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HUMAN ERRORS IN PROCESS CONTROL

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"Knowledge and error flow
from the same mental sources,
only success can tell the one
from the other."

Ernst Mach 1905

Position paper for NATO Workshop on the Origin of Human Error,
September 1983, Bellagio, Italy.

DEFINITION AND CHARACTERISTICS OF HUMAN ERRORS

Basically it is very difficult to give a satisfactory definition of human errors. Frequently they are identified after the fact: If a system performs less satisfactorily than it normally does due to a human act or to a disturbance which could have been counteracted by a reasonable human act – the cause will very likely be identified as a human error. When compared with technical components, human operators have some peculiar features which must be analysed more closely to see whether the present general. attitude towards faults and errors is reasonable and expedient. How are faults and errors defined?

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 the present man-machine context we can define faults and errors as <u>causes of unfulfilled system purposes</u>. If system performance is judged below the accepted, present 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 o r 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 break-down, a "component" failure is generally accepted as the cause at the component level where replacement is convenient. In some cases, however, component failure will not be found an acceptable cause; for example, if it occurs too frequently. In such cases, the search will often continue to fin 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. In all these respects, the human operator is in an unlucky position. Due to human complexity, it is generally very difficult to "pass through" a person in causal explanations. In addition, it is generally accepted that "it is human to err" and finally, you can always ask people to "try harder".

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. Ultimately, a thorough analysis will always end up with a human error, probably during design or manufacture, or by an act of God.

ERRORS AS UNSUCCESSFUL EXPERIMENTS IN AN UNKIND ENVIRONMENT

A more fruitful point of view is to consider 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 typically caused by variability on part of the system or the man and can be considered system failures or human errors, respectively.

However, 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. Typically they 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 effect's of his "errors", or because they are irreversible.

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*.

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.

THE SKILL-RULE-KNOWLEDGE FRAMEWORK

To discuss the interaction between an occasionally changing system and a varying and adaptable human, we have to consider the different ways human behaviour can be controlled, depending upon the degree of familiarity of 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.

