influenced by various features. The information needed for control of actions and for observation of errors may be related to different time spans and to different levels of abstraction. The information used en route to control activity in pursuit of an intention or goal may be totally unrelated to the intention itself. In a habitual sequence of skilled action complexes, the individual complexes are released by stereotype cues. Judgement of system responses in terms of intended outcome may require simultaneous functional evaluation at the knowledge-based cognitive level. Whether the knowledge basis required for this is maintained also for the more frequent tasks and the information necessary is available depend very much upon details in the human-task interface - in particular in tasks like process control. This makes objective data collection very difficult, since the bias caused by error recovery features of the various data sources is difficult to determine.

HUMAN ERROR TAXONOMY

The conclusion of this discussion will not be that data collection cannot be organized, only that data collection should be arranged according to a taxonomy which focuses on human-task mismatch characteristics. In addition, the taxonomy should not consider the causes of a certain category of events such as accidents, but represent the dynamic interaction between human and task. This interaction is only a part of the chain of events, which can be analysed further in terms of antecedent as well as consequent events. According to the discussion above, it is important that a taxonomy represents the structure of the cognitive functions which are involved in a task and that it reflects a model of human control of behaviour. An attempt to develop such a taxonomy has been based on the analysis of incident reports from nuclear power plants. It has been described elsewhere (Rasmussen, 1981), but is shown on Figure 3, to illustrate the different domains of description which we have found important to characterize a human-task mismatch (in the taxonomy called "malfunction" to avoid the term "error").

The taxonomy appears as a multi-faceted categorization of a human-task mismatch, of which each facet characterizes human behaviour in subsequent stages of the analytical backtracking from an incident. From right to left the different stages are:

- "External mode of malfunction" characterizes the mismatch in terms of inappropriate elements of the overt task. This facet includes direct observable items.

- "Internal mode of malfunction" reflects how the same overt "error" can be due to errors or misunderstanding in different mental tasks, such as diagnosis, evaluation and decision, planning or coordination of acts. The detailed categories required for adequate description probably depend on the task context. The present have been useful for process plant operation. In general, the structure of the taxonomy is more

important for the present discussion than the resulting classification system. The items of this facet are errors in covert functions which can only be identified from the person's explanation of the detailed circumstances.

- "Mechanisms of malfunction" reflect the psychological mechanisms which are involved in the error of the mental process. To represent this facet in the analysis, a model of human cognitive control and related error mechanisms are necessary. The members of the category are therefore theory-dependent, but again the structure rather than the details of the taxonomy is important here.
- "Causes of human malfunction" reflect the fact that the internal error mechanisms may not only be due to inherent human variability, but can be directly released by external events.

The taxonomy was developed from analysis of several hundred incident reports from nuclear power plants (Rasmussen, 1980), and was found to represent these cases in a useful way. It should be considered, however, that the categories of the different facets reflect the conditions under which the reports were collected, and the kind of information included in such reports. It is, for instance, characteristic that the resolution of errors during inference tasks is very low, in fact only one category.

USE OF HUMAN ERROR DATA

Data on human-task mismatch occurrences can be useful for several applications. One major application area is risk and reliability assessment. If we accept the arguments in the preceding sections, however, such data are only reliable for work situations very similar to those during which they are

