DTU Library

The human data processor as a system component. Bits and pieces of a model

Rasmussen, Jens

Publication date:
1974

Document Version
Publisher's PDF, also known as Version of record

A. E. K. Risø

Risø-M-1722

Risø-M-1722

Title and author(s)

The Human Data Processor as a System Component
Bits and Pieces of a Model

Jens Rasmussen

Date June 1974

Department or group

Electronics

Group's own registration number(s)

R-8-74

51 pages

Abstract

During recent years the systems engineer designing control rooms for industrial process plants has been faced with complex human factors problems. In conventional control rooms the arrangement of meters, recorders, and control keys on the control desk and the choice of properly designed knobs and dials are the chief objectives for human factors consideration. The advent of computer-controlled display systems with the variety of modes for data conditioning and presentation available to support the operators calls for an integrated systems design. The formatting and encoding of displays should be properly matched to the characteristics of human mental data processing, and close interaction is needed between systems engineering expertise and psychology. For information and results from another professional area to be identified and digested an interdisciplinary working hypothesis or reference frame is needed, and the present report describes such a preliminary model aiming at the support of future reading, discussions, and experiments.

Using as reference the tasks of process operators, the report discusses the role of the perceptive generalizations, dynamic modelling and motor coordinative functions of subconscious data processing, and of the different types of mental models and procedures used in conscious data processing.

Revised edition of internal memo, N-30, June 73.

Copies to

Available on request from the Library of the Danish Atomic Energy Commission (Atomenergikommissionens Bibliotek), Risø, DK-4000 Roskilde, Denmark
Telephone: (03) 35 51 01, ext. 334, telex: 43116

XAVIER DE MAISTRE, 1794:

"Ce chapitre n'est absolument que pour les métaphysiciens. Il va jeter le plus grand jour sur la nature de l'homme: c'est le prisme avec lequel on pourra analyser et décomposer les facultés de l'homme, en séparant la puissance animale des rayons purs de l'intelligence.

Il me seroit impossible d'expliquer comment et pourquoi je me brûlai les doigts aux prémiers pas que je fis en commençant mon voyage, sans expliquer, dans le plus grand détail, au lecteur mon système de l'ame et de la bête. - Cette découverte ménta-physique influe d'ailleurs tellement sur mes idées et sur mes actions, qu'il seroit très-difficile de comprendre ce livre, si je n'en donnois la clef au commencement.

Je me suis apperçu, par diverses observations, que l'homme est composé d'une ame et d'une bête. -Ces deux êtres sont absolument distincts, mais tellement emboîtés l'un dans l'autre, ou l'un sur l'autre, qu'il faut que l'ame ait une certaine supériorité sur la bête, pour être en état d'en faire la distinction.

Je tiens d'un vieux professeur (c'est du plus loin qu'il me souvienne) que Platon appeloit la matière l'autre. C'est fort bien; mais j'aimerois mieux donner ce nom par excellence à la bête qui est jointe à notre ame. C'est réellement cette substance qui est l'autre, et qui nous lutine d'une manière si étrange. On s'apperçoit bien en gros que l'homme est double; mais c'est, dit-on, parce qu'il est composé d'une ame et d'un corps; et l'on accuse ce corps de je ne sais combien de choses, bien mal-à-propos assurément, puisqu'il est aussi incapable de sentir que de penser. C'est à la bête qu'il faut s'en prendre, a cet être sensible, parfaitement distinct de l'ame véritable individu, qui a son existence séparée, ses goûts, ses inclinations, sa volonté, et qui n'est au-dessus des autres animaux, que parce qu'il est mieux élevé et pourvu d'organes plus parfaits.

Messieurs et mesdames, soyez fiers de votre intelligence tant qu'il vous plaira; mais défiez-vous beaucoup de l'autre, sur-tout quand vous êtes ensemble.

J'ai fait je ne sais combien d'expériences sur l'union de ces deux créatures hétérogènes. Par exemple, j'ai reconnu clairement que l'ame peut se faire obéir par la bête, et que, par un fâcheux retour, celle-ci oblige très-souvent l'ame d'agir contre son gré. Dans les règles, l'une a le pouvoir législatif, et l'autre le pouvoir exécutif; mais ces deux pouvoirs se contrarient souvent. - Le grand art d'un homme de génie est de savoir bien élever sa bête, afin qu'elle puisse aller seule, tandis que l'ame, délivrée de cette pénible accointance, peut s'élever jusqu'au ciel.

Mais il faut éclaircir ceci par un exemple.

Lorsque vous lisez un livre, monsieur, et qu'une idée plus agréable entre tout-á--coup dans votre imagination, votre ame s'y attache tout de suite et oublie le livre, tandis que vos yeux suivent machinalement les mots et les lignes; vous achevez la page sans la comprendre et sans vous souvenir de ce que vous avez lu: - cela vient de ce que votre ame, ayant ordonné à sa compagne de lui faire la lecture, ne l'a point avertie de la petite absence qu'elle alloit faire; ensorte que l'autre continuoit la lecture que votre ame n'écoutoit plus."

"S'il est utile et agréable d'avoir une ame dégagée de la matiére au point de la faire voyager toute seule lorsqu'on le juge à propos, cette faculté a aussi ses inconvéniens. C'est à elle, par exemple, que je dois la brûlure dont j'ai parlé dans les chapitres précédens. -Je donne ordinairement à ma bête le soin des apprêts de mon déjeûné; c'est elle qui fait griller mon pain et le coupe en tranches. Elle fait à merveille le café, et le prend même tressouvent sans que mon ame s'en mêle, à moins que celle-ci ne s'amuse à la voir travailler; mais cela est rare et très--difficile à exécuter; car il est aisé, lorsqu'on fait quelqu'opération mécanique, de penser à toute autre chose; mais il est extrêmement difficile de se regarder agir, pour ainsi dire, -ou, pour m'expliquer suivant mon système, d'employer son ame à examiner la marche de sa bête, et de la voir travailler sans y prendre part. -Voila le plus étonnant tour de force métaphysique que l'homme puisse exécuter.

J'avois couché mes pincettes sur la braise pour faire griller mon pain; et quelque--tems après, tandis que mon ame voyageoit, voilà qu'une souche enflammée roule sur le foyer; -ma pauvre bête porta la main aux pincettes, et je me brûlai les doigts."

VOYAGE AUTOUR DE MA CHAMBRE, chapter 6 & 8, Paris, 1794.

CONTENTS

1. INTRODUCTION

In previous reports the task of the human operator as an information receiver and processor in man-machine systems has been discussed and the following conclusions have been drawn:

- The human operator in modern technical systems has to be considered mainly as a versatile data processor. Rasmussen, 1968

- The task of the operator will be to transform the observed data describing the state of the system into a set of manipulations appropriate to his current goal. Rasmussen, 1969

- This data processing will be based upon a transformation model of the system and a data handling procedure used to predict the system response, and thus to select and control the appropriate manipulations.

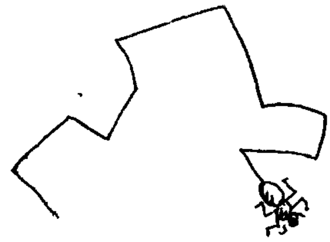
- A system operator normally has available several sets of models and procedures which can be used for a specific data handling task. The actual choice of the procedure depends upon several factors: the work condition, his training and experience, as well as his subjective formulation of the task and his performance criterion. Rasmussen and Jensen, 1973

- The various models and procedures used by an operator may differ greatly with respect to several basic features, such as the amount of state information or the complexity of the transformation model and procedure implied in the data handling, the cognitive strain imposed upon the operator, etc.

The present report attempts to present a simplified model of a human data processor in interaction with a physical system. It is not the aim to discuss the internal neurological functioning of man, but rather to create a frame of reference for further reading and discussions and for future experiments with man-machine interface systems; a reference frame illustrating the different typical modes of human data processing as seen from a systems engineer's point of view.

2. A MAN IS QUITE SIMPLE - BUT IN A COMPLEX WAY

A human data processor is an extremely adaptive system component and therefore the complexity of his behaviour follows directly from the complexity of his working conditions. His behaviour therefore has to be studied in very close relation to the task he is supposed to do and to the features of his environment. H.A. Simon explores the hypothesis: "A man, viewed as a behaving system, is quite simple. The apparent complexity of his behaviour over time is largely a re- Simon, 1968, p.25



flection of the complexity of the environment in which he finds himself". He also states: "-- his behaviour will reflect characteristics largely of the outer environment (in the light of his goals) and will reveal only a few limiting properties of his inner environment,of the physiological machinery that enables him to think".

op. cit. p.24:

"---Viewed as a geometric figure, the ant's path is irregular, complex, hard to describe. But its complexity is really a complexity in the surface of the beach, not a complexity in the ant.---"

"---An ant, viewed as a behaving system, is quite simple. The apparent complexity of its behavior over time is largely a reflection of the complexity of the environment in which it finds itself.---"

"---In this chapter, I should like to explore this hypothesis, but with the word "man" substituted for "ant".

A man, viewed as a behaving system, is quite simple. The apparent complexity of his behavior over time is largely a reflection of the complexity of the environment in which he finds himself.---"

This is a very fruitful hypothesis, but clear evidence exist that man has several basically different internal modes of data processing, which are put into operation by different types of outer environments, and which have different limiting properties, such as data capacity, speed,etc. It is therefore important to be able to characterize the different modes of data processing and to identify the generic features of tasks and environments which will initiate the different modes of data processing.

Miller, 1956, p.87:

"---You may have noticed that I have been careful to say that this magical number seven applies to one-dimensional judgements. Everyday experience teaches us that we can identify accurately any one of several hundred faces, any one of several thousand words, any one of sevral thousand objects, etc. The story certainly would not be complete if we stopped this point. We must have some understanding of why the one-dimensional variables we judge in the laboratory give results so far out of line with what we do constantly in our behaviour outside the laboratory. ---"

Such evidence is found, when psychological laboratory experiments indicate a low data capacity, although the man is able to recognize faces and to drive a car in heavy traffic.

Huggins, 1971, p.160:

"--- Study of the relation between visual imagery and symbolic forms such as natural language is currently enjoying a revival among American psychologists who at last seem to have overcome the classical prejudices which earlier in this century led them to separate perception from thought. (The inappropriateness of this separation is clear to anyone who

Accordingly, there is now a trend to distinguish between verbal and visual thinking-

has studied L.G. Roberts' important, but neglected, doctoral dissertation (1963).
The mechanisms which Roberts describes provide an elegant model of the process of perception. And since logical operations are explicit in this model, it is evident that perception likewise involves thought (albeit at a subconscious level) in much the same way as that discussed by Arnheim (1969). Of particular interest is the major, recent work of Bugelski (1970), who supports Arnheim's thesis that visual imagery plays a central role in thinking when he writes: "My current leaning is toward the belief that few of us, if any, actually think in abstract terms when we are doing our everyday routine thinking. I rather suspect, with Mowrer (1960) and Bower (1970) that we think with our gut and some rather individual imagery and that our idiosyncratic reactions are responsible for the considerable lack of communication in conversations that relate to serious social problems. Words have a way of arousing images and, if the images are not the same, communication fails. ---"

-` and between

rational and intuitive thinking.

Sloman, 1971, p.270:

"---Within Philosophy there has long been a conflict between those who, like Immanuel Kant (9), claim that there are some modes of reasoning, or adding to our knowledge, which use "intuition", "insight", "apprehension of relations between universals", etc., and those who claim that the only valid modes of reasoning are those which use logically valid inference patterns---"

The point has also been raised by Dreyfus, who critizises the viewpoint of Simon that human thinking can be simulated by a sequential, heuristically guided search of a digital computer.

Newell, Shaw and Simon, 1958, p.341:

(The theory)

"---rests its claims on other considerations:

1. It shows specifically and in detail how the processes that occur in human problem-solving can be compounded out of elementary information processes, and hence how they can be carried out by mechanisms.

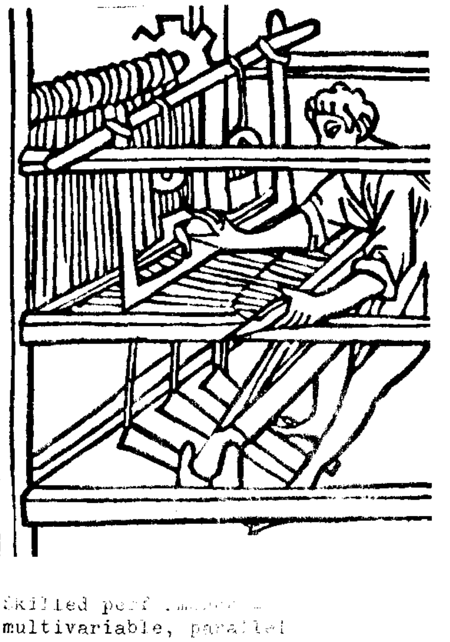
2. It shows that a program incorporating such processes, with appropriate organization, can in fact solve problems. This aspect of problemsolving has been thought to be "mysterious" and unexplained because it was not understood how sequences of simple processes could account for the successful solution of complex problems. The theory dissolves the mystery by showing that nothing more need be added to the constitution of a successful problem-solver.---"

Dreyfus, 1965, p-21:

"---We need not appeal to introspection to discover what a (chess-) player in fact does before he begins to count out; the protocol itself indicates it: the subject "zeroed in" on the promising situation ("I notice that one of his pieces is not defended"). Often, of course, locating the promising or threatening area involves more than simply noticing that a Rook is undefended. It may involve noticing that "here something interesting seems to be going on"; "he looks weak over here"; "I look weak over there"; etc. Only _after_ the player has zeroed in on an area does he begin to count out, to test, what he can do from there.---"

To conclude: the fact that a man is able to recognize faces, drive a car while unaware of his manipulations and "see" generalized features of a dynamic situation seems to indicate that a model of the human data processing should include more functions than a sequential processor of low capacity. Some kind of a parallel or holistic processing network of high capacity and operating subconsciously seems to be needed in the model.

If one supposes that the human data processing capability is due to different cooperating subsystems having basically different functional characteristics, then it is without meaning to discuss codes, procedures, and information capacity, unless careful reference is made to the particular subsystems.



Skilled performance – multivariable, parallel data processing.