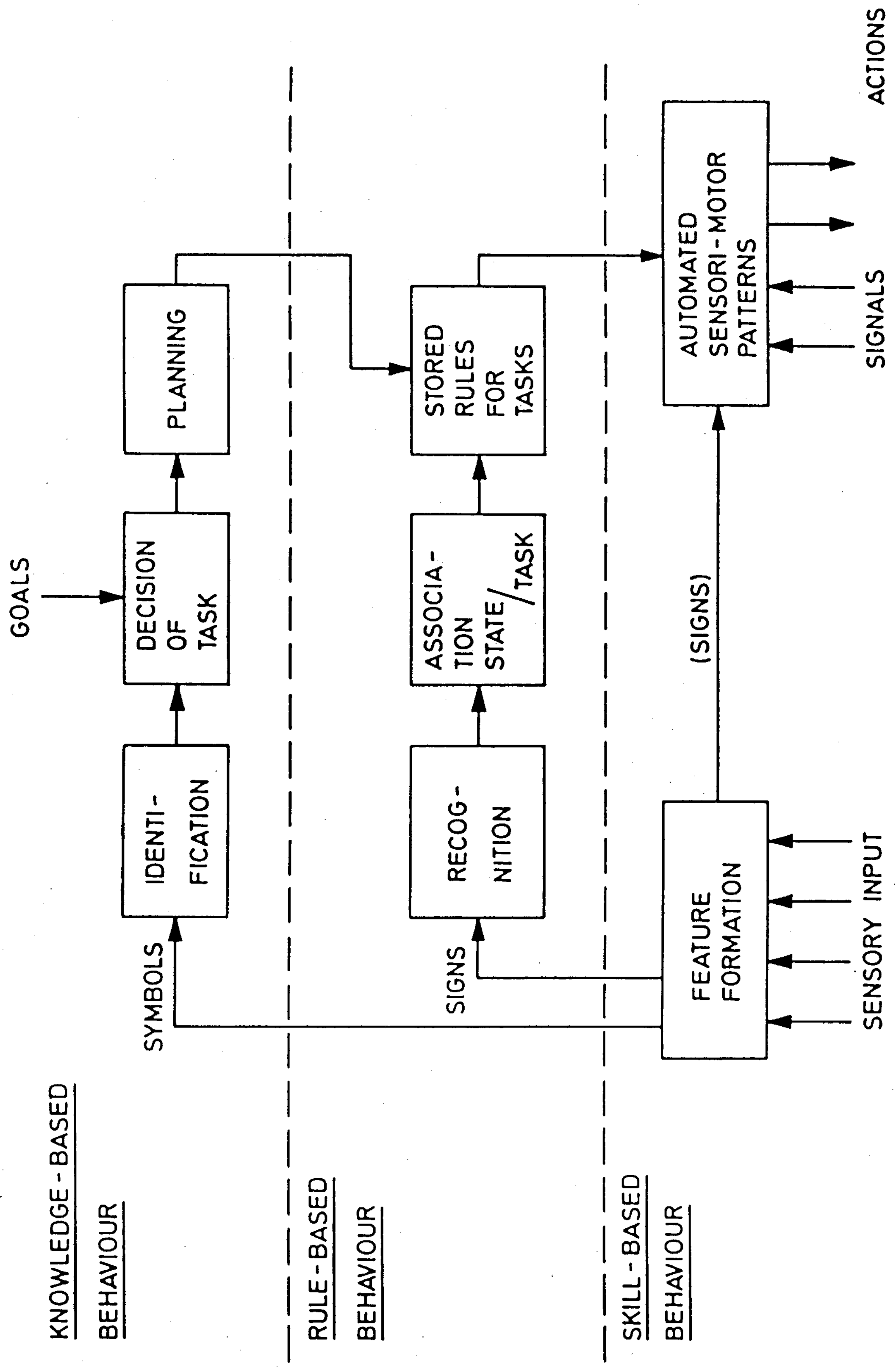

Figure 1

The <u>skill-based behaviour</u> 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 <u>signals</u>, 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 <u>signs</u> activating the organism. Performance is based on feedforward control and depends upon a very flexible and efficient dynamic internal world model.

At the next level of <u>rule-based behaviour</u>, the composition of a sequence of subroutines in a familiar work situation is typically controlled by a <u>stored rule</u> 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, bull 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 <u>Signs</u>. 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 mav 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.

Within this framework we will discuss different typical mechanisms which can lead to man-system mismatch.

MECHANISMS BEHIND MAN-SYSTEM MISMATCHES

Discussing these mechanisms, we are considering those occasions when a man-system interaction is judged a mismatch which needs correction - either by the person himself or by somebody else, we are not considering the success of the correction - i.e. the ultimate effect of the mismatch. Typically, mismatches are corrected immediately by the person, but the success of the correction depends very much upon qualities of the task and environment, such as observability and reversibility, and must be 'discussed separately from the mechanisms behind the initial mismatch which led to a corrective action or adaptive change in behaviour.

Human Variability during Familiar Tasks

We will first consider intrinsic human variability which leads to mismatches during normal work situations, i.e. we consider the effect of variability upon skill- and rule-based behaviour.

Motor variability. The time-space precision of sensori-motor control may not be adequate for the task at hand, leading to occasional mismatches.

Examples:

- Inadequate precision leads to short-circuit of terminals with screw driver.

- Inadequate precision in replacement of relay cover leads to short-circuit of relay terminals.
- Varying use of force in manipulating a bank of valves occasionally leaves a valve leaking.

Topographic mis-orientation is another mechanism of mismatches during sensori-motor performance, occurring when the internal world model of some cause looses synchronism with the external world.

Examples:

-A failure in one of several pump trains in the basement leads to the decision in the control room to switch off the "north train". However, during passage down stairs an operator looses orientation and switches off the southern train, even though he has the proper intention.

