Off-Loading, Prevention, and Preparation: Planning Behaviours in Complex Systems Management

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There is a growing need for understanding the cognitive processes involved in the management of complex systems. Yet observations made in a recent field study in anaesthesiology and related studies have revealed some interesting phenomena that existing schools of thought have avoided, or are unable to account for satisfactorily. These phenomena are: it is often required for actors to prepare physically and mentally for future responses; prevention of a problem has priority over solving the problem; and it requires cognitive effort to maintain an action. A new paradigm is needed to account for the richness of human behaviours in the interaction with complex systems. A review of studies in action theory and motor skill development has provided a good basis for creating such a new paradigm, referred to as the planning theory of human behaviour in this paper. The new paradigm requires a shift of emphasis in the study of human behaviour in complex domains, and has potential impact on research in human error, mental workload, decision making, and human planning.

Introduction

In their paper, Roth and Woods [1988] give an exemplary analysis of a problem solving situation in a complex[1], dynamic working environment. The essence of that analysis is to build two models: (1) how a task environment imposes itself onto the habitant—a model of task demand, and (2) how the habitant responds to the demand—a model of performance. They have argued and shown that, in order to build effective aids to improve human performance, it is necessary to build these two models.

[1] See [Woods, 1988] for a comprehensive description of the concept of *complexity* and its impact on human operators.

However, the complexity of many real-life tasks often presents task demand in numerous fashions, and forces problem solvers to adopt a repertoire of effective strategies to meet the demand. One of the central challenges in the modelling process is to characterise these different strategies, and the consequent cognitive load on the problem solver in adopting these strategies. There is therefore a growing need to explore task demand across different work domains, and build up frameworks that will account for the various adopted strategies (*e.g.*, [Amalberti & Deblon, (in press)a; Klein & Calderwood, 1991; Xiao *et al.*, 1992]).

In this paper, by synthesising our own field studies and related research, a framework is put forward to explain a category of behaviours observed in managing complex systems, which for the most part has been neglected in the modelling of human-machine interaction. The field study was carried out in surgical operating rooms. The 'human operator' is the anaesthesiologist, who is responsible for the patient's well-being and providing proper conditions for the surgery. The 'plant' is the human body—the patient, a complex system. Major sources of data came from transcripts of verbal protocols of 'thinking aloud', inter-personnel communication, and answers to 'probing questions', while the anaesthesiologists performed their duties.

Units of Analysis

To deal with the complexity of human behaviour, a so-called "spartan" strategy is usually adopted, which involves selecting "only a single time slice of a dynamical process or only a subset of the interconnections between parts of a highly coupled world" [Woods, (in press)]. One manifestation of this strategy is that most studies (especially those on human error) usually focus on *incidents*, and the basic unit of behaviours studied is the cycle: *event* → *mental process* → *response* (EPR), *i.e.*, how a problem is identified and solved.

There are some serious consequences associated with choosing this event-driven responsive cycle, however. For example, the expertise studied will concern only how to respond to a problematic situation, instead of how to prevent it. The cognitive load associated with coordinating efforts beyond the basic EPR cycle, or in maintaining an action once it is taken, are hardly considered. Mental workload studies that confine subjects to a single EPR cycle do not reveal strategies for workload management [Raby & Wickens, 1990; Hart & Wickens, 1990].

In order to enlarge the scope of inquiry beyond basic EPR unit, it is necessary to consider coordination of actions, from which the human's active role in anticipation and preparation will emerge. Such an inquiry will, of necessity, deal with the problem solver's ability to generate response plans, to maintain them, and even to devise plans to maintain the response plans.

The use of the concept of *planning* here is not incidental. Miller *et al.* [1960] chose the concept in their seminal book to expand the scope of stimulus-response unit and to "put the last nail on the coffin of behaviourism"[2].

