

Experimental Study on Human Experience of Complexity in Supervision Control

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Abstract

This paper describes a study on the human experience of complexity in supervisory control of complex industrial processes. A conceptual framework is used to describe the relation between objective and subjective complexity, a laboratory plant consisting of five subsystems is used. Four typical structured operation environments together with 17 sessions have been designed, and subjective measures are applied to assess perceived complexity. Extrapolation of the results revealed that more than 8 subsystems will become too complex for human operator.

Introduction

During the last decades, complexity has received extensive attention in various fields of learning, including human-machine systems (for example, Rasmussen, 1983; Henneman and Rouse, 1986; Dorner, 1987; Scuricini, 1988; Johanssen, *et al* 1992; Stassen *et al* 1990; Ntuen *et al* 1996; Treu, 1996; Wieringa and Stassen, 1993; Woods, 1987, etc.).

It is a common opinion that there exists a distinction between objective and subjective complexity. While, it is also widely agreed that a system is complex when it is built up of a plurality of interacting elements, of a variety of kinds, in such a way that in the holistic result no evidence can be traced of the characteristics of the single elements.

In this paper, the human perception of complexity will be studied in supervisory control of complex processes, a topic to which relatively little contribution has been made. Firstly, a conceptual framework will be used for the human perception of complexity in supervisory control of industrial processes. Then a laboratory plant installed with a TDC 2000 series operation and control system (Honeywell Corp.) and up to five subsystems is used. Four typical structured operation environments with 17 sessions have been designed to test how the human operator experiences the complexity as a function of the number of subsystems and the interaction between the subsystems. Finally, remarkable conclusions are made for human perceived complexity in supervisory control of typical slow-response processes.

Complexity in supervisory control and conceptual framework for human perception of complexity

The main tasks during human supervisory control are: plan the task, teach the computer, monitor the automation system and occasionally intervene when failure occurs. The field operators will also have to go to the field in case problems occur.

In this paper, two general types of complexity are identified in human supervisory control: objective complexity and subjective complexity. Furthermore, the objective complexity may be itemized into task complexity, and technical complexities that include process complexity, process system complexity, control system complexity, and human-machine interface complexity.

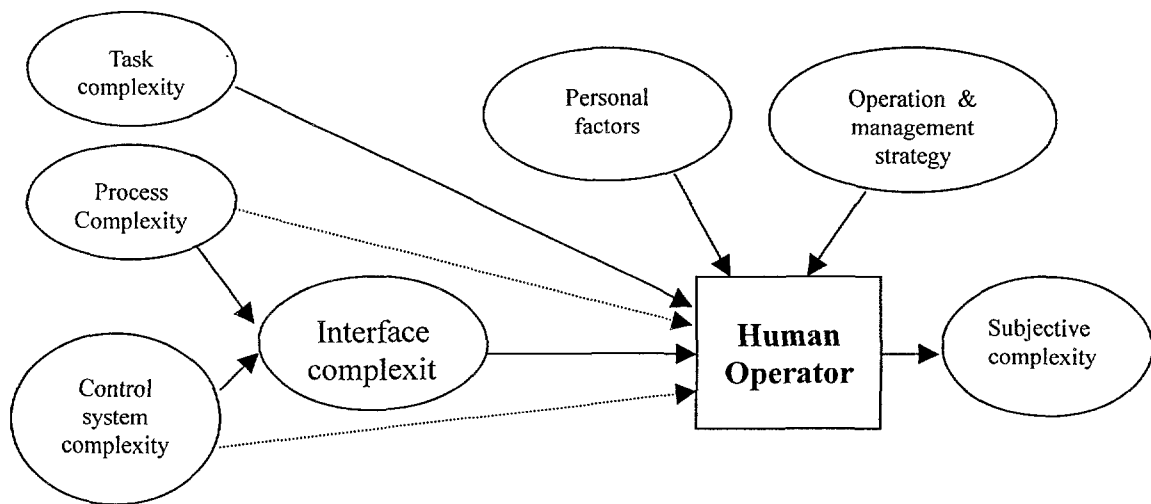


Fig.1: Conceptual framework for human perception of complexity in supervisory control

Among these different complexities, task complexity and interface complexity have the direct impact on the human operator. The process complexity, process and control system complexities generally affect the human operator through the human-machine interface. Only the field operators may experience these complexities directly.

