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Rasmussen, Jens

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Human Error Mechanisms in Complex Work Environments

Jens Rasmussen

Risø National Laboratory, DK-4000 Roskilde, Denmark
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HUMAN ERROR MECHANISMS IN COMPLEX WORK ENVIRONMENTS

Jens Rasmussen

ABSTRACT. Human error taxonomies have been developed from analysis of industrial incident reports as well as from psychological experiments. In the paper, the results of the two approaches are reviewed and compared. In both cases, it is found, a fairly low number of basic psychological mechanisms will account for the majority of action errors observed. In addition, error mechanisms appear to be intimately related to the development of high skill and know-how in a complex work context. This relationship between errors and human adaptation is discussed in detail for individuals and organizations. The implications for system safety is briefly mentioned, together with the implications for system design.

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1. INTRODUCTION

When designing installations for hazardous industries it is important to be able to analyse the effect of human errors upon all critical tasks. To this end, the sensitivity of the system to errors must be judged from some kind of error-mode-and-effect analysis based on a classification of basic types of human error (Rasmussen, 1982). To be useful also for the application of new technology in the human-machine interface, a taxonomy in terms of psychological mechanisms is necessary rather than a taxonomy derived from behavioristic classification of overt human action errors. In practice, an error-mode-and-effect analysis will only be feasible if a reasonably low number of error modes has to be taken into account. Fortunately, recent research in human error causation tends to show that the wide variety of errors found in case reports are not stochastic events but can be accounted for by a rather low number of psychological mechanisms leading to system failure under certain conditions.

2. TWO APPROACHES TO MODELS OF HUMAN ERROR MODES

Two approaches to modelling human error mechanisms will be reviewed in the present context. One is based on analysis of actual error reports from industrial plants, and another one is based on psychological experiments with human memory functions.

To facilitate a comparison with results of the two approaches, a brief review will be given of the error mechanisms identified from event analysis with reference to the skill-rule-knowledge framework.

2.1. Analysis of Industrial Incident Reports

An analysis of human error contribution to industrial incidents (Rasmussen, 1980) has shown that the majority of the cases can be accounted for if a multi-faceted classification system is used to characterise the human role (Rasmussen et al, 1982). The taxonomy of this classification is based on separate descriptions of the 'external error model related to action errors; the 'internal error model related to the different phases of decision making and planning; and the psychological 'error mechanisms' involved. Finally, if an 'external cause' can be identified, this is described in a separate category. The advantage of this approach is that a large variety of observable errors can be accounted for by rather few categories in each facet. Therefore, error-mode-and-effect analysis is possible by using a low number of error mechanisms, as the starting point and by folding, these onto the decision and planning functions and the ultimate control acts required by the task (Rasmussen and Pedersen, 1982).

Based on analysis of incident reports, error mechanisms are related to three different levels of cognitive control:

At the level of highly skilled performance typical error mechanisms are related to inadequate precision, such as lack of spatial or temporal precision, lack of topographic co-ordination, or lack of precision in using physical force. Other error mechanisms are related to systematic interference between the schemata needed for an intended action and for other, typically more frequently used patterns of acts. If a sequence of acts is necessary for the intended activity which has a sub-sequence in common with a more frequent task, this task will very like take over control, leading to a "capture error".

At the rule-based level, typical error categories are related to memory characteristics, e.g., forgetting to perform isolated acts' such as, for instance, forgetting to switch back to operation after test (a category accounting for 60-70% of the test and calibration error cases analysed; Rasmussen, 1979). Another category is mistaking alternatives such as + and -, left and right, up and down, etc.

A category which may lead to serious mistakes is related to the inadequate human ability to follow changes of system behaviour. This type of error is caused by the association of convenient but not defining, stereotypical signs or cues signalling very familiar situations, directly to routines which are normally effective (such as referring abnormal instrument readings to lack of calibration). This association is normally very effective, but may be dangerous when work conditions are changed during plant disturbances (the reading may be due to a leak). Again, an important error mechanism related to systematic interference from a highly trained, and usually successful behavioural pattern. This category in fact represents the failure of an operator to switch to the rational analysis based on knowledge about the functioning of the plant which is needed to perform a proper diagnosis.

