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TRENDS IN HUMAN RELIABILITY ANALYSIS[1]

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Abstract: The approach to human reliability has been changing during the last decades, partly due to the needs from probabilistic risk assessment of large scale industrial installations, partly due to a change within psychological research towards cognitive studies. In the paper, some of the characteristic features of this change are discussed.

Definition of human error and judgement of performance are becoming increasingly difficult concurrently with the change of tasks from routine activities towards decision making during abnormal situations. The nature of human error and the relationship with learning and adaptation are discussed, and the recent development of models of cognitive mechanisms behind errors is mentioned.

The present approaches to human reliability within different application areas are reviewed. In industrial risk analysis, attempts are made to develop models of operators' decision making during emergency situations, and to obtain the necessary error data by simulator experiments and by systematic use of expert judgement. Simplifying assumptions are necessary for analytical risk assessment including human activities, and to make the results practically acceptable, a close co-ordination of risk analysis and risk management during operation appears to be necessary. In work safety, the analytical approach of risk analysis seems to be fruitful as a supplement to statistical analysis of accident reports, in particular if supported by application of cognitive models to judge the psychological feasibility of improvements. Finally, an approach to the study of traffic safety from the point of view of intentions and reasons behind behaviour is reviewed and related to the cognitive models described.

The question is finally raised as to whether the development of cognitive models will be able to serve a more effective transfer of results between these traditionally rather separate lines of research.

INTRODUCTION

The approach to human reliability analysis has been changing significantly during the recent decade, partly due to new requirements from industrial safety assessment, partly as a consequence of a change in research paradigms within psychology towards cognitive studies. The aim of the present paper is to present for discussion some topics in this development which, from my personal point of view are important. It has not been my aim to present an exhaustive review, and parallels from my experience with human reliability in process control will be drawn to fields from which I have only second hand experience.

The concept of human reliability implies the interaction of humans with an environment, and an occasional failure of this interaction to meet some-

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body's expectations. The concept, therefore, depends on three elements: an acting human, an environment which responds in a way not matching some criteria of goodness, and a judge having references for judgements and a specific aim with the analysis of performance.

The effect of the unsuccessful performance may be immediate injury to the acting person or, through the work context, loss of production, damage to equipment or injury to third person. The approach to analysis and improvement of human reliability have therefore been pursued by research groups with different aims and traditions. Consequently, the approaches have been different and have typically been discussed under the labels of "work safety" and "reliability and risk assessment", respectively. Discussions of human reliability inevitably raise the question of "human error". The definition of human error adopted, is closely related to the identity and situation of the person who is judging the particular incident.

As mentioned, the approach to the problem of predicting human reliability has been changing in two respects. First of all, a change has been caused by the rapid technological development. The trend towards large, centralised installations for which consideration of human involvement in complex, rare events for which direct empirical probability data are not available, has given rise to an analytical approach based on the concept of "human errors" seen as elements of human behaviour for which data can be collected for use in prediction of performance in future systems. Concurrent with this development, there has been a swing from the more strict "behaviouristic" schools of psychology towards studies of mental processes, which directly leads to an interest in the cognitive mechanisms behind "human errors". This will be discussed in some detail since the perception of the nature of "human error" in general determines the approach taken towards the improvement of human reliability.

JUDGEMENT OF HUMAN ERROR

Assignment of the cause of unsatisfactory performance to less than adequate human reliability depends on a judge who identifies a case of "human error". This judge may be the acting person himself or another person trying to explain an accidental event after the fact. For the acting person, the question of error is typically rather clear, since a reasonable reference for judgement will be the intentions behind the act. In general people know very well what they "intended" to do and realise their slips, i.e., the acts were not as intended, and their mistakes, i.e., the effect did not turn out as expected, given the acts.