In his treatment of action theory, Bratman [Bratman, 1987] rightly pointed out the two central functioning roles of planning in human behaviour—*deliberation* and *coordination*. Deliberating beforehand is "because deliberation requires time and other limited resources, and there is an obvious limit to the extent to which one may successfully deliberate at the time of action" [Bratman, 1987, p.2] (see also [Simon, 1969]). The value of coordination is obvious, as many activities, including strategies for solving problems, require coordination. This functional view of planning should serve to eliminate most of the confusion in the use of the concept. It is the authors' belief that, because of this confusion, research into human planning and action has been limited. For the most part, current research on planning has little to do with action, but focuses on the algorithmic part (*i.e.*, the ordering of actions) of human planning (*e.g.*, [Haye-Roth *et al.*, 1988; Hayes-Roth & Hayes-Roth, 1979; Hoc, 1988]). Some researchers not only improperly limit the concept to the mere algorithmic part, but also deny the role of the planning concept in explaining human behaviours (*e.g.*, [Suchman, 1987; Payne, 1991]).

Phenomenology of Non-Event Driven Processes

In the management of complex systems, unprepared crises do occur that require on-site "inspiration", however "deliberation" precedes most crisis situations. Deliberation acts to limit the range of possibilities, and to prepare response plans (mental resources) and required materials (physical resources). Under such circumstances, problem solving can be regarded as *non-event driven*. Cognitive processes are activated not by a problematic situation, but by anticipation of the need for deliberation and coordination.

In the anaesthesiology field studies and during informal on-site observations, occurrences of this type of non-event driven phenomena were obvious. Below is a taxonomy of the phenomena.

Off-loading strategy

Unevenly distributed workload is the hallmark of the working environment in process control types of tasks. One strategy to prevent one's self from being overloaded is to reduce workload during subsequent busy times by doing in advance some of the steps

[2]Miller *et al.* [1960] are probably responsible in part, unfortunately, for limiting the notion of *plan* to an algorithmic nature, perhaps because the often quoted definition of *plan* appears on page 17, whereas a very important explanation of that term does not come until page 178, leaving room for misunderstanding by impatient readers.

that will be required during busy times. For example, it is almost a prescribed norm to draw up syringes prior to the starting phase of anaesthesia, which is usually a very busy time. It is not uncommon, in the middle of a case, for an anaesthesiologist to prepare for the following cases, to “even” out workload and to meet the demand of high production pressure.

Preventive strategy

The strategy of actively identifying potential problems is probably more obvious in the practice of anaesthesiology than in other process environments. As noted by Gaba: “the experts were more aggressive at preventing problems” [Gaba, 1991, p.46]. Anaesthesiologists usually, for example, mentally compile a list of concerns as a guide to preventing troublesome situations from happening. Such a strategy is the anaesthesiologist’s analogue of the cliché that a superior pilot will *avoid* situations in which he has to exercise his superior skills. Although there is a tendency to say that everything one does in any case is to prevent certain other things, the active nature of the preventive strategy used by anaesthesiologists certainly demonstrates the uniqueness. It is important to emphasise this, as the practitioner’s final performance is usually measured according to the final outcome, which is not a good indication of how sensitive an anaesthesiologist is. (Cook *et al.* [April 1991] document the peer review process of one’s practice and expose how anaesthesiologists measure their own performance.) For example, in certain cases there is a possibility to regain the patient’s consciousness as soon as possible in the middle of the case. Few anaesthesiologists would count on their skill of doing that effectively, but most will, from the very beginning, act to avoid the situation of being pressed to waken up the patient while the patient is deeply anaesthetised.

Resource preparation strategy

The variation of cases in anaesthesia usually means that each case requires a different resource profile. Preparing for resource requirement, particularly for emergency situations, is almost a routine. Certain emergency procedures require a long preparation time, constraining anaesthesiologists to reconfigure or create their workplace to accommodate the eventuality of each case. For example, a patient with a very rare blood type will prompt some anaesthesiologists to check blood supplies with the blood bank, even though the chance of a surgical hemorrhage may be small. In one case, the anaesthesiologist prepared a nitroglycerin infusion setup to deal with a possible wide range of fluctuations of blood pressure for the following case. This re-organisation of the workplace provides anaesthesiologists with the necessary physical resources to deal with expected contingencies.