Relations between the human operator, ontological complexity, and subjective complexity may be integrated in a conceptual framework shown in Fig.1.

In Fig.1, the arrow with a dashed line means that the corresponding factor generally has indirect influence on human perception of complexity, while the arrow with a solid line means that the corresponding factor generally has direct influence.

Experimental design

Experimental system description

In this experiment, a set of laboratory systems installed with a DCS system TDC 2000 from Honeywell Corporation is used. This operation and control system has provided multiple functions, according to which we may design our controller parameters, and the operation and control system configuration. The controlled plan

consists of up to five heat-exchange subsystems with possible interconnections, which may be defined by us.

The I/O points of the system were the controllable valves for the cold water flow and the thermometers to measure the temperatures in the reservoirs.

The configuration of this experimental system is shown in Fig.2. The interconnection between subsystems may be realised electronically.

A big display CRT is provided to display the process data and control information. Process information is refreshed every 2 seconds. Numerical and Operation keys are provided to set the system parameters, to give instructions to start and control the plant, and to display different kinds of information. An armchair is provided for the operator.

Two-operation statuses are provided:

- MAN — Direct Manual operation on the controlled plants;
- AUTO — The system in automation.

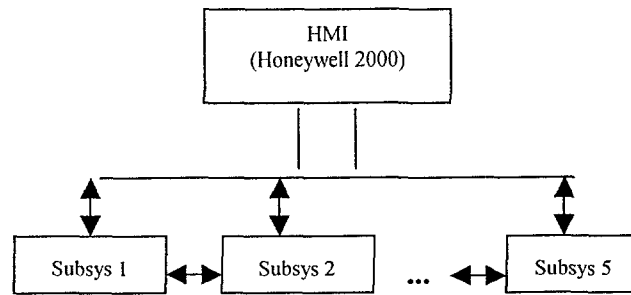


Fig.2: System configuration in the experimental laboratory

The operator has multiple choice for key operation.

The system configurations for the five controlled plants are similar, though the model parameters for each subsystem may be different. The theoretic model for each subsystem is described as follows:

$$y(s) = \frac{k}{Ts + 1} e^{-\tau s} u(s) + \sum_{i=1}^3 \frac{k_i}{T_i s + 1} e^{-\tau_i s} w_i(s) \quad (1)$$

Where, y is the temperature of water to be heated in reservoir as the output variable. $w_i, i = 1, 2, 3$ are the temperature of cold and warm water and the flow of warm water. The variable u is the control variable: the flow of cold water. Ranges of $T_i, i = 1, 2, 3$ and T vary from 20 to 100 (seconds), ranges of $\tau_i, i = 1, 2, 3$ and τ vary from 5 to 50 (seconds), ranges of $k_i, i = 1, 2$ vary from 0.2 to 10 (non-dimensional), k_3 , and k ranges from 10^4 to 10^6 ($^{\circ}C/m^3/s$).

There exist differences between theoretic models and experimental models, and we also examine the practical model for these 5 subsystems around several different working points.

We have designed a decentralised controller for the whole controlled plant, e.g., each subsystem has its own controller, and there exists no coupling among the control loops of subsystems. The control algorithm takes the form of normal PID as follows:

$$P_c(s) = K \left(1 + \frac{I}{sT_1} \right) \frac{(sT_2 + 1)}{(s\alpha T_2 + 1)} \quad (2)$$

According to the theoretic and practical model of subsystems, K in (2) ranges from 6 to 30, T_1 ranges from 0.5 to 2, T_2 arranges from 0.05 to 0.15, α is larger than 10.