However, frequently the judge will be somebody else who judges the effect of the act, often with some substantial delay and probably without having been present on site, such as supervisors, inspectors from safety authorities, insurance investigators or court judges. In that case the identification of errors will depend on an analytical backtracking from the effect of the unreliable performance until a cause has been identified. This cause may be inappropriate performance of a human, and hence a human error is found. However, the decision to cease search, i.e., the stop rule applied, depends on purely pragmatic considerations.

When considering manual routine tasks such as manual assembly tasks, repair and calibration, there will be no great ambiguity in the identification of human errors. In general, such tasks can be decomposed into more or less separate, manual routines , and analysis can be based on the overt activity which to a large extend is controlled and sequenced by the physical work content. Another important feature is that many tasks have been repetitive, and that performers have reached a stable level of skill and their "normal performance" can be identified and used as a reference for judgement.

The application of modern information technology is rapidly changing the basis of these assumptions. Automation has removed many repetitive tasks and given humans the role of supervisors and trouble-shooters. This means that their performance is more related to decision making and problem solving, involving cognitive information processing related to diagnosis, goal evaluation, prioritising, and planning. Such mental functions are much less constrained by the external task conditions than purely manual tasks. They can be solved successfully by several different strategies and the individual choice will depend on very subjective criteria (Bruner et al., 1956, Rasmussen et al. 1974, Pejtersen, 1979). Another important point is that performance in a task can no longer be assumed to be at a stable level of training. Learning and adaptation during performance will be significant features of many situations which are now the typical sources of case stories involving human errors in industrial accidents.

When performance can no longer be judged with reference to a stable, normal performance, the definition of "human error" becomes dubious. Considering a highly skilled performance of a task there will generally be no difficulty in identification of errors and no dispute between a performer considering his actual goals and intentions and a posterior analysis. However, considering performance during complex, abnormal situations which are part of an accidental scenario there is no clear reference for the judgement of "errors". They are found during the search for "causes" in the accidental chain of events, but the identification in terms of component fault, operator error, manufacturing error, or design error depends entirely upon the stop rule applied for termination of the search. This stop rule will be purely pragmatic and be something like: An event will be accepted as a cause and the search terminated if the causal path can no longer be followed, or if a familiar, abnormal event is found which is therefore accepted as explanation, and a cure is known. The dependence of the stop rule upon familiarity and the availability of a cure makes the judgement very dependent upon the role in which a judge finds himself. An operator, a supervisor, a designer, and a legal judge may very likely reach different conclusions.

It is the fate of the humans involved in accidental courses of events that everybody in hindsight, and typically lacking definitive evidence for the cause, can imagine a cure for human errors in terms of more care, better training or instruction, or direct punishment. Paradoxically, human errors seem to be allocated under two typical circumstances. On one hand, human errors are found when normal human variability occasionally brings task performance outside acceptable limits. On the other, human errors are found when human variability or adaptability proved insufficient to cope with variations in task content; i.e., if it was found, on hindsight, that a "reasonable" human ought to be able to cope with disturbances. Frequently, the concept of a "reasonable" person seems to assume much more rational thinking in human behaviour than is to be expected during a familiar task.

THE NATURE OF HUMAN ERROR

The nature of the tasks in modern systems, being related to supervisory control involving problem solving and decision making in which adaptation to unfamiliar situations is crucial, makes it very doubtful whether a category of behaviour called errors can be meaningfully maintained and, consequently, whether "error data" can be collected for reliability prediction. Basically, human "errors" should be seen as a result of human variability which is an integral element in human learning and adaptation (Rasmussen 1984).

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. Errors, then, have a function in developing and maintaining a skill, and they neither can nor should be removed. Also at the more consciously controlled **rule-following** level, development of know-how and rules-of-thumb are depending upon a basic variability and opportunity for experiments to find shortcuts and identify convenient and reliable signs which make it possible to recognise recurrent conditions without analytical diagnosis; in short, to develop quasi-rational heuristics. Involved in genuine **problem solving**, test of hypothesis becomes an important need. It is typically expected that operators check their diagnostic hypothesis 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. And-"the best simulation of a cat is - a cat." In this way, acts which on afterthought are judged to be mistakes, may very well be reasonable acts intended to gain information about the actual state of affairs. 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.