Once an operator has succeeded in shifting to functional reasoning at the knowledge-based level, it is very difficult to characterise the psychological mechanisms leading to errors by means of an ana lysis of incidents. Only very broad distinctions were made from this source, related to the difficulty of linear thought in navigating in a causal network, leading to failure to consider preconditions or side effects of the decisions made. In order to explore the cognitive mechanisms of knowledge-based behavior, more detailed analysis involving direct contact with the individuals involved will be necessary, such as the analyses of Pew et al. (1981) and Woods (1982). Such detailed analysis have provided very important insight, an more effort should be spent on a combination of analysis of case reports and subsequent detailed interrogation.

The categories identified in this way by this analysis of performance in real-life tasks from the point of view of human information processing appear to be closely related to memory characteristics, and to interference between behavioural patterns and the findings of experimental psychology come into focus.

2.2. Experimental Psychology Findings

A significant development during recent years has been that the approach taken from the point of view of systems and reliability analysis described above has been supported by similar results from psychological research. The interest by psychologists has been from the idea that errors 'are windows on the mind' (Baars, 1987). In this research, human errors are the vehicle of research because they present instances when the inner mechanisms of the highly adaptive human system become observable.

In particular the results presented by Reason are very compatible with the findings from analysis of case reports. First of all, Reason also finds that a limited number of psychological mechanisms related to memory characteristics will account for a large variety of errors, when multiplied by the task requirements (1987c). He identifies eight 'primary error groupings' as 'the points of interaction - or nodes' between basic error tendencies and the cognitive domains.' Basic error tendencies include categories like ecological constraints, change enhancement, resource limitations, schema properties, and strategies/ heuristics. The cognitive domains include eight categories representing cognitive information processes related to sensory input, memory and recognition functions, inference and judgement, and action control. The basic structure of this taxonomy is similar to the one derived from incident report analysis, even if the dimensions of the space are defined differently, and the projections of the cases onto the basic categories will be different. The mapping between the two approaches is not a simple one and needs to be explored. A first attempt to do this is presented in Reason (1987e) where he explores the mapping of his taxonomy onto the srk-framework. A recent development of Reason's taxonomy (1987b) shows even greater similarity with our results. In this taxonomy, one prime dimension is defined by 'error types' which relate to the origin of error within the stages involved in conceiving and carrying out an action sequence; a dimension which is the same projection of error characteristics as the internal error model dimension of our taxonomy, although the categories are different. Reason distinguishes the main classes to be 'planning', 'storage', and 'execution'; classes which he considers to be correlated with mistakes, lapses, and slips, respectively. Another of Reason's basic dimensions is represented by 'error forms, which include varieties of error mechanisms, 'fallibilities" appearing in all kinds of cognitive activity, such as similarity-matching', and 'frequency-gambling' both of which are closely related to the effective human adaptation to regularity in the behaviour of the environment and which are related to the cue utilization heuristics found at the rule-based level.

At the knowledge-based domain, where the cognitive activities are very situation and person dependent, categories of mechanisms underlying mistakes and decision errors can not be derived from event reports or historical evidence. Recently, a number of experimental programs have been started to study decision processes involved in . control of complex systems by means of simulated systems. Doerner (1987) studies decision making involved in control of the social, economic, and ecological relations of a small town, and Brehmer (1987) studies complex forest fire-fighting. From these studies, insight into problem solving strategies in terms of operations in a defined problem space is emerging which serves to cast light on the heuristics applied by decision makers when the context is too complicated for simple, linear causal reasoning. Doerner has identified a number of heuristics applied by decision makers managing the affairs of a town which are also relevant for disturbance control in industrial plants. Examples of the heuristics found are: thinking in causal series instead of in causal nets, thematic vagabonding, lack of will to make decisions, etc. Doerner and Brehmer both are considering co-operative decision making and find important features related to intuitive attribution of causes, for instance related to delegation of control which depends on the difficulties met and on time delays in communication. Brehmer finds that decision makers tend to explain time delays in communication in a hierarchical Organisation by attitudes or incompetence of co-operators rather than by the actual, functional causes. This view, typically, leads managers to withdraw delegated decision making which is a counterproductive solution. This kind of result refers attention to the findings of causal attribution research (see for instance Kelley, 1973).

The conclusion of this discussion is that human error modes are tightly related to the cognitive mechanisms in control of the interaction with a work environment. In consequence, it appears to be very feasible to seek a formulation of such mechanisms to be used as a failure-mode-and-effect analysis of new system interfaces already in the conceptual phase of a design. The tight relationship between error modes and the cognitive control structure also suggest an approach to design of interfaces which could support such control structures and, therefore, decrease the likelihood of error. However, before this topic is discussed in more detail, the relationship between errors and human adaptation to characteristics of the work environment will be reviewed.