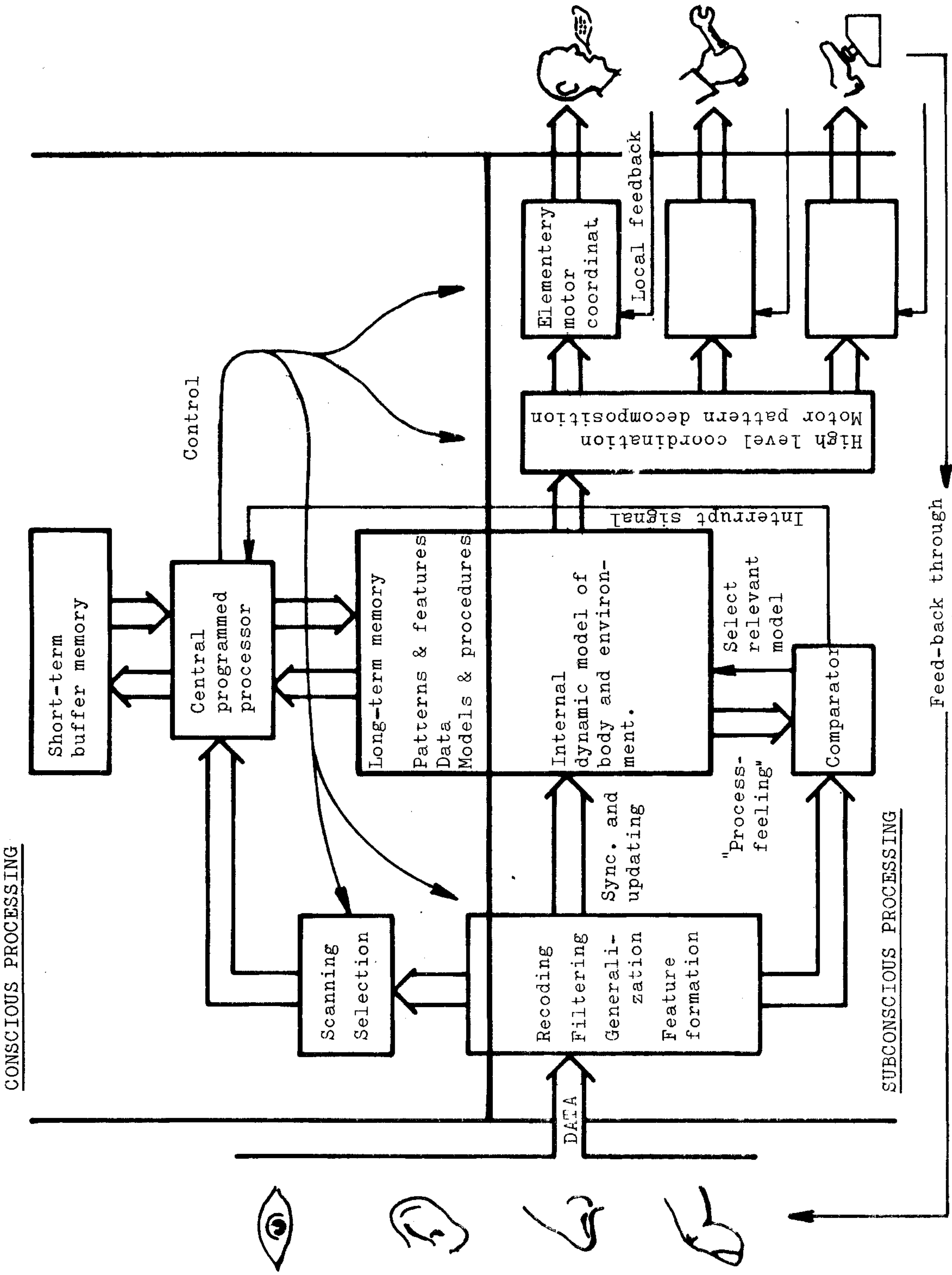
3. GENERAL OUTLINE OF A SIMPLE MODEL

As mentioned previously the only aim of the present discussion is to suggest a frame of reference for our future work related to design of man-machine interface systems. In this context man is considered a data processor through which input information received from the environment is connected to the output, which is the physical actions upon the environment.

The model will be a very crude sketch. Man is far more than a mechanistic data processor, but in man-machine systems the designer has to consider him as a versatile but predictable data processor, and the designer has to plan the data processing allocated to the man and to the instrumentation system as one integrated system. The man-machine interface has to be based upon compatible models of the data processing in man and in instruments, and a model of man drawing heavily upon engineering analogies may be fruitful in this respect.

The general outline of the model is illustrated on page 6 and comprises two basically different subsystems. One is a programmable, sequential processor which operates consciously to the man. It has a rather limited capacity and speed and its main task is to take care of the data handling in unique conditions calling for improvisations, rational deductions; and symbolic reasoning. It functions as a higher-level coordinator or controller of the second part, the main data processor.

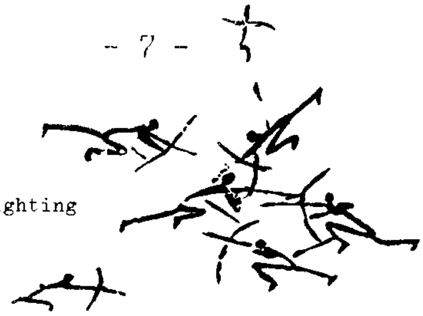
The main processor has many features of a distributed, parallel processing analog computer with high processing capacity. It functions mainly subconsciously to the man, although the conscious processor may to some extent control and monitor the data processing. The functions are distributed in a highly interconnected network which is able to decode information from the sensing receptors, and to extract higher level features or patterns. These control the external actions through several levels of coordinating functions in the motor system, which is an integral part of the processor. An important implicit function of this distributed network is a continuously dynamic modelling of the environment and the body. This internal model is up-dated or trained slowly, but it operates in real time and serves to control the actions and thus to synchronize the body with the dynamic environment.

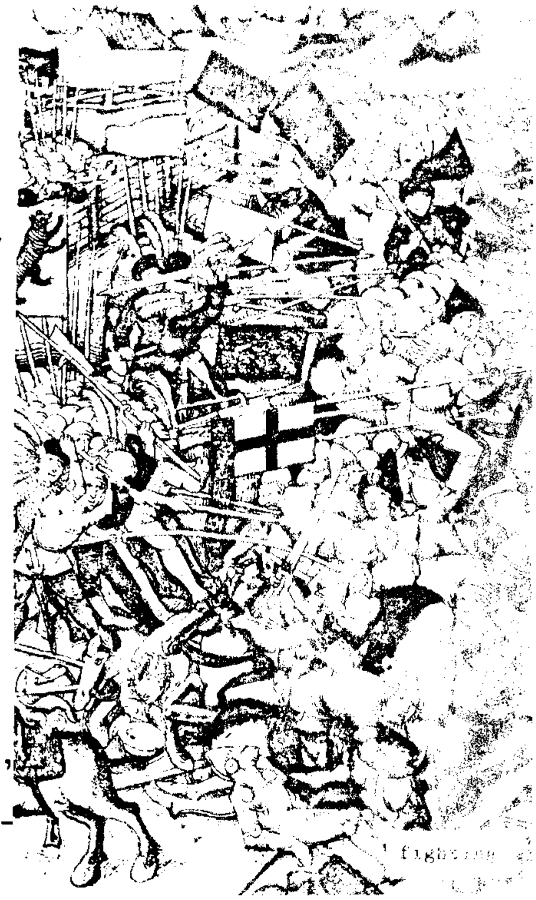


Outline of the human data processor.

escaping

fighting





4. THE SUBCONSCIOUS MAIN PROCESSOR

It will be reasonable to expect that the basic nature of the information generalization and the derivation of control information to the motor system and thus the coding of the subconscious dynamic model, are closely related to the basic needs man has met during his evolution. During the evolution of man survival has been granted most probably to those individuals who were best at identifying quickly by direct pattern recognition the appropriate goal implied in a situation, such as approach, escape, eat, don't eat, etc., and who had the most efficient control of fast critical sequences during hunting, fighting, escape, etc.

This dynamic interaction with the environment calls for a very efficient feature extraction and classification and dynamic coordination of the motor system with the environment. The receptors and the muscels of the body serve as input and output systems of a complex multivariable control system having a high data processing capacity. The subconscious main processor may therefore be assumed to have evolved into a data processing system with particularly high capacity in functions needed in the control of the body, i.e. when operating in a spatial, temporal domain. Johnson refers to the work of Heidbreder, which should be studied in this context.

Johnson, 1950, p.305:

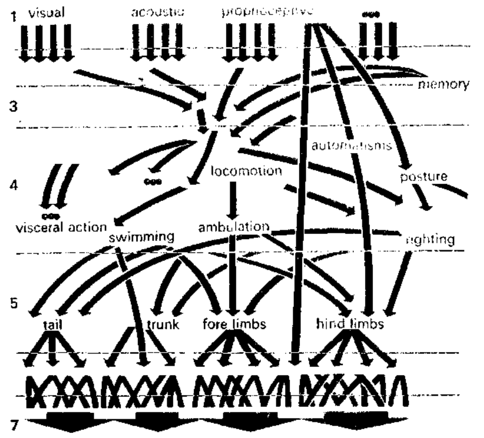
"---To account for these results Heidbreder has put forth the hypothesis that the perception of concrete objects is the dominant mode of cognitive reaction, related to the phylogenetic priority of locomotive and manipulative capacities of the organism, and that conceptualization is, therefore, easier the more it resembles the perception of concrete objects.---"

This function may quite probably be organized similarly in man and in higher-order animals.

4.1 Generalization and feature extraction

In engineering terms, the main processor may be viewed as a complex, distributed analog computing network although the signals of the nerve tissue are coded as pulse trains. It is simulating features of the control task rather than performing symbolic calculations. The high data processing capacity needed in its real time tasks is due to an extensive parallel processing of data in the network. The function of this processing system is based upon a generalization of the input information represented by the signals from a large number of receptor cells. This generalization takes place through several levels of processing, informationally speaking, as well as seen from the organization of the processing network. When the determining, higher-level features of the control task are formed in this way, another multilevel processing decomposes these features into control signals for the individual parts of the motor system. See e.g. Weiss.

Weiss, 1972:



1 sensory data
2 intrasense integration
3 intersense integration
4 visceral activity
5 intermember coordination
6 intramember coordination
7 muscle contraction

Diagram of levels in the hierarchy of coordinating functions

In the task of controlling the body in the dynamic environment, the most important generalizations to be made from the input information will be to isolate and identify spatial entities and their temporal characteristics. This means to identify objects which are moving or which are able to move and for which generic dynamic models are present in the internal dynamic modelling system. Furthermore, the generalizing function has to extract those generic features from the background - the scenery in which the dynamic actions take place - which are determining the behaviour of the movable objects.

Lettvin, 1959

Research on visual perception has identified fixed programmed networks in several animals which generalize the visual information into this kind of dynamically determining features. In the retina of a frog's eye at least four types of preprogrammed detectors has been found: edge, bug, dimming, and event detectors. Similar detectors identifying form and movements of objects against the background are also found in higher order vertebrates, although the feature extraction does not in all cases take place in the retina, but in preprogrammed parts of the nerve tissue at a higher functional level (visual cortex). A review of this research is given by Michael.

Michael, 1969

Hubel, 1963

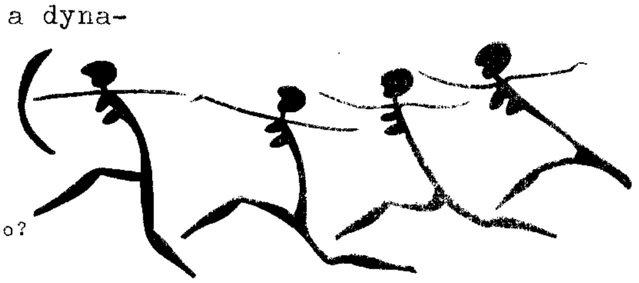
Although the programming of the nerve tissue of man may be more flexible, there is reason to believe that similar features have developed in the subconscious information handling of man during his long evolution. This is in good agreement with the statements of Lashley.

Lashley, 1942:

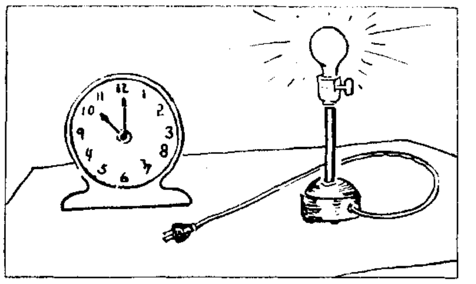
"---there is some reason for believing that generalization is one of the primitive, basic functions of organized nervous tissue---". "In spite of the enormous differences in structural arrangement of the visual systems of different animal classes, the functional activity seems essentially the same --- in the bird, the rodent and the man .---"

(from 1969 ed. p. 236)

Neurological research thus supports the proposition that the neural system has inherent properties which result in a particularly high data processing capacity for generalization in the spatial, temporal domain, needed to control the body in a dynamic environment.



-escaping too?

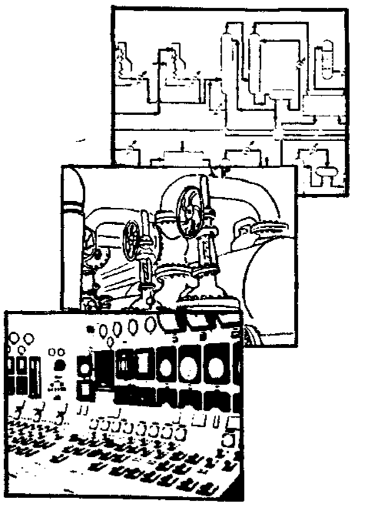


4.2 Generalization of input signals from man-made systems

The hypothesis is then that the subconscious main processor has a particularly high data capacity when it is allowed to operate in a temporal spatial domain by extracting dynamically meaningful features and patterns directly from the receptor signals.If this is true, it leads directly to implications for the design of man-made systems.

Such systems fall into different typical groups, seen as part of man's environment.

In many instances man-made systems act as dynamical objects in the environment like some kind of artificial animal, such as other peoples cars, vending machines, etc. In other cases they act as extensions of man's motor system. Examples are tools- also tools like bulldozers or cars you are driving yourself. In both cases man's interaction with the systems can be based upon the generalizing functions and the internal dynamic model of the subconscious processor. To these subconscious generalizing and modelling functions there will be no great difference between the input information related to the body itself and to the environment, i.e. whether a tool is considered an extension of the body or part of the environment may not be important. The important thing will be that it is possible for the main processor to define a control surface in the environment; a surface from which the information needed for the task can be perceived and processed in the temporal, spatial domain, i.e. the data should be available in a code fitting the main processor.



Another typical class is the systems in which a communication system is inserted between the actual physical process and the man, a system converting the information into symbolic representations of the state of the process. This is typically the case in industrial process plants controlled from a control console presenting to the operator the data collected by the measuring channels. Whether the main processor selects the surface of the controle console as the control surface or accepts the measuring channels as an extension of the sensing system and thus places the control surface close to the internal physical functioning of the system, probably depends upon the compatibility of the display coding and the code of the main processor.

This leads to the following considerations for the design of man-machine interface systems:

To activate the subconscious main processor, information should be presented in parallel by means allowing feature extraction or pattern formation in a time, space domain. The visual representation of the information then can be used directly by the processor; it will not have to operate upon the symbolic value of the presented data. Sequential presentation of digital or alpha-numeric information will not be accepted by the subconscious main processor, but will instead initiate conscious reasoning because direct visual generalization is not possible.

Which of the two unusual features in the drawing on page 9 did you notice first ?

Guilford 1967, p. 197

When information is presented by analog devices such as meters and recorders, the visual representations form by themselves a spatial, temporal world, which may be accepted by the subconscious processor; the operator may work "from the expression on the face of the system". The control surface will be the face of the operator's console, and familiar "face expressions" or data patterns may initiate trained routines, which are repetitions of actions earlier found successful. The closer the temporal, spatial world formed by the visual representations of the information is related to the internal physical function of the system, the more capable the man will be to improvise subconsciously if new, unique situations appear. Every car driver has met unique and critical situations in traffic which have only been managed because of the improvisations of the subconscious main processor (---whew!).

This has been used litterally by Chernoff (1971) for control of mineral sample classification:

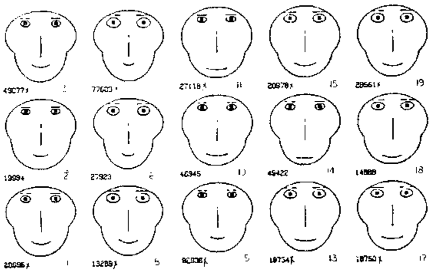
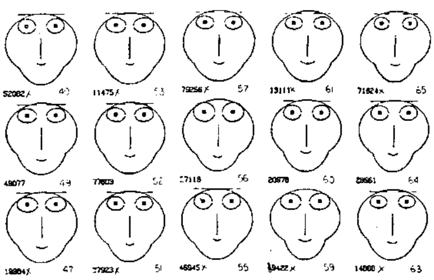


FIG. IA

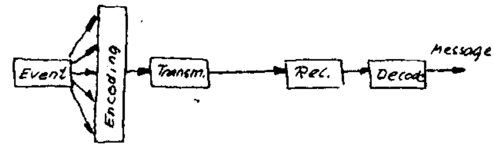


THE USE OF FACES TO REPRESENT POINTS IN n-DIMENSIONAL SPACE GRAPHICALLY

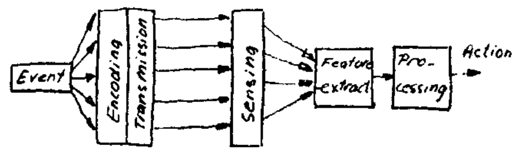
In many industrial systems man has to monitor and control a process which is a complex system of energy and mass flows. The balance of this system may be disturbed owing to faults, and the man then has to improvise, especially if he has to take over from a failed automatic control. Will the operator be able to improvise in the same efficient way as he does in busy traffic if the visual representation of the information displayed to him is closely related to the spatial, temporal properties of the primary process? If the information is displayed in pictures showing how something, i.e. some kind of substance, mass or material, or symbols substantiating energy or information, moves through a physical system and piles up if a balance is disturbed?

