FEEDBACK DELAYS AND CONTROL IN COMPLEX DYNAMIC SYSTEMS[1]

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Modern technology makes great demands upon people's ability to understand and control complex dynamic systems, such as process plants. In such systems, feedback delays are inevitable; everything takes time, and there is little hope that a person will be able to observe all, or even the most important, consequences of his actions immediately. For example, in some industrial processes, the effects of certain control actions may not be apparent until hours later. Whether or not a person is able to develop adequate strategies to cope with such delays will determine the extent to which he/she will be able to control a complex dynamic system. Thus, this is a question of considerable practical importance, as well as a question of theoretical interest.

Surprisingly, there are very few studies of the effects of delays in complex systems. Most psychological research on the effects of delays has been conducted in the S-R tradition and tends is limited to the learning of simple responses in a conditioning context.

The results from studies on more complex tasks, such as concept learning and problem solving, are confusing: some results indicate negative effects of feedback delays, other results no effects of delays and some even positive effects (see Brehmer & Allard, 1988a). Thus, the problem of the effects of feedback delays is in need of study. This paper will review some of the results from a research program designed to investigate the problem of delays in a relatively complex computer simulated micro world which subjects must learn to control.

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Feedback delays and strategies. Feedback delay are quite complex. First, they can occur in different locations of the feedback loop. Second, the information about the delays can be presented in different ways.

Delays can occur in every part of the feedback loop. Thus, there may be delays in the transmission of commands, in the response to commands, in the execution of commands, in the reports about the effects of commands, and in the transmission of these reports. Of course, the consequence for control are the same, regardless of where the delays occur. It is that the system cannot be controlled optimally on the basis of feedback information alone. That is, optimal control cannot be achieved by simply correcting the current state as they are observed, for the state as observed always lags behind the current state. Consequently, attempts at feedback control are likely to force the system into oscillation.

To avoid this, the person must develop a feedforward strategy that helps him infer the actual state of the system, or delegate decision making to units that have more up to date information than he has.

The former of these strategies would involve creating a mental model of the system that helps him predict. Consequently, it is important to know the extent to which the system makes it possible to develop adequate mental models. Therefore, we must consider other characteristics of the system, such as how the delays are represented, which may affect the ability to develop such models.

One important factor here may be the extent to which the delays can be seen to occur. For example, a delay due to the time take to transport some item from one place to another can actually be seen by looking at a person moving from one location to another, while other forms of delay may require the person to make inferences , e.g., from measurements to detect the delay, as is the case for many of the delays that occur in a process plant.

Closely allied to this is another dimension, viz., whether the delays agree with one's understanding of the nature of the system. For example, delays due to the execution of commands, i.e., moving from one place to another, may be much easier to understand than delays due to slow reporting, since the first can be seen to be a necessary consequence of the nature of the system, while the second is not.

<u>The experimental task</u>. As noted above, we investigate these problems by studying how people interact with computer simulated micro-worlds where the task is to achieve control over some aspect of these worlds.

Most of our experiments so far have been conducted with a fire fighting-task. The conceptual model for this task is illustrated in Figure 1. The subject's task is to play

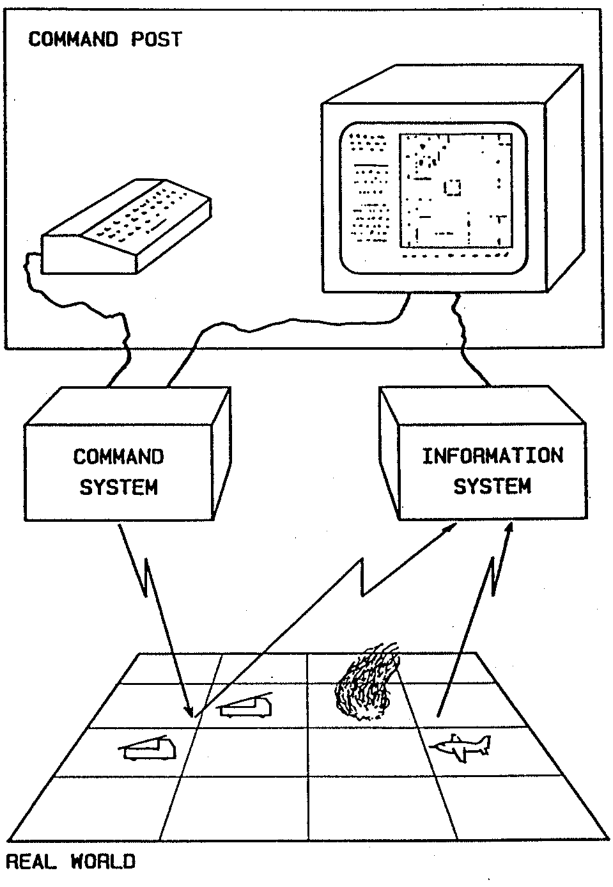

Figure 1. The general nature of the experimental task.

the part of a fire chief. He is seated in front of a computer terminal, see Figure 2.