3. ERROR MECHANISMS AND LEARNING

3.1. Individual Learning

In the three-level model, the final stage in adaptation to a task environment is the skill-based level. During training the necessary sensori-motor patterns develop, while the activity is controlled by other means. It may happen directly at the skilled level by imitation and trial-and-error such as, for instance, learning to play an instrument by ear or children learning to talk, walk, etc. In other cases, control at the rule-based behavioural level will be efficient during development of the automated skill. The rules may be obtained from an instructor or a textbook, as is typically the case when learning to drive a car, to operate tools and technical devices supplied with an instruction manual, or to manage social interactions from "rules of good manners". And, finally, persons with a basic knowledge of the structure and functioning will be able to generate themselves a set of rules to control activities related to various purposes during early phases of learning. This involves what Anderson (1983) calls 'compiling declarative knowledge.,

Human errors appear to be very closely related to this learning process. In a manual skill, fine-tuning depends upon a continuous updating of the sensory-motor schemata to the temporal and spatial features of the task environment. If the optimisation criteria are speed and smoothness, adaptation can only be constrained by the once-in-a-while experience gained when crossing the tolerance limits, i.e. by the experience of errors or near-errors (speedaccuracy trade-off). Some errors, therefore, have a function in maintaining a skill at its proper level, and they neither can nor should be removed.

An important consequence of this view is that solutions like training programs, instruction, or requests for greater care have only short term effects, since the task itself very rapidly will retrain people through normal adaptation. One possible solution will be to introduce physical barriers at the boundaries of acceptable human variability blocking the propagation of the effects, as it is done to prevent the effects of loss of control along highways. - Another approach to system design is to indicate to the actors the limits of acceptable variability before the loss of control becomes irreversible.

Support of this hypothesis can be found in the results of traffic accident research. In general, this research has been f rom the point of view of social psychology. Accidents appear to be related to the actors' risk perception which in turn has been related to a number of social factors, such as social disorganisation due to the difference between formal (legal) and informal rules; tendencies to "follow the leader"; etc. (Wilde, 1976). The general conclusion is 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 fac tors such as perceptual, decisional, and control skills, will have only temporary influence.

This point of view has been stressed by Taylor who applies a hermeneutical analysis of traffic accidents. He observed that drivers tend to try to keep their arousal at a desired, constant level and, consequently, to go faster if conditions become too undemanding, in order to generate more arousing incidents (Taylor, 1980). This point of view matches the arguments presented above very well. The consequence drawn by Taylor (1981) is that traffic safety is hard to improve beyond a certain limit. He criticises the present mechanistic, approach and argues that accidents cannot be studied in terms of causes, but should be analysed in terms of reasons. Considering the discussion of human errors mentioned in a previous section, there seems to be no need to resolve the question whether accidents should be explained by reasons or causes; both will play a role at the same time. Reasons will be conditioning the organism while causes release the particular course of events (Rasmussen, 1987c; Taylor 1987). If errors are considered the consequence of adaptive processes, the reason for a particular behaviour may be to optimise skills, whereas risk perception is to be considered a representation of the constraints given by the environment, not the reason itself.

Wilde's attempts to explain traffic behaviour by a model describing risk homeostasis have been subject to considerable controversy (Wilde, 1985; Shannon, 1986). His arguments are that an actor in traffic tends to modify behaviour according to the actual circumstances in a way that keeps the level of perceived risk constant. According to the previous discussion, however, limits of adaptation can be detected by a perceived loss of control which is not directly related to the risk which, in turn, depends on the ultimate effect of such loss. The difference is important since in the latter case, detection of an approaching loss of control can be arranged at a reversible stage of behaviour, i.e., at a low level of risk.

Also at the more consciously controlled rule-based level, development of know-how and rules-of-thumb are depending upon a basic variability and opportunity for experiments to find shortcuts and to identify convenient and reliable signs making it possible to recognise recurrent conditions without analytical diagnosis. In other words, effective, rule-based performance depends on empirical correlation of cues to successful acts. Humans typically seek the way 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 <u>in the particular</u> <u>situation</u>. This implies that the choice is lunder-specifyed' (see Reason, this volume) outside this situation. When situations change, reliance on the cue sub-set which is no longer valid, and will cause an error due to inappropriate "expectations". Another heuristic may be related to the principle of "the point of no return". When information is observed sequentially, evidence (Rasmussen et al., 1974) seems to 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.