If so, abstract information such as temperatures, pressures, etc., should be transformed into physical, visual properties of the time space world formed by the visual representation, rather than displayed directly. This may for instance lead to display of a temperature as a visual indication of the level resulting from an integration - a pile up - due to a flow of energy, which can also be visualized.

Primitive use of communication theory generally leads to a statement of the need to reduce the amount of information presented to the man to avoid saturation of his data capacity. Normally this is due to



Channel in communication theory.



Channel in Man-Machine systems.

use of the simple analogy of a transmission channel - depicting something like the transatlantic telegraph cable. In our context, however, the principal problem is not the information transmission, but the capacity and reliability of information processing.

To facilitate the high processing capacity of the subconscious generalization function it is important to display all the information possibly available, but as an integrated, meaningful environment in which to operate. This is important to give the man the best opportunity to draw upon direct visual generalization and to form his own generic features. Redundant information should not be omitted. Redundancy depends upon the reference frame applied. Information which is redundant from a rational, deductive point of view may be extremely important in general search procedures or in feature and pattern generation. It does not sound reasonable to expect a car driver to operate more efficiently when presented with only an abstract indication of the vital physical parameters via a control console; reading a book will not be eased by removing all redundant letters and words in order to avoid overload of the data input capacity.

In other words: the process operator lives in a symbolic world. The information presented to him is a code for the physical, dynamical process in the interior of the plant. He is able to - and by the designer normally expected only to - operate upon the physical meaning of the symbols by rational deductive reasoning. During frequent routine tasks, however, he may be operating the control desk - not the process - by his subconscious routines. He may be able to improvise rapidly and subconsciously - as a car driver is able to do - if he is allowed to break down subconsciously the information patterns of new situations into familiar generic units. This is only possible if he can control the process directly - the display system therefore should be "transparent" and the physical process should be directly "touchable" on the control desk.

4.3 The internal dynamic model

The very efficient behaviour of man - and animals - as multivariable control systems in dynamic sequences which are too fast to allow perceptual feed-back correction is possible only if the subconscious main processor includes an internal dynamic model of the body and its environment. It is important, that the model includes the body itself, since only then can it operate as an efficient reference frame for fast, predictive, open loop control of the body. The internal model is a dynamic model in the engineering sense - a kind of functional analogy to the external spatial, temporal world - cap-

-quick recovery on slippery ground.

able of simulating the dynamic processes in a way similar to analog computer simulations.

In the present discussion of human data processing we distinguish between a number of discrete functions with different data handling properties seen from an engineering point of view. This does not imply a similar separation of the nerve system in corresponding biological parts performing the functions. On the contrary the holographic description of the functioning of the nerve tissue as interference patterns of exitation waves (Lashley, Pribram) leads to a distributed model in which generalization, simulation and coordination may be various aspects of the function of a distributed and highly interconnected network.

The internal dynamic model stores spatial, perceptual patterns and trained patterns of coordinated muscle movements and their interrelation through time. The state in time of the model is continuously synchronized by the information from the patterns perceived. The formation of generic features of the movable objects and the background scenery is due to a slower updating of the model; a kind of averaging function adjusts the structure and parameters of the analog model to the information perceived during the training and adaptation period.

The closely integrated nature of the entire system is also demonstrated by the way the internal model and the generic features build up. The model and the generalization are not the result of passive processing of the perceived information, but a result of active, physical interplay with the environment. This statement is supported by experiments, see for instance the experiments of Held and Hein.

These aspects are not only of academic interest but may have important practical implications. The movements of the head needed to read instruments in a control room may take part in the identification of the source of the information. The physically well defined data, such as distance or speed which are used as discrete data for inputs in a mathematical treatment of a dynamic process, are not defined or used by the subconscious data processing as separate parameters, but implicitly as part of a pattern having a functional meaning. For instance distance is not judged or measured by a two eye stereoscopic vision, but by the operational consequence experienced by walking or reaching along it.

Together with the need for data presented in sets facilitating generalization, it may therefore be important that abstract data are converted into

Pribram, 1966
1969 ed. p. 255:

"--- The properties of the hologram are just those demanded by us to account for ordinary perception. I have already made the suggestion that arrival patterns in the brain constitute wave fronts which by virtue of interference effects can serve as instantaneous analogue cross correlators to produce a variety of moiré-type figures.---"

Lashley, 1942 :

"--- Details of the theory are of little immediate importance. But the principles of the establishment of interference patterns at successive levels in the nervous system, of the modification of these patterns by superimposed patterns from earlier stages in the series of levels, from retina to motor cells, and the reduplication of memory traces as a consequence of the properties of the interference pattern are, I believe, reasonable conclusions from the organization of behavior and the structure of the nervous system. The visual system is primarily concerned with spatial orientation and for it the transition from a sensory to motor pattern can be most adequately conceived as an interplay of polarized systems or of interweaving dynamic patterns in which the spatial properties of the visual stimulus are translated by intergration at a series of levels into modifications of the general pattern of postural organization.---"

(from 1969 ed. p.250)

Held and Hein, 1963

Barlow et al., 1972 :

"--- The organization of the visual system hints that each relational feature is first detected by many separate units on a local level, and is then generalized by combining the outputs of these separate units. This would require very extensive reduplication of the "relation detectors", but eye or head movements might lessen this requirement. The extraordinarily disruptive consequences of dissociating or disturbing the relation between selfinitiated movements and visual experience suggests that spatial relations in the visual field may be encoded in terms of "motor schemata" the movement associated with producing or removing a spatial relation.---"

information man will be able to perceive directly from its dynamic functional implications. He will then be able to store them in his internal model closely related to the coordinating patterns of his motor system. Practically speaking this leads to different preconditioning or encoding of the data presented to a man if he is expected to control the process itself, compared to the case when control of the display surface is aimed at.

The function of the internal dynamic model is not only clearly demonstrated in fast sequences of open-loop control of the body. Also in slow sequences it supplies information to the processor and decreases the amount of information required from the environment. This is indicated clearly by instances found in our control room studies as well as by common, everyday experience.

See also Bainbridge, 1969 :

"--- In this way he apparently maintains a "mental picture" of the present and future status of the furnaces. There is evidence that he often makes use of his stored data rather than reading values from the display panel each time they are needed.---"

Warning signals in process plant control rooms are generally meant by the designer to be signals to alert the operator, who is then supposed to consult the instruments to identify the cause. In case of rather frequent warning signals which appear as a normal part of a work sequence, during plant start up for instance, the internal model of the operator apparently gives him a "process feeling" which continuously keeps him "set" for the proper action. He often only needs to be triggered to take action. He "knows" from the general behaviour of the system and from his prior actions what has to be done without consulting the instruments. He may even - without realizing it - correctly respond differently to the same warning signal in different operational phases - for instance during start-up.

and Bainbridge, Beishon et.al., 1968 :

"--- This arises because people appear to work from an internal "model" of the system they are controlling. Very little is known about the form of this internal model, but studies on the subjects' running memory for variables in the system show that they keep mental track of important variables even through these may be displayed in front of them.---"

The importance of the internal model for the subconscious data processing is clearly demonstrated when the internal model loses synchronism with the real environment. This sometimes happens in daily life when a very familiar routine sequence of actions is disturbed, for instance if one occasionally has to enter the sequence not at the usual opening but at a later link downstream. This may be the case if a very familiar city area is occasionally entered along an unfamiliar route, resulting in mistakes at familiar street corners until a conscious reorientation has taken place. Another experience: Have you ever had a door in your house moved to another position in the wall?

Consider also what Pribham (1969) calls "The Bowery-el Phenomenon":

"---For many years there was an elevated railway line (the "el") on Third Avenue in New York that made a fearful racket; when it was torn down, people who had been living in apartments along the line awakened periodically out of a sound sleep to call the police about some strange occurrence they could not properly define. Many such calls came at the times the trains had formerly rumbled past. The strange occurrences were of course the deafening silence that had replaced the expected noise.--"

The output from the internal model controls the physical activity of the body. The result of this control is currently checked and the state of the model adjusted by the perceptual feed-back system. If the internal model loses synchronism; i.e. if the environment does not proceed "as expected" or the model is incapable of simulating an unfarmiliar environment, an interrupt signal will alert the conscious data processor.

In a man-machine system it is important to consider the role of the internal model which gives the "process feeling" and to display the information needed for the subconscious synchronization and updating of the model. It may not be feasible to have information displayed only at the operator's order, some information may be needed in continuous display.

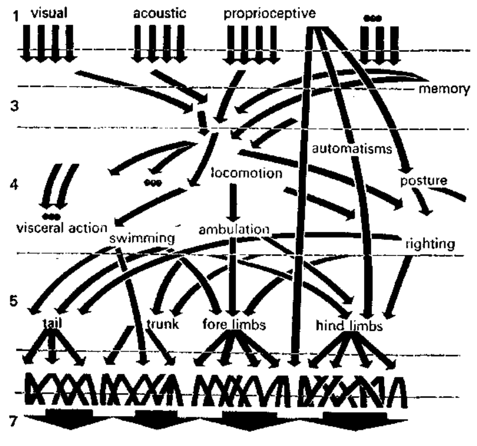
It may further be important to consider that the state of the internal model is not only controlling the actions based upon the subconscious data processing, but may also control the intuitive guesses and hypotheses which underlie the conscious dataprocessing.

4.4 Output system, motor functions

The output from the subconscious data processing system is always a motor function. The motor system consists of a great number of muscles which are controlled and coordinated by a complex, highly interconnected nerve system. It is generally accepted that this coordination and control is hierarchically organized and experiments show that the modelling function of the subconscious data processing is distributed also in the different levels of the motor system. This makes the motor system of the body an active part of the human data processor. A few implications of this statement have been touched, see page 12.

The role of the perceptual part of the processing system is to generalize, to compose from the signals coming from the individual receptive cells the generic features characterizing the dynamic interaction with the environment. The coordinating function of the motor system is to decompose through several levels the appropriate complex response of the body into detailed control sequences which are based upon information from the higher-level data processing as well as upon local motor feed-back signals.

Weiss, 1952:



1 sensory data
2 intrasense integration
3 intersense integration
4 visceral activity
5 intermember coordination
6 intramember coordination
7 muscle contraction

Diagram of levels in the hierarchy of coordinating functions

4.5 Overall system functions

When discussing data handling functions and procedures one normally has to define determining parameters such as task, goals, performance criteria etc. These are not explicit parameters of the subconscious data processing, but are found implicitly in the features defining the state of the environment or in the trained patterns of the internal dynamic model.

The conscious decision to go home sets the initial conditions of your internal model and no further decisions are needed explicitly to leave the room, take your coat, or start the car. Very often you don't even have to decide to go home - you are short of cigarettes, you get hungry, you are "set" by your wife in the morning to go home at four o'clock, etc. One action creates implicitly the scene for the next.

However, the conscious data processor may overrule the function of the subconscious processor at several different levels to keep track of a plan for a special sequence of actions, to evaluate the state and decide the subsequent plan, etc. The function of the conscious data processor is initiated by interrupt signals when the internal model loses synchronism with the environment; when it proves inadequate to control the interaction with the environment; or when the model reaches predetermined states for which interrupt demands have been assigned.

5. THE CONSCIOUS DATA PROCESSOR

The main data processor operates subconsciously upon information derived by generalization and feature formation from the data supplied by the receptive organs. The information treated and the model used for the data processing have a direct relation to the external time, space world in the same way as an analog computer model has a direct relation in structure and variables to the process simulated.

The conscious data processor is capable of operating in several basically different modes. It can simulate the external world in the domain of the sensed information - e.g. make "visual experiments" in which a visual imagination of a process is used to "foresee" the response of the process to planned manipulations. Or it can process symbolic data by following a prescribed plan, a sequential procedure - e.g. to do numerical calculations and abstract logical reasoning.

Whereas the subconscious processor from an engineering point of view has great similarities to a distributed analog computer, the conscious data processor has many characteristics of the programmed, sequential digital computer. The data processing is based upon a model or representation of the physical system underlying the problem to be solved, and upon a plan or procedure to make the model operate upon the input data.

5.1 Input information

In the physical world the data which are chosen as observations by the conscious data processor have no meaning individually; they only get their meaning through the constraints imposed upon their interrelationship by the physical processes of the environment.

The generalizing functions of the subconscious data processor derive these functional constraints from large sets of input data. The conscious data processor may scan the input data provided by the receptive system and then select and process physical variables directly by abstract reasoning. However in most cases input information is selected from a rather high generalization level in the subconscious processor - you "see" directly that a man is angry, not at all the detailed physical changes of his face, or you "see" directly that the water in your teakettle is boiling. You hear a tune, not a sequence of individual notes, or you see a bottle ready to turn over, not the data describing the interaction between gravity and support. From an engineering point of view this type of dataconditioning fits the holographic capabilities of a highly interconnected nerve tissue.

However, in some cases the conscious data processor cannot take the situational meaning of a set of physical variables as input information, but it has to operate directly upon individually selected and observed magnitudes of such variables, for instance numerical data obtained from instruments or written messages.

5.2 Processing models and procedures

To be able to interact successfully with a physical system, the state of the system and its response to the actions intended have to be identified from the observations or data received from the system. Generally the observations have no meaning individually, only the interrelationships in a set of data will define the state of the system and allow a prediction of future behaviour. This interrelationship is due to the constraints imposed upon the set by the internal anatomy and processes of the system.

Forundring er begyndelsen til tænkning.

"Mental Model"
Bo Bojesen in "Politiken"

The human data processing has to be based upon a representation of such system-given constraints. This representation is a data processing or transformation model of the system and can be present as an internal representation, i.e. a mental model; or external models, i.e. drawings, diagrams, etc., can be used to support the data processing. The mental model is not necessarily a visualization of the physical system, but can be a more abstract data processing model in the engineering sense. Such models have been discussed from the psychological point of view by Craik.

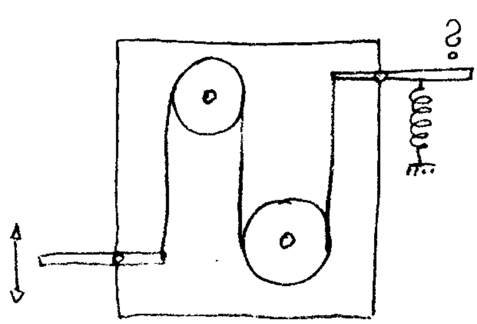
Craik , 1943

Furthermore, a procedure is needed to use the model for data processing. The conscious data processor has several different models and procedures at its disposal and the choice in a specific task depends upon different characteristics of the tasks.