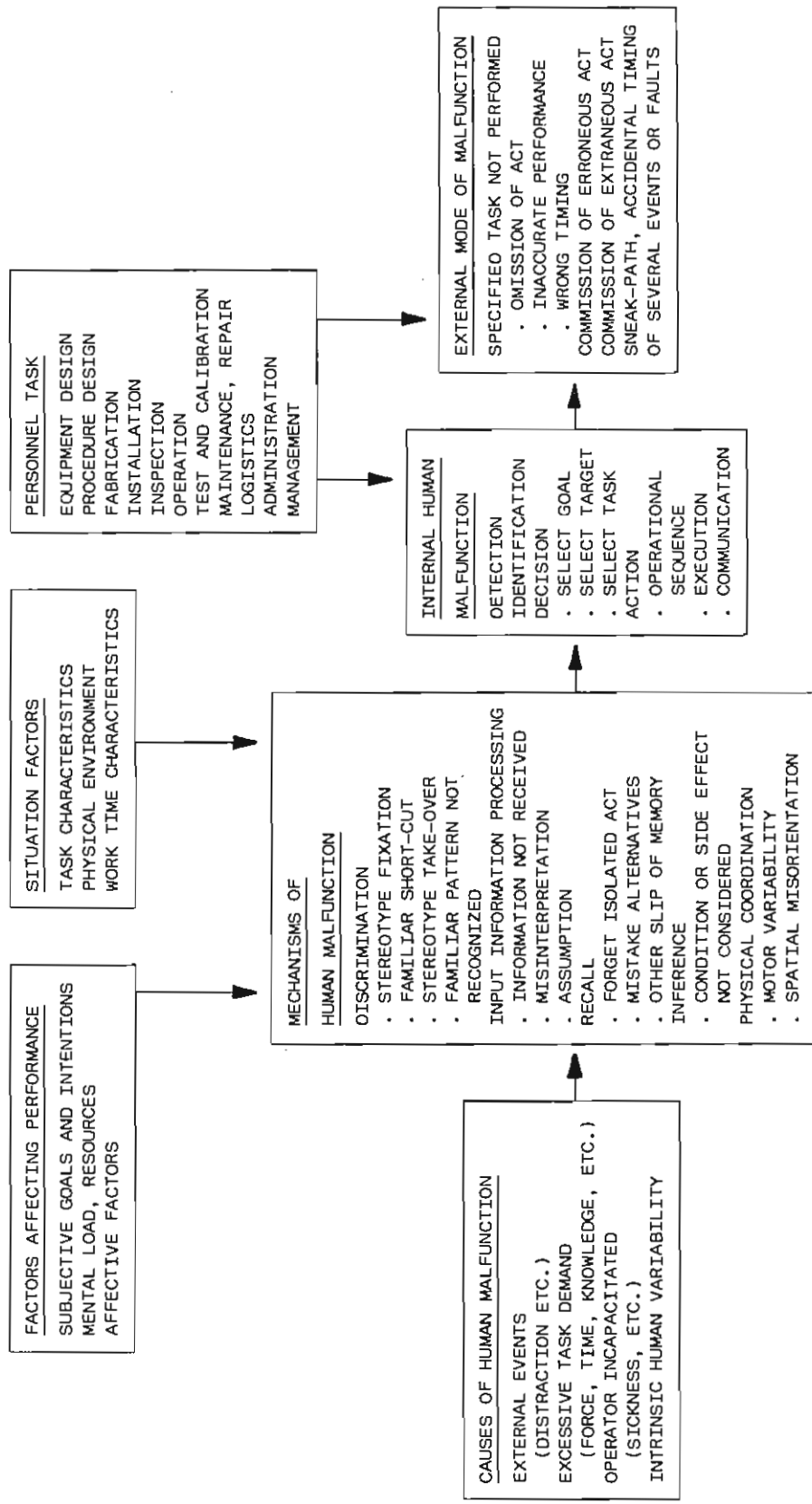


Figure 3. Multifaceted taxonomy for description and analysis of events involving human malfunction.

collected. This means that data are only reliable for work situations based on similar technology and physical layout and only for the normal, planned activities for which the work procedures can be identified by task analysis and which are representative as data sources. Transfer to other work contexts, for instance for prediction of human reliability in new systems for which error recovery features are not known, should be done with great care.

For design use, however, the qualitative aspects of the information available from data collection according to a taxonomy like the one on Figure 3 are of great importance.

From the mismatch descriptions referring to the cognitive tasks and the psychological mechanisms, possible human error scenarios can be postulated and their effects on task performance including the features related to selfdetection and correction can be analysed. This is necessary for safety improvement. From the discussion in previous sections, it appears that beyond a certain limit it is not possible to improve safety level related to human errors by better motivation or training. Nor can it be expected that design of a task situation which will accept a wider span of human variability will in all cases result in lower error rates. Basically, it appears that humans should be allowed to be flexible and variable, and important features of safe task designs are therefore related to error observability and reversibility. For such an analysis, the structure and mutual relationships between categories of a taxonomy which emerges from attempts to collect data from accidents and incidents are more important and useful than the quantitative information in error frequencies.

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