Part III

A Planning Model

9 A planning model

> ...the decision-ladder is not a model of the decision process itself, but a map useful to represent the structure of such a model.
>
> —*J. Rasmussen, 1986, p. 70*

This chapter is to present a model of planning and action control in the context of interacting with complex work environments. The purpose of the model is to describe one way in which one can prepare for the future, and how that preparation affects subsequent behaviour. In the next chapter, the model is used to reanalyse the findings of the field study. The detailed usage of the model will also be shown there.

9.1 Introduction

"Toronto is to the west"

> On the way back to Toronto, as I approached Highway 401, I knew that I had to decide which direction of the highway to take: eastbound or westbound. Then I realised that Toronto was to the west, so I told myself to look for the sign for 401 West. Without having much trouble in finding the sign, I took the exit, and got onto Highway 401 westbound.

This is a personal account of an episode of a trip back to Toronto from a friend's cottage. It presents a phenomenon central to this thesis: human beings do not always wait for problem-solving situations to arise, but rather, quite often, we anticipate the future and start processing future situations mentally *before* we actually encounter them. In the above episode, for example, the driver could have used a different strategy. Instead of anticipating that there would be a choice, he could have checked every exit sign to Highway 401: "Will this exit get me to Toronto?" Depending on the answer to that question, he could then decide whether or not to exit at that sign.

The two strategies elicit different mental processes and levels of complexity in processing, both in searching for exit signs and in responding to them. In the recounted episode, after prior mental processing, the task of finding the correct exit is simply a matter of match-and-trigger. The driver could concentrate more than he otherwise would on the traffic and other tasks. He did not have to think about the question of which direction of the highway would lead him to Toronto, and he would not spend much time in processing the non-matched signs (*i.e.*, the exits for the eastbound).

This episode is a trivial, everyday life example of anticipatory and preparatory behaviour. Generally, the scope of our conscious thinking covers matters over a continuum of time from the past to the future. Some of our thoughts concern things days or even years from now, while others with events just a few seconds away. We anticipate the future and deliberate on future activities that are at different points in that continuum of time. We usually have some anticipation of future situations, and often start to deliberate about those situations before we actually encounter them. Such anticipation can lead to (1) coordination among our own and/or with others' activities, (2) preparation of needed knowledge or action rules, as well as the materials and information necessary for carrying out those actions, and (3) rehearsal of procedures. Most of us would agree that the mental activities involved in anticipation and prior deliberation are of great importance and have significant impact on subsequent activities.

The question to be addressed in this chapter is: What is the effect of the anticipatory and preparatory activities, as observed in the field study on anaesthesiologists and illustrated by the episode "Toronto is to the west"?

9.2 The unit of analysis

The crux of the problem of understanding anticipatory and preparatory behaviour seems to lie in the unit of analysis that one chooses in studying behaviour. (See Figure 8.1.)

9.2.1 Anticipation as an emergent feature of molar behaviour

To deal with the complexity of human behaviour, a divide-and-conquer strategy is often 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, 1993, p. 229). One manifestation of this strategy is to assume that a behavioural stream consists of a *linear* assembly of stimulus-response (S-R) pairs, and that one can justifiably study each pair in isolation (as has been done for example in the Model Human Processor by Card *et al.*, 1986, in which human cognitive activities are segmented into a concatenated, linear sequence).

Tolman is probably the first who, himself as a behaviourist, argued that emergent features in the behavioural stream could not be studied by examining behaviour at the level of individual, molecular units (Cf. the chapter *Behavior, A Molar Phenomenon* in Tolman, 1932/1968). His argument directly addressed the inadequacy of the S-R paradigm in studying behaviour, and he claimed: "it is ... the molar properties of behavior-acts, which are of prime interest to us as psychologists."

Thus, at least to Tolman, it is clear that one needs to examine an *assembly* of more than one basic unit at the same time to understand emergent features in behaviour, that is, the structures of the assembly made of the basic units. Often attributed as putting the last nail on the coffin of behaviourism, the book *Plans and the Structure of Behavior* (Miller *et al.*, 1960/1986) went further than Toman did. Miller *et al.* assumed that not only do there exist different levels of *description* of behaviour, but behaviour is itself *organised* at different levels. Convincing evidence to support this assumption come from studies of human languages (see examples given by Miller *et al.*, 1960/1986, p. 14) and of motor skills (*e.g.*, Gallistel, 1980; Pew, 1974).

If there were one area of cognition that should lend itself to be investigated satisfactorily in an isolated, S-R style, it would have to be perception. Vision research has long been dominated by the S-R paradigm. Subjects are shown stimuli very briefly[1] to ensure no more than one S-R cycle occurring. However, Neisser (1976) has argued eloquently about

[1] "Such displays come very close to not existing at all" (Neisser, 1976, p. 35). Neisser describes in this way when commenting on the perception research in which the subject's exposure time is along the order of 20 milliseconds.

the importance of studying perception over time. In his opinion, *temporal continuity* is one of the aspects that are essential for ecological validity (p. 34).

When we observe subjects behaving over time, one of the first emerging properties in behaviour would be anticipation. Neisser (1976) has made this point explicitly with his perceptual cycle (see also Figure 4.2 on page 57 in this thesis), in which exploration of the perceptual world is governed by prior anticipation (schema). In naturalistic settings, there is no clear onset of problem solving activities when observing behaviour over a period of time. An experienced problem solver often can detect precursor(s) to a problem solving situation, and often starts processing the problem before it is actually presented. He or she may choose to prevent the anticipated problems from occurring, which is in most cases more favourable.[2] So the nature of problem solving, just as in the case of perception, is drastically different when the subject is allowed to do it over time, and at his or her own choice of methods.

Nevertheless, viewing the human as a "passive cognitive machine" remains a prevailing assumption, albeit often implicit with many researchers. "As we have seen, in the laboratory the technique of study has continued to be through firing stimuli at a person who sits and awaits them" (D.E. Broadbent, 1986, in *Foreword* to Miller *et al.*, 1960/1986, pp. xxvi–xxvii). The subject is stripped of opportunities to actively organise subsequent behaviour through anticipation of the future. The focus of inquiries has been on behaviour related to how to respond to given problems.

The next segment gives an overview of some of the activities that would not be studied if the S-R paradigm were followed exclusively.

9.2.2 Consequences of anticipation

Experienced workers usually can and do anticipate the future. Considerable effort is spent on organising activities (*e.g.*, Beishon, 1974). This effort can change task properties in significant ways, as shown in studies on flight missions (Amalberti & Deblon, 1992) and air traffic control (Redding & Cannon, 1992). Rasmussen has emphasised the importance of studying the active, anticipatory nature of behaviour:

> A crucial feature to include in a model is that humans are not only responding to "input." They actively seek relevant information; they constantly orient their senses towards important features in the information available, and they respond to information present as well as information missing—they have expectations (Rasmussen, 1986, p.74).

In most complex work settings (actual or simulated), workers are well experienced. In order to understand their current activities involved in anticipation and preparation, it is critical to understand the influence of those activities on subsequent behaviour as well. We need to study expertise concerned not only with responding to problematic situations, but also with anticipating, preparing, and preventing. In workload research, for example, we need to understand cognitive workload associated with coordination efforts beyond basic S-R cycles, and activities in sustaining actions over a period of time. Mental workload studies must include those strategies for workload management (*e.g.*, Sperandio, 1971; Raby & Wickens, 1990; Hart & Wickens, 1990) to reflect the active, adaptive nature of human behaviour.

Examples in preview control (*e.g.*, Sheridan, 1967; Xiao *et al.*, 1988) have demonstrated the impact of anticipation and feedforward information, and the tendency for humans to incorporate the future (previewed or anticipated) into the present response.

[2] A counter-example would be chess playing, in which people are actively seeking challenging problem solving situations.

9.2.3 Plans and the structure of behaviour

In studying behaviour over an extended time frame, in which anticipation and preparation are possible, we essentially deal with the basic question of how one's anticipation and prior deliberations influence subsequent behaviour. This is also the central question addressed by Miller *et al.* (1960/1986). They used the concept of "plan" to outline such influences. Starting on the first page of the first chapter, Miller *et al.* stated their conviction that plans, though sketchy, have an impact on subsequent behavior:

> The authors of this book believe that the plans you make are interesting and that they probably have some relation to how you actually spend your time during the day. We call them "plans" without malice—we recognize that you do not draw out long and elaborate blueprints for every moment of the day. You do not need to. Rough, sketchy, flexible anticipations are usually sufficient. As you brush your teeth you decide that you will answer that pile of letters you have been neglecting. That is enough. You do not need to list the names of the people or to draft an outline of the contents of the letters. You think simply that today there will be time for it after lunch. After lunch, if you remember, you turn to the letters. You take one and read it. You plan your answer. You may need to check on some information, you dictate or type or scribble a reply, you address an envelope, seal the folded letter, find a stamp, drop it in a mailbox. Each of these subactivities runs off as the situation arises—you did not need to enumerate them while you were planning the day. All you need is the name of the activity that you plan for that segment of the day, and from that name you then proceed to elaborate the detailed actions involved in carrying out the plan. [pp. 5–6]

The remainder of this chapter basically follows the concept of a "plan" as perceived by Miller *et al.*, and proposes a model of planning and action control that captures the key aspects of the role of anticipation and preparation in the interaction between a proficient worker and a complex work environment.

9.3 Action and the role of planning

9.3.1 Planning and feedback

Although the definitions of a "plan" vary greatly, the gist of the concept is probably best understood by the *role* of a plan in action. Hoc (1988) provides a definition along this line (p. 84): "A plan is a schematic and/or hierarchical representation whose function is to guide activity." This thesis uses this as the working definition of a plan.

This thesis is interested in situations where

- plans are largely for personal consumption (as opposed to plans made as *products* for others).
- the task is sufficiently repetitive that there is rarely a need for making a completely new plan, but is sufficiently non-routine that the task is not completely proceduralised.