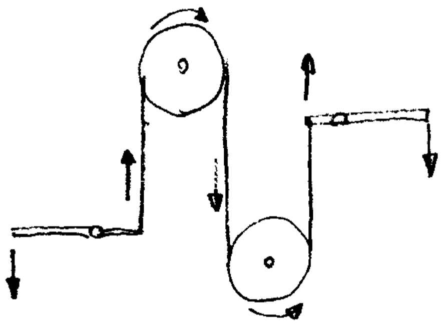
Rasmussen and Jensen , 1973

Some examples:

The problem is to judge the movement of a mechanical lever when another lever is operated by hand. The levers are connected internally in the system by a mechanism of ropes and pulleys. This problem may be solved by an internal visualization of the system or by a simple sketch on paper. Some may be "experienced enough" to grasp the solution as a whole, others may have to proceed through a series of intermediate steps - if I move this lever this way, then --- and so forth. The procedure then will be a stepwise tracing through the system of the



flow of movements, a stepwise visualization of the effects of a simulation. This problem has been discussed in a more philosophical context by Aaron Sloman. The model as well as the procedure used has a close relation to the actual physical problem.



Sloman, 1971

This sort of direct visual experiment is possible if the physical system and the relevant variables are directly visible; if not, some kind of visual analogy can be used. For instance this is done when a primary school teacher uses "water-pipe-and-jar-explanations" to explain simple electrical circuits and when mechanical mass-and-spring systems are used to visualize electrical resonance phenomena.

In this type of data handling the model supplying the system constraints between the individual observations is either the physical system itself or some kind of physical or visual analogy, and the procedure to obtain the desired resulting data is a visual experiment; i.e. you visualize the process itself.

If the process or the system is too complicated other types of models are generally used. A model of the constraints often used in a design or research task is the abstract or symbolic model constituted by mathematical equations. A system of equations models the constraints between the individual variables or observations. The characteristic feature of such a model is that it is generalized. The data-handling problem has been transferred to a symbolic world where neither the model itself nor the procedure by which it is used now has a clear relation to the physical world.

Several procedures are available and used to process data by equations. One is a sequence of logical, symbolic decisions and manipulations based upon a set of mathematical theorems. The written equations then is a visual support for the symbolic mental operation on numbers, sets and relations. But the written equations live their own lives, and the procedures used for treating familiar types of equations look more like direct visual manipulation of the physical signs on the paper. You know how they behave when you move them around. Signs change when symbols are transferred from one side of the equation to the other; dx^2/dx changes almost by itself to $2x$ and so forth. The display aspect of solving algebraic equations has been discussed by Mymon Goldstein.

Goldstein, 1969:

$$
\begin{aligned}
(3x-7)+2x &= 6+(x+19)\\
3x-7+2x &= 6+x+19\\
5x-7 &= 25+x\\
5x &= 32+x\\
4x &= 32\\
x &= 8
\end{aligned}
$$

The power of the mathematical data processing is due to the generality of the model and existence of a comprehensive system of established procedures, which are only related to the formal model itself, not to the physical problem. Other mental models related to the physical world are of course needed to transform the problem to the formal domain. However, they do not represent the total system, but only the behaviour of the parts at the level where the individual equations are formed.

Complex data processing by mathematical models and procedures are typically used by system planners and designers rather than system users and operators. If the data processing implied in system operation in a certain situation call for a complex data handling procedure, e.g. solving of mathematical equations - this has very reasonably been foreseen by the system designer, and he has by means of experiments in the laboratory, by simulation using some sort of analogy - physical or mental - or by use of mathematical equations, performed the data processing necessary to decide upon the appropriate sequence of manipulations or actions. From the results of this data processing he can then extract a set of operating instructions or operational procedures to be used by the system operator.

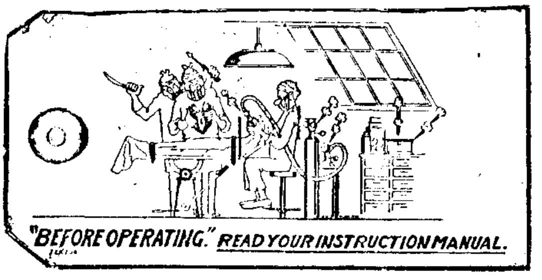
Beishon 1966 , p. 242:

"--- These are information-decision-action procedures which utilize the facts and results of the perceptual observations and direct the sequence of activities of the operator in time. ---"

"--- This third part of the skill is the "central" program which directs activity and in a sense is the "skill" itself. This part, together with the first category, can be envisaged as a "rule book" which contains the necessary facts in "look up tables" and the procedures in a hierarchically structured network. ---"

The data handling procedures of the operator are now simple - to execute a stored sequence of predetermined actions. The system model supporting the data processing now has to supply the operator with state-defining data sets, to initiate the stored program, and to provide a description correlating the prescribed actions with the manipulation surface of the system, i.e. some sort of topographic map. The functional model of the interior of the system is now found implicitly in the stored program.

Whatever the nature of the transformation model has been in initial system operation, experienced system operators develop work procedures or rules by storing sets of state-defining observations and goal-directed procedures in a kind of decision matrix, as discussed by Beishon. Even when operating instructions have been issued by the system designer, system operators often tend to form their work procedures directly by an initial cut-and-try operation - i.e. to derive the transformation model needed directly from the system behaviour, - rather than spend the effort reading the manual.



Instrument manufacturer's prayer ("Tektronix" tag)

The aim here has not been a thorough discussion of different typical conscious data processing methods but rather to illustrate that mental data processing has several basic elements:

- The observed information describing the state of the system to be operated, which can be used at several levels of generalization as input to the processing.

- The system model used for the processing and supplying the system constraints upon the interrelationship of the observations. This model can be the system itself, a visual model or analog of the system or a purely general or abstract model. Furthermore it may be found implicitly in a set of instructions or rules.

- The procedure or plan to let the model operate upon the input. The procedures can be experiments, visual or real, with the system or an analog; it can be a set of general rules closely connected to the representation used, or it can be a set of procedures closely connected to the specific system and its actual operational state.

Furthermore, it is important to realize that an operator may have several basically different sets of procedures and models available for a task, and that his choice depends upon his subjective formulation of the task and of the performance criterion. This has been discussed in detail for a specific task by Rasmussen and Jensen.

Bruner et al. , 1956

Rasmussen and Jensen, 1973

5.3 Memory functions

Owing to its distributed nature the subconscious data processor can perform several subtasks simultaneously. "Consciousness" however, has to be switched between the different subtasks, and the conscious processor therefore is a sequential processor, which normally runs different subtasks on a time sharing basis. Every task implies the subtasks of selecting input data or observations, of generating or memorizing the system model needed, of operating the model by a procedure which may not be immediately available, but may require formulation or memorizing. Furthermore, quite different tasks may run simultaneously, and the decisions resulting from the data processing may need conscious coordination and control of the motor system.

To perform the processing a memory is needed, and it is generally accepted that two different memory mechanisms are implied. A short-term buffer memory with low capacity for storage of input data, of intermediate decisions and results and of models and procedures, and a long-term memory with a very high capacity.

The capacity of the memory system is an important limitation of the processing capability, and the results published from psychological laboratory experiments have to be studied in our context to relate the capacity to the different means of encoding and formatting displays which are now available to system engineers. The influence upon memory capacity from the context in which the information is stored has long been known - see for instance Fuller's (1898) description of the mnemotechnics of Simonides (500 B.C) mentioned by Miller. This indicates the influence of the mental data processing model used by the conscious processor upon the capacity of the memory.

The effect of recoding has also been discussed by Miller. In his paper Miller exemplifies his view mentioning perception of telegraph coded signals. However, in the present reference frame the learning of the Morse code by a highly trained operator may be due to training of his subconscious modelling system. This raises the question of the cooperation or interaction between the internal dynamic model of the subconscious processor and the long-term memory of the conscious processor. Recall of a poem learned long ago may only be possible if it is spoken out loud in the proper rythm - is it stored in the subconscious dynamic model which also includes trained patterns in the motor system of speech?

Miller, 1968 :

"--- People like to locate information spatially, and the fact tells us something important about the way men and information interact.---" --- mnemotechnics, ---, is concerned with devices and procedures to improve our memory---. There is one basic psychological principle underlying all these schemes, but it can be exploited in many different ways. The principle is that concrete visual images are easy to remember, especially if they are remarkable or even a little bizarre.---"

Miller, 1956 :

"--- Since the memory span is a fixed number of chunks, we can increase the number of bits of information that it contains simply by building larger and larger chunks, each chunk containing more information than before---"

"---A man just beginning to learn radiotelegraphic code hears each dit and dah as a separate chunk. Soon he is able to organize these sounds into letters and then he can deal with the letters as chunks. Then the letters organize themselves as words, which are still larger chunks, and he begins to hear whole phrases.---"

6. COOPERATION BETWEEN CONSCIOUS AND SUBCONSCIOUS PROCESSING

The task allocation between the conscious and subconscious processor does not take place on an all or nothing basis, but depends upon the nature of the task. The conscious processor is only taking care of that part of the processing for which the corresponding internal, subconscious dynamic model of the situation has not yet had an opportunity to evolve.

A person starting to learn to drive a car has to make very detailed observations, to formulate the detailed subtasks, to identify the prescribed procedure and to manipulate consciously: Now! I'm accelerating - in 2nd gear - have to change at 30 mph - what's the speed? - Now - ok - release the throttle, that's the right foot - then disengage the clutch -- etc. -- etc. --- now the throttle, whew! ok - where am I now? Later you hear directly that it's time to shift gears, you take the decision, and the rest happens automatically. Finally, you just get an interrupt - oh, I have to go to that meeting - and your conscious processor may continue to plan the meeting except for strategically important decisions called for by interrupts during driving - e.g. to damn the idiots whose cars did not behave as your internal model predicted.

The conscious processor is the high-level controller, taking care of the unique, special tasks, controlling the body as long as it takes to have the subconscious system adapt to the situation. During the adaptation the internal model is updated, the input system forms efficient features and the motor system appropriate coordinating patterns. The input to and output from the conscious processor move to higher and higher data and coordination levels typical for the situation.

An important aspect is that the input data used by the subconscious processor may not at all be the same as those used consciously, and you may not be able to tell what information you use in a routine task. The conscious processing may only be used during training, and when high routine skill has been attained the initial conscious procedure may degenerate completely.

In some cases interference may obstruct the task if one tries to take over by conscious control. An amusing experience - known at least to Danes of some age - is encountered with the coded locks used on bicycles. If you occasionally try to remember the code after a long period of trouble-free operation, you may then find it completely impossible to unlock the bicycle. After several unsuccessful attempts the only way to succeed may be to turn your back to the lock and to think of something else - and then suddenly to see your chance to operate the lock before the conscious control has time to interfere again.

This possibility of interference between the conscious and the subconscious processing has to be studied in relation to the reliability of human operators. Is there, for instance, a critical time interval during the learning phase, when the transition from conscious to subconscious processing takes place, and is "mental black-out" during operation due to such interference?

Several of the aspects of modelling of human behaviour discussed here have been recognized and treated by Miller et al., who also relate the problem to generally established psychological concepts. From a systems engineer's point of view their approach leads to several difficulties. Their description of human behaviour is based upon a hierarchy of "Plans", having the "TOTE-unit" (Test-Operate-Test--Exit) as a modular unit. This focuses the interest upon the sequential aspects of behaviour and incorporates the "internal representation" as an implicit property of the "Plan". This may be an appropriate scheme for a description of a particular behaviour, but it seems as inadequate for predicting behaviour as a sequential description of the behaviour of a multivariable continuous control system would be to a control engineer. A model should rather deal explicitly with the internal representation as well as the sequential aspects of "procedures" or "Plans". In some cases it will be the "Plans" which are given implicitly, as when the internal dynamic model processes the input under the constraints of the actual initial conditions and control parameters ("intentions", "goals"). Furthermore, the description tends to be a "one channel" model covering all types of human behaviour. Although the similarities of conscious behaviour and automated skills to digital respectively analog computers are mentioned, the skills are related to an analog output system connected to a sequential processor rather than to a separate system operating parallel to the sequential processor.

Miller et al. 1960, p. 90,91:

"--- Once the subplan is mastered and turned over to his muscles, however, it can operate as if it were a subprogram in an analogue computer.---"

"--- That is to say, planning at the higher levels looks like the sort of information-processing we see in digital computers, whereas the execution of the Plan at the lowest levels looks like the sort of process we see in analogue computers. The development of a skill has an effect similar to providing a digital-to-analogue converter on the output of a digital computing machine.---"

7. LIMITATIONS OF THE MENTAL DATAPROCESSING

The mental data processing of man is very flexible and adaptive and the internal organisation is of interest especially when task demands violate the internal constraints on the functions. In the planning of complex man-machine systems the limitations of man's data processing capacity have to be given due consideration. It is, however, not very sensible to discuss the limits of this capacity without referring carefully to the mode of operation under consideration.

There is a current trend in the discussion of man-machine communication and of man's data capacity to adopt the concepts and measures developed by Shannon in his theory on the information capacity of noisy communication channels. The adoption and use of concepts like information, entropy, and redundancy often seems to be very crude, and the results have not been convincing. There seems to be several fundamental problems underlying the current use of information theory, problems which have to be studied carefully before the final conclusion can be made:

Shannon and Weaver, 1949

Chapanis, 1971 :

"--- I have yet to find a single instance in which psychological research on communication theory has contributed to the solution of any practical psychological problem. For one thing, the bits, bytes or chunks of communication theory are like mouthfuls of sawdust. They are as mindless as they are tasteless.---"

- The information theory is developed to handle problems related to the transmission of information by a sequence of symbols through a channel of limited capacity. In our case of man-machine communication, the transmission of information will only in special cases be a sequence of symbols, and the limitations in man's data capacity are probably due to limitations in his data processing capacity rather than limitations in the transmission capacity.

- The concepts of the information theory, such as information, redundancy an entropy, are closely related to the probablity of the relevant symbols and sequence of symbols. In human communication, the basic concepts should rather be related to the structure of the information source and to the structure of the data processing models and procedures used by the man.

- With reference to Miller's classical paper on the "magical number seven", it is often stated, that man has a low data capacity. In his paper Miller is aware that this is not in accordance with every day experience, as already mentioned.

Miller, 1956

This controversy is important in our context. It is a general viewpoint that the amount of data in modern complex plants is so great that a data reduction should be attempted so as not to overload the input capacity of the operators. This may not be appropriate under all circumstances as also discussed on page 11. It is important to examine by a review of the literature and by experiments whether the controversy is due to the setting for experiments on human data capacity in psychological laboratories. Very often such experiments deal with conscious classification of information according to prescribed and verbally formulated definitions of the attributes of the different items. Such experiments indicate a low data capacity. However, in every day situations, experience indicates a high data capacity when dealing with recognitions (e.g. of faces) or operations in familiar routine environments (car driving).

Is it important that man in the second case operates by "information units", "chunks" with a very high degree of redundancy in the information, and has a possibility to choose his own characterizing attributes? And operate subconsciously? Text is difficult and slow to interpret if redundancy is removed; you may recognize a person, but not recall if he wears glasses. Experiments on recognition of non-verbal sound pictures tend to show a low capacity - because the subjects are asked to verbalize the characteristic attributes? You may recognize people by their footfall, but <u>not</u> verbalize why. In other words: Does the laboratory experiments measure the data processing capacity of the conscious processor, while every-day experience indicates a high processing capacity of the subconscious processor?