The purpose of introducing the decentralised PID controller is to make the whole system run automatically when operator presses "AUTO" button in the operation station.

Structured operation environments and experimental design

In order to study how the two major factors (number and interaction) influence the human perceived complexity, we design 17 sessions with four structured operation environments and up to 5 subsystems.

The four different structured operation environments for our participants are described in Table 1.

Table 1: Four structured operation environments for a process consisting of two subsystems

| Type No. | Properties using two subsystems |
|----------|---|
| 1 | Fully decoupled operation environment $\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} H_1 & O \\ O & H_2 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$ |
| 2 | Cascade operation environment $\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} H_1 & O \\ K_{21}H_1 & H_2 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$ |
| 3 | Fully coupled operation environment (The operation environment is a stable one) $\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} H_1 & K_{12}H_2 \\ K_{21}H_1 & H_2 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$ |
| 4 | Fully coupled operation environment (Unstable operation environment for decentralised operation strategy). $\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} H_1 & K_{12}H_2 \\ K_{21}H_1 & H_2 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$ |

We use the interaction gain between the subsystems to create these four structured operation environments. The interaction gains among subsystems are chosen among -0.5 to +0.5, considering the system operability (here we choose such interaction

gains as to make the coupling among subsystems as strong as possible for each structured operation environment). In brief, one may choose appropriate interaction gain among subsystems such that entries in the relative gain array of corresponding plant satisfy some criteria (Seborg, *et al*, 1989).

In this experiment, six students participated voluntarily. All are from Delft University of Technology, with strong study background in engineering (average 23 yrs). They received a fixed fee for per experimental hour. And before the experiment, we told them that rewards would be given to those that had the best job performance for each task.

The major task of the operator is to bring the output of each subsystem to its setpoint, stabilise the whole plant and finally put the whole plant in automation.

In this experiment, several questionnaires are designed to assess the perceived complexity (following the method from Zijlstra, 1993). The operation time and the number of key operation of each participant for each task are recorded. These data is used to analyse and quantify human perceived complexity, and its relation with other human factors, such as mental load, physical load, and operation performance.

Training for the participants

The participants receive three training stages. In the first stage, they are introduced about the system configuration, rating scales for complexity and difficulty, and other policy. In the second stage, they learn in practice how to operate subsystems and the overall system. In the third stage, they are required to practice the operation for several different sessions, and we study their learning curves, make sure that their performance is stable. Because this is a time-consuming experiment, all sessions have to be carried out in several times, therefore, for each experimental period, they are also required to do some sessions again before starting new sessions.

Table 2: Mean value, stand deviation of perceived complexity, difficulty, operation time and key-stroke rate

| Sess. No. | Type | Mean Comp | Stdev Compl | Mean Diff | Stdev Diff | Mean OT | Stdev OT | Mean Stroke rate | Stdev Stroke rate |
|---|------|-----------|-------------|-----------|------------|---------|----------|------------------|-------------------|
| One subsystem | | | | | | | | | |
| 1 | 1 | 14.3 | 9.0 | 21.7 | 8.2 | 5.3 | 1.9 | 8.7 | 7.7 |
| Two subsystems, four types of operation environment | | | | | | | | | |
| 2 | 1 | 24.2 | 8.6 | 31.7 | 12.1 | 8.7 | 4.2 | 16.8 | 26.1 |
| 3 | 2 | 26.3 | 9.1 | 32.7 | 14.1 | 9.8 | 2.8 | 13.4 | 18.3 |
| 4 | 3 | 29.8 | 10.6 | 35.0 | 10.0 | 9.3 | 5.5 | 16.8 | 20.3 |
| 5 | 4 | 38.3 | 12.1 | 43.3 | 14.7 | 13.5 | 4.6 | 12.6 | 15.4 |
| Three subsystems, four types of operation environment | | | | | | | | | |
| 6 | 1 | 30.8 | 8.0 | 40.2 | 8.8 | 10.8 | 3.2 | 14.4 | 14.9 |
| 7 | 2 | 40.0 | 8.9 | 48.8 | 11.8 | 10.0 | 3.0 | 18.9 | 23.8 |
| 8 | 3 | 49.7 | 15.1 | 49.8 | 16.4 | 13.2 | 4.9 | 17.4 | 19.7 |
| 9 | 4 | 53.3 | 14.7 | 55.0 | 14.5 | 20.2 | 2.6 | 14.7 | 16.7 |

