Internal representation of a process, fault diagnosis and fault correction

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Internal representation of a process, fault diagnosis and fault correction

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This paper reports on an investigation into the relationship between the internal representation of a process on the one hand and on the other, control behaviour when diagnosing and correcting faults. The subjects were 87 process operator trainees, performing certain tasks in a simulated process control situation. Two modes of internal representation are distinguished: a more verbal or abstract mode of the functioning of the process (the mental model) and a more visual or concrete mode of the structure of the process (the mental image). It is concluded that the mental model probably plays an important rôle in fault correction and in the verification process in diagnosing faults, while the mental image seems to play an important rôle in the search for information in the process of diagnosis. Some implications for operator training are discussed.

1. Introduction

Many investigators have studied human operator performance in process control. It has often been suggested that mental models or mental images might play an important rôle (e.g. Crossman 1960, Bainbridge 1972, Brigham and Laios 1975, Kragt *et al.* 1973, Kragt and Landeweerd 1974). We shall use the term internal representation (IR) as a more general concept for the mapping of a process in an operator's mind. The investigation reported here concerns the relationship between the quality of the IR's of operator trainees on the one hand and their performance in a process control situation when they are dealing with a disturbance and when they are diagnosing faults, on the other.

Generally, two modes of internal representation are reported in the literature (e.g. Paivio 1971, Norman and Rumelhart 1975, Denis 1974), although there are critics (e.g. Pylyshyn 1973). The modes are: a more *verbal* or abstract mode of representation and a more visual or concrete mode of representation. In the process control situation we shall call the first one a mental model of the process and the second one a mental image of the process. The mental model refers to the functioning of the process ('what leads to what'); the mental image refers to the structure of the process ('what is located where').

2. Hypotheses

The following hypotheses were tested:

(1) Subjects with a good IR of the process will show better scanning and control behaviour when dealing with a disturbance than those with a less adequate IR.

(2) Subjects with a good IR of the process will have better system output results when dealing with a disturbance than those with a less adequate IR.

(3) Subjects with a good IR of the process will use better information-searching strategies when diagnosing faults than those with a less adequate IR.

(4) Subjects with a good IR of the process will give a greater number of correct diagnoses than those with a less adequate IR.

3. Experimental procedure

The investigation was part of a research project at an operator training school of a chemical company (Landeweerd 1978). The subjects were 87 operator trainees; their average age was 25·2 y (s.d. = 3·9).

The experimental procedure is illustrated in figure 1.

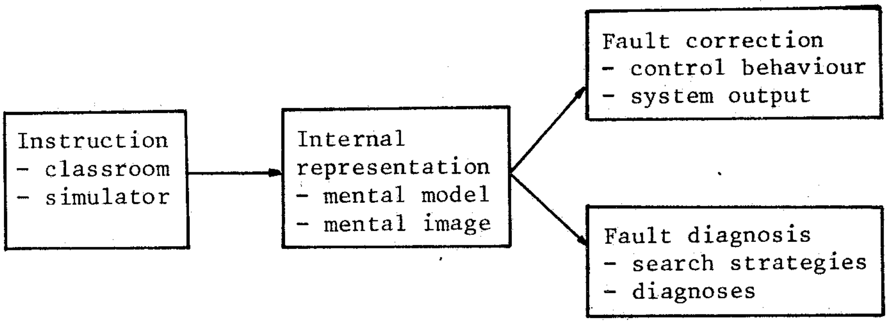


Figure 1. The experimental design.

3.1. *Instruction*

The subjects received instruction, both in the classroom (1·5 h) and at a pneumatic simulator of a distillation process (1·5 h). The instrument panel of this simulator contains 14 indicators or indicator-controllers. In the distillation process a feed flow (a binary liquid mixture) is separated in two flows (top product and bottom product) by means of sequential distillation on trays in the column. The top product is partly led back into the column, the so-called reflux flow.

The reflux-ratio (ratio of reflux flow to top product flow) is normally held constant. More detailed descriptions of the instruction and the simulator may be found in Landeweerd (1978).