8. THE SEQUENCE OF MENTAL ACTIVITIES IN OPERATOR TASKS.

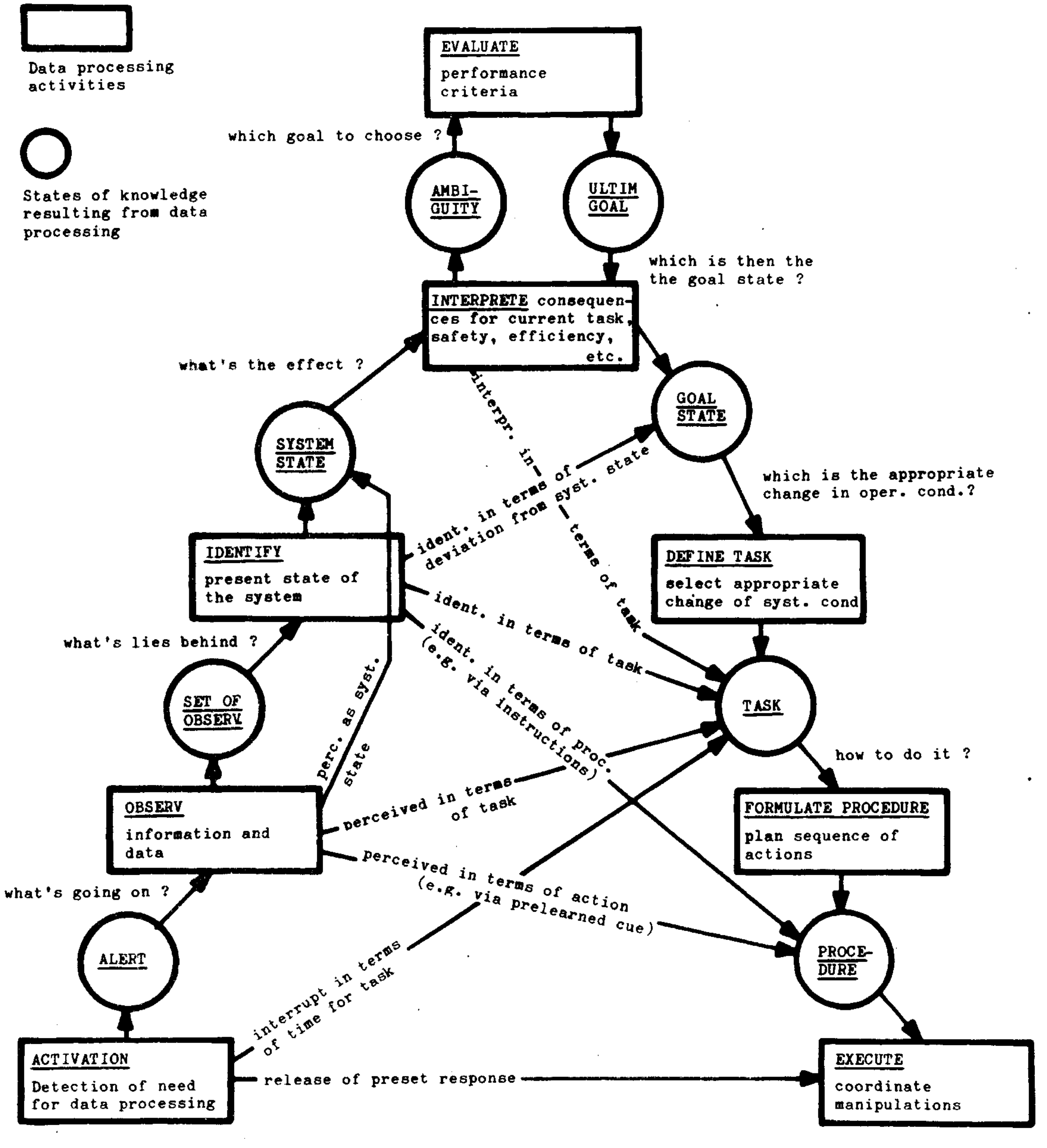
The aim of the model of a human data processor discussed in the present report in engineering terms is to facilitate the matching of the formatting and encoding of data displays to the different modes of perception and processing used by human process controllers. To do this, the work situation of the process operator necessarily has to be structured in some kind of generalized model and the tasks he is supposed to perform have to be identified and characterized in relation to his mental operations as well as to the system he operates.

This is a difficult problem. Very often the process operator has a sequence of interacting activities which it is difficult to break down into identified sub-tasks without crude generalizations; the lengthy discussion in the literature of task taxonomy has not resulted in the structurization needed in our context. However, model or no model, display systems are designed all the time, and a crude model is better than no model, even if it is only useful for giving a preliminary break down of our engineering problem into sub-problems more manageable in interdisciplinary discussions.

The adaptability of the human process operator to routine situations makes the interest of display designers focus upon the problem of supporting the operator in his diagnostic task during abnormal plant conditions. However, this task cannot be studied in isolation, as experience from accidents clearly shows that performance in abnormal task conditions is strongly influenced by the normal routine tasks. A description of the diagnostic task must be imbedded in a general description, also covering routine tasks.

The model of the sequence of mental activities suggested below has evolved during different attempts to analyse verbal protocols and observations of the start up sequence in a power plant, made in a control room. It is based upon a previous crude model, which resulted from analyses of accident records. The line of reasoning is based upon the following assumption: the characteristic steps of a mental task-i.e. the sequence of steps between the initiating cue and the final manipulation of the system - can be identified as the steps a novice must necessarily take to carry out the sub-task. Study of actual, trained performance may then result in a description of this performance in terms of shunting leaps within this basic sequence.

Rasmussen, 1969



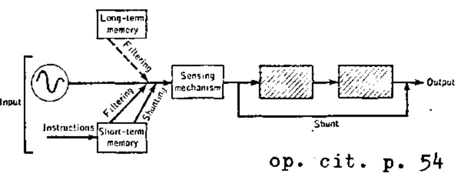
Simple model of the sequence of human processing activities between initiation of the response and the manual activity.

The diagram shows consequetive states of knowledge separated by mental activities to transform one state of knowledge to the next. Typical shunting effects evolving during training, resulting in symbolic data processing leading directly to a state of knowledge later in the sequence, are shown. Direct association leading to leaps directly between states of knowledge is not shown.

Study of the verbal protocols shows that it is difficult in real control room environments with highly practised tasks to identify the mental activity as such. The verbal statements are normally more like statements of different states of knowledge resulting from covert data processing.

The model of the activity sequence is shown on page 27: The basic sequence is based on a set of consecutive states of knowledge about the system state and the task requirements, separated by mental activities to transform one state of knowledge to the next. This is clearly a very idealized description. The individual mental activities may not be clearly separated in time, and leaps backwards and forwards in the sequence may often occur.

see also Gagně, 1963



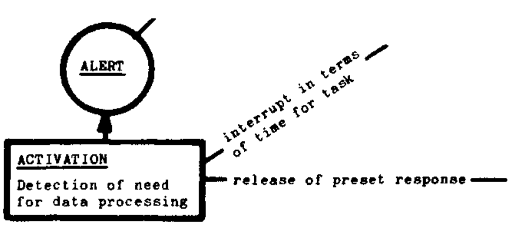
op. cit. p. 54

A trained operator will only occasionally have to move through all the steps of the basic sequence. Two types of shunting effects - often resulting from subconscious or intuitive data processing - normally take place:

- Mental activity may take place at a symbolic level, resulting directly in a knowledge state later in the sequence. E.g. holistic perception may lead directly to an observation of the system state or identification of the relevant task, rather than to an observation of a set of separate items of information.
- An association based upon previous experience may result in a leap directly from one state of knowledge to another one in the sequence.

A given conscious mental activity will be initiated only if an uncertainty is recognized at the preceding state of knowledge. If there is no uncertainty, either the state is simply accepted and the current sequence stopped, or a leap in the sequence takes place. The leaps are equivalent to a shunting out of activities at higher levels of abstraction which call for complex conscious reasoning; as a result they give rise to a considerable increase of data handling capacity.

8.1 Initiation of the operator's activity

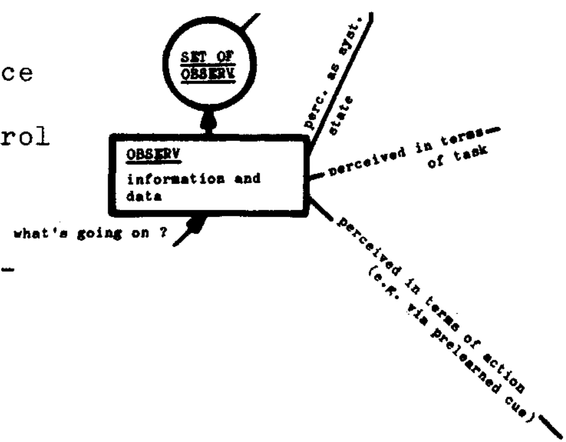


The activity of an operator can be initiated in different ways. He may be alerted by an external signal or message from the system or he may receive an interrupt from his subconscious dynamic model - i.e. his "process-feeling" tells him that the time has come to act. Only if he is caught by an external interrupt when his dynamic model is not properly updated or is unsynchronized, will he have to start the basic sequence at its entry. Depending upon his degree of training, i.e. the development of his subconscious model, the internal interrupt will arrive at higher levels of abstraction in terms of time for an expected functional state of the system or a familiar task to perform. He may then proceed from this state of knowledge in the sequence or leap back to the observational activity to verify or elaborate on the interrupt.

It is important to realize that the subconscious model not only depends upon instrument readings, but upon all sources of information available, e.g. noise from the system like relay clicks in controllers or noise from recorders; the previous operations upon the system; slight changes in the response of the system to manipulations, etc.

In an automated process plant his subconscious model may readily lose its proper synchronization, and he is generally alerted by a warning signal from the control system, especially in case of abnormal plant conditions.

8.2 Observation and selection of information



Being alerted, the question in the basic sequence is: "What's going on?", and the operator must look around to get information from the system. In a control room he basically obtains readings on temperatures, flows etc.

He can not possibly read or store all the available information; he must select relevant sources and the reference system for this choice will be his subconscious model. If this is not developed, he has to rely on learned rules or to base the choice upon higher level identification of the functional implications of different sets of data. When the subconscious model is highly developed, it will not only efficiently control the selection of data, but its generalizing influence upon perception leads to observation not of individual symbolic data, but of integrated sets in terms of their higher level implications as functional status of the system or presence of the need for a familiar task.

Our records from process-control rooms indicate that the subconscious model or process feeling of highly trained operators is developed to a degree where he is not "reading instruments", but rather asking yes/no questions to the control panel to test whether his intuitive guesses of plant state are correct or not. This leads to a very efficient shunting out of low-capacity, higher-level conscious activities. However, at the same time it results in very selective attention, which does not leave the operator open to unexpected variations of the entire task situation. The extreme case is when the operator has a very high expectance of the task to come; the external interrupt may then release an immediate preset response without any consideration of further information from the environment.

On the other hand, it should be realized that also the limited data capacity of higher level mental activities decreases the sensitivity and span of attention when operation moves to such higher levels in the sequence.

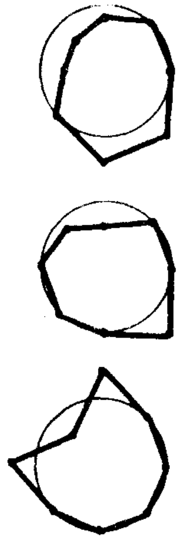
The large data processing capacity of the intuitive shunt paths is also needed during periods when the operator is constantly alert and monitoring plant operation to detect abnormalities. In our experience, the process operator may be left with a critical monitoring task, for instance during initial plant operation or periods following major repair or modifications. During such periods the plant may not be completely protected by the automatic monitoring system.

Detection of an abnormal situation takes place when man's environment deviates from the expected course and thus initiates his action. The operator has to know the "expected course", i.e. to have a reference frame defining the normal state. To have specified limiting values of individual variables is trivial, and is the way automatic alarm systems normally operate.

To follow or monitor a start up to see " if everything is normal" will rather be a check of plant structure and parameters by monitoring the constraints interrelating the displayed data. If he has to resort to higher level mental activities such as conscious identification and interpretation, his capacity, i.e. speed of operation will seriously decrease; he will become selective and his attention will then be focused upon preconceived hypotheses. The monitoring task consists instead of being open to the unexpected events.

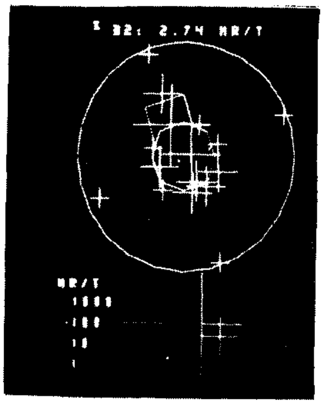
To be open to unexpected events and not locked by preconceived ideas may imply that the data presented by the environment should be related to the subconscious dynamic model of the environment. If so, the information displayed should be arranged in graphical patterns for which general subconscious models are easily formed, as for instance the display suggested by Wohl for monitoring servo loops. Or the display configurations should be related to subconscious models which are maintained by the man during his normal professional activity. Depending upon the staffing and task allocation during check-out, the normal activity of the man given the monitoring task during plant start-up, or restart following major repair, may be plant design or maintenance as well as plant operation. The subconscious model in use may therefore vary in its relation to the different subconscious "control

Coekin, 1969:



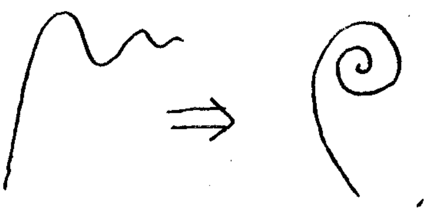
"A versatile representation of parameters for rapid recognition of total state"

Rasmussen and Goodstein, 1972:

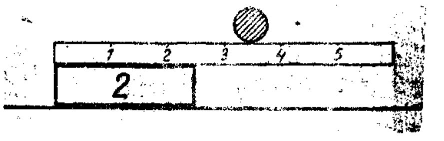


Size of crosses indicates radiation levels around reactor DR-2.

Wohl, 1965:



Irregularities of a transient are easier to see in a spiral than in an oscillation



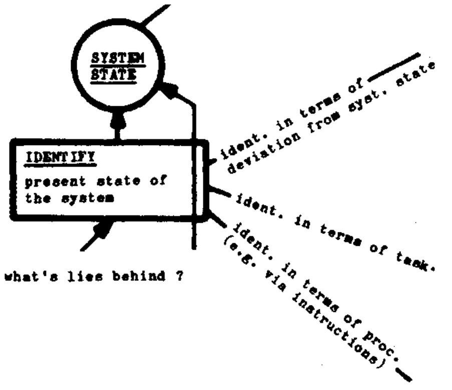
Display of unstable condition suggested by F. Skanborg (internal report 1972)

see also Goodstein et al., 197

surfaces", located at different levels in the system, as discussed on page 9.

A problem in the design of displays is to present the information so as to support such holistic perception and at the same time to find coding formats ensuring that the information patterns adopted as state-characterizing patterns are also adequate as state-defining patterns; i.e. that variables only relevant in special, but important states are significant parts of the pattern.

8.3 Identification of system state



Activity within the basic sequence following the observation and selection of information phase is initiated by the question: What lies behind this information?". In order to judge the situation and later plan the relevant action, the operator has to identify the internal state of the system, from the constraints interrelating the observed information.

This is a complicated cognitive process which is very poorly understood in real-life tasks. Basically, different data processing procedures may be used by the operator depending upon the mental processing models he has available and chooses, and upon his preconception of his immediate goal:

-He may correlate sets of observations to prelearned or previously experienced sets of data characterizing - and hopefully defining - specific, known system states.

-He may use information on system topography or anatomy to trace abnormal states through the system.

-He may use information on physical functioning of the system to trace cause-and-effect chains through the system.

-He may base his activity upon intuitive guesses and use his mental models to test such hypotheses.

It is obvious that he will frequently need supplementary observations during this processing and therefore he will return to the observational phase, but such observations will be either very specific or simple yes/no questions to the system, not open-minded observations.

The shunting effects leading to direct perception of the system state from the observations have been discussed previously. Such identifications may be used without questioning, or they may be taken as hypotheses and tested by conscious data processing.

Basically different modes of human data processing may thus be in operation during a specific task, not unlike the "zeroing-in" and "count-out" phases of a chess player's procedure, as discussed by Dreyfus, which range from subconscious pattern recognition and appre- Dreyfus, 1965 ciation of a dynamic situation to consciously guided sequential search or reasoning. Correspondingly, quite different types of data conditioning and presentation may be appropriate for support.