| Sess. No. | Type | Mean Compl | Stdev Compl | Mean Diff | Stdev Diff | Mean OT | Stdev OT | Mean Stroke rate | Stdev Stroke rate |
|--|------|------------|-------------|-----------|------------|---------|----------|------------------|-------------------|
| Four subsystems, four types of operation environment | | | | | | | | | |
| 10 | 1 | 38.3 | 8.2 | 46.3 | 11.1 | 13.8 | 2.5 | 13.6 | 8.5 |
| 11 | 2 | 51.7 | 14.4 | 53.3 | 10.8 | 17.0 | 4.2 | 12.8 | 7.5 |
| 12 | 3 | 51.8 | 10.3 | 56.7 | 13.7 | 16.7 | 3.4 | 11.2 | 4.5 |
| 13 | 4 | 59.5 | 9.4 | 61.0 | 13.3 | 21.0 | 2.4 | 12.8 | 9.0 |
| Five subsystems, four types of operation environment | | | | | | | | | |
| 14 | 1 | 39.7 | 10.1 | 46.5 | 11.5 | 14.3 | 1.2 | 12.5 | 7.6 |
| 15 | 2 | 55.0 | 17.9 | 59.2 | 12.4 | 21.2 | 5.2 | 10.0 | 5.7 |
| 16 | 3 | 57.8 | 9.7 | 58.8 | 10.1 | 21.5 | 4.1 | 10.5 | 5.6 |
| 17 | 4 | 66.8 | 6.2 | 64.2 | 9.7 | 23.5 | 5.1 | 12.0 | 5.5 |

Experimental results and analysis

Table 2 shows the experimental data for plant start-up, e.g. teaching and instruction (Sheridan, 1992) under four structured operation environments, including mean value and standard deviation of perceived complexity, perceived difficulty, operation time (unit: minute) and key-stroke rate for each subsystem (unit: times per minute).

Fig. 3, 4, 5 and 6 are the diagrams for perceived complexity, difficulty, plant operation time and key stroke rate as a function of the number of subsystems for the four structured operation environments.

According to the experimental results, we may draw the following conclusions:

Conclusion 1: Human perceived complexity increases with the number of subsystems. While if perceived complexity increases, human perceived difficulty also increases and human operation performance (operation time) decreases correspondingly.

Conclusion 2: Linear extrapolation revealed that the perceived complexity will exceed 100 (the full scale for human perception), if, for the first uncoupled operation environment, the number of subsystems is more than 15; if, for the second and the third operation environments, the number exceeds 9; if, for the fourth operation environment, the number exceeds 8.

Conclusion 3: Linear extrapolation revealed that the perceived difficulty will exceed 100 (the full scale), if, for the first uncoupled operation environment, the number of subsystems is more than 15; if, for the rest three operation environments, the number exceeds 9. Linear extrapolation also revealed that, in case 15 subsystems are controlled in the first operation environment, as well as in case of 9 subsystems are controlled in the rest three operation environments, the required operation time will exceed 30 minutes.