The role of cue-pattern/action matching involved in the rule-based performance brings into focus the studies of cue utilization in the social judgement paradigm (Brehmer, 1987) as well as the judgement biases studied in psychological decision theory discussed by Reason (1987a). An attempt to use the Brunswik (1957) lens-model of the social judgement paradigm as a basis for simulation of operator errors in the rule-based domain (Rasmussen, 1987d) also has shown good compatibility between the error mechanisms identified from these research pardigms.

An important issue is that error mechanisms cannot be separated from very effective adaptive mechanisms. Reason (1987c) stresses a similar view: He finds that examination of a wide variety of error forms suggests that they reflect basic error tendencies. "These tendencies, it is argued, constitute the root of most, if not all, of the systematic varieties of human error. Each of these error tendencies is necessary for normal psychological functioning. It is from this necessity that they derive their great power to induce systematic error." In his recent work, Reason (1987b) studies the cognitive basis of predictable human errors. In this approach, similarity and frequency are considered 'cognitive primitives, in that heuristics like similarity-matching, and 'frequency-gambling, are powerful operators in memory retrieval. This relates error mechanisms to basic memory access mechanisms, such as the influence of frequency and recency of encounter of items 'coming to mind, in memory experiments, and again the close connection to error mechanisms has been stressed.

In genuine problem solving at the **knowledge-based** level during unusual task conditions, test of hypothesis becomes an important need. It is typically expected that operators check their diagnostic hypotheses conceptually - by thought experiments - before operations on the plant. This appears, however, to be an unrealistic assumption, since it may 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 net. For such a task, a designer is supplied with effective tools 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 guide the termination of conceptual analysis and the start of action. This means that the definition of error, as seen from the situation of a decision maker, is very arbitrary. Acts which are very rational and important during the search of information and test of hypothesis may, in hindsight without access to the details of the situation, appear to be unacceptable mistakes.

3.2. Organizational Learning.

In the context of industrial safety, an analogy can be drawn between the adaptive mechanisms involved in the skill attainment of the individual, as discussed in a previous section, and the role of management decisions which may be errors seen f rom a safety point of view - in the adaptation to the requirements of functional effectiveness. Errors in management and planning are intimately related to the organizational attempts to adapt to the requirements of a competitive environment (cf. Perrow, 1986), just like the errors related to an individual's striving towards smooth, integrated performance at the skill- and rule-based levels and, like these, they cannot be avoided. The only reliable remedy is the introduction of error detecting and correcting features in the planning of the work context. At the organizational level, this approach requires, during operational optimization, a conscious, knowledge-based awareness of the constraints posed by the preconditions of safe operations as they are identified by the risk assessment performed during system design (Rasmussen, 1987d). It has, however, not always been fully realised that a risk analysis is only a theoretical construct relating a plant model and a number of assumptions concerning its operation and maintenance to a predicted risk level. This fact implies that when a plant has been accepted on the basis of the calculated risk, the model and assumptions should be taken to be <u>specifications for safe operation</u> which,, in turn, should be carefully monitored by the operating Organisation through plant life.

An important implication of a design philosophy based on extensive use of safety and standby equipment which is not normally in operation is that many errors and faults do not directly reveal themselves. Humans can operate with an extremely high level of reliability in a dynamic environment when slips and mistakes have immediately visible effects and can be corrected. Survival when driving through Paris during rush hours depend on this fact. In a system designed according to the defence in depth principle, several independent events have to coincide before the systems responds by visible changes in behavior. Consequently, violation of safety preconditions during work on the system may not result in immediate functional response and the effects of erroneous acts can be latent in the system unless <u>thev are explicitly looked</u> for, with reference to the specifications given by the risk analysis.

Again, this aspect underlines to the importance of using a systematic risk analysis as the basis of decision support tools for risk management.

4. EVOLUTION OF CONTROL STRUCTURES DURING TRAINING

An important point of this discussion of the relation between human adaptation and error is that it is not the behavioral patterns of the higher levels that are becoming automated skills. Automated time-space behavioral patterns are developing while activity is controlled and supervised by the higher level activities - the basis for which in terms of knowledge and rules may deteriorate. In fact, the period when this is happening may lead to errors due to interference between a not fully developed sensorimotor skill and a gradually deteriorated rule system. This kind of interference is known to highly skilled musicians when they occasionally start to analyze their performance during fast passages. It seems to be plausible also that this ef f ect can play a role for pilots' of about 100 hours flying experience, which is known to be an error-prone period among pilots.