A large part of the research on human planning is therefore irrelevant to this thesis (*e.g.*, studies on errand planning by Hayes-Roth & Hayes-Roth, 1979 and planning by artificial intelligence systems by Sacerdoti, 1974; McDermott, 1978; Firby, 1989). The reason is that research by others on human planning seems to be completely occupied with the process of generating a plan representation (*e.g.*, Johannsen & Rouse, 1983; Miller, 1983; Sanderson, 1989), and not with the question of how such a representation influences activity. However, the effects of plans on actions are unclear. Simplistic, extreme assumptions on those effects often lead to misunderstandings. For example, Suchman (1987) uses the example of canoeing down a series of rapids to show that prior planning has little effect on subsequent behaviour. Payne (1991) uses the evidence that even experts can not predict exactly the effects of actions to argue against the importance of anticipation and planning.

In contrast, admirable progress has been made in the area of motor skills, to investigate the effect of anticipation and planning on action (see the review book by Holding, 1989 and a chapter by Keele, 1986). For example, Rosenbaum (1983) studied the effect of anticipation and of prior specification by the precuing technique. In experiments using this technique, the subject is provided with lead information about the characteristics of the upcoming stimulus. Rosenbaum's study supports the view that prior specification reduces response complexity, and consequently, the response time. The more one knows about the characteristics of the upcoming stimulus, the faster the response.

The issue confronting motor skill research is somewhat similar to the one addressed in this chapter: Given that we almost always have to rely on feedback information about exact circumstances in order to control our actions, what is then the role of plans (or motor programs)? Which part is more important in action control: the motor program (*i.e.*, the control from central nervous systems) or feedback (*i.e.*, the corrective control based on peripheral sensory inputs)? Weinstein and Schmidt (1989) summarise the motor skill research on this issue as follows:

> The motor behavior literature from the last few decades has generally abandoned the controversial question of whether "central" or "peripheral" processes govern motor behavior .... Instead, it is now generally acknowledged that most skilled actions are accomplished through an integration of open- and closed-loop processes—a so-called "hybrid control system"—and research has begun to focus on the nature of this integration. [p. 18]

It seems that motor skill research has made considerable headway in understanding the relationship between feedback control and plan control. In contrast, its counterpart in presumably more cognitive behaviour research has not moved far in delineating the role of plans.

This thesis does not attempt to resolve the general question regarding the relationship between local feedback and plans. Instead, it proposes a model of planning and action control that is *useful* for analysing some of the phenomena observed in the field study, to provide some guidance to future research on human problem solving in complex work environments.

9.3.2 Functional roles of plans

In his treatment of action theory, Bratman (1987) pointed out the two central functional roles of planning in human behaviour—*deliberation* and *coordination*. Deliberating occurs beforehand "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). The value of coordination is obvious, since many activities, including those involved in solving problems themselves, require coordination and planning at different levels of detail (Koedinger & Anderson, 1990). The limitations in the human cognitive system restrict the number of items held in dynamic memory, the speed at which information can be processed, and the depth to which an environmental event can be processed before a response has to be made. Hoc (1988) provides a similar description of the functional roles of plans in action control (p. 116).

Examining the functional roles of planning should serve the purpose of eliminating much of the confusion in the use of the concept of a "plan." It is the author's belief that, because of this confusion, research on human planning and action has not progressed as rapidly as would otherwise be possible. Refuting the role of plans in action control and the role of the concept of a "plan" in explaining behaviour (*e.g.*, Payne, 1991; Suchman, 1987) only limits us to the S-R paradigm.

In short, in order to understand human planning, one has to understand the need for plans and planning, and how these provide guidance for subsequent actions.

* * *

This chapter started with the question about understanding the role of anticipation and preparation in behaviour, and then expanded the scope of inquiry to understanding the general structure of behaviour, since anticipation is one of the emergent features of behaviour that one can observe under not so constrained behavioural conditions. The issue about the role of anticipation thus becomes one of understanding the influence of plans on the execution of actions.

The following will examine a particular framework—the "decision ladder" (Rasmussen, 1976, Fig. 1)—to build a model of planning and action control. The reason for choosing the decision ladder is simple: the decision ladder is one of the only frameworks that reflect the essence of flexible action control in complex, dynamic work environments (such as those that one would find in operating rooms).

9.4 Decision ladder: A representation of action resources

9.4.1 Decision ladder and action control

Refer to the review of the concept of decision ladder in Chapter 2 (starting on page 15). Although the concept of the decision ladder was constructed as a means of capturing observed sequences of activities, it has a direct relationship with action control: It can be used to represent the many ways in which an organism can control its actions during interactions with its environment. Whenever a stimulus in the environment is perceived, information processing activities are triggered along the "legs," or the "rungs," of the decision ladder, and a response is generated. Depending on the state of affairs, prior expectations of it, and the experience of the organism, different paths of information processing in the decision ladder will be taken.

For example, a car driving task can induce different paths in the decision ladder. Deviations of the car position in the lane are corrected directly by actions, without having to evaluate the consequence of the deviation; traffic signs may cause the driver to think of the destination and to evaluate whether or not changing lanes is desired; if it is, a sequence of manoeuvres is initiated (*e.g.*, signaling, shoulder checking, steering to a new lane, and so on). If the traffic is heavy, a more complicated sequence of activities may be triggered: choosing a desired point of entry to the new lane, adjusting the speed, watching other drivers' responses, and changing lanes when the situation allows. This sequence may also be determined by nodes high in the decision ladder. If the time pressure is large (*e.g.*, very close to the exit point), and the cost of missing the exit is large (*e.g.*, late for an important appointment), the driver may cut into the new lane sooner and the manoeuvre is riskier than otherwise.

The above examples demonstrate that the decision ladder inherently contains the notion that action control occurs at different levels. (See Rasmussen, 1983). Multi-level action control is a concept that has been around for a long time. The concept was argued to be central to the understanding of skilled human behaviour and indeed has been exploited as such (*e.g.*, Bruner, 1970; Allport, 1980; MacKay, 1982; Moray, 1986). The functional value of multi-level action control should be clear: "If only the upper levels are available, performance would be slow, awkward, and demanding as when we learn a new skill. On the other hand, if only lower levels were available, performance would be effective only when the novel or unexpected do not occur" (Woods *et al.*, 1987, p. 1746).

Miller *et al.* (1960/1986) actually provide a concrete example to illustrate what hierarchies of action control look like. (That example is the well-known TOTE unit: *t*est-*o*perate-*t*est-*e*xit, which emphasises that behaviour is oriented towards a hierarchy of goals). The basic idea of the concept was summarised by Broadbent (1977, p. 181):

> The general principle ... is that human processing of information takes place on many levels. Some of these levels modify or control the operation of others; those systems which are subject to control deal with parts of the total activity of the person, and are perfectly capable of getting on with those parts if the higher centres are otherwise occupied.

The taxonomy of cognitive control of action proposed by Rasmussen (1983) extends the multilevel concept to the *association* between the way in which environmental cues are interpreted (as *signals*, *signs*, or *symbols*) and the way in which action is controlled (in *skill*-, *rule*-, or *knowledge*-based manners). Environmental stimuli can be used to drive motor movements directly (the stimuli are perceived as *signals*), to start actions (the stimuli are perceived as *signs*), or to evoke goal evaluations and response choices (the stimuli are perceived as *symbols*). A direct conclusion of such an association is that the human operator uses environmental cues differently at different levels of cognitive control (see an example in Hansen *et al.*, 1990, Fig.11). While at the rule-based level the information searching activity is oriented towards finding differentiating cues for releasing proper rules, at the knowledge-based level this activity is oriented towards finding cues that activate option evaluation and goal selection.

The knowledge and skills needed for action control are different at various levels of action control. At the knowledge-based level, action is under direct control of goals, and novel situations can be dealt with even without existing procedures to go by. At the rule-based level, action is controlled by procedures and rules, and thus involves less demands on problem solving. At the skill-based level, action is controlled by tight sensory-motor loops and the skill of coordination in spatial-temporal space.

The knowledge and skills needed in action control at these levels can be viewed as *resources* that a human being possesses. They do not specify exactly the way in which one controls action, but they provide one with the ability to make decisions, to formulate response plans, to activate rules, and to execute plans.

In the following we examine the relationship between the resources for action control, or *action resources*, and the decision ladder.

9.4.2 Action resources represented by the decision ladder

When a stimulus is perceived, a response is generated, just as in the case of when a car driver sees a red light, he stops. A link between the stimulus and the response either exists before perception of the stimulus, or is built (or modified) after the perception. An operator in a control room usually knows immediately how to respond to the events of his or her plant, whereas an untrained person usually does not. An experienced operator may not have to go through complicated information processing to generate a response in a situation in which the less experienced operator may have to. In any case, whatever path in the decision ladder it may take one to process a stimulus and to generate a response, one needs knowledge and skills along the path to do so. A "short-cut" in the ladder, for example, would save one from processing the stimulus further. Without such a rule, one has to make use of knowledge and skills in nodes that are otherwise shunted by that rule.

In other words, the decision ladder can be viewed as a framework upon which the potential resources (*knowledge and skills*) for action control, or action resources, can be represented and how they are distributed. For an experienced worker, the decision ladder contains not only rich interconnections ("rungs") among knowledge states and activities, but also the knowledge needed for directing the flow of a decision path in the ladder. For a well practiced procedure, for example, the signal of the end of a step automatically triggers the next step in the procedure and the actor does not have to think about what needs to be done next. For a less experienced worker, the available resources are not as rich. Not only does he or she have less discriminative power in deciding which direction the information processing should take, there are fewer interconnections, or "short-cuts," among the nodes in the ladder. He or she is more likely to have the need to formulate low level goals from higher ones, as well as the need to outline the range of options.