The view that "errors" are integral parts of learning mechanisms has long roots. Already Ernest Mach (1905) notes: "Knowledge and error flow from the same mental sources, only success can tell the one from the other", and Selz (1922) found that errors in problem solving were not stochastic events, but had to be seen as results of solution trials with regard to a task, which is somewhat misconceived. Hadamard, the mathematician, states (1945): "-- in our domain, we do not have to ponder with errors. Good mathematicians, when they make them, which is not infrequent, soon perceive and correct them. As for me (and mine is the case of many mathematicians), I make many more of them than my students do; only I always correct them so that no trace of them remains in the final result. The reason for that is that whenever an error has been made, insight - that same scientific sensibility we have spoken of - warns me that my calculations do not look as they ought to".

The consequence is that the ultimate error frequency is largely depending upon the features of the work interface which support immediate error recovery which in turn depends on the observability and reversibility of the emerging unacceptable effects. The feature of reversibility largely depends upon the dynamics and linearity of the system properties, whereas observability depends on the properties of the task interface which will be dramatically influenced by the modern information technology.

Error observability depends on the perception of a mismatch between the expected and the actual response of the work environment to the human acts. The information needed for control of actions and for observation of errors may be very different, and be related to different time spans and levels of abstraction. The information used en route to control activity in pursuit of an intention or a goal may be totally unrelated to the intention itself. In a habitual rule-based sequence of skilled action patterns, the individual patterns are released by stereotype cues. Judgement of system responses in terms of intended outcome may require a concurrent analytical evaluation at the knowledge-based cognitive level - or something like Hadamar's "scientific sensibility.

Whether the knowledge required for this is maintained and the appropriate information present depends very much on details in the human-task organisation. This means that human errors cannot be studied in isolation, and generic error data characterising human performance cannot be collected independent of the context of the performance. Error frequencies derived from incident reports will be very much dependent upon the task characteristics and the opportunity for people to detect and correct the errors immediately.

It also follows, that "human error" it not a separate psychological research field. The topic can only be studied as a feature of human performance in general. Only quite recently has research in cognitive psychology again taken up the interest in such studies (Reason, 1982; Norman, 1981). Their findings match very well our analysis of industrial accidents (Rasmussen, 1980), and indicate that the great variety of errors can to a large degree be explained as the effect of a very limited number of psychological mechanisms when folded onto the variety of the work environment - as Simon (1969) argues: --man is quite simple, complexity of his behaviour reflects largely the complexity of the environment. The practical consequence of this condition has been that studies of human reliability have taken different directions depending upon the structure of the work context. Particularly visible is the distinction between human reliability studies related to **risk assessment** of industrial process plant, which are functionally bounded and well structured; vehicle control and **traffic safety** which imply highly skilled continuous control; and **work safety** which is related to immediate physical interaction in a rather unstructured environment. The recent interest of cognitive psychology in human adaptive mechanisms and their significance for errors now seem to lead to model frameworks which may be able to relate the findings in these hitherto separated areas.

HUMAN RELIABILITY IN INDUSTRIAL RISK ASSESSMENT

The industrial trend towards very large centralised production units has led to a drastic potential for losses and injuries in case of malfunction. This potential has been released in several major accidents, and has led to large efforts in development of methods for probabilistic risk assessment. Nuclear power has recently been leading in the development of prediction techniques, and although it has long been realised that it is necessary to consider human reliability prediction as an important ingredient, the efforts to develop suitable prediction tools have increased dramatically since the Three Mile Island reactor incident.