In abnormal plant conditions, the diagnostic task of an operator can be very critical and therefore the aid given him through suitable design of display equipment is important. In this respect, the environment and task of the operator have special features which will be considered in more detail.

The plant operator is only able to protect the plant, or plant operation, against the consequences of a fault if there is a reasonable delay between the primary fault and its possible consequences. Thus diagnosis by the operator during plant operation will be related to events characterised by a delay, typically due to pile-up of energy in the plant system (i.e. "integration" due to a disturbed mass or energy balance - such as high temperature due to a power imbalance or high pressure due to a mass flow imbalance), to transport delays (such as cold plugs in once-through boilers) or to delay in control system data processing.

Relevant to the present discussion is the feature that an important group of events is related to a spatial, temporal system - something moves around in a stationary scenery - not unlike systems, e.g. traffic systems, which man handles very efficiently in the proper setting. The problem is that the "moving something" is inside the system or an abstract quantity - e.g. energy - and has to be visualized in a proper way. Can computer graphics so visualize the process that it matches the ability of the subconscious processor to handle spatial-temporal systems?

This depends presumably upon the actual goal of the operator in a specific situation; i.e. whether he is considering the continuation of normal plant operation, the security of the plant system, or he is aiming at a repair of the system. The ability to efficiently handle spatial-temporal systems is presumably of most importance when the operator considers plant security. He then has to identify "what is wrong" in order to correct the operational state. The task is to identify the balance which has been upset so as to be able to re-establish the balance before dangerous "pile up" has taken place. In the first instance, an identification of "why" is not of importance. A power balance, for instance, can be re-established by a decrease of power input irrespective of whether the cause of the upset is abnormal input, load, or coolant flow.

When the plant has been brought to a preliminary, stable and safe state of operation, the operator can turn to another mode of diagnosis and determine "where is the fault" and localize the faulty component in the system. This is another type of task. Typically the time pressure is lower and the operator will probably have available different types of conscious search procedures based upon different mental models of the system, as discussed for electronic systems in a previous report. Rasmussen and Jensen, 1973

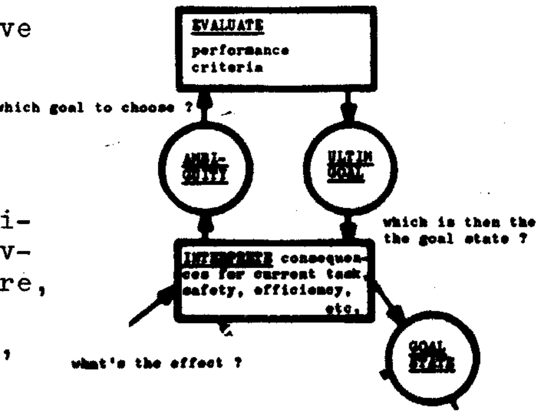
The mental model and data processing procedure needed by the operator depend then upon the situation in which he has to identify the system state, and the display system should be able to support his model by information related to the relevant type of constraints, e.g.:

- prelearned sets of descriptors,
- plant topography (locations),
- plant anatomy (connections),
- plant function (cause and effect relations).

If the system condition identified is familiar to the operator, the shunting and associating effect normally leads to later phases in the sequence, as illustrated by the figure (p. 27). If not, his uncertainty will lead him to ask the next question within the basic sequence: "What are the implications of this state?" and thus to proceed to the next activity - interpretation of the system state.

8.4 Interpretation of the situation and the performance criteria

When the operational state of the system has been identified, the trained operator will generally know what to do and therefore he may bypass the interpretive phase.



The novice, or the trained operator finding a unique plant state, must go through an interpretation of the operational consequences of the plant state. This implies that he has to make decisions. The identification of the state will probably be ambiguous, leaving him with different possible hypotheses. Furthermore, the consequence of a plant state has several aspects such as the effect upon efficiency of plant operation, upon the risk of plant damage, or the influence upon other current tasks.

The operator will have to predict such different aspects of the consequences, and find a system state minimizing them. The different aspects may very readily lead to conflicting requirements for the proper system state, and the operator must decide on the relevant goal to persue. This initiates a higher level task of interpretation of his performance criteria, i.e. his own evaluation of what is expected from him in terms of cost and risk consciousness and of efficient and dependable performance.

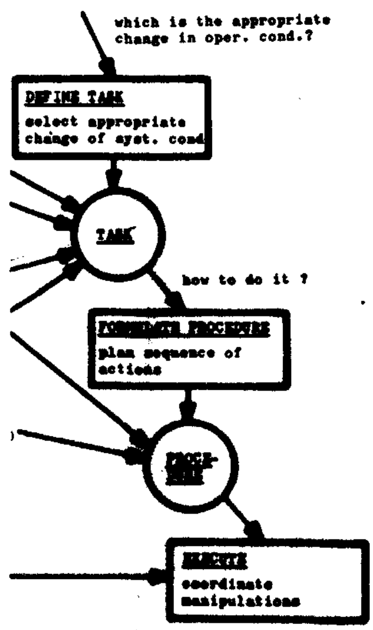
The mental model required in this interpretation and prediction phase can be based upon different types of system constraints, such as basic knowledge of the anatomy and functioning of the system, or sets of descriptive and defining data which may be prelearned from the system designer or collected by the operator during his prior activities.

Only in very unique situations will a trained operator have to move to this high level of abstraction. However, it can be crucial in critical situations that he does not bypass this activity, and therefore suitable support from the display system is important. This is especially true because the mental data processing may be very complex and stressing since the operator will have to consider several lines of reasoning to arrive at his decisions.

The display should not only attract his attention and initiate his conscious consideration in unique situations so as to avoid leaps, but it must also support the relevant mental models by relating the data to the proper sets of system constraints. It will also be important to call the attention of the operator to possible ambiguities in the situation demanding his consideration of alternative sets of states, consequences or goals in his hypotheses and judgements.

see also Rasmussen, 1969

8.5 Evaluation of the appropriate task and procedure



Knowing the operational state to which the control actions should lead the plant, the operator has to decide upon the change of operating conditions which will bring the plant from the actual to the desired state; i.e. he has to formulate his task with reference to the internal state of the plant.

The operator is now about to move down from the higher levels of abstraction towards more specific technological details: he has to identify the possible changes in the anatomy of the plant (like switching or valve manipulating) and the operating conditions of the plant and its sub-systems which will lead to the desired plant state.

To support this mental task, the display system should relate not only measured state data but also the means available for changing the operating condition (valves, switches, control parameters) to the plant anatomy and function. This may be important if the operator has to improvise in unique situations and thus also has to consider the use of control means which are only occasionally used.

The final mental task will be to plan the procedure for manipulations; i.e. to relate the desired internal changes in the system to a seuqence of manipulations at the surface of the system, e.g. via the control panels. The suitable support of the operator in planning and execution of the manual procedures will depend upon the specific tasks and work conditions; e.g. whether the step from an identified task to the proper procedure is based upon his knowledge of plant anatomy and functioning or instead should be based upon work orders and instructions. Equally relevant is the consideration of whether he is in an irreversible situation, where mistakes cannot be corrected immediately, or whether the manipulations are reversible and experimentation possible.

The novice will have to compose his sequence of manipulations consciously from elementary autonomous manual routines. As training expands, he develops more and more integrated and complex autonomous sequences which will be executed subconsciously when initiated and which will finally be labelled in higher level terms, such as task or even plant state.

8.6 Preferred mental sequence in familiar tasks

The preceeding discussion illustrates how training gradually changes the very detailed functions of a novice, who extracts his knowledge about the system state from individual observations and coordinates the elementary operations of a manual sequence, into the holistic perception of states and the repertoire of autonomous manipulations, available to a skilled operator in routine tasks. The low-level functions become increasingly integrated as they are transferred to subconscious data processing.

Analysis of a protocol from routine work conditions - start up of a power plant boiler - indicates this clearly, and shows frequent use of the following steps in the mental activity sequence:
Observations directly in terms of plant state → statement of the task to perform → execution of a manual sequence.

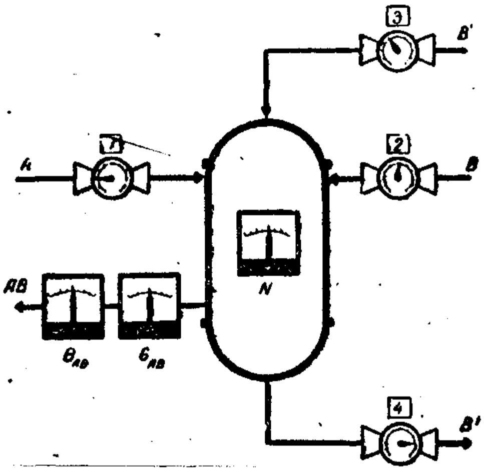
The model of the mental activity sequence is only to be seen as an illustration of basic aspects of the mental sequence and, as expected, variations are found in our protocols. A frequently used variation in the protocol is:

-The internal model, which is updated subconsciously by previous tasks and observations, interrupts and makes the operator aware that the time has come to execute a specific task that is directly stated in terms of the task or sometimes the procedure.

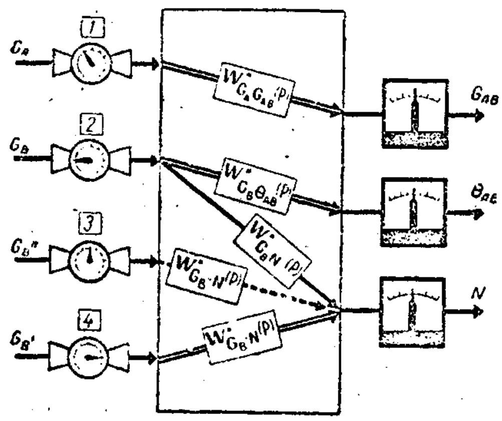
-The operator then makes some observations and the information perceived is stated in terms identifying plant state; often the observation is a yes/no question to the system as to whether the appropriate plant state is present or not.

Venda, 197o:

Data displays and control keys arranged for different mental models

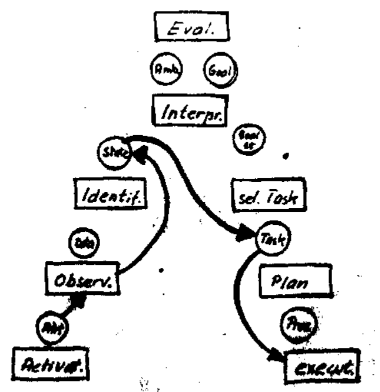


Related to system anatomy.



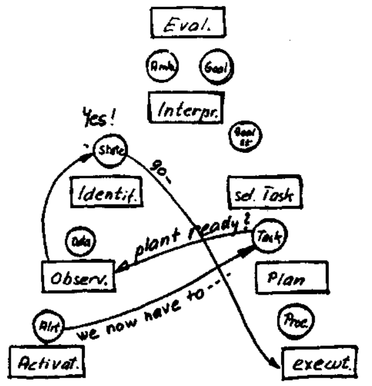
Related to system response (control sensitivity and time constants).

Related to procedure.



The work situation during which the protocols are collected, is described by Pedersen, 1974

-If not, he goes on to a more detailed identifying activity; if yes, he executes a trained sequence.
-The operator next makes some observations in terms of plant state to verify whether the execution of the task brought the system to the expected state.



The activity of a man "operating by experience" can be seen as a conscious control of the relation between sets of familiar plant states and tasks, while the transformation from the displayed information to plant state and the coordination of the associated manual task sequence is taken care of by the subconscious modelling system.

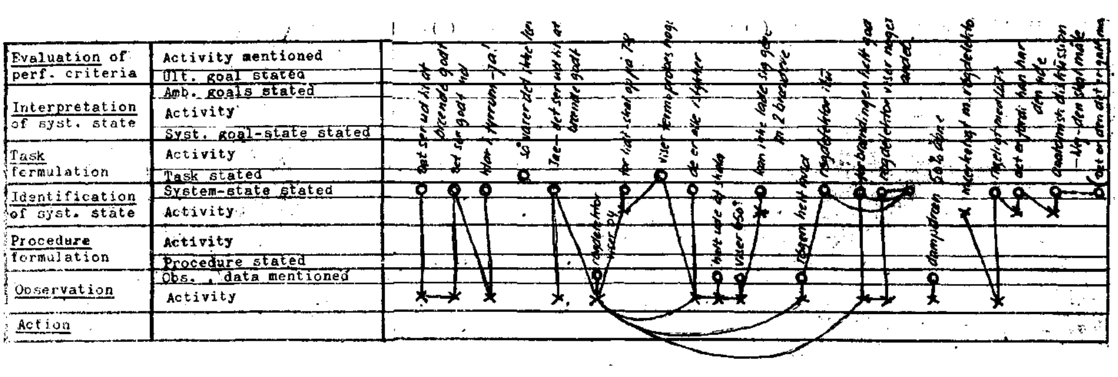
Clearly it is difficult to study the mental procedures and models used by trained operators. The highly practised routines are not immediately accessible through verbalization, and it is difficult to obtain detailed verbal records during rapid work sequences in abnormal situations. The relationship between the level of training and the corresponding mental procedure available to an operator suggests a study of the change of the procedures during the learning of a technical skill. A study illustrating the change from a procedure based upon the understanding of the internal properties of the problem to a procedure based upon the external visual features has been reported by Nielsen, who studied counting supported by pencil marks. This study indicates that a shift in mental procedure may be identified in verbal protocols and interviews during training periods.

Nielsen, 1964:

Count:
1-2-3-4-5, 1-2-3-4-5,---
Then try to count:
1-2-3-4, 1-2-3-4,---
but continue marking in sets of five.

"--- In the beginning, the subjects did not give the strokes any significance beyond the fact that one of them was drawn each time a number was spoken. The subjects then experienced some pencil marks which evolved visually and/or through motor responses into certain figurative entities which had nothing to do with the spoken numbers"---.
op. cit. p.75.

Short-hand diagram used for quick access to protocols during analysis. X indicates activity. O indicates statement of knowledge. The sample illustrates the most frequently used states in the sequence and the use of leaps.



8.7 Shunting effects and mental capacity

It is often stated that the amount of information presented to the operators of a modern plant has reached a size which makes it important to find means for reducing the number of data, so as not to overload his input capacity. But the problem is not that simple. It has prevously been touched upon (p. 11) that the limiting factor in real-life environments may not be input but processing capacity.

Rasmussen and Jensen, 1973

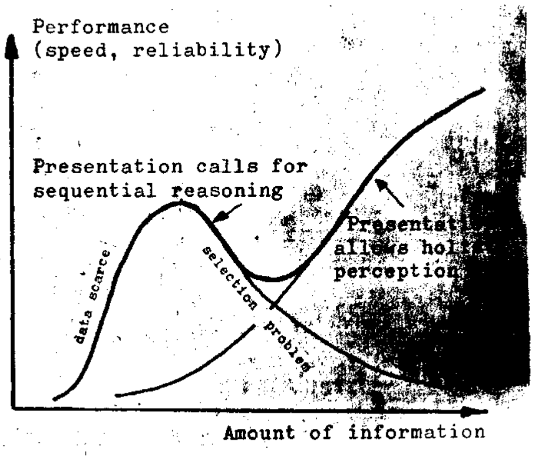
Analysis of trouble-shooting records indicates a complementary relationship between the complexity of the conscious processing and the amount of data used for the processing. The same relationship is found in the processing sequence discussed above. Intuitive data processing performed by subconscious leaps and associations bypassing more complex higher level reasoning relies upon the large capacity of holistic perception and recognition, as well as the large data processing capacity of the subconscious functions of generalization and modelling. However, this mode of processing depends upon simultaneous presentation of a set of "data" large enough to allow for discrimination by holistic identification.