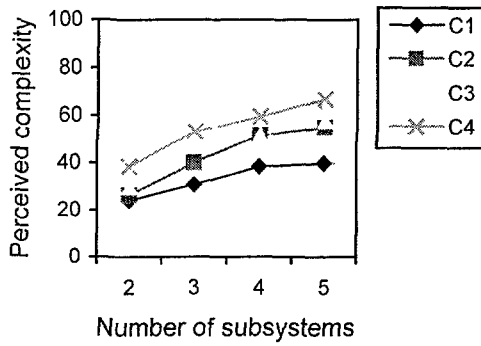


Fig. 3: Perceived complexity for plant operation

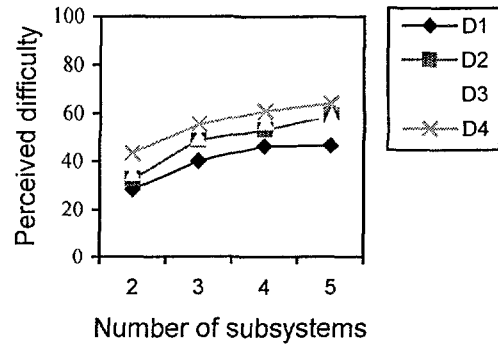


Fig.4: perceived difficulty for plant operation

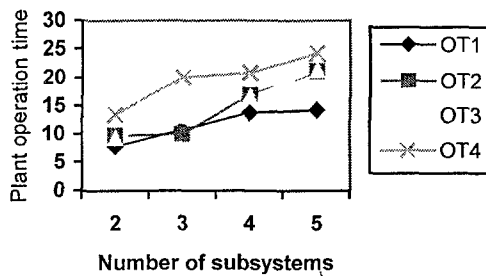


Fig.5 Plant operation time

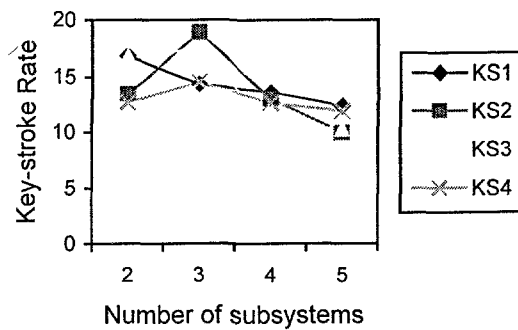


Fig.6 Key-stroke rate

Conclusion 4: The student t-test revealed:

- There exist distinct differences between the first and the forth-structured operation environments.
- The second and the third operation environments do not have distinct difference.
- In these 17 sessions of experiment, there dose not exist distinct difference between perceived complexity and perceived difficulty, which reveals that complexity is the most major factor contributing to operation difficulty.

Conclusion 5: According to the experimental data, key-stroke rate varied a lot among subjects in case 2 subsystems were used. For 4 and 5 subsystems, key-stroke variability was surprisingly small.

Conclusion and general discussion

This paper summarised a study on the human experience of complexity in supervisory control of complex processes. Firstly, a conceptual framework is introduced to discuss the relations between the subjective and objective complexities. Laboratory system with up to five subsystems is used to test the human perception of complexity. Four structured operation environments together with 17 sessions are designed to identify how different shaping factors influence human perceived

complexity in supervisory control of complex processes. These four structured operation environments correspond to the typical types of interaction in human supervisory control of industrial processes.

The role of human operator is just like an intelligent controller in human supervisory control of modern industrial processes, though his specific role varies from "teaching and instruction" to "monitor and intervene", or to anything else. The operation strategy, the training, the operation skill, the creativity, the willingness to be involved, and especially the personal types of the operator, determine the types of the intelligent controller and the robustness of the controller.

We believe that, the research methods presented and the results acquired on perceived complexity and its relation with perceived difficulty, work performance may be generalised to human supervisory control in a wide scope of industrial processes

The four structured operation environments are typical to human supervisory control, where the first and the second structured operation environment are more or less related to teaching and instruction tasks in supervisory control, such as plant start-up, normal manual operation, etc., where the tasks are mainly skill-based. The third and especially the fourth are related to monitoring, intervening, and learning, where the tasks are mainly problem-solving, thus knowledge-based.

The results may be applied to specific areas such as dynamic task allocation.

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