TRENDS IN HUMAN RELIABILITY ANALYSIS

The methods used for human reliability prediction were until rather recently closely related to the models used for technical reliability analysis. In analogy to the decomposition of a technical system into components for which empirical reliability data are available, human activities are broken down to elementary task units for which reliability figures are sought in terms of error rates. The methods of analysis are related to the tradition from Tayloristic work studies and are compatible with behaviourist psychology, only being dependent on observable categories of human activities. In consequence, they are depending on a model of successful or normal task performance, rather than on a model of human behaviour. In general, prediction was limited to prediction of the probability of success in a task, and therefore can be based on gross error data, i.e. whether an act was successfully performed or not. This is the primary aim of analysis of performance related to industrial production and military missions, and the approach will be adequate as long as only routine tasks are considered for which a stable level of training can be reached and, therefore, a "normal" task sequence identified as reference for judgement of errors. Such methods were developed and refined in particular by Alan Swain for analysis of human activities related to manufacture and handling of nuclear weapons, and have been applied extensively in safety analysis of nuclear power plants since they were first used in the now well-known "WASH-1400" report on nuclear safety. The method is well documented in a recent handbook, (Swain et al. 1983), in which an attempt is also made to extend this "behaviourist" approach to cover higher level diagnostic (cognitive) activities, which clearly appeared to be necessary after the extensive analysis of the Three Mile Island and other major incidents.

Another line of development was pursued by Siegel and Wolf who developed simulation models of human performance based on a conception of activities as a network of tasks similar to PERT models (Siegel et al., 1969), and which can be used for Monte Carlo simulations to determine time spent, work load and probability of success. The method has primarily been used for military missions, but has recently been suggested for maintenance activities in power plants (Siegel et al., 1984).

Other studies of operators' roles in industrial accidents have shown a difficulty in performing a reliable diagnosis during disturbances (Rasmussen, 1969, 1980) and the need to include cognitive tasks in human reliability analysis. In addition, it became clear (Rasmussen, 1979) that it was not sufficient to predict the probability of success in a task, the probability of particular, risky erroneous actions should also be estimated. The consequences of this has been a need of a structured taxonomy to distinguish between different human "error modes" and to be used in planning of practical data collection. This problem was studied by an OECD group of experts and a taxonomy proposed (Rasmussen et al., 1981), but in spite of the efforts made to establish useful data bases of human error, reliable error data remained scarce, partly because of difficulties in establishing the proper on-site analysis of data, partly because of difficulties in defining and quantifying the denominators of error rates, the frequency of opportunities for error. This situation has led to several different lines of development.

The interest in operators' diagnostic performance after the TMI incident led to a number of careful analyses of real-life cases (Pew et al., 1981; Woods, 1982) and of training simulator sessions (Woods et al., 1981). These studies have given important information for the efforts to develop models of cognitive functions during emergency situations and for the development of predictive risk analysis.

In one line of development, attempts are made to include operators' decision making in the prediction, and it is realised that generic error data cannot be obtained. Therefore, the approach is focused on those task sequences which, from a preceding probabilistic risk analysis, are found to be critical, and data are collected for relevant categories of activities in training simulators. The operators' roles in a critical course of events are analysed by means of "operator action trees" (Wreathall, 1982) which represent the branching of paths towards success or failure depending upon the operators' choice at various stages in decision making, including also recovery from errors. These models are descriptive models based on the studies mentioned above. To some extent, the approach also makes it possible to predict the consequences of erroneous decisions, since the direction of branching in the action tree is identified from consideration of "confusion matrices" representing the cue sets of a whole repertoire of operating instructions. Data for a first order quantitative estimation in this approach have been sought in training simulator sessions. Fragola observed from the evidence (Hall et al. 1982) that error data from training simulators are clustered in three categories when plotted in lapsed-time/probability-of-termination plots, and has proposed the hypothesis that these categories are correlated with levels in the cognitive control required, i.e. whether performance is based on manual skills, know-how rules, or analytical problem solving. This proposal has been developed further by Hannamann et al.(1984), and the method seems to offer a first approximation for prediction of operator responses to accidental events based on data collected from an identical work context.