Four important sources can be identified for contributing to the action resources:

- training,
- experience,
- on-line help (check-lists and procedures), and

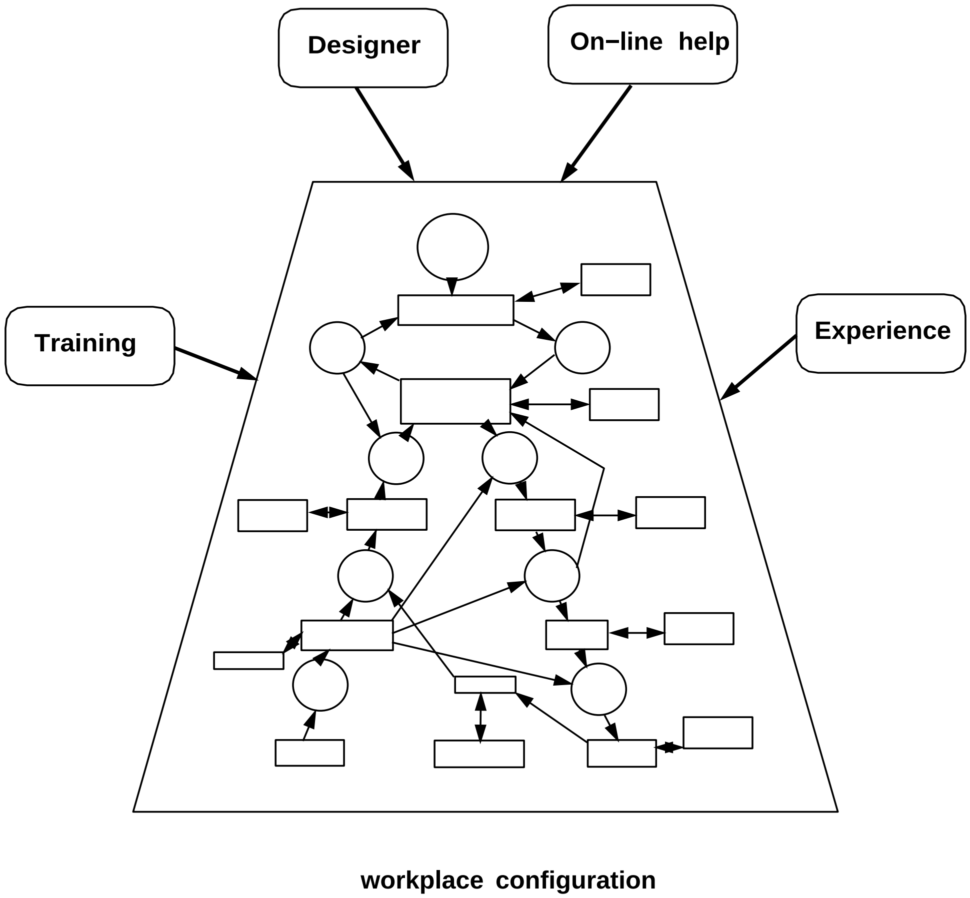

Figure 9.1: Four sources of action resources. The central portion represents the decision ladder. Refer to Figure 2.2 (page 17) for details about the decision ladder. The exact location of each source is arbitrary on the figure.

- the system designer.

Figure 9.1 is a schematic illustration of the influence of these four sources of action resources. The first three sources are straightforward and need no explanation. What is worth noting is the fourth source, the role of the system designer, who provides the operator with the means to interact with the system. A push of a button, so to speak, can trigger a sequence of events that have the effect desired by the operator. Rasmussen (1986) shows two examples (Figs. 6.4 and 6.5) of how the respective decision ladder of the designer, an on-line computer, and the operator jointly contribute to making a decision.

The thrust of this chapter, however, lies with a fifth mean of contributing to action resources, namely, planning.

9.5 A model of planning and action control

9.5.1 Planning as preparation of action resources

An experienced worker usually generates a response more quickly and much more efficiently than a less experienced worker can. This observation can be viewed, from the perspective of this chapter, as that the experienced worker has action resources that the less experienced worker does not have. The less experienced worker can, on the other hand, remedy the difference to some degree through anticipation and preparation. This thesis proposes that planning is a way to prepare action resources.

In the example "Toronto is to the west" at the beginning of this chapter, the driver knew that he was approaching the highway and that, in order to exit properly, he had to choose a direction for that highway. This anticipation led him to prepare a rule (or a "rung" in the decision ladder) that links a road sign to the goal of getting to the direction of the highway that would lead to Toronto. To an experienced driver (*i.e.*, someone who has driven that path before), such a planning process is not necessary. In fact he or she may not need to read the exit sign at all, as experience will have supplied other signs for triggering the task of exiting. Nevertheless, the associative rule that the driver in the example prepared guided his later actions and facilitated his interaction with the environment. The process of planning prepared a rule—a part of action resources—for the driver.

As hinted in the above analysis, planning can prepare only certain kinds of action resources. For example, no amount of planning will give the driver the same kind of action resources that he would have if he had driven the same route before. In the following, two categories of action resources are listed as possible objects of planning.

Mental resources The first category of resources that planning can prepare are *mental* resources. These include *local models* of a system—*i.e.*, models of the system that are easy to use to give predictions. Amalberti and Deblon (1992) observed in their field studies that pilots generated local models of the aircraft for easy calculation. For example, one local model used by pilots during the flight is: "for the next 60 miles, one degree to the left, or to the right should correct a discard of 1 nautical mile" (p. 649).

Another type of action resources belonging to this category is *triggering signs* for actions. By knowing, or inferring, what signs to look for to start actions, the operator can be more responsive and act faster.

Contingency action plans can also be prepared. Instead of waiting until a problem solving situation arises, a list of action plans can be prepared. The operator has only to look for discriminative cues to start the proper action plans (see also Amalberti & Deblon, 1992).

Rehearsing a procedure is another means of planning. In a rehearsal, one can make the chaining between steps smooth. One can also detect problems in the procedure before it is implemented, and modify it in advance (see also Klein, 1989).

Last but not least, planning can provide *action specification* information for an action to be executed. Due to the multi-level nature of action control, and to the fact that an action can be executed in many ways (*i.e.*, the one-to-many mapping problem; see Figure 9.2), the operator faces a potentially complicated action specification process. One may assume that a prototypical pattern of action execution is possible in most situations, but modifications to the prototypical response are often necessary to fit the actual circumstances. Planning can prepare this type of resource.

Physical resources The second category of resources are *physical* resources. Although physical resources are *not* represented by the decision ladder, the physical environment of the operator plays an important role in supporting the operator's cognitive activities. In most industrial settings, the work environment is designed to fit the needs of the operator. Nevertheless, operators are often found to tailor their workplace to reduce response complexity and facilitate the sustaining of actions (*e.g.*, Norman, 1991; see a review of this study in this thesis on page 18). As seen in the current field study, anaesthesiologists configure the workplace in significant ways.

The preparation of physical resources can take the form of *arranging* the workplace in such a way that a subsequent procedure can be executed smoothly, without having to pause and think. It can also take the form of *placing triggering cues* in the workspace to ensure the execution of actions. Prepared contingency plans may require materials and arrangement not ordinarily present in the workplace. Preparing *materials* and their *access* for contingency plans is important, too.

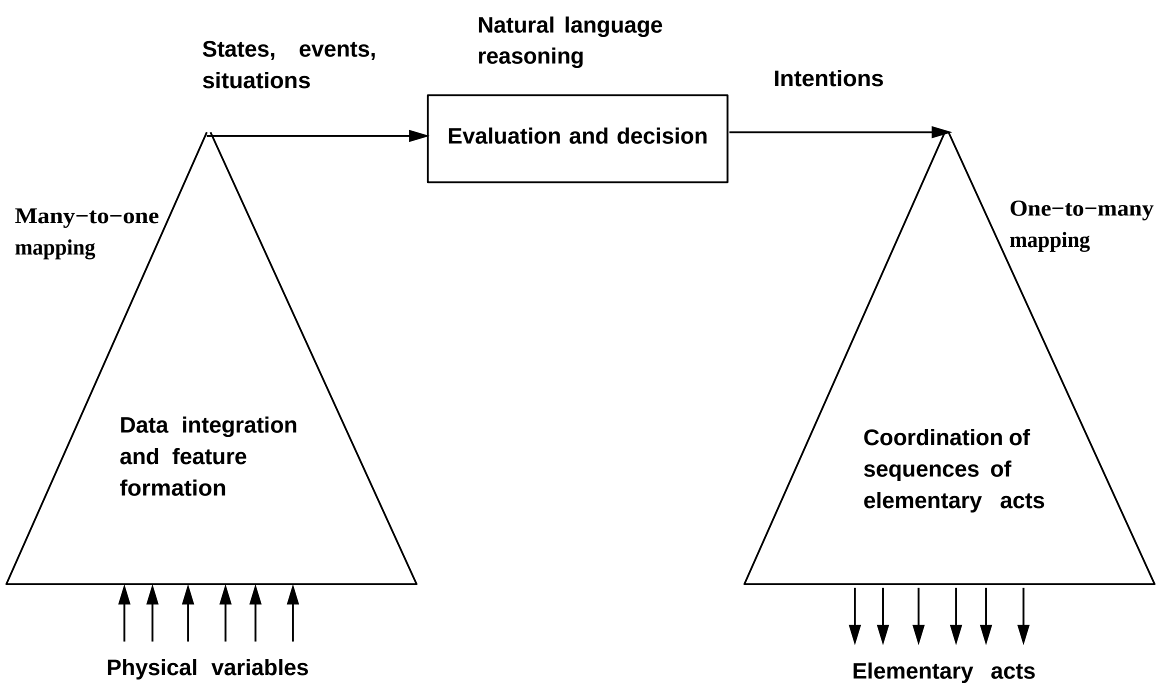

Figure 9.2: Complexity in action control: Many-to-one and one-to-many mapping. Adopted from Fig. 1 of Rasmussen and Lind (1981). Also available as Fig. 40.18 in Moray (1986). On the left side, relevant features in the physical variables or environmental stimuli are extracted (many-to-one mapping) to drive goal oriented activities; on the right side, a chosen action is implemented as sequences of elementary acts (one-to-many mapping).