Newman, 1966:

"(It was) found that properly formatted displays allowed people to tolerate and absorb much more information than would normally be expected. There seems to be an important principle operating here, one of considerable generality: People don't mind dealing with complexity if they have some way of controlling or handling it--- (If) a person is allowed to structure a complex situation according to his perceptual and conceptual meeds, sheer complexity is no bar to effective performance."

The problem here is not to limit the amount of information, but to present a large amount of information in a way suited to holistic perception, and at the same time to ensure that the information used by the subconscious processing as state-characterizing information will also be sufficient as state-defining information. This is important to avoid routine leaps in a non-routine situation.

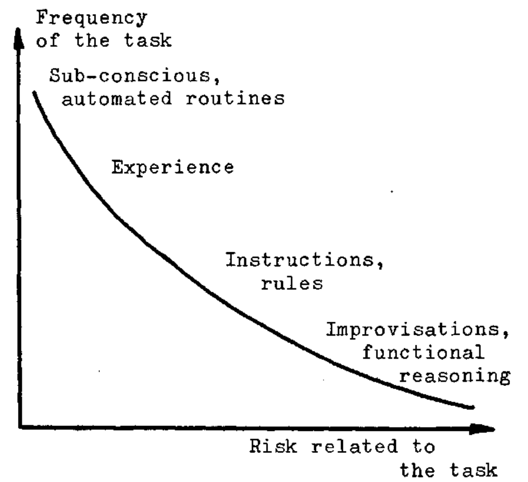
The capacity of higher level mental operations is less due to the use of conscious reasoning with the sequential use of individual observations, and the use of the small capacity, short term memory, etc. If the amount of data presented is large, the capacity may decrease due to the selection problem. The reliability of processing may be low, due to the need to limit the number of observations taken into account to within the limits of the short-term memory capacity, thus narrowing the attention to a subset of the state-defining data. Again the solution may not be to reduce the information given to the operator, but to present the available measurements and data in suitable sets and configurations allowing perception and processing at an appropriate level of information or data "chunks".



It is not unrealistic to expect a relationship as shown on the sketch between performance and amount of data available in a specific task. If the number of data in a given presentation is reduced the performance may increase, but it may very well be that performance is increased even more if the amount of data presented is increased.

8.8 The relationship between the frequency of an operator task and the risk implied

As discussed in the previous sections, the ways and means used by an operator in his data processing activities vary fundamentally with the task conditions and the level of training of the operator. To match the display coding to the way an operator will solve a specific task, it is therefore necessary to correlate at least the basic characteristics of the operator's mode of data processing to his work conditions in the different types of tasks.



Generally, it can be assumed in a well designed plant, that the events calling for the operator's intervention will have a frequency which is inversely related to the risk related to the event. This leads to the assumption of the relationship shown between the frequency of a task and thus, implicitly, the level of training, the basic features of data processing and the risk involved. In the very frequent tasks, such as set point adjustments, switching operations during frequent start-stop operations, etc. the operator will act by a holistic perception and an integrated manual sequence forming a complete autonomous sequence. This sequence of subconscious leaps will develop during training , irrespective of whether learning was based upon an education in plant anatomy and function, or on work instructions. Normally the risk involved in such tasks will be low. The designer will protect the system against simple mistakes and maloperations because the task will be recognised and considered in the design phase. Furthermore, the task will very often have a reversible effect upon the plant and the operator may readily correct maloperations.

In less frequent tasks, such as infrequent start procedures, calibrations,and response to more trivial fault conditions (e.g. in instruments), the operator may operate by direct pairing a perceived plant state with familiar trained manual routines from his previous operating experience,

Normally the plant designer find some operator tasks to be too infrequent and important to rely upon routines developed by the operator and he therefore issues work instructions. The data processing of the human operator then is expected to follow a predetermined sequence and the data presentation has to be related to this mode of operation. The"data processing model" is then given implicitly in the prescribed sequence, and the presentation should support the identification of the attributes defining the event covered by the instruction and the physical items to be operated. In addition, the recall of the sequence should be supported.

It is a general experience that operators tend to "improve" instructions operationally, but can this be avoided without presenting the instructions to him? If the instructed sequence is not stored in his subconscious internal model by proper training through exercises, how does he then store the sequence? By training of his speech motor system like learning a nursery rhyme in primary school or by visualization of the text? Or most probably by deducing the necessary steps from the supposed aim of the instruction? .

However, situations involving high risks in a well-designed plant may be due to a coincidence of several abnormal events. Normally such situations will have a very low probability, wherefore it is extremely difficult for the designer to envisage all relevant situations. As a rule he will protect the system against this type of event by an automatic safety system which detects events in a later and more general state of the cause-and-effect-chain. However, experience shows that due to the variability of human faults, human actions may lead to system states not covered by the automatic protection system. Especially during periods following major repairs and modifications of the system, when faults leading to such unique situations may be present. In these situations the operator will be forced to improvise and base his intervention upon his fundamental knowledge of plant anatomy and functioning. Therefore he must work consciously through several steps of the basic mental task sequence.

8.9 Support of the operator in critical, infrequent plant conditions

The general conclusion from analysis of accident records tends to be that an important problem in planning of the man-machine interface is to make it possible for the operator to correctly identify the work condition in cases of infrequent, but critical operating states of the system by:

-counteracting the operator's inappropriate leaps and associations based upon subsets of the information presented by initiating and reinforcing in the operator a state of uncertainty which will thus lead to higher level mental activities.

-supporting the mental models and procedures needed by the operator in accordance with the mental task he is supposed to execute, especially in identifying plant state and evaluating consequences and choosing the goal to pursue. This includes assistance in identifying and recalling existing, relevant, written work instructions.

The digital computer provides a very flexible means of supporting the operator but in order to avoid conflicts of responsibility, a clear general philosophy should be followed. If the operator is responsible and is supposed to make real decisions, the data processing and display system should support him in a way which will not interfere with the ways of reasoning and reacting which are felt to be reasonable and natural in the actual situation.

In a process plant, especially in abnormal situations, plant dynamics will be forcing the operator's work sequences. He will be in time stress, and it may be unrealistic to try to compel him to consider very unlikely, but possible and dangerous system states, if hypotheses suggesting more probable causes are at hand. His procedures will very likely be controlled by the preference for "the way of least resistance" and have "points of no return" as discussed for electronic trouble shooters.

Rasmussen and Jensen, 1973, p. 54:

"---A main rule for the structuring of the procedures seems to be that as soon as an observation is found to give a topographic reference to a more restricted field for which a familiar search routine is at hand, a decision is taken to switch to that field, to follow the"way of least resistance".
There seems to be a "point of no return" in the attention of the man the moment he takes such a decision, as discussed by Bartlett. Although more information, indicating possible short-cut methods or important hints for the next search, is clearly available from the observation and is recorded by the man, the decision prevents any influence from such information; hence the next search is a routine, starting from scratch.---"

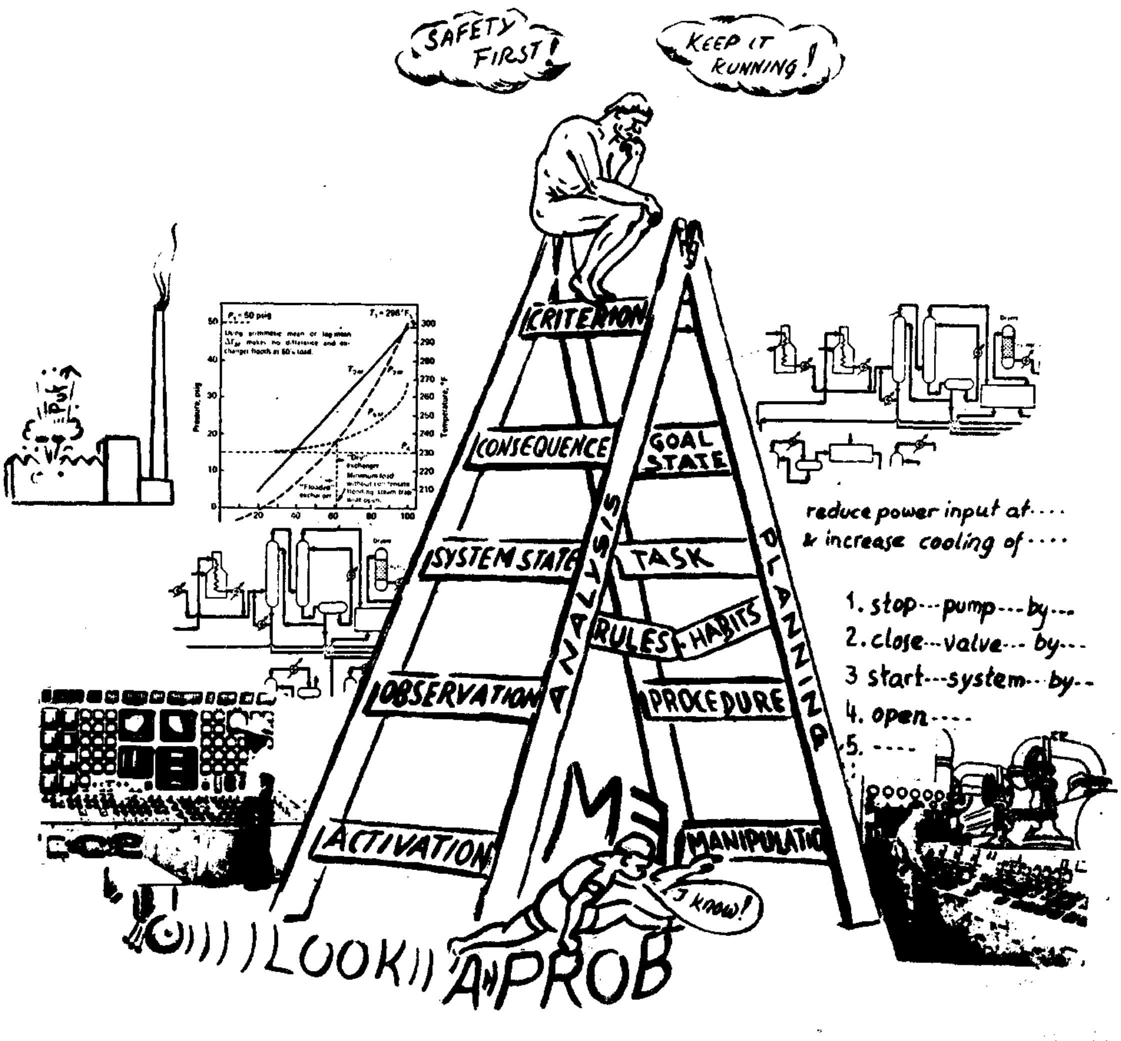
In other words, the trained operator can be assumed to try out hypotheses from the high probability end of the curve shown (page 38), whereas the safety officer would tend to be conservative and want him to first consider hypotheses covering possible high risk situations. If safety considerations therefore lead the designer to introduce automatic diagnostic programmes to counteract the operator's natural tendency, the designer should assume full responsibility and the programmes should lead to automatic actions or presentation of clear orders.

Such programmes will have to be conservative since they cannot possibly take into account all possible plant and operating conditions. Therefore they should not lead to presentation of hypotheses to be considered by the operator leaving the decision to him. There is a good chance that such hypotheses may either be trivial or too conservative. The operator should be allowed to trust the information presented to him, and rather than force him to consider possible, but a priory improbable,hypotheses resulting from conservative automatic diagnoses, the computer and the display system should assist him in referring his attention to the relevant part of the system and supporting him in a rapid verification of the hypothesis he considers most reasonable and probable.

Facilities to assist the operator's tests of his hypothesis can be based on the designers analysis of normal plant function, which is far more realistic than a complete analysis of the plant under conditions of failure.

The large storage capacity of the digital computer can also assist the operator in a systematic use of plant operating experience; e.g. by storing sets of data related to verified plant states which the operator can use later to check the consistency of his diagnosis in the event of reoccurrence of the related hypothesis.

The operator's "LADDER OF ABSTRACTION"



9. HUMAN RELIABILITY

Post-event analysis very often identifies the human element as a critical factor in serious system failures and, too often, the conclusions of the analysis classify the cause as operator error and recommend "Stricter administrative control" of the work procedures. There is, however, a great need for a far more differentiated view of human failures in system design as well as in post-event analysis if effective countermeasures are to be found.

System design and system operation seem traditionally to be the activities of two different worlds. If it has been demonstrated during system development and commissioning that the operating staff can operate the system satisfactorily it is generally assumed that they will be able to continue satisfactory operation througout the life of the plant if they are sufficiently careful. Therefore, maloperations not due to technical faults are classified as operator errors and this seems to be a general definition of operator errors today.

To improve system reliability, more integrated consideration must be given to human errors during system design and operation. If operator failure is due to normal psychological mechanisms during the actual event, the cause should rather be ascribed to the work situation and therefore possibly to a human fault during design. Therefore, to require the operators to "be more careful" has only little effect. This point of view has been advocated strongly by Rigby and Swain. Rigby, 1969 Swain, 1969

The appropriate means for counteracting operator failures depend upon which step in the mental data processing sequence is the most vulnerable in a specific work situation. The present model of the sequence suggest the following examples of failure mechanisms:

- Conscious mental activity is not activated at a step in the sequence needed in the specific task, due to leaps bypassing the step. The cause may typically be that features of the perceived information closely match features related to another familiar situation, for which the operator has a fixed response available.

- Conscious mental activity is activated at the appropriate level, but performed as a test of a hypothesis generated from an intuitive leap. The observations made for the test may then be in the form of yes/no questions to the system, and use of an inappropriate subset of information may readily follow.

- Conscious mental activity is activated at the appropriate level and the relevant observations made, but the data processing is incorrectly performed, due to the difficulty -following e.g. from the limited capacity of the short-term memory- in taking into account all the available information. This tendency may very likely be increased during periods of stress.

- Incorrect performance can follow when the appropriate mental model for conscious processing is insufficiently developed or has degraded. If this is recognized by the operator he will have to update the model by memorizing, consulting diagrams and manuals, etc., a subtask which will take time and further load his short memory.

In process plant environments it is of importance that incorrect data processing normally not only leaves an operator task undone, but leads to the execution of another task, which may be inappropriate in the specific situation and thus lead to a coincidence of two undesired events in the plant.

These are only a few illustrative examples of failure mechanisms following from the proposed model of the sequence of mental activities. The importance of these mechanisms and other possible sources of human failures can only be judged from detailed analysis of real life events.

The main issue at the present state will be that the likelihood of human failure and the appropriate counter measure does not only depend upon the work condition during the specific task but, equally important, on the individual operator's data processing during his daily routine work which results in a great repertoire of normally extremely efficient leaps and associations in the data processing. If a sub-set of features in a state of his mental activity in a specific task closely matches a step in a highly trained sequence, the attraction from such a sequence very likely causes a switch-over, resulting in a bypass of higher level activities.

Such affinities between mental procedures leading to erroneous performance in a specific task cannot be found from analysis of this task alone. Only a model structuring the sequence of mental activities and states and enabling a comparison of the states passed in different tasks will make it possible to judge when and how a switch-over may take place.

It is not always realised that the appropriate means for counteracting human failures depend strongly upon the mechanisms involved in the fault. Does it, for instance, improve the performance of a trained driver involved in a traffic accident to force him back

See also Russel Davis, 1958.