One major problem with this approach is that it is only applicable for those installations and tasks for which empirical data are available. Consequently, several attempts have been made to get error data from other sources. One approach has been generation of data by "expert judgement". Subject matter experts are asked in a structured way to generate error frequencies and the data are then tested and verified in different ways. This approach has been advanced in particular by Embrey et al. (1984). The method is not as yet well established. For instance, the identification of "experts" leaves some open questions, as does the delimitation of their domain of expert intuition.

Even though these methods may turn out to be successful, they will only be useful for systems for which data or expert intuition are well established, not for designs based on new technology such as for instance computer based decision support systems. This has led our group at Risø to try to turn the problem around, saying that designs should only be accepted if the human contribution to risk can be estimated (Rasmussen et al. 1984). The consequence of this view in terms of requirements for the design will be the need to consider several different categories of human activities in a system. One includes activities for which the effect of human errors is in the categories already identified from component faults and for which the human contribution to the total probability will be insignificant compared with the general quality of data. This category calls for no further analysis. Another category includes human activities for which the reliability can be estimated from data collected in other systems, as for instance for test and maintenance activities. A further category includes human activities for which no predictive model is presently available and which can have significant influence upon the basic assumptions behind a risk analysis by introducing couplings between otherwise independent events. Examples are operator responses to plant emergencies during which one may find incorrectly performed emergency procedures based on incorrect diagnosis, or inappropriate interference with protective systems due to miss interpretation of their behaviour . In that case an error tolerant design is considered necessary so that the prediction can be based on a feed-back consideration: probability is bounded by the reliability of detection and recovery. If this is not possible, human interference with critical functions should be controlled by interlocks or physical barriers.

Another fundamental aspect of this approach is the reliance on risk management by feed-back of operating experience. Any attempt to predict risk and reliability will depend on a set of simplifying assumptions, and the reliability of prediction clearly depends on the adherence of the system with these assumptions. The problem is, therefore, not to predict human reliability in a particular system design, but rather to design systems in which human reliability for critical functions can be predicted with the available methods under explicitly formulated assumptions. These assumptions should then afterwards be considered specifications for acceptable operation and, consequently, controlled by an "operations quality assurance" program.

WORK SAFETY

Another approach to analysis of human reliability has been taken in studies of work safety. In contrast to the situation in the industrial risk field, there is no lack of empirical event data in the work safety field. Data have been collected systematically for nearly a century by work safety authorities and analysed by routine. The data available in these data bases have typically been used for different kinds of correlational analysis and epidemiological studies, considering only rather general features, such as branches of industries, types of machinery, level of education, error proneness of individuals, etc. These analyses have generally been useful for insurance purposes and for management of safety measures. The analyses have been based only on the information available from the accident reports collected by the various authorities. More detailed analysis requires careful consideration of the work processes which have been the source of the event reports. During the latest decade there has been an increasing interest in a more functional approach to the analysis of work accidents, and attempts have been made to transfer the methods of analysis which have been used for the study of safety of technical systems. This has led to studies of work accidents considered as the consequence of deviations from the normally successful work process (for a recent review, see Kjellen, 1984). In addition to the data in the accident reports, the approach requires a detailed description of the actual, normal not the prescribed, normative - work process in order to have a reference for identifying the "deviations". This is a considerable task if reliable conclusions and generalisations are to be made. The most systematic formulation of the method is the "variation tree analysis" developed by the French INRS institute (Leplat, 1978). Compared with the purely statistical analysis of accident reports, such functional analyses add immensely to the understanding of the accident mechanisms, and more detailed and constructive suggestions for improvements can be derived from the identification of recurrent deviations from a joint analysis of a larger set of accident reports.