9.5.2 The planning model

Starting with the notion of planning as the preparation of action resources, this section has essentially outlined a conceptual model of planning and action control, which is summarised here:

> *Planning is a process of preparing action resources, which is largely represented by the decision ladder. Planning is triggered by anticipation of the need for preparation. The goal of such preparation is mainly for reducing response complexity when subsequently interacting with the task environment.*

Figure 9.3 illustrates the model through the decision ladder. As explained earlier, the role of planning is not to specify or control actions in detail. Rather, it is a process of preparing the operator to interact with the environment effectively. On the one hand, the uncertainty and complexity of actual work settings makes detailed planning impractical. On the other hand, experience and the workplace provide support in various ways (*e.g.*, specifying temporal and spatial details of actions) for *on-line interaction*, that is, responding to events in the environment and monitoring actions. Thus planning can also be viewed as a way to carry out some of the activities that the operator *has to do* in order to accomplish his or her goals. Whether planning occurs or does not occur is only a matter of at which time these activities are carried out. From this point of view, planning has advantages in comparison with on-line interactions, as more resources (*e.g.*, information sources and time) are available. But it does not deal with specifics well. Figure 9.4 is presented to show such a complementary relationship between prior planning and on-line interactions.

The above model is an extension to the preparatory framework (Figure 4.5, page 61). While the preparatory framework is based on the event → mental process → response (EPR) cycle, the model proposed in this chapter is based on the decision ladder. Thus the model establishes a link between preparation and action control, and provides a better understanding of the ways in which one can prepare and in which preparation can affect behaviour in subsequent interactions with the task environment. As a consequence, it is intended to provide better guidance for future theoretical and empirical studies, both in the field and in the laboratory, on anticipatory and preparatory behaviour.

9.5.3 The nature of planning as preparing action resources

The discussion above has explored how planning can be viewed as a process of preparing action resources, relative to the framework of the decision ladder. This subsection will attempt to answer a few critical questions about this view of planning, as expressed in the model of planning and action control.

The level of detail in planning

Preparation of action resources occurs at different levels of detail. The operator can set a general goal for the activities to come and set subgoals as landmarks. He or she can also rehearse in detail the actions to be executed, that is, what signs to look for, and what to do when the actual situations occur.

Given that planning is viewed as the preparation of action resources, the level of detail in planning will then depend on the experience of the operator. An experienced operator does not have to plan as much as an inexperienced one in order to ensure successful operation, because he or she already possesses much of the action resources that are needed for successful interactions with the task environment. He or she may need only to find out a few missing nodes or links in the decision ladder and to prepare them accordingly. These missing nodes and links are likely to be in lower positions in the decision ladder and are likely to be those associated with the exact circumstances.

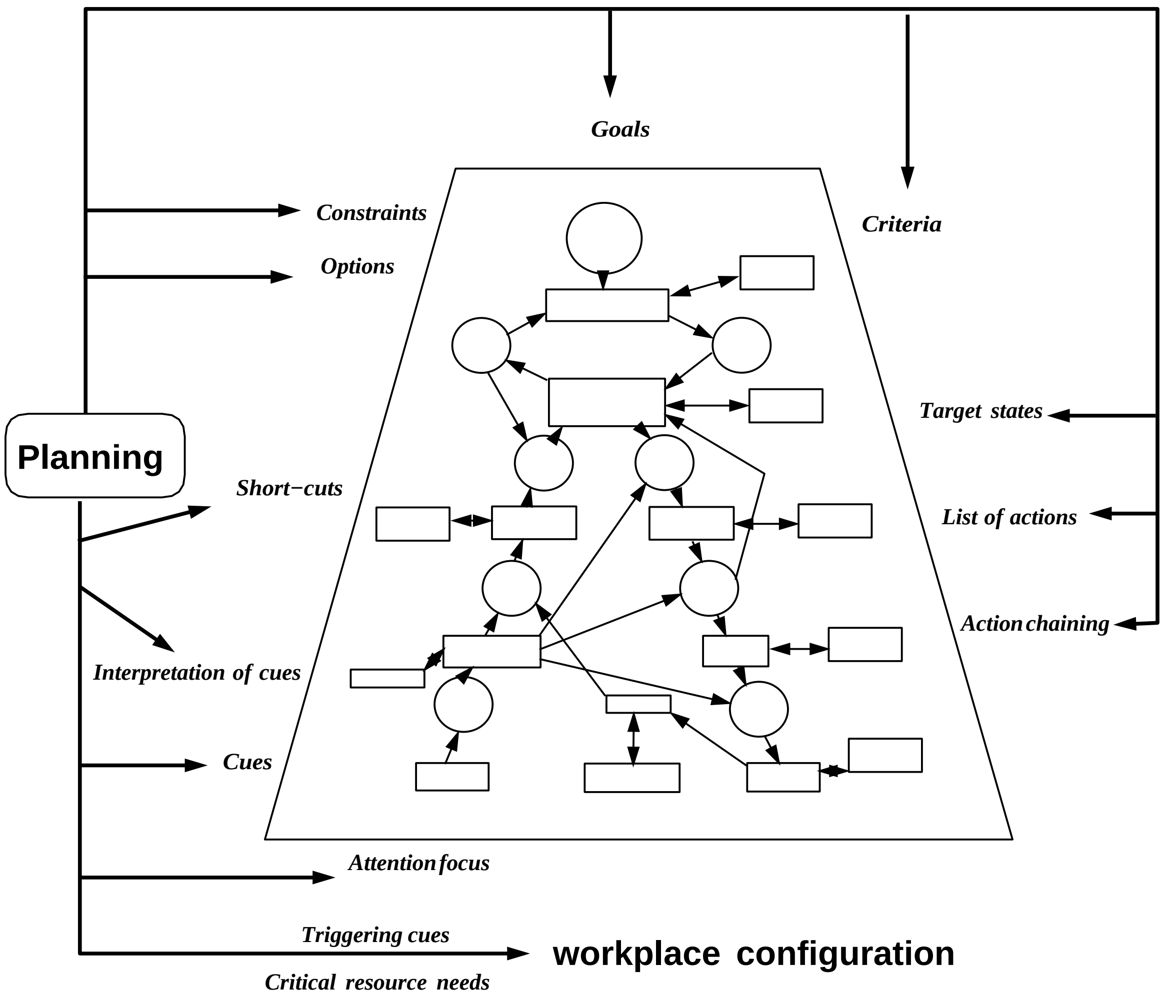

Figure 9.3: A conceptual model of planning and action control. Compare it with Figure 9.1. Planning activities are scattered in various locations in the decision ladder, and can be viewed as a process of "feeding" the needed action resources. Planning also acts on the workplace configuration. The effect of planning is more efficient action control. The middle portion represents the decision ladder, here viewed as a representation of action resources. The results of planning are located correspondingly to the nodes or links in the decision ladder, and to the physical workspace.

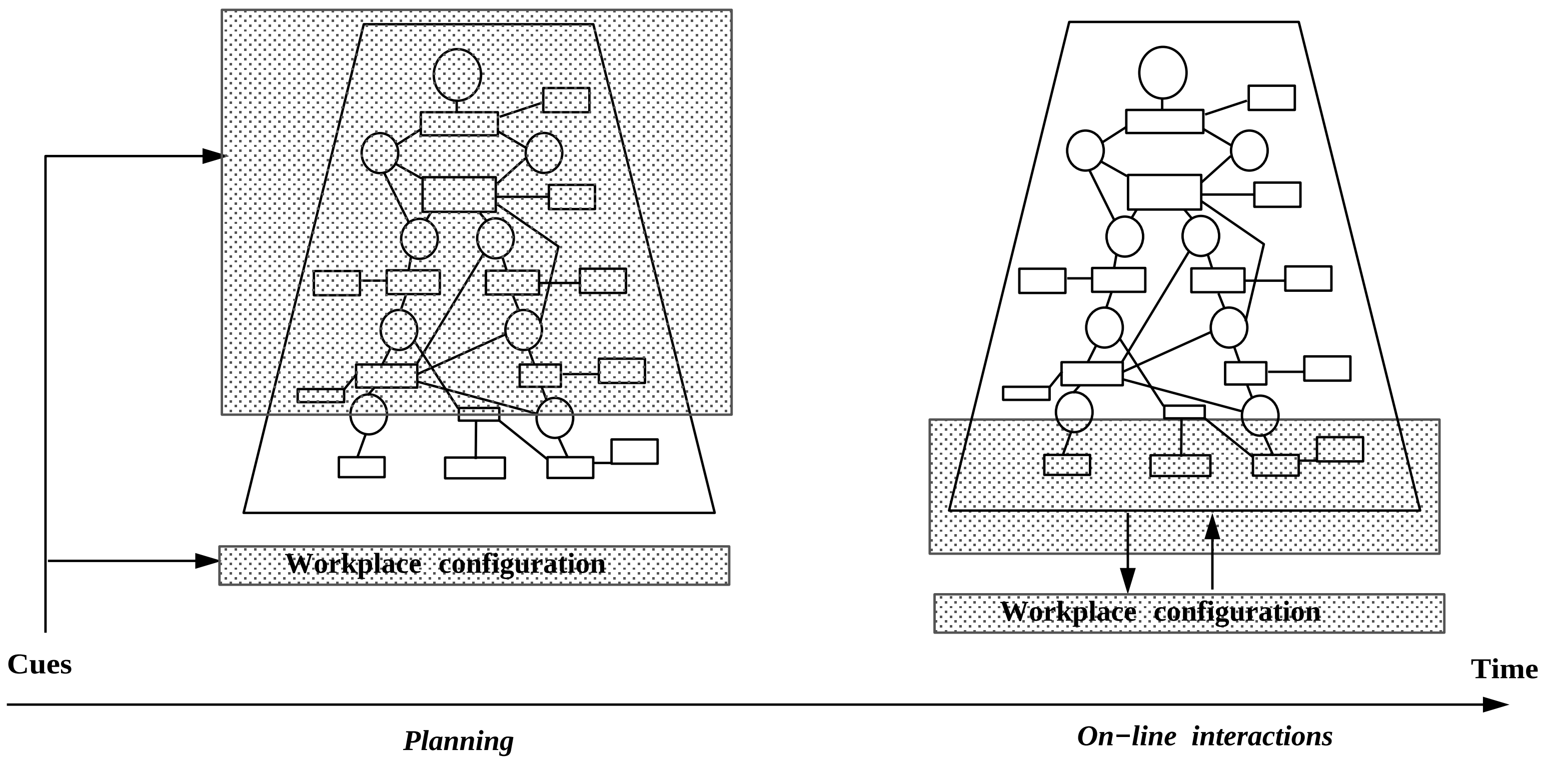

Figure 9.4: The complementary role of planning and on-line interactions. The shaded area in the left ladder indicates the focus of planning activity relative to the decision ladder. The shaded area in the right ladder indicates the potential routes of decisionmaking in the decision ladder during on-line interactions. Planning activities are triggered by precursoring cues. Planning deals mostly with nodes and links higher up in the decision ladder, such as goal states and ranges of options. On-line interactions deal with nodes and links that are mostly lower in the decision ladder and closer to the physical environment.