These are mechanisms within a single motor schema; other mechanisms are related to the fact that skilled operators have a large repertoire of schemas, and that a schema may involve a long sequence of acts. A single conscious statement of intention may activate a schema, whereafter the attention may be directed towards planning of future activities or monitoring the past. The current, unmonitored schema will then be sensitive to interference leading to stereotype-take-over. This means another schema takes over the control, either because a part of current action sequence is also part of another frequently used schema, or due to interfering intentions of the detached attention.

Examples: -

- During normal operation of a process plant the power supply to the instrumentation disappears. Investigation reveals that the manual main circuit breaker in the power supply is in the off posit--'on. The conclusion was that a roving operator, checking cooling towers and pumps, inadvertently had switched from a routine check-round to the Friday afternoon shutdown check-round and turned off the supply. The routes of the two check-rounds are the same, except that-, he is supposed to pass by the door of the generator room on the routine check, but to enter and turn off the supply on the shutdown checks. Something "en route" obviously has conditioned him for shutdown check (sunshine and day dreams?). The operator was not aware of his action, but did not reject the explanation.
- An experimental plant shuts down automatically during normal operation due to inadvertent manual operation of a cooling system shut-off valve. The valve control switch is placed behind the operating console, and so is the switch of a flood-light system, used for

<u>special</u> operations monitored through closed circuit television. The switches are neither similar nor closely positioned. The operator has to pass the valve switch on his way to the flood-light switch. In this case the operator went behind the console to switch off the flood light, but operated the shut-off valves which caused plant shutdown through the interlock system.

- During start-up of a process plant, the plant is automatically shut down during manual adjustment of a cooling system. During start-up the operator monitored the temperature of the primary cooling system and controlled it by switching off and on the secondary cooling pumps to avoid water condensation in the primary system due to the cold cooling water. On this occasion, he observed the temperature to pass the low limit, signalling a demand to switch off the secondary pumps, while he was talking to co-operator about another matter over the phone. He then switched off -,he primary pumps and the plant immediately shut down automatically. He did not recognize the cause immediately, but had to diagnose the situation from the warning signals. The control keys for the two sets of pumps are positioned far apart on the console. However, a special routine exists, during which the operator the primary pumps on and off to allow an operator in the basement to adjust pump valves after pump overhaul while they communicate by phone. Is the event caused by schema interference due to the phone call?

Since the repertoire of automated sensori-motor schemas and their complexity increases with ' the skill which operators develop during their daily interaction with their system, the role of this kind of mismatch becomes more important with their experience, and can only be counteracted by making systems more “error" tolerant.

At the rule-based level, human variability during performance of the normal, familiar tasks is most frequently found as incorrect recall of rules and know-how. A characteristic category is <u>forgetting an isolated</u> item, i.e. which is not an integrated part of a larger memory structure. Typical is <u>omission of an isolated act</u> which is not a necessary part of the main task sequence.

The fact that the omitted steps are frequently unrelated to the verbal label of the task may be a condition directly contributing to their frequency. Analysis of industrial fires led Whorf (1956) to the conclusion that "the name of a situation affects behaviour".

Examples are abundant:

- "Jumpers" not removed from terminals after repair, switches not turned back to "operation" after instrument calibration; by-pass valves not reopened after pump repair; cables not reconnected after instrument repair, etc.

In an analysis of test and calibration reports from nuclear plant, it was found (Rasmussen, 1980) that this category accounted for 50% of the analysed reports. The high frequency can be due to high initial probability, but can also be due to the fact that the isolated acts are less likely to be observed and corrected immediately by the person.

A closely related mechanism is the <u>incorrect recall of isolated items,</u> such as quantitative figures, numbers, etc.

Examples:
- Incorrect recall of numbers of valves and switches.
- Incorrect recall of figures, such as calibration references, set-points, instrument readings.

Another frequent mechanism of variability during familiar tasks is the mistake <u>among alternatives,</u> which frequently appears as incorrect choice of one of a couple of possible alternatives to use, such as left-right, up-down, plus-minus, A-B, etc.