However, since the analyses incorporated in the variation diagrams are still at the purely behaviourist level and expressed in overt task terms, the proposals for improvements which can be identified are rather general in nature, such as improvement in machinery, better adherence to safety precautions, more training, etc. From such analysis alone it will not be possible to judge whether the proposals are psychologically feasible. In a highly skilled, automated manual task it will not, for instance, be effective to ask a worker to remember safety related work procedures which are only occasionally necessary ("remember, that the safe distance to the car in front is twice the braking distance at the speed you are driving"). To avoid a given accident in the future, someone in the total system, a designer, a supervisor, or a worker, will have to take a decision different from the one related to the accident. However, a proposal to do so should be directed to someone for whom it is psychologically possible to change his decision in the practical situation, i.e., a person who will be in a conscious decision situation, not an automated routine.

There seems to be a possibility for a combination of the "variation tree analysis" and a model of the cognitive control of human activities and the related mechanisms leading to "human errors" discussed above (Leplat et al., 1984). This approach implies the development of variation diagrams from a set of related accident reports by an analyst closely familiar with the work conditions. These diagrams are not analysed in order to identify typical causes of accidents as usual, rather each diagram is analysed to identify all the points at which the course of event would have been terminated if decisions or conditions had been different, i.e., an identification of possible "variations" towards safety. Finally, it is considered where in the total system including equipment designer, work planner and supervisor, and worker, it would be psychologically feasible to propose a change in decision. First at this stage is the analysis screened for ad-hoc proposals by statistical analysis. This approach should be able to identify very specific improvements based on a more effective use of the available accident data by a supplement of detailed information on the "normal" work situation. The proposal is at present subject to practical test.

TRAFFIC SAFETY

In general, consideration of human reliability in vehicle control has traditionally followed a separate line of development. The task is typically a highly integrated behavioural pattern which cannot be decomposed into elements for separate data collection. Consequently the classical approach has been to collect data from real life performance or simulator studies in terms of error rates with time as the denominator, rather than opportunities for error, and to relate these to general conditions by correlation analysis. Pilot behaviour has been studied as stochastic processes and error data collected from simulation sessions (Regulinsky, 1976). In general, however, the research on traffic safety has been from the point of view of social psychology (Wilde 1976). Accidents have been related to the actors' risk perception which 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. The general conclusion being 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.

This point of view has been stressed by Taylor who applies a hermeneutic analysis of traffic accidents. He has observed that drivers tend to try to keep their arousal at a desired, constant level, and consequently if conditions become too undemanding, will go faster to generate more arousing incidents (Taylor, 1980). The consequence will be that safety is hard to improve beyond a certain limit. It seems as if the reason for accidents may be an intention to take a risk, and Taylor (1981) 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 reason for a discussion 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. 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.

If the view that control of behaviour depends on a balance between a drive towards optimising skills and the constraints posed by the environment in terms of risk, the mechanistic studies of human errors in process systems and the social studies of traffic safety seem to close in on the same problem of the fundamental control of human behaviour from the two opposite sides. A fruitful exchange should then be possible. The uniformity and extent of for instance the task of car drivers make possible studies of social factors in risk acceptance which would be very difficult in process plant environments, where they are probably equally important. It is known that management styles in industrial process plants may be as different as between a faculty of a technical university and a submarine, but little is known about the influence on risk perception and adaptive modifications of formal procedures.

CONCLUSION

The conclusion of this discussion will be that the development of cognitive models of human performance is very much needed in response to the requirement for assessment of human reliability in higher level decision tasks in modern systems. The effect of this development seems to be a greater possibility of cross fertilisation between the different approaches to human reliability. It also seems to be important to realise that the scientific basis for human reliability considerations will not be the study of human errors as a separate topic, but the study of the normal human behaviour in real work situations and the mechanisms involved in adaptation and learning. The findings may very well lead to design of more reliable systems, without improving the basis of quantitative prediction of reliability in the higher level mental tasks required in new systems.

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