Guidance and control of actions

As a representation of action resources, the decision ladder specifies actions at different levels of abstraction. It needs feedback information from the environment to jointly specify the exact way of executing an action. Interactions with the task environment, in other words, are *guided* by the knowledge and skills that can be represented by the decision ladder, in which goals at a higher level propagate their influence on the lower goals through specification of actions (*i.e.*, solving the one-to-many mapping problem).

The role of local feedback

Many actions are inherently tightly coupled with the environment and need constant input from the environment. For example in driving, the action of keeping the car in a lane needs feedback information at almost all times. The role of local feedback is thus critical. However, this coupling of action with environment stimuli is also influenced by other levels, which are less closely coupled with the environment stimulus. For example, one parameter that needs to be controlled is how large a deviation (from the center of the lane) is subjectively acceptable to a particular driving condition.

For those actions that are not tightly coupled with the environment, an action often needs a triggering stimulus for it to start. It may also need a triggering event for it to stop. Thus although the *content* of an action may not need feedback information from the environment, it needs the triggering event for starting and/or for ending. In other words, one may plan an action, but the exact situation and time for it to be executed might not be planned.

Uncertainty and action guidance

Uncertainty is a reality of actual work environments. By means of action resources, the decision ladder represents how actions could be executed at different levels of the hierarchy. What would appear to be an ambiguous set of options at a low level of action control may not be regarded as ambiguous at all at a higher level of control. Such multi-level control of actions not only ensures that important goals are satisfied, but also allows the utilisation of opportunities. A prototypical response may be less economical in a novel situation than a non-prototypical response, for example. Substituting the prototypical response may violate some lower level goals, but may in fact achieve important higher level goals more effectively.

9.6 Summary

The chapter first reviewed the issue of the unit of analysis in studying behaviour, and then directed attention to the *necessity* of considering the role of anticipation, especially in situations in which the operator is well experienced. In an attempt to understand the effect of planning on behaviour, a model of planning and action control has been proposed using the decision ladder. In this model, the decision ladder is used to represent various types of action resources, and planning is viewed as one of the ways to prepare the action resources. Through anticipation and preparation, compatible action resources are prepared and response complexity is reduced.

10 Reanalysing Results of the Field Study

> If you know the patient has aortic stenosis, if you observed hypotension, you'll give epinephrine faster. You'll be very concerned and intervene early. On the other hand, I might have a plan to prevent in the case to develop hypotension. But some residents do not realise that, and only wait for things to happen before treating that.
>
> *From a subject of the field study, in a post-case interview*

In the previous chapter, a conceptual model was proposed to characterise the relationship between planning and action control. This model, which will be referred to as the *planning model*, provides a basis for understanding preparatory behaviour from the viewpoint of facilitating subsequent interactions with the work environment. The present chapter first summarises the major findings of the field study, and then uses the planning model to reanalyse several key behavioural patterns. The chapter finishes by presenting the findings as a generic, context-independent strategy.

10.1 Major empirical findings

In any study on problem solving behaviour, it is natural to focus on those activities that occur after problems have been imposed onto the subject. In naturalistic settings, however, problem solving activities are always embedded in the context of some other activities. Thus problem solving activities can occur not only as a result of confronting problematic situations, but also as a result of anticipating potentially problematic situations.

The current field study found that an important class of problem solving activities occurs when anaesthesiologists actively anticipated problems and take measures either to prevent troublesome situations from arising, or to prepare for them. Some of these preparatory activities are physical (and thus directly observable), while others are mental (and thus must be inferred). Two conceptual workspaces were proposed to present the observed or inferred preparatory activities.

In essence, the findings from the field study demonstrate that anaesthesiologists do not wait for problem solving situations to arise, but rather they can, and do, anticipate and prepare for future situations. At a macro level, the anticipation and preparation are oriented towards major decisions and events, and occur to a large extent prior to the start of a surgical case. At a micro level, anticipation and preparation are intimately involved in managing the patient (*i.e.*, maintaining surgical anaesthesia and stable patient conditions).

In the following, the major findings of the field study are summarised in terms of two workspaces: mental and physical. The section finishes with an outline of the properties of the observed preparatory activities.

10.1.1 Preparing the mental workspace

The activities in preparing the mental workspace are not usually directly observable. The *results* of such activities are a mental state of readiness for responding, for making decisions and judgments, and for executing planned actions.

One type of preparatory activity is associated with the identification of a list of concerns. This type of activity is most detectable during pre-operative interviews, at which time the anaesthesiologist identifies major potential obstacles to the success of a case. (Anaesthesiologists call these concerns "*anaesthetic considerations.*") They include special conditions in the patient's physiology, expected or potentially non-routine events during the surgery, expected or likely troublesome situations, and errors that one is prone to commit. The concern list functions as a set of "tripwires," or "warning flags," that guide the anaesthesiologist's attention in behaving in a dynamic, multi-task environment and in achieving multiple and sometimes conflicting goals.

The preparation of the concern list often leads to the formulation of contingency response plans for those troublesome situations which are either anticipated or likely to occur. It can also lead to decisions about the general approach to the conducting of the case. These decisions include, notably, those about situations to be avoided and solutions which should not be applied or are not realisable.

During the surgical operation, in comparison, the scope of anticipation and preparation is on a short-term basis, involving the monitoring and controlling of the patient's status, and the execution of planned actions. One type of preparatory activity is associated with the formulation and the use of local rules, which are *ad hoc* rules that can be used to control and monitor the patient's status. In one case, for example, just before the surgeon cannulated an artery, the anaesthesiologist predicted that ECG display would show dysrhythmias and he verbalised his monitoring rule to the resident that the anticipated dysrhythmias could be ignored.

10.1.2 Preparing and interacting with the physical workspace

In many situations, the contingency responses require not only mental readiness, but also readiness in terms of materials. A good response plan may not be realisable simply because of a lack of materials. Some materials (*e.g.*, intravenous drugs that require dilution) may be available but need complicated and time consuming setups before use.

At the beginning of each case, the anaesthesiologist essentially *configures* a work environment with materials needed for busy periods (*e.g.*, induction) and emergency scenarios. Anaesthesiologists often arranged these materials (*e.g.*, syringes, ETT, laryngoscope, etc.) in ways that made the action execution easier (*e.g.*, placing syringes in the anticipated order of their usage).

Anaesthesiologists were also found to place "triggering cues" for planned actions into their work environment. Some of the drugs (*e.g.*, antibiotics) to be given to the patient are not an integral part of anaesthesia and often require specific timing. Apart from rehearsing the action of giving these drugs, in some cases anaesthesiologists place them in a certain way on the drug cart as reminders.

The proposed preparatory framework (Figure 4.5, page 61) encompasses the major findings in a single framework and highlights eight areas of preparatory activities.

10.1.3 Properties of the preparatory activities

Before the start of a case, anaesthesiologists, almost without exception, reviews potential problems or indications of problems in the course of anaesthesia. considerable amount of mental activities were reported by the subjects in this field study. The importance of pre-operative preparation is also stressed in textbooks in anaesthesiology (*e.g.*, Aitkenhead & Smith, 1990), and is supported by anecdotal evidence (*e.g.*, Miller, 1986).

Aside from the issue about the importance of preparation, the field study revealed some general properties of the preparatory activities. Two prominent properties are summarised below.

First of all, evidence from the pre-operative interviews and the case round discussions seems to suggest that only a small number (around three to eight) of aspects of a case are usually examined and prepared. In other words, the mental preparation is *fragmentary* and is not systematic. Some of the concerns and decisions reported were general (*i.e.*, "the patient was weak," "the patient has poor venous access"), others were more specific (*i.e.*, "the patient has capped teeth," "use small tube even the surgeon likes bigger one").

Second, not only does the preparation seem fragmentary, it also seems to be more concerned with the *identification* of problems than with the *solution* of problems. In round discussions, for example, it was often the case that the proper identification of concerns alone (*e.g.*, difficult i.v. access) was sufficient, without actually offering any solutions.

It is indeed possible that, in spite of the number of preparatory activities identified, the anaesthesiologists may have actually gone through extensive mental preparation, weighed a much larger set of alternatives, and examined many aspects of a case, including possible solutions to potential problems, etc., but he or she reported only a small number of these. However, such an explanation does not concur with the data from the PRP study on case round discussions. How these types of mental preparation affect the behaviour in the OR has been a central question for the field study. The excerpt from a post-case interview quoted at the beginning of this chapter offers an explanation, from the practitioner's point of view. In the remaining part of this chapter, the planning model proposed in the previous chapter will be used to explain the relationship between preparation and on-line interaction.

10.2 "Old wine in new bottles"

In this section, the key findings from the field study associated with preparatory activities are reanalysed using the planning model. The planning model provides *explicit* linkages between preparation (or planning) and actions (or on-line interaction).

Recall that in the proposed planning model, the decision ladder is viewed as a *representation* of action resources, which are used in the interaction with the task environment. A general decision (*e.g.*, "use less anaesthetic") or a concern (*e.g.*, "the patient is weak") may not produce identifiable physical activities, but, according to the proposed model, the preparation of this kind changes the action resources, which are represented by the decision ladder. The action resources then direct actions (*i.e.*, on-line interactions).

In the following, the effects of various preparatory activities on action resources are illustrated on the decision ladder. This is similar to Hollnagel *et al.*'s use of decision ladder in their analysis of protocol data (1981, Fig. 33). In Hollnagel *et al.*'s analysis, however, the decision ladder was used as a "sketch pad" for representing *activity sequence*; the observed activity sequences were drawn directly on the decision ladder to show the transition of knowledge states and activities. In the current analysis, highlighted nodes and links represent *plausible* areas of action resources to which preparation has contributed. Refer to Figure 2.2 (page 17) for labels and the meaning of symbols in the decision ladder.