Examples:
- Using positive correction factors instead of negative; using increasing, instead of decreasing signal in calibration.
- Disconnect pump A instead of B.

These are all mismatch events caused by human variability in normal, familiar task situations. Other mechanisms lead to mismatch, when humans fail to adapt adequately to variations and changes in the task environment.

<u>Improper Human Adaptation to System Changes</u>

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. This means that mismatches cannot - and should not - be avoided, but a system must be tolerant and not respond irreversibly. This discussion relates to mismatches which are needed to control adaptation within the skill-based level. More serious mismatch categories are met when changes in the environment are not met by proper activation of higher level control of behaviour.

Two types of mismatch mechanisms are related to improper activation of rule-based control: stereotype fixation, and stereotype takeover, similar to that discussed in the previous section.

Stereotype fixation represents the situation when a sensori-motor schema is activated in an improper context, and the person on afterthought very well knows what he should have done. He does not switch to proper rule-based control.

> Examples:
> - An operator presses air out of a plastic bag containing dust in order to seal it, although he knows it contains radioactive material. He gets contaminated in the face.
> - During a clean-up operation in a radioactive area, a vacuum cleaner fails. A foreman opens it for a possible rapid repair, despite the fact that he knows it contains radioactive dust.
>
> In both cases, normal everyday reactions are carried over to abnormal context. Also this appears to be a reasonable and effective learning mechanism - in a reversible context. Here the radioactivity makes the environment "unkind".

In other cases people realize the need for use of special procedures, but relapse to familiar routines, i.e. stereotype takes over because of overlapping sequence elements.

> Examples:
> - You have noticed icy road and decided to drive carefully, but when a dog enters the road you kick the brake and --.
> - An operator enters an emergency procedure and executes a sequence of actions correctly but then stops a pump, an act which follows the sequence in another, more frequently used procedure, but which is here wrong and risky.
> - An airplane is below acceptable altitude approaching a runway. The pilot orders "full power" and the co-pilot responds correctly but also retracts landing gear, resulting in a "wheels-up" landing. The act follows "full power" in low altitude, during take-off.

Subconscious control of sensori-motor sequences quite naturally has a high affinity to the very familiar routine sequences which are likely to "capture" (Norman, 1980) the control. As we saw previously, this interference can happen between sets of familiar sequences, but is more probable in less frequent situations when conscious rule-based control is needed. This is in particularly the case during situations when the need for forward planning occupies the conscious attention as soon as the necessary rule has been rehearsed, i.e. before it has been executed.

Similar difficulties in proper adaptation to system changes by switching to knowledge-based behaviour are caused by the reliance on signs during all familiar situations. The high efficiency of human interaction with objects and other persons of everyday life is due to a large repertoire of skilled subroutines and of rules, know-how for updating, the routines and linking them together. The control is based on recognition of the state-of-affairs in the environment in terms of signs, which relates to the appropriate rules by convention or experience. Even in direct interaction with the physical environment, will these signs be convenient correlates in the given context rather than defining attributes. This makes the interaction susceptible to mistakes if the environment changes in a way which does not affect the signs, but makes the related behaviour inappropriate. This is the basic idea behind all kind of traps.

In the direct interaction with a physical world, identification of signs takes place by perceptual categorization, which can be based on complex patterns and therefore also be rather sensitive to changes. This is typically not the case for human interaction with complex industrial systems, where operators are controlling more or less invisible processes. They have to infer the state and select proper actions from a set of physical measurements which is seldom presented in a way which allows perceptual identification of the state; operators are supposed to apply conceptual categorization based on rational reasoning, i.e. to exhibit knowledge-based reasoning. For several reasons, this leads to difficulties for human operators to adapt appropriately to changes in the system as for instance caused by technical faults.