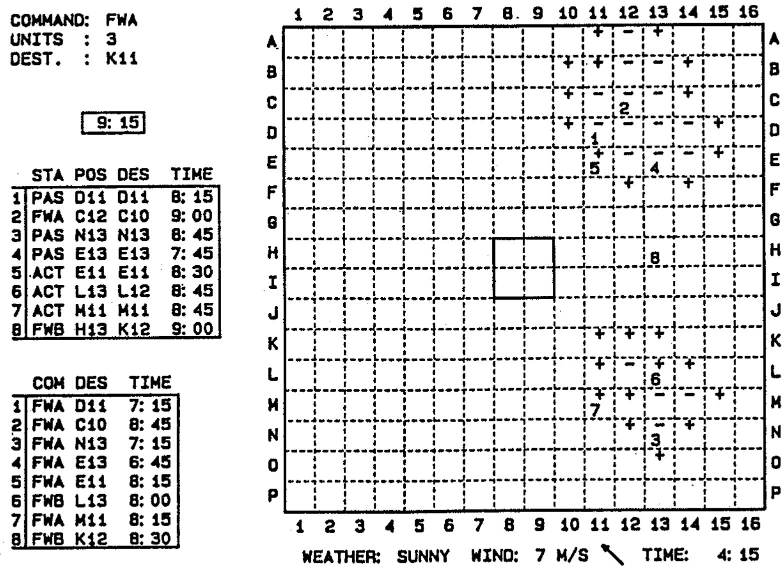

Figure 2. The subject's view of the experimental task

On the screen, he has a map ofa large forest. He receives information (without delays) from a spotter plane about the location of fires, and this is shown as "+" signs at the map. Burnt-out fire is shown as "-" signs. The location of the base, where the subject finds himself, is the four squares in the middle, which is outlined with heavier lines of the screen. The subject has two tasks: to prevent the fire from reaching the base and to extinguish it as quickly as possible, with the obvious priority ordering. He can send out anyone of his 8 fire fighting units (FFUs) by typing in the name of the unit (e.g., its number), a map reference, and code indicating whether the unit is to proceed under centralized control, or under decentralized control. The former code (FWA) means that the unit cannot start fighting fire until it has reached its destination, while the latter (FWB) means that the unit can start fighting any fire that it encounters en route to its destination. A unit's position, as reported by that unit, is shown by the location of its number on the map.

To the left, there are a four information displays. The first shows the command being typed in and the second the time. The third shows the positions and activity of the various FFus as reported by the these units. They report their position in terms of a map reference and their activity as ACT meaning that they are active in fighting fire or PAS meaning that they are not fighting a fire. They also report the time when the report was issued. The fourth display shows a list of the commands given to the various FFUs and when these commands where issued. Finally, under the map, there is a weather report, showing the general weather conditions, e.g., "dry", and the direction of the wind.

The subjects come to these experiments over a period of two or three days, and go through two or three trial each day. On each trial, a fire first starts in one location, and then another fire starts somewhat later, so that the subject actually has to fight two different fires on each trial.

In the experiments reviewed here, there are two kinds of delays. The first is constant in all conditions, and is caused by the fact that it takes time for the FFUs to move and to put out fire. To compensate for this delay, the subjects have to respond rapidly and massively to a fire, because the fire will have spread before the FFUs are in position, and more FFus will be required to put out the fire when the FFUs are in position than when the fire starts. This delay is inherent in the task, it is easy to understand and it can be seen to happen.

The second kind of delay, introduced in some conditions (the delay conditions) is a delay caused by slow reporting about actions and positions from the FFUs. This kind of delay is not inherent in the task, it is not neces-sarily part of the understanding of the na-ture of the task, and it cannot be seen to happen.

Results. The results for the two kinds of delays are dramatically different. Thus, the results show that subjects quickly learn to cope with the first kind of delay. Thus, they learn to respond rapidly and massively as required by the nature of the system. They do so better when there are no delays caused by slow reporting, but there is evidence of the development of the correct kind of strategy in both conditions (Brehmer & Allard, 1988a).

Figure 3 shows the effects of delayed re-porting. Specifically, it shows the area destroyed by fire when there are delays and when there are no delays in reporting. As can be seen from the figure, subjects improve over trials in the latter condition but not in the former.