Discussing human errors and transport accidents:

The false hypothesis: "---These experiments, with many others, show that one tends to perceive what one expects to perceive."--- In other cases what is seen may be determined by the observer's previous experience, recent or remote,---" "---It is usual for a person to have expectations, or to hold to what may be called an hypothesis, about every situation he meets, even the information is notably incomplete. This hypothesis, which is in some degree the product of his previous experience of similar situations, governs the way in which he perceives the situation and the way in which he perceives the perceptual material available to him.---"
"--People may fail to see what stares them in the face if their looking is guided by a false hypothesis.---"

Preoccupation: "---When anxiety was at a low level at the beginning of a test, the subject tended to respond to the instrument panel as an integrated whole. As his anxiety increased, the several components of his task tended to become disarticulated. His attention then tended to be directed more and more to the particular component of the task which had gained a special importance.---"

to driver's school for verbal rehearsal of the instructions, e.g., how the distance between cars should be related to the braking distance, as derived from speed, reaction time and road conditions? In other words, attempts to improve performance of a highly trained man by updating his knowledge of system function and of operating instructions mainly relevant for conscious higher level processing, may not help at all since such processing is very likely to be bypassed in the actual work situation.

A general, basic way of changing the work situation of the operating staff is to automate a task by means of suitable control equipment. This does not remove the operator from the system, but, used in a proper way, it may improve the reliability of his performance. Automation of routine tasks during plant operation and start-stop operations will reduce his repertoire of stereotyped leaps and associations, and, by replacing his routine tasks with other meaningful technical tasks, it is possible to give him a better opportunity to maintain the basic knowledge of the system needed under abnormal task conditions.

A plant can be automatically brought to a safe operating condition, when it is malfunctioning, by means of automated protective systems, if the necessary automatic diagnosis can be based upon rather general criteria related to overall effects of failures upon mass and energy flow balances. This removes the operator from task conditions calling for improvisations in stressed situations when he is forced by the system dynamics; instead, he is given the role of inspector and repairman. If the protective system keeps the system operating under safe conditions with equipment within operating range, the operator will have the best possible working conditions.

Generally speaking, proper use of automation will not remove the operator from the system, but eliminate a wide range of possible tasks calling for improvisations during stressed situations and replace them by a much more uniform class of tasks related to inspection, test, fault-finding and maintenance. These are more easily foreseen and planned in advance and therefore more accessible for human reliability prediction. Ideally, no critical task for which the human reliability can not be reasonably well estimated should be left to the operator, but rather transformed by the proper use of automation to predictable tasks.

10. PREDICTION OF HUMAN RELAIBILITY

Several important approaches have been made towards the development of methods for predicting human reliability. Such methods have recently been reviewed by Meister. The basic assumptions of these methods are typically: Meister, 1972

1. The task is well defined and the procedure followed can be formulated in detail.
2. The procedure can be broken down into a sequence of behavioural units, i.e. subtasks or task elements.
3. Data on the reliability of the individual sub-task are available together with the parameters characterizing the relevant task situation.

Typically these assumptions do not fit the work procedures found in process control room environments: Rasmussen, 1973

Re. 1: The work procedures may be known in detail under task conditions, where the physical environment paces the man in a way which forces him to use a known sequence of subtasks, as is the case in e.g. manual assembly processes. In automated process plants today, however, the human function is typically higher level mental data processing and decision making, and the human work procedures are far less constrained by the physical environment. As discussed in this report, the creativity and adaptability of man often results in the evolution of several basically different mental procedures for the same type of task, all capable of ending up with the same result. The mental procedure adopted in the actual task is therefore difficult to predict.

Re. 2: A prerequisite to be able to use the classical reliability methods for evaluation of human behaviour is the breakdown of the procedures used into a sequence of typical and generally used units. This breakdown also can be done for a task in which the work steps are defined and cued by the environment as it is the case for manual tasks in production. But again this is not the case for higher level data processing tasks in plant environments. As we have seen, important and complex steps in the mental work sequence may be based upon holistic or integrated processes causing intuitive leaps and associations which cannot be broken down into elementary and general elements. Furthermore, the "process feeling" of the operator constantly keeps him prepared for the normal tasks to come. This means that he may only be prepared to look for very little information at the actual time of a task, and it is not possible to predict whether the information actually underlying his decisions is properly updated. Furthermore, the source of information chosen may be a convenient source during the normal working condition, such as noise from the system, e.g. relay clicks, rather than the information planned by the designer to be task defining and therefore displayed to the operator and considered in a prediction. Fundamentally this effect of the "process feeling" links the elements of a task sequence together, and these elements cannot be treated individually. A control room operator typically does not perform isolated actions on well-specified bits of information; he is an integrated part of a dynamic situation. This causes difficulties which are hard to predict when abnormal plant conditions suddenly demand that the operator switches to other tasks and performance criteria. The reaction to abnormal plant conditions can only be treated in the light of the normal working conditions prior to the event which establish the process feeling and thus the expectations of the operator. The reactions can only be treated in isolation if the man-machine interface can be designed to disrupt routined responses of the operator and to set the initial conditions of his data processing in a predictable way at the start of a mental activity.

Re. 3: Data for reliability prediction in control room environments are very scarce, and it is questionable whether the field data collected from process plant environments according to present schemes are sufficiently related to the characteristic features of the task conditions present during the abnormal events generating the data. The variety of different modes of mental data processing used by the operator and the relation between their use and the familiarity with a specific task, may very readily lead to the conclusion that fault data related to a specific subtask collected from minor, isolated events and incidents will not at all be representative of the performance of the same sub-task in more complex and unique situations, due to the fundamental shift in mental mechanisms.

Finally, it should be repeated that the great flexibility of man as a data processor and a system component leads to another fundamental difficulty in prediction of systems reliability: the real risk may not be due to his not doing a specific task, but to the consequences of what he selects to do instead.

Before a large-scale collection of human failure data is planned, it is necessary to formulate a taxonomy of tasks and work conditions related to different modes of mental activities, and to verify the foundation by careful analysis of the work conditions in process plants and by analysis of detailed post-event records from the same plants.

11. CONCLUDING REMARKS

Being a working hypothesis, the model is based upon premature generalizations from rather unsystematic reading and from preliminary experiments and analyses. However, the work has supported the experience that a general model covering many aspects of the great variety of human abilities is useful as a frame of reference in interdisciplinary exchange. For analysis of real-life working conditions it is important to have a model which is related to a specific task situation, rather than to specific human abilities.

To a systems engineer concerned with the everyday tasks and working conditions of, for instance a process operator, it seems as if the controversy between different schools within psychology is often due to generalizations based upon different models or experiments considering only subsets of human abilities. During the study it has sometimes been fruitful to study the conclusion emerging if both parties in such a controversy were considered to be right, but on the basis of different premises.

Also it is important to consider the experimental methods of different schools. For instance, the approach taken by behaviourists is a proper way to study the aspects of subconscious data processing in tasks when a man is operating as a multivariable control system, whereas the differentiation between the various mental procedures employed in a conscious processing task can be properly studied by listening to a man verbalising his internal activities.

The discussions with colleagues, operators, and technicians at and outside the department have been highly appreciated as have L.P. Goodstein's many hints about good references.

REFERENCES

Arnheim, R., Visual Thinking. (University of California Press, Berkeley, Calif., 1969) 345 pp.

Bainbridge, L., Beishon, J., Hemming, I.H., and Splaine, M., A Study of Real-time Human Decisionmaking using a Plant Simulator. Oper. Res. Quart. Spec. Conf. Iss. 19 (1968) 91-106.

Bainbridge, L., The Nature of Mental Model in Process Control. In: International Symposium on Man-Machine Systems, Cambridge 8-12 September 1969. IEEE Conference Record No. 69 (58- MMS Vol. 3).

Barlow, H.B., Narasimhan, R. and Rosenfeld, A., Visual Pattern Analysis in Machines anu Animals. Science 177 (1972) 567-575.

Beishon, R.J., A Study of Some Aspects of Mental Skill in the Performance of Laboratory and Industrial Tasks. Thesis(Ph. D.), University of Oxford, 1966 293 pp.

Bower, G.H., Imagery as a Relational Organizer in Associative Learning. J. Verbal Learn. Verbal Behav. 9(1970) 529-533.

Bruner, Jerome S., A Study of Thinking (Wiley, New York, 1956) 330 pp.

Bugelski, B.R., Words and Things and Images. Am. Psychol. 25 (1970). 1002-1012.

Chapanis, A., Prelude to 2001: Explorations in Human Communication. Am. Psychol. 26(1971) 949-961.

Chernoff, H., The Use of Faces to Represent Points in n-Dimensional Space Graphically. AD 738 473(1971) 48 pp.

Coekin, J.A., A Versatile Presentation of Parameters for Rapid Recognition of Total State. In: International Symposium on Man-Machine Systems, Cambridge, 8-12 September 1969. IEEE Conference Record No. 69 (58-MMS Vol. 4).

Craik, K.J.W.The Nature of Explanation (Macmillan, Cambridge, 1943) 123 pp.Excerpt in: Thinking and Reasoning. Selected Readings. Edited by P.C. Wason and P.N. Johnson-Laird (Penguin, Harmondsworth, 1968) 431 pp.

Davis, D. Russel, Human Errors and Transport Accidents Ergonomics 2 (1958) 24-33.

Dreyfus, Hubert L., Alchemy and Artificial Intelligence. RAND-P-3244 (1965) 98 pp.

Gagné, R.M., Human Functions in Systems. In: Psychological Principles in System Development. Edited by R.M. Gagné (Holt, Rinehart and Winston, New York, 1963) 35-73.

Goldstein, Myron, Display Aspects of Algebra. Psychol. Rep. 24 (1969) 937-938.

Goodstein, L.P., Pedersen, O.M., Rasmussen, J., and Skanborg, P.Z. The Operator's Diagnosis Task under Abnormal Operating Conditions in Industrial Process Plant. Risø-M-1729 (1974) 16 pp.

Guilford, J.P., The Nature of Human Intelligence. (McGraw-Hill, New York, 1967) 538 pp.

Hammond, Kenneth R., Computer Graphics as an Aid to Learning. Science 172 (1971) 903-908.

Held, Richard and Hein, Alan, Movement-Produced Stimulation in the Development of Visually Guided Behaviour. J. Comp. Physiol. Psychol. 56 (1963) 872-876. Reprinted in Perceptual Learning and Adaptation. Edited by P.C. Dodwell (Penguin, Harmondsworth, 1970) 502 pp.

Hoffman, Paul J., Slovic, Paul, and Rorer, Leonard G., An Analysis-of-Variance Model for the Assessment of Configural Cue Utilization in Clinical Judgement. Psychol. Bull. 69 (1968), 338-349.

Hubel, David H., The Visual Cortex of the Brain. Scient. Am., 209 No. 5 (1963) 54-62.

Huggins, William H., Iconic Communications. IEEE Trans. Educ. E-14, (1971) 158-163.

Johnson, Donald M., Problem Solving and Symbolic Processes. Annu. Rev. Psychol. 1 (1950) 297-310.

Lashley, K.S., The Problem of Cerebral Organisation in Vision. In: Visual Mechanisms. Edited by H. Klüver (Cattell, Lancaster, 1942) (Biological Symposia, 7) 301-22. Reprinted in K.H. Pribram, Perception and Action (Harmondsworth, Penguin, 1969) (Brain Behaviour, 2) 575 pp.

Lettvin, J.V., Maturana, H.R., McCulloch, W.S., What the Frog's Eye Tells the Frog's Brain Proc. I.R.E., 47 (1959) 1940-1951.

Meister, D., Comparative Analysis of Human Reliability Models. AD-734 432 (1971) 481 pp.

Michael, Charles R., Retinal Processing of Visual Images. Scient. Am., 220 No. 5 (1969) 105-114.

Miller, George A., The Magical Number Seven Plus or Minus Two. Psychol. Rev. 63 (1956) 81-97.

Miller, G.A., Psychology and Information. Am. Docum. 19 (1968) 286.-289.

Miller, G.A., Galanter, E, and Pribram, K.H., Plans and the Structure of Behaviour. (Holt, Reinhart, and Winston, London, 1970) 226 pp.

Mowrer, O.H., Learning Theory and the Symbolic Processes. (Wiley, New York, 1960) 473 pp.

Newell, Allen, Shaw, I.C., and Simon, Herbert A., Elements of a Theory of Human Problem-Solving. Psychol. Rev. 65 (1958) 151-166.

Newman, Robert J., Extension of Human Capability through Information Processing and Display Systems. AD 645435 (1966) 14 pp.

Nielsen, Gerhard, Færdighed og indsigt. Nogle emner indenfor indlæringens og problemløsningens psykologi. (Munksgaard, København 1964) 277 pp. (in Danish).

Petersen, O.M., An Analysis of Control Room Operators' Needs for Information from Plant Instrumentation During Start-Up of a Power Plant Boiler. Risø-M-1738 (1974) (to be published) (Danish edition, Risø-M-1693 (1973)).

Pribram, K.H., Some Dimensions of Remembering: Steps Toward a Neuropsychological Model of Memory. In: Macromolecules and Behaviour. Edited by J. Gaito. (Appleton, New York, 1966) 165-187 Excerpt in: K.H. Pribram, Perception and Action (Penguin, Harmonusworth, 1969)(Brain and Behaviour, 2) 575 pp.

Pribram, K.H., The Neurophysiology of Remembering. Sci.Amer. 220 No. 1 (1969) 73-82.

Rasmussen, Jens, On the Communication between Operators and Instrumentation in Automatic Process Plants. Risø-M-686 (1968) 24 pp.

Rasmussen, Jens, Man-Machine Communication in the Light of Accident Records. International Symposium on Man-Machine Systems Cambridge, 8-12 September 1969. IEEE Conference Record No. 69 (58-MMS. Vol. 3).

Rasmussen, Jens and Goodstein, L.P., Experiment on Data Presentation to Process Operators in Diagnostic Tasks. In: Aspects of Research at Risø. A Collection of Papers dedicated to Professor T. Bjerge on His Seventieth Birthday. Risø Report No. 256 (1972) 69-83

Rasmussen, Jens, and Jensen, Aage, A Study of Mental Procedures in Electronic Trouble Shooting. Risø-M-1582 (1973) 71 pp.

Rasmussen, Jens, The Role of the Man-Machine Interface in Systems Reliability. Paper presented at the NATO Conference on Generic Techniques in Systems Reliability Assessment. Liverpool, 17-28 July 1973. Published as Risø-M-1673 (1973) 11pp.

Rigby, L.V., The Nature of Human Error. SC-DC-69-2062 (1969) 12 pp.

Roberts, L.G., Machine perception of three-dimensional solids , Mass. Inst. Technol. Lincoln Laboratory Tech. Rep. 315, May 22, 1963. Reprinted in Optical and Electro-Optical Information Processing, Tippett, J.T. et al. (M.I.T. Press, Cambridge, Mass., 1965) 159-197.

Shannon, C.E., and Weawer, W., The Mathematical Theory of Communication (Univ. of Illinois Press, Urbana, Ill., 1949) 117 pp.

Simon, Herbert, A., The Sciences of the Artificial. (M.I.T. Press Cambridge, Mass. 1969) (Karl Taylor Compton Lectures, 1968) 123 pp.

Sloman, Aron, Interaction between Philosophy and Artificial Intelligence: The Role of Intuition and Non-Logical Reasoning in Intelligence. In: Proceesings of the International Artificial Intelligence Conference (The British Computer Society, London, 1971) 270-278.

Swain, Alan D., Human Reliability Assessment in Nuclear Reactor Plants. SC-R-69-1236(1969) 29 pp.

Venda, Valeriy Fedorovich, Informational Technology and Ergonomics. JPRS 51123 (1970) 47 pp.

Weiss, P., Central Versus Peripheral Factors in the Development of Coordination. In: Patterns of Organisation in the Central Nervous System. Proceedings of the Association, D December 15 - 16, 1950. Edited by P. Bard (Williams and Wilkins, Baltimore, Md., 1952) 3-23. Reprint in: Perception and Action. Edited by K.H. Pribram (Penguin, Harmondsworth, 1969) (Brain and Behaviour, 2) 575 pp.

(Wohl, Joseph G.) Man-Machine Relationship in Prelaunch Check-out of Advanced Space Vechicles. Dunlap and Associates 510-QR-5, SSD-65-236,1965.