The use of a set of measured variables requires knowledge of the system in terms of engineers' conception as a network of quantitative relations among variables. Natural language reasoning which is typically used for control of the systems, is, however, not based on nets of relations among variables, but upon linear sequences of events in a system of interacting components or functions. To circumvent the need for mental effort to derive states and events from the sets of variables and their relations, operators generally use indications which are typical for the normal events and states, including informal signals as motor and relay noise, as convenient signs for familiar states in the system. This is a very effective and mentally economic strategy during normal and familiar periods, but leads the operator into traps when changes in plant conditions are not adequately reflected in his set of signs. Such mental traps often contribute significantly to the operator's misidentification of unfamiliar, complex plant states. Therefore, to adapt performance to the requirements of a system in a unique and unfamiliar state, the operators must not only switch to knowledge-based reasoning based on a mental model of the system's internal, functional properties; he must also replace his perception of information as signs with an analytical interpretation symbols. This appears to be very difficult, since the use of signs basically means that information from the system is not really observed, but is obtained by "asking questions" which are heavily biased by expectations based on a set of well-known situations.

The difficulty in shifting to higher level analytical reasoning is further aggravated when inference must be based on a number of information sources which are sequentially attended. From analysis of verbal protocols recorded by skilled technicians in diagnostic tasks, we found (Rasmussen & Jensen, 1974) several principles in operation which served to minimize memory workload. Reading a sequence of measurements, they did not try to remember the original observations; each reading was immediately judged according to their expectations and only the result of the judgement was later to be recalled. Furthermore, they followed a "way of least resistance" in that they made a decision about what to do next, as soon as a familiar approach seemed to be possible, without considering the possibility of alternative, more effective ways. Rather, there seemed to be a "point of no return" which had the effect that information observed after a decision would rarely lead to a reconsideration of the situation.

Taken together, these aspects force one to draw the conclusion that there is a considerable probability that highly skilled operators with a large repertoire of convenient signs and related know-how will not switch to analytical reasoning when required, if they find a familiar subset of data during their reading of instruments. They will rather run into a "procedural trap" and be caught by a "familiar association shortcut".

Examples from major industrial incidents are legio, but my favourite case story tells about Lalande, who failed to switch from his rule-based recording of star positions to an analytical interest for moving stars (quoted from Bruner et al., 1956) - -

> The incident in question occurred in 1795, nine years after the discovery of the planet Uranus, and the principal figure involved was the great French astronomer Lalande. In that year Lalande failed to discover the planet Neptune, although the logic of events should have led him to it. Lalande was making a map of the heavens. Every night he would observe and record the stars in a small area, and on a following night would repeat the observations. Once, in a second mapping of a particular area, he found that the position of one star relative to others in that part of the map had shifted. Lalande was a good astronomer and knew that such a shift was unreasonable. He crossed out his first observation of the shifting point of light, put a question mark next to his second observation, and let the matter go. And so, not until half a century later did Neptune get added to the list' of planets in the solar system. From the aberrant movement, Lalande might have made the inference not that an error

> had been made but that a new planet of the solar system was present. But he was reasonable. And it was more reasonable to infer that one had made an error in observation than that one had found a new planet.

Or, from a butadine explosion in Texas City; the investigation considers:

> "Loss of butadine from the system through the leaking overhead line motor valve resulted in substantial changes in tray composition ..."The loss of liquid in the base of the column uncovered the calandria tubes, allowing the tube wall temperature to approach the temperature of the heat supply. The increased vinylacetylene concentration and high tube wall temperature set the stage for the explosion which followed". ..."The make flow meter showed a continuous flow; however, the operator assumed that the meter was off calibration since the make motor valve was closed and the tracing of the chart was a straight line near the base of the chart. The column base level indicator showed a low level in the base of the column, but ample kettle vapour was being generated."

Given an unstable flow meter, only wisdom after the fact will make you consider a leak.