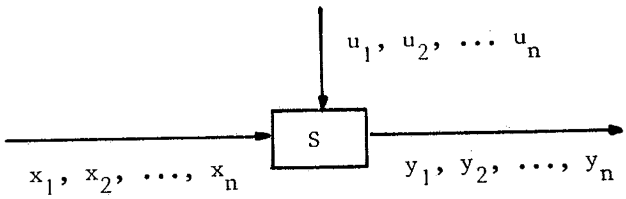
3.2. *Assessment of IR*

It was assumed that, after the instruction, a mental model and a mental image had been formed. The quality of each was then assessed. The mental model was assessed by means of a questionnaire, consisting of "what leads to what" questions. The mental image was assessed by asking the subjects to make a drawing of the "plant behind the simulator".

3.2.1. *The Mental Model Questionnaire:* The mental model questionnaire was based on the control theory model presented in figure 2.

A multiple-choice questionnaire consisting of 38 items was used. It required the subject to state the effects of inputs or control actions on various outputs. An example of the type of questions asked is as follows: "What is the effect of input $x_1, x_2, \ldots, x_n$ (or the effect of control action $u_1, u_2, \ldots, u_n$) on output $y_1, y_2, \ldots, y_n$?"

3.2.2. *The Mental Image Drawing:* The mental image was assessed by counting the number of 'correct' items in the subject's drawing (the items being: column, vessels, pipe-lines, control mechanisms, etc.).



x_1 = input

u_1 = control action

y_1 = output

S = system

Figure 2. Basic model of control theory.

3.3. *Fault Correction*

The subjects were asked to deal with the effects of a disturbance at the process simulator. Of course, in every simulation there is the problem of validity. In pneumatic simulation, for instance, the system's response is faster as compared with the real situation, involving for example lags of about one minute instead of about 30 min.

We believe this is not a serious problem in our investigation, because we are mainly interested in relationships between inputs (or, for that matter, disturbances) and process variables. The disturbance the subjects were asked to deal with concerned a drastic reduction of the main steam supply. The subject's task was to restore the normal product quality as soon as possible. Two important aspects of task performance were:—control behaviour, i.e. eye-fixations on panel instruments and control actions at control knobs;—system output, i.e. outputs of the distillation process that are related to quality.

3.3.1. *Control behaviour:* Three functionally related measures of control behaviour were used:

(i) Fixation score $= \dfrac{\text{number of seconds spent in observing relevant instruments}}{\text{total number of seconds of fixating (300 s)}}$

A relevant instrument in this sense was taken to be an instrument that was important in correcting the fault.
The training staff unanimously considered five instruments to be relevant.

(ii) Action score $= \dfrac{\text{number of seconds in performing relevant control actions}}{\text{total number of seconds spent on control}}$.

A relevant control action in this sense was defined analogously to the procedure just described. It was unanimously agreed that two control actions were relevant.

(iii) Link score $= \dfrac{\text{number of correct links}}{\text{total number of links}}$.

A link between two instruments was defined as the concurrent or sequential occurrence of fixations or actions at these two instruments: a link between instruments A and B existed, if:—either a fixation or action at A was followed by a fixation or action at B;—or a fixation (action) at A occurred at the same time as an action (fixation) at B. A correct link involved two relevant instruments, as defined above.

The three scores were combined by adding up each (standardized) score. This is termed the 'control behaviour index' (CBI).

3.3.2. *System output*

Three measures of system output were used:

(i) TT-score: This was the absolute deviation of the top temperature value from the desired value at the end of the trial (in °C).

(ii) RR-score. This was the absolute deviation of the reflux-ratio from the desired ratio (in this case: 3).

$$\text{RR-score} = \max.\left\{\frac{\text{ratio obtained}}{3}, \frac{3}{\text{ratio obtained}}\right\}$$

(iii) MAD-score. This was the mean absolute deviation of bottom-product flow from the desired value during the trial.