Following the lines of reasoning suggested above, the transfer of control to new mental representations is a very complex process involving change along several different orthogonal dimensions. First, when trained responses evolve, the structure of the underlying representation shifts from a set of separate component models toward a more holistic representation. This is discussed by Bartlett (1943) in relation to pilot fatigue, and Moray (1987) analyses how such model aggregation can lead process operators into trouble during plant disturbances, because the process is irreversible, i.e., the regeneration of part-models needed for causal reasoning in unfamiliar situations is not possible from the aggregate model. The learning model implied in the skill-rule-knowledge framework indicates that skill aquisition involves more than an aggregation of mental models. Typically, control by a structural, functional model will also be replaced by empirical procedural knowledge concurrent with a shift from a symbolic to a stereotypical sign interpretation of observations. This means that training involves at least three concurrent and structurally independent changes, in terms of aggregation, of the shift of functional->procedural knowledge, and of a symbol->sign shift in the interpretation of information.

If this model of learning a skill is accepted and skill/rule-based performance is characteristic of professional activities in general, one would expect the basic causal or functional understanding to deteriorate. This is in fact what is found by Ackermann and Barbichon (1963) from their analysis of the organization of knowledge and the explanation of phenomena as presented by electrical and chemical technicians in industry.

5. CONCLUSION: IMPLICATIONS FOR SYSTEM ANALYSIS AND DESIGN

Several important conclusions can be drawn from this discussion. First of all, human errors are not in general to be considered stochastic events for which statistical data can be collected independent of the structure of the task and task environment. Errors are tightly related to the cognitive control of behavior, and several important error categories are manifestations of the efficient human adaptation to system characteristics.

System analysis includes the analysis of the effects of human error in a given design concept and for this task important conclusions can be drawn of the present discussion: A taxonomy of psychological mechanisms which are potential causes of human error is emerging which can be used for analysis of the sensitivity of a design to error by an error-mode-and-effect analysis. An important f eature is that the great variety of erroneous actions can be accounted for by a limited number of basic mechanisms, making an analysis practically feasible. A crucial part of an analysis is evaluation of the observability and reversibility of the effects of error immediately by the actor. For this problem, the conceptual model relating error mechanisms to the cognitive control of action is mandatory.

Design of safe system implies the decision whether to change a design in order to remove the human errors identified by the analysis or to compensate their effects. In order to resole this question, it is practical to consider different categories of error mechanisms. The discussion presented in this paper tend to show four such categories (which, by no means, should be considered mutual exclusive, only illustrative for the discussion):

1. Errors depending on stochastic human variability appear to be only a minor group, typically related to features like accuracy of force applied or movements in manual skills, precision in recall, etc. For safety related analysis and design they are, probably, not very significant because they can be considered single events not introducing systematic couplings between actions. In addition, this variability will be necessary for some learning modes.

2. Errors due to inadequate **resource.** is an important category during unfamiliar system conditions and should be carefully considered by interface design. 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. 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 (Vicente and Rasmussen, 1987)

3. Errors related to interference between internal control structures, i.e. , between dynamic patterns of movements, between cues and rules for action, or between mental models. For this category, design of interfaces that will support cognitive control thereby minimizing likelihood of interference can be considered (Rasmussen and Vicente, 1987).

4. Errors related to learning mechanisms are reflections of human adaptation to the particular system and probably neither can, nor should be removed by redesign. In stead, focus should be on support of learning opportunity and experiments while, at the same time, trying to control the effects of errors. The task of a designer is to aim for error-tolerant systems in which errors are observable and can be reversed before unacceptable consequences develop or, in other words, they will have to stabilize the performance of the variable human component by a feedback function as it is always done with less then adequately stable technical components. In other words, regarding the human role in modern systems, human errors should rather be considered to be "unsuccessful experiments in an unfriendly environment", and design efforts should be spent on creating friendly, i.e. error tolerant, systems.

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Abstract (Max. 2000 char.)

Human error taxonomies have been developed from analysis of industrial incident reports as well as from psychological experiments. In the paper, the results of the two approaches are reviewed and compared. In both cases, it is found, a fairly low number of basic psychological mechanisms will account for the majority of action errors observed. In addition, error mechanisms appear to be intimately related to the development of high skill and know-how in a complex work context. This relationship between errors and human adaptation is discussed in detail for individuals and organizations. The implications for system safety is briefly mentioned, together with the implications for system design.

Descriptors

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