From the melt-down of fuel elements in a nuclear reactor:

> Certain test required several hundred process coolant tubes to be blocked by neoprene disks. 7 disks were left in the system after the test, but were located by a test of the gauge system that monitors water pressure on each individual process tube. For some reason the gauge on one tube was overlooked, and it did not appear in a list of abnormal gauge readings prepared during the test. There was an additional opportunity to spot the blocked tube when a later test - was performed on the system. This time the pressure for the tube definitely indicated a blocked tube. The shift supervisor failed, however, to recognize this indication of trouble. The gauge was adjusted at that time by an instrument mechanic to give a midscale reading which for that particular tube was false. This adjustment made it virtually certain that no flow condition would exist until serious damage resulted.

<u>Errors during knowledge-based reasoning</u>. Once an operator has succeeded in shifting to analytical functional reasoning at the level of knowledge-based behaviour, it is very difficult to characterize his mental data processing and the related mechanisms leading to mismatch.

At the skill- and rule-based levels, behaviour is controlled by motor schemas and know-how rules, the goals are implicitly specified, and “error” mechanisms are described in terms related to established, "normal" action sequences in a rather behaviouristic way. At the knowledge-based level, this is not possible. The sequence of arguments an operator will use during problem solving cannot be described in general terms, the goal to pursue must be explicitly considered, and the actual choice depends on very subjective and situation-dependent features. At the skill- and rule-based levels, it is known per definition that adaptation to changes is within the human capability. This is not the case when knowledge-based performance is required during complex disturbances. Therefore, different kinds of mismatch situations may occur:

- Adaptation is outside the limits of capability, due to requirements to knowledge about system properties which is not available; to data which are not presented; or excessive time or workload requirements.
- Adaptation is possible, but unsuccessful due to inappropriate decisions, which result in acts upon the system, not conforming with actual requirements. It must be noted here that this is only "errors" if they are not corrected timely; as discussed below actions not conforming with system requirements can be an important element during problem solving.

In the present context only the latter category is considered, and again different typical categories of mismatch situations can be found during any of the necessary phases of the decision making, such as identification of system state; evaluations and choice of ultimate goals; and planning of proper action sequence:

- Human variability in a cognitive task, slips of memory, mistakes, interference from familiar lines of reasoning, etc. Mechanisms similar to those discussed above. They are difficult to identify or to use in prediction, when the problem solving process is as unconstrained as it is in a real life task in a control room.
- Errors caused by the difficulty of keeping track of sequential reasoning in a causal structure, which is in fact a complex network, unsuited for linear reasoning. The mental workload involved may lead to adoption of premature hypotheses from the influence of factors as the "way of least resistance" and the "point of no return", leading to lack of consideration of important conditions or unacceptable side effects of the ultimate decision.
- Actions not conforming with system requirements may not be related to the ultimate result of erroneous decision making, but a reasonable act to test a hypothesis or get information which, however, may bring the system into a more complex and less controllable state.
- The need for human decision making during disturbed system conditions basically depends on functional redundancy in the pur-

> pose/function/equipment relationships of the system. There is a complex many-to-many mapping between the levels in this hierarchy and during search for resources to resolve the various goals in a complex situation, operators may very likely be caught by familiar or proceduralized relationships serving goals which are not relevant in the present situation. Decision errors during complex disturbances are not stochastic events, but probably mistakes caused by interference in this mapping.

The conclusion is that in present day control rooms based on individual presentation of the measured variables, the context in which operators make decision at the knowledge-based level is far too unstructured to allow the development of a model of their problem-solving process, and hence, to identify typical "error" modes, except in very general terms, such as "lack of consideration of latent conditions or side effects" (Rasmussen, 1980).

As a basis for a useful model, the conceptual framework within which the operators have to make decision, has to be modelled in a consistent way in terms of the system's purpose/function/equipment hierarchy. As Simon notes (Simon, 1956) "the complexity of human behaviour largely reflects the complexity of his environment Before his behaviour can be modelled, a systematic description of his decision making context must be found in order to identify likely interferences. Secondly, realistic models will probably only be possible, if his choice of goals and strategies is more constrained and controlled than is the case in present day control rooms. This is possible if a computer-controlled presentation of a symbolic framework is developed, which may lead to skill- and rule-based problem solving in an externalized context.

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