The three scores for system output were combined to form the 'system output index' (SOI), in the same way as described for the 'control behaviour index'.

3.4. *Fault Diagnosis*

The subjects were asked to diagnose six faults. The experimental set-up was based on the somewhat comparable procedure used by Duncan and Shepherd (1975). For each of the six fault conditions the values indicated by the panel instruments were assessed and a slide was made of each panel instrument indicating that value. The slides were mounted on an overhead-projector transparency in the same positions as those on the simulator. Moreover, the experimenter was able to cover or uncover each instrument. The subject was shown the projected panel on which only one instrument was uncovered. The value of this uncovered instrument was different from normal. This process variable with its 'signal value' was to be regarded as a 'first discovered symptom'. The subject's task was to identify the fault. He could ask for more instruments to be uncovered until he thought he could identify the fault. Two processes can be distinguished: Firstly, the information search (i.e. the strategies used when requesting information about instrument values) and, secondly, the diagnosis given. The two aspects of task performance that were assessed were accordingly:—search strategy, i.e. the sequence of requests for uncovering panel instruments,—diagnosis, i.e. the final diagnosis of the fault itself. Finally one has to realize that our set-up has the problem of forcing the subject to react sequentially. In practical process control situations parallel information gathering (as in pattern recognition) may also take place.

3.4.1. *Search Strategy:* The order of uncovering the various panel instruments under each of the six fault conditions was recorded. Experts (instructors from the training school) were asked to perform this experiment as well and a number of correct strategies were deduced. The scoring procedure for the subjects was based on a comparison of the strategies used by the subjects (their order) with the 'nearest' correct strategy, and the number of errors was counted. Three error categories were distinguished:

(i) errors of omission (the subject's failure to ask for one or more relevant instruments);

(ii) errors of redundancy (one or more irrelevant instruments were nevertheless asked for);

Hypothesis 2 is mainly confirmed by the relationship between the mental model scores and the system output scores. Knowledge of 'what-leads-to what relations' appears to be related to system output. The correlations between each of the two IR measures and reflux-ratio seem to be very low, possibly as a result of a lapse of memory of the subjects, who might have forgotten to adjust the reflux to the changed input-flow. Hence the insight into relations between process variables (the mental model) correlates with RR to a lesser degree than to TT or MAD.

4.3. *Search Strategy and Diagnosis*

The third and fourth hypotheses were as follows:

Subjects with a good IR of the process will have better strategies of information search when diagnosing faults than those with a less adequate IR.

Subjects with a good IR of the process will give more correct diagnoses than those with a less adequate IR.

The relevant correlations are given in Table 3.

Table 3. Correlations between IR-scores and strategy and diagnosis scores ($N = 87$).

	Search strategy score	Diagnosis score
Mental model	0·12	0·20*
Mental image	0·31*	0·22*

* = $p < 0{\cdot}05$

Hypothesis 3 was mainly confirmed with respect to the relationship between the mental image and the strategy score. Knowledge of process structure appears to be related to the quality of the search strategy. Obviously, a good visual image of structure allows the subject to trace 'in his mind' the various connections from the point in the process introduced as 'first symptom'. The subject probably proceeds from the 'problem area' towards possible 'causes'. In the mental model questionnaire, this order is just the reverse. There, the subject has to deduce effects from inputs or disturbances; this fact probably causes the very low correlation between the mental model score and the strategy score.

Hypothesis 4 was also generally confirmed. Here not only the mental image, but also the mental model is important.

A possible reason that, with respect to 'searching', only the mental image plays a role, is that during the search for information the thinking process probably proceeds from symptoms to causes as follows:

$$\text{symptom} \rightarrow \text{causes}$$

When diagnosing, a further, verification process is added:

$$(\text{symptom} \rightarrow \text{causes}) \rightarrow \text{effects}$$

In the latter case the subject is reasoning from causes (inputs) to the possible effects; this can be seen as a way of verifying a hypothesis as to the cause of the trouble, which is

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