Response preparation strategy

Not all preparations involve overt changes in the workplace. Some of the preparatory processes are visible to observers only by means of verbal protocols. For example, a frequent phrase recorded prior to some actions is: “aware of the consequences”, even though no instances were found where, after deliberation, the action was changed. There are probably two types of processes involved in this deliberation. One is rehearsal for responses to plausible adverse side effects; the other is the checking of availability of emergency responses (or so-called "bail-out" protocols). Instead of using a 'wait-and-see' strategy, anaesthesiologists often prepare responses to several possible events, so that once the actual course of an event is clear, no complicated decisions will be needed. As in the example of nitroglycerin infusion mentioned above, the anaesthesiologist had already decided what to do if the blood pressure went too high.

Action maintenance strategy

As in other complex domains, anaethesia requires physicians to maintain several threads of action plan. A number of interesting strategies were learnt that help them keep track of actions. For example, leaving a hand on the ventilator switch, which has been turned off transiently, should ensure that the switch will be turned back on again soon. Making use of labels on syringes helps to keep track of how much drug has been injected. Manual charting helps anaesthesiologists to ensure regular checking and assessment of the patient's status.

In the self-report recorded, there is much evidence to show that anaesthesiologists frequently generate local control rules to maintain actions. For example, an anaesthesiologist would report that he is trying to regulate the blood pressure below a target value, and, because the blood pressure is in an up trend, the local control rule will be to turn up the concentration of anaesthetic agent once the blood pressure reading reaches a certain number. The virtue of this strategy is that, instead of continualy assessing the significance of each reading of the environment, the operator processes the significance of a *category* of situations beforehand and therefore subsequent actions will be maintained at local, lower level. This is, in fact, an active strategy to transform a reading as *symbol* to a reading as *sign*, or even as *signal* [Rasmussen, 1983].

Evidence from other domains

In a long series of studies of cognitive processes in flying an aircraft, Amalberti [Amalberti & Deblon, (in press)a; Amalberti, 1992; Amalberti & Deblon, (in press)b] has obtained similar findings. In particular, he found that mental preparation has a significant impact on performance, as each flight mission is preceded by a lengthy planning session. The planning stage is not only to schedule the exact steps to be completed, but to formulate some contingency responses as well. Thus seemingly split second life-or-death decisions are in fact an adoption of preprogrammed solutions. During the flight, pilots were found to anticipate high workloads and to employ various strategies to 'off-load' beforehand. Generating local control rules, or even local models of the aircraft were also reported.

Another study of aircraft control, made by Norman [1991], underscores the importance of action maintenance, and various "tricks" that human operators adopt to achieve that goal. For example, pilots were found to use the placement of coffee cups, in a manner similar to the anaesthesiologist's placing a hand on the ventilator switch, to remind themselves of the status of the action plan.

Planning theory of human behaviour: a new framework

The phenomena presented here demand a wider view of human interaction with complex systems than has been conventional, not limited by the process between the perception of events and the generation of action plan. This is especially critical in the management of complex systems, as both physical and mental resource management are at a premium.

From our field observations and the review of related work, a new framework begins to emerge for capturing the phenomena listed above. First of all, it is assumed that human problem solvers are actively engaged in the process of anticipation, deliberation and coordination. To maintain an action, several levels of guidance have to be sustained, as the difficulty of action changes according to the particular situation. To ease the pressure of responding promptly, and to reduce the level of action complexity at the time of response, human operators actively seek lower levels of control signs or signals. Mental simulation and rehearsal of future events and responses are therefore required to provide the basis for preparing mental resources and physical resources, and identifying potential problems.

Conclusion

To account for the active nature of human behaviour in the management of complex systems, there is a pressing need for a new framework to characterise the richness of various strategies, and for assessing the cognitive load as a consequence of adopting these strategies. This paper has addressed some of these strategies, phenomenologically labelled as "off-loading", "preventive", "preparatory". A planning theory of human behaviour is outlined here as a framework for capturing the strategies. Detailed theoretical work and further field studies will provide a solid background for the framework, and provide us with a basis for modelling task demands and operator performance.

Acknowledgement

This research is supported by grants from NSERC and IBM Canada, Inc. The research would not have been possible without the support of the anaesthesiologists of Toronto General Hospital.

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