10.2.1 The concern list

Three examples are provided here to show how the identification of a concern changes action resources.

Concerns about anticipated difficulties in procedures Two of the most common forms of concern in anaesthesia are difficult intubation (*i.e.*, inserting an ETT into the patient's trachea) and difficult i.v. access (*i.e.*, cannulating an i.v. catheter of a desired size into the patient's veins). Both procedures are routine and are done in the majority of cases, and only in rare cases can one manoeuvre to avoid doing them. Figure 10.1a represents one set of nodes that are likely to be prepared when such concerns are identified.

Concerns of forgetting planned actions Sensing something being atypical in a case often triggers preparation. For example, the case may have extra steps (*e.g.*, injecting steroids) that are likely to be forgotten. One often find that each anaesthesiologist has his or her own ways, or tricks, to ensure the execution of the extra steps, among which is the use of association (*e.g.*, "Just before off-pump, I will give this drug to her"). See Figure 10.1b. An *ad hoc* link is established between an event and the planned action. Placing cues in the prominent spot in the workplace is probably the most reliable way of all (Figure 10.1c).

Concerns of anticipated troublesome situations The identification of a troublesome situation (*e.g.*, a situation in which the patient is in stress or in imminent danger, or the anaesthesiologist is operating in an overloaded condition) can lead to avoidance of the situation (*e.g.*, using regional anaesthesia to avoid difficulties in intubation). It can also lead to increased sensitivity to the anticipated troublesome situation (see the quote from an anaesthesiologist at the beginning of the chapter). Plausible areas of preparation are shown in Figure 10.1d.

10.2.2 Action rules

Decisions verbalised by anaesthesiologists are often general. In one case, for example, the anaesthesiologist verbalises "I'll use less anaesthetic" without giving specific doses. It is likely that she may not even have decided exactly *which* anaesthetic to use at the time of making such a decision. What is the effect of such preparation? Four groups of examples of such general decisions are provided below.

Action guidance One type of preparation takes the form of providing general guidance for future actions, as show in Figure 10.2. General guidance rules are those verbalised in terms of target states (or states to be avoided).

For example, it is not uncommon for an anaesthesiologist to mention "When intubating this patient, watch for the capped teeth." This action guidance rule is placed into action resources for activation. What is activated in this model is not an action, but a rule to modulate actions. In the given example, such modulation can make the anaesthesiologist avoid contact with the patient's teeth during intubation, and cause extra attention to be paid to the process of intubation. In the OR environment, managing one's attention is critical, so such attention guidance is important to direct the anaesthesiologist's attention effectively.

Contingency planning Formulating response plans on line can be difficult. Apart from the time pressure that one is likely to endure when dealing with critical situations, required information and materials may not be available or easily accessible. Figure 10.3 shows two forms of contingency planning. In one form (Figure 10.3a), a single response is prepared for a single situation, and a link is established between the cue associated with the situation and the response. In the other form (Figure 10.3b), parallel responses are prepared for a few possible situations, and the practitioner needs to find discriminative cues to select a proper response.

In the study done by Amalberti and Deblon (1992), the subjects (airplane pilots) were found to adjust the system's (*i.e.*, the airplane's) status so that prepared responses could be applied. In this sense, the situations to which responses have been prepared become target states for the practitioner, as he or she may not want to get into a situation where no known solution exists.

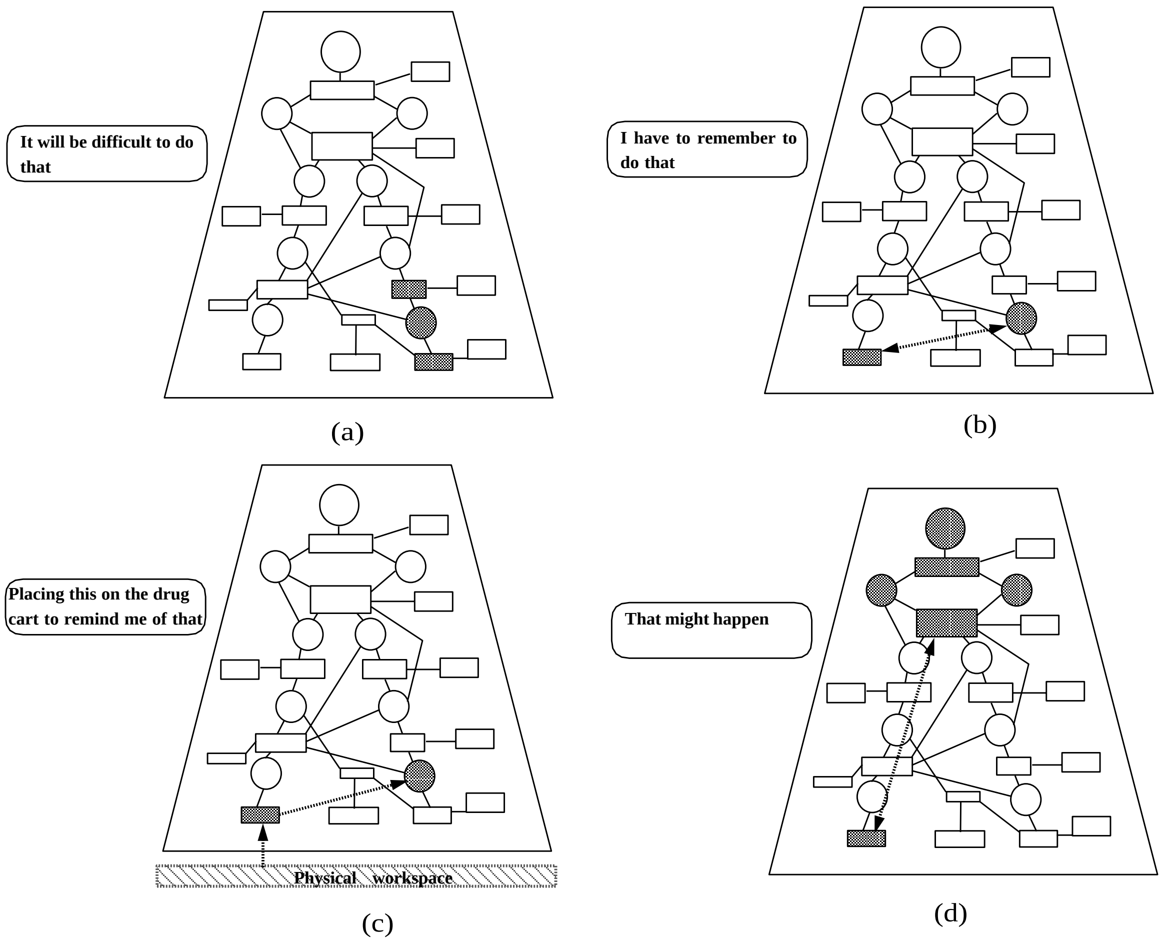

Figure 10.1: Concern list and action resources. **(a)** Difficulties in executing a procedure may force the practitioner to modify the procedure (*e.g.*, having a nurse to help in intubation), and to change the attention sharing strategy (*e.g.*, concentrating more than otherwise). **(b)** Certain non-routine actions are easy to forget. One way of increasing the chance that the action will be triggered is through associating a procedure, that is, an event in the environment, with that action. **(c)** Workplace can be used to remind about planned actions. The “display” nature of the physical workspace can provided triggers for the planned action. **(d)** Anticipation of a troublesome situation can lead to increased sensitivity to certain types of problematic trends and scenarios to be avoided. Other changes include those in the range of options, goals, and criteria.

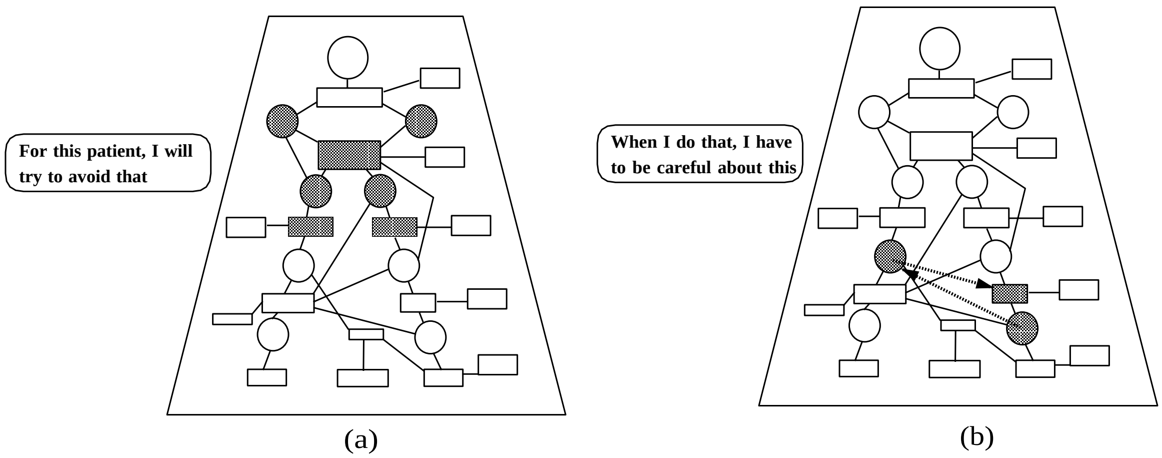

Figure 10.2: Generating action guidance. (a) The decision ladder on the left represents a decision made at a general level, which specifies target states, criteria for evaluating the patient's states, and ways for achieving a task. (b) The decision ladder on the right represents a decision about specific action guidance. It specifies particular ways of executing an action (*e.g.*, avoiding contact with the teeth) and recommended foci of attention.