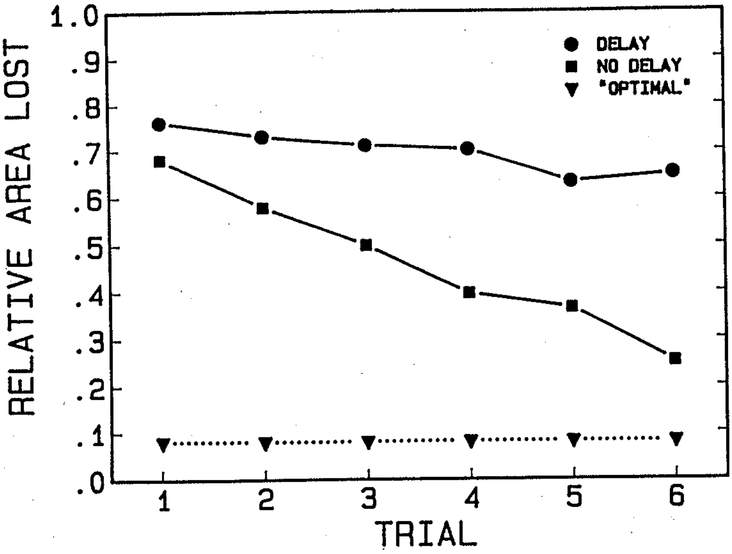

Figure 3. Effect of feedback delay on performance.

Figure 4 shows the reason for the inferior performance in the delay conditions. This

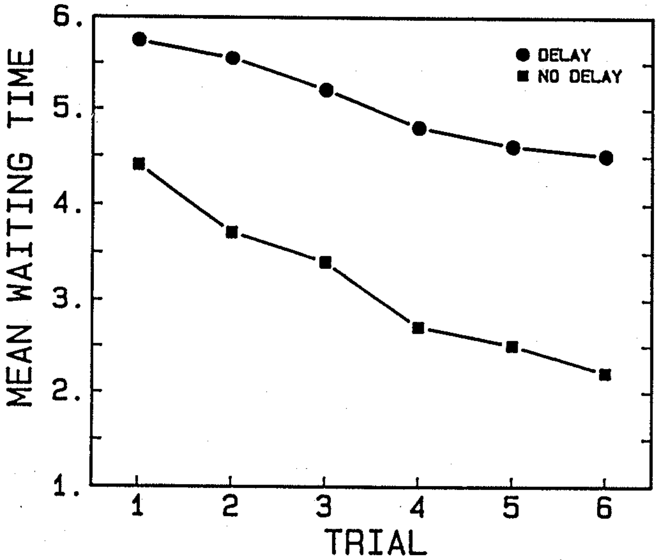

Figure 4. Mean number of time units a FFU is left inactive after having carrioed out its task.

figure shows how long a FFU is left inactive after it has carried out the command given to it. The time a unit is left inactive is proportional to the delay. This means that the subjects did not compensate for these delays, but treated the information about the locations and activities as reported as information about the current state. This is because the delays were in any way hidden from the subjects, they could readily infer bott the fact that there were delays and the nature of these delays from the information provided in the displays. Moreover, the subjects actually detect that there are delays (Brehmer & Allard, 1988a).

These results have now been replicated in a series of experiments (Brehmer & Allard, 1988a,b,c, d). These experiments have shown, among other things, that the same effects are obtained when subjects are told about the possibility of delays beforehand as when they are not, and when they are given a chance to combat the delays by giving series of com-mands, instructing the FFUs to a new location contingent upon having extinguished the fire in one location (Brehmer & Allard, 1988d). Moreover, the results show that subjects do not use the possibility to delegate decision making to the FFUs by means of the FWB command.

Discussion. The results reviewed above suggest that the subjects have problems in developing a strategy to compensate for the delays of the second kind, but not for delays of the first kind.

As noted above, the delays different in many respects. When considered in conjunction with other results, the present results suggest that the important factor is whether or not the delay can be seen to happen. Thus, Sterman (1988), using a simulation of an economic system found strong effects of feedback delays, despite that these delays were clearly inherent in the nature of the task and due the fact that it takes time to produce the items needed to fill the orders. However, these delays could not be seen to happen, but were revealed only by the fact that there was some delay between the start of production and the subsequent appearance of the items.

Brigham and Laios (1975) used a simulated process control task which involved level control. Here, the delays were also due to the inherent characteristics of the task, i.e., the time taken to fill and empty various tanks. They found that subjects were able to control this task if they were allowed to actually see the flows of liquid, but not if they had to infer these flows from instruments.

These results, then, would suggest that it is easier to handle delays that can be seen to happen than delays that have to be inferred, regardless of whether or not the delays are due to inherent, and presumably easily understood, features of the task (see also Brehmer, 1989).

This agrees with Johnson-Laird's (1983) conjecture that mental models have their origin in perception. This conjecture predicts that it would be easier to develop an adequate mental model from direct observation of the relations to be included in the model than from inferred relations, just as the results reviewed above suggest.

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