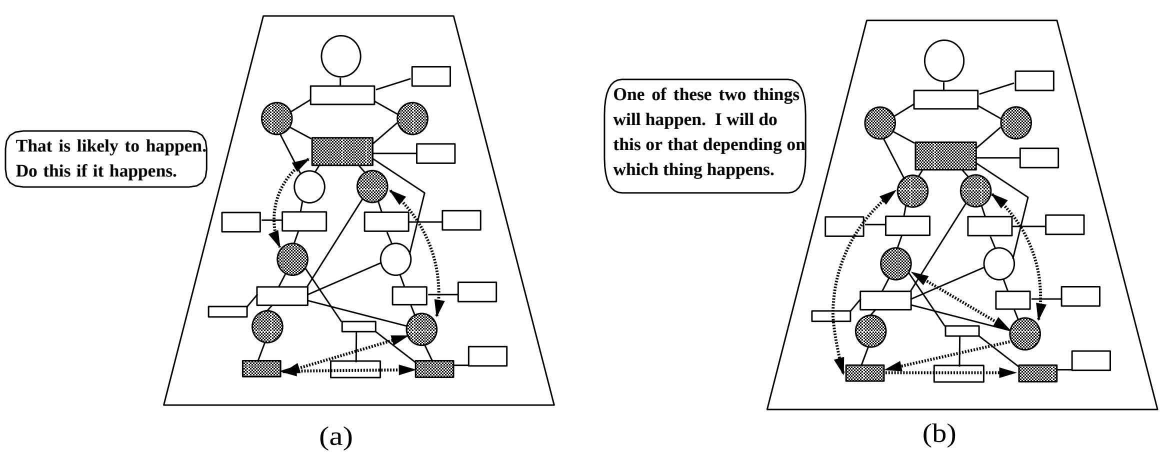

Figure 10.3: Generating contingency responses. Responses are prepared for anticipated situations.

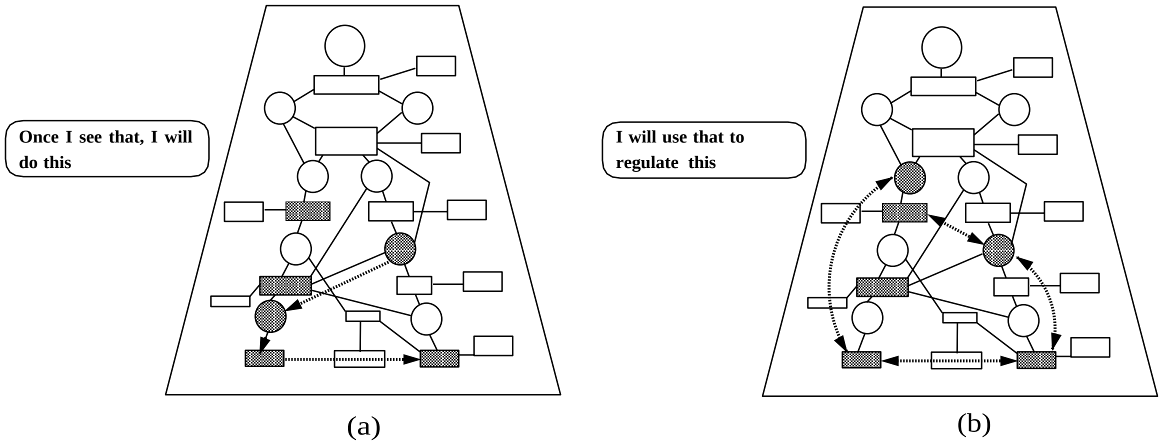

Figure 10.4: Action triggering rules. (a) On the left, the triggering cue for an action is prepared, and a link is prepared between the triggering cue and the action to be carried out. (b) On the right, a link between a cue and an action is prepared. The cue signifies a system state, and the action signifies a task for correcting the system state.

Action triggering rules Among the behavioural patterns found in the protocol study is the active search for triggering cues. This is interesting because often humans are viewed as passive reactors (see Broadbent's criticism on this view in the quote on page 125). In Figure 10.4a, upon the anticipation of what needs to be done, the anaesthesiologist searches for the triggering cue (*e.g.*, testing the patient's eyelash for the start of intubation).

Another form of action triggering rule is a local (*i.e.*, *ad hoc*) regulating loop (Figure 10.4b). An often found example in anaesthesia is regulating the depth of anaesthesia (*i.e.*, the level at which the patient is anaesthetised) through (re)setting the vapouriser according to blood pressure and heart rate readings.

Monitoring rules Another type of action modulation is about expectation and monitoring. For example, the anaesthesiologist can verbalise "be aware of dysrhythmia when injecting ketamine to this patient." What is the effect of preparation of this type? One plausible way of expressing it is a link between the event that the action (*i.e.*, "injecting ketamine") is done and a system state ("dysrhythmia"). The link raises the expectation of dysrhythmia after the injection of ketamine, and consequently, it causes the anaesthesiologist to look for signs of dysrhythmia after the injection (*e.g.*, checking ECG display). See Figure 10.5.

10.2.3 Planning as a way to examine the adequacy of action resources

During the study of peer review protocols, it was noticed that anaesthesiologists could examine an option and detect concerns in a solution very quickly. In the PRP study, the staff member[1] often pinpointed specific concerns of a solution with ease (*e.g.*, roller valve cutting the pilot line in Figure 6.6, page 104). Experienced anaesthesiologists seem to have a meta-knowledge about their action resources and are able to locate where the preparation is needed.

This sort of planning behaviour—examining weak spots in action resource—calls for the study of planning different from those on scheduling. It involves instantiating a general

[1] The speaker was not identified in the charts shown in Chapter 6, unfortunately.

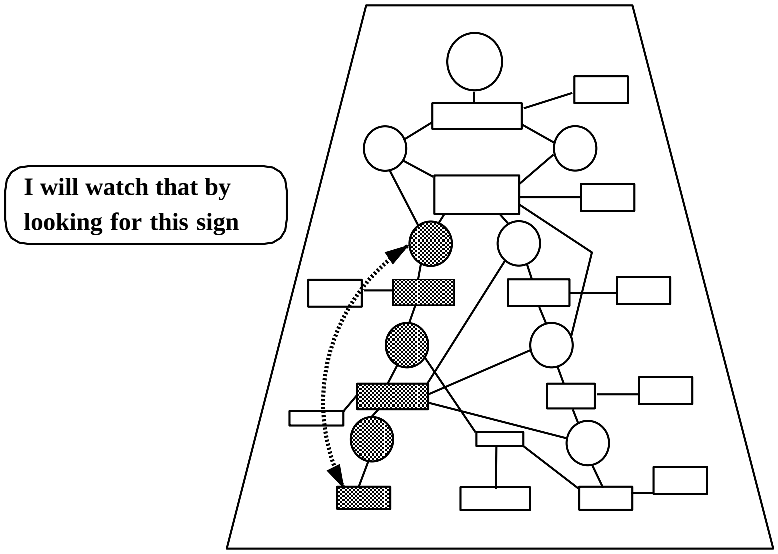

Figure 10.5: Monitoring rules. In preparing a monitoring rule, a link is established between a cue and the identification of a system state. To verify the system state, a particular cue is sought and, conversely, when the cue is perceived, the system state is identified directly.

solution in a specific situation and examining potential problems. Note that a special kind of problems identified by anaesthesiologists are errors that one is prone to commit. The examination does not always call for modification of the solution, but only awareness of a few concerns or special guidance that should be considered when the solution being implemented. The PRP study showed a number of examples in which the need for materials, access, and/or special guidance to actions was quickly detected.

* * *

This section uses the planning model to illustrate the effect of preparatory activities through the decision ladder. Figure 10.6 illustrates, in a summary, some of the preparatory activities based on the pre-operative interviews.

10.3 Findings represented at different levels

As seen in the above, the preparatory activities observed in the field study can be viewed as planning that prepares action resources for future interactions with the task environment. The intended *result* of such preparatory activities is more compatible action resources, which will reduce the *response complexity*, that is, what one needs to do (physically and mentally) in response to the events occurring in the environment. In other words, some of the nodes in the decision ladder will have been pre-processed, and they may be shunted by direct associations among the nodes. Through the above analysis, a generic strategy can be identified from the observed preparatory activities: *Reduce response complexity through planning—anticipating future situations, mental preparation, and reorganising the physical workspace.*

Table 10.1 represents the major findings of the field study at three different levels of abstraction (Cf. Hollnagel *et al.*, 1981). At the bottom level, the findings are represented by domain strategies (or "performance fragments," as defined by Hollnagel *et al.*, 1981, p. 10). Findings represented at this level can be detected directly in the data collected from the field. However, these findings are difficult to generalise to domains outside anaesthesiology, and they do not reveal the underlying cognitive activities. After removing the domain context and adding in cognitive descriptions, the domain strategies are represented by specific

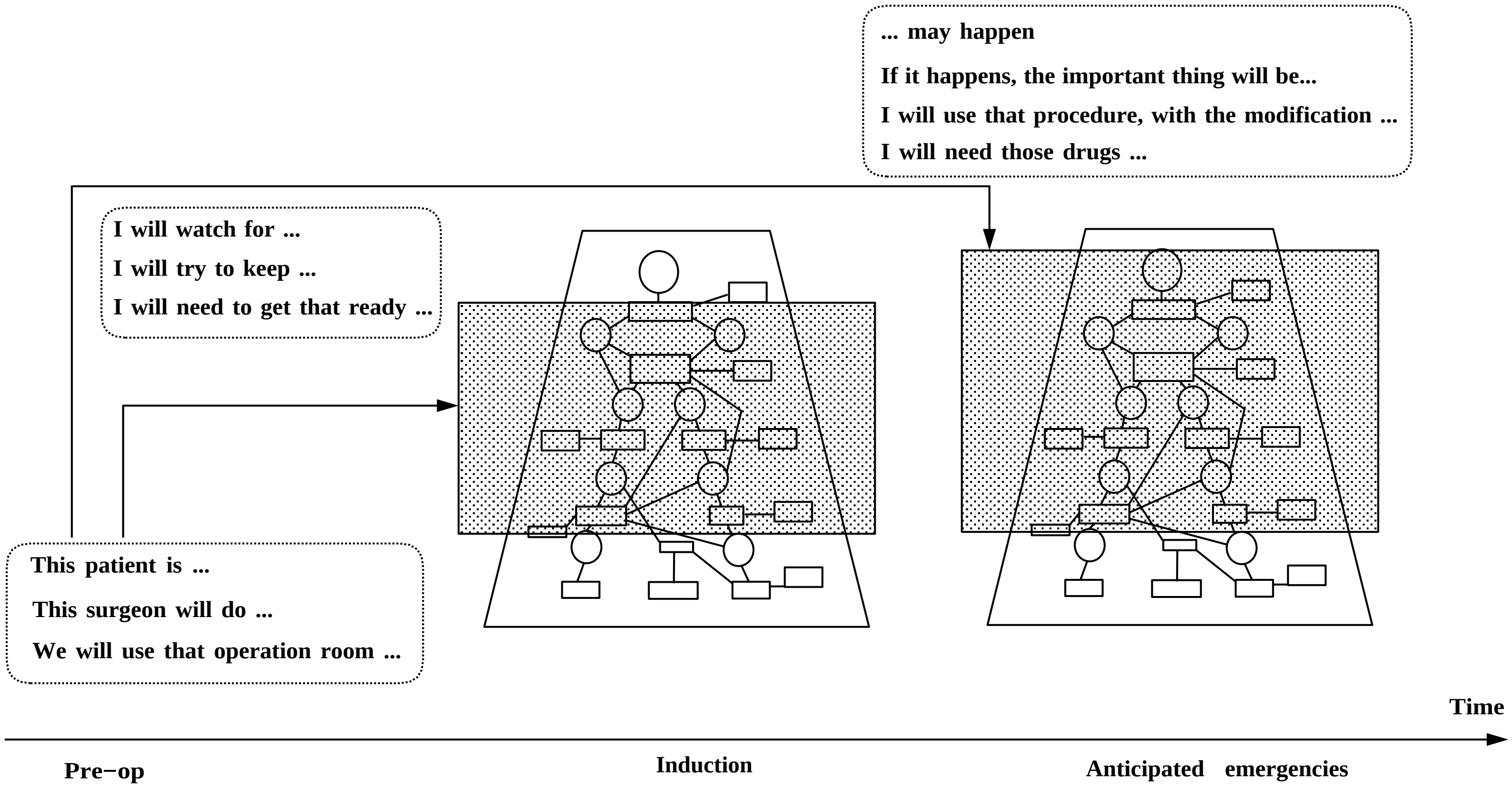

Figure 10.6: Pre-operative activities viewed through the planning model. Text in the oval boxes are sentences and phrases that are typically encountered in pre-operative interviews. They reflect the preparation of action resources (as represented by decision ladders) for anticipated scenarios (induction and emergencies). The prepared action resources help the anaesthesiologist in interactions with the task environment.

Level of abstraction	*Findings*
Generic strategies	• Reduce response complexity through anticipating future situations, mental preparation, and reorganising the physical workspace
Specific Strategies	• Schedule tasks (off-load) • Build local models and rules • Be preventive: think of probably side effects, pitfalls and predictors of these side effects • Preparing necessary materials and access • Rehearsing pending procedures (mental simulation)
Domain strategies extracted from activity trajectories in field data	• Prepare induction and emergency syringes • Pay more attention to muscle relaxation • If BP fluctuates too wild, start nitroglycerin i.v. • Prepare nitroglycerin whenever there is a chance • Tape vaporisers: prevent the use of vaporisers (in a total i.v. anaesthesia) • Use only short acting drugs of surgery length is uncertain

Table 10.1: Findings represented at different levels of abstraction

strategies at the middle level. These strategies are no longer context specific, and thus can not be verified directly by empirical data. Rather, they can be "illuminated" by examples in the empirical data, as has been done in this thesis. However, findings represented at this level have wide implications in terms of design and training. At the top level, specific strategies can be synthesised into a single generic strategy. It represents the gist of the preparatory activities observed in the field study. It reveals a fundamental characteristic in the interaction between a proficient worker and a complex, dynamic task environment, and it can direct the search for other kinds of specific strategies.

10.4 Discussion

In comparison with the preparatory framework, the planning model *explicitly* points out the types of preparatory activities that may happen in relation to how such activities influence (facilitate) subsequent interactions with the environment. It also provides a basis for studying the structure of behaviour in the natural work environment, and for resolving the seemingly paradoxical relationship between planning and action.

Through the planning model, the preparatory activities are explained from the perspective of their functional value, that is, how they influence the practitioner's on-line performance. At the same time, the divergent behaviour patterns found in the field study are synthesised into one generic strategy.

Part IV

Conclusions

11 Summary, Implications, and Future Work

> One could . . . visualize the progressive development of scientific theory to take place as the development of the system of concepts at an increasingly higher level of "layers" or strata, each layer having fewer and fewer direct connections with the complexes of sense experiences. In this way, a more phenomenological theory at the early stage of science . . . gives way to a more independent set of concepts and axioms . . . .
>
> There is of course a cost in this developmental process. By going cyclically through several stages of theories, each stage is forced to use conceptions more removed from direct experience . . . . [T]he contact with common sense is more and more tenuous. But the fundamental ideas and laws of science attain a more and more unitary character.
>
> —*G. Holton, 1986, pp. 48–49,*
> *on Einstein's model for constructing a scientific theory*

11.1 Summary of the field study

In order to design effective interfaces and training programmes in support of the human operator's cognitive functions, there is a growing demand for an understanding of how the human operator interacts with the work environment. The rationale for such an understanding is that, without it, design is likely to be driven by technology instead of principles, and the resulting design could in fact decrease overall system safety and productivity (Bainbridge, 1983; Reason, 1987). Two key questions to the understanding of human behaviour in the work environment are (Hollnagel & Woods, 1983): What kinds of problems are being solved by practitioners, and how are they being solved? In answering these questions, a number of methodological issues are encountered: Which settings should one choose to observe behaviour: in a laboratory, in a simulation, or in the field? If field setting is chosen, how does one collect behavioural data and analyse them? The current study took the domain of anaesthesiology as a "laboratory" to study how proficient practitioners (with years of training and experience) solve problems in their actual work settings: surgical operating rooms (ORs). It used the method of field study to observe behaviour directly in naturalistic settings.

11.1.1 Phase 1: The direct observation study

Over a span of two years, a series of direct observations were conducted in ORs, in combination with informal contact with the anaesthesiologists. This phase (referred to as the *direct observation study*) of the field study attempted to answer a general, exploratory question: What problems are being solved by anaesthesiologists?

It was found during this phase that an important class of anaesthesiologists' problem solving activities were associated with anticipating future events and task demands, and with preparing for them. This class of cognitive activities has largely been overlooked by other researchers, as the focus of attention has mostly been on how the human operator reacts to events such as critical incidents, and on activities within the event → mental process → response (EPR) cycle (*i.e.*, the cycle of generating responses upon perceiving an event in the environment).

The direct observation study established a phenomenological basis for anticipatory and preparatory behaviour in four categories:

- *Preparing the physical workspace.* A considerable portion of anaesthesiologists' activities can be viewed as designing and tailoring the "*physical workspace*"—the work environment surrounding the anaesthesiologist—to facilitate his or her interactions with the patient and the equipment.
- *Preparing the mental workspace.* Considerable mental efforts were expended on anticipating potentially and likely troublesome situations, and on reviewing response plans to those situations, related options, and goals. Such mental preparation can be viewed as the establishment of a proper mental state, or a "*mental workspace,*" for efficiency in execution of planned actions and responses to critical events.
- *Feedforward control.* Feedforward or *predictive* control of the patient's status has been used extensively. The anaesthesiologist controls the patient's status through both observing current system inputs (*i.e.*, the surgeon's actions to the patient) and anticipating future system inputs.
- *Off-loading.* Unevenly distributed workload is the hallmark of the working environment in process control types of tasks. One strategy to prevent oneself from being overloaded is to reduce workload during subsequent busy times by doing in advance some of the steps that will be required during busy times.

A framework (Figure 4.5) was proposed to summarise these diverse activities that bear the characteristics of anticipation and preparation. In this framework, the observed preparatory activities were assigned to eight areas, three of which are associated with physical preparation, and the rest are with mental preparation. The framework was based on a conceptual model of an EPR cycle, and the eight areas of activities were distributed around the three components in an EPR cycle: triggering event, cognitive processing, and responses.

11.1.2 Phase 2: The protocol study

With the experience gained in the direct observation study and guided by the proposed framework, the field study started the second phase, the *protocol study*: recording and analysing protocols directly from the field. Although protocol analysis has been used widely as a means of studying cognitive activities, using it in actual work settings has been rare, especially in settings like the OR. It became a methodological challenge to analyse protocol data that consisted of a mixture of on-line communications, hand-written notes, limited and fragmented thinking-aloud verbalisation, interviews, and retrospective reports.

By examining each episode in the recorded cases in detail and understanding activities in their context, the protocol study identified and categorised mental activities during the course of each case. A number of conceptual operations on the mental workspace were proposed to represent inferred mental activities. Relationships among the mental workspace, situations and events in the environment, and the anaesthesiologist's activities were established and represented as event-state-flows (ESFs): flow diagrams that depict these relationships. A large number of micro-patterns of anticipatory and preparatory behaviour were discovered. By extending the concept of ESF, activities remotely in time but related to each other were analysed in terms of their relationships. These analyses and the resulting behavioural patterns collectively contributed to the understanding of the role of anticipation and preparation in the interaction with a complex work environment. The results of the protocol study can be looked upon as fragments of a complete picture of how behaviour is *organised* over time by practitioners in accomplishing their demanding tasks in a dynamic environment.

The protocol study uncovered some basic characteristics of preparatory behaviour in anaesthesiology, two of which are summarised here. First of all, preparatory activities included a special category: identification of *concerns*, which are problems or potential obstacles to the successful conduct of an anaesthesia case. They include expected non-routine events, obstacles to routine procedures, and notably, the errors that one is prone to commit in the particular case. Second, the preparation for a case is not comprehensive, that is, only a small fraction of all possible aspects of the case is examined. In addition, the decisions made at the time of preparation are frequently non-specific and, in fact, some concerns are identified without any decisions being made at all. (The most prominent example is the concern for difficulty in intravenous access.)

From the point of view of methodology, the protocol study was an experiment in analysing protocol data collected under field conditions, both at a relatively detailed, micro level and at a macro level. One of the contributions of the protocol study is the scheme (shown in Figure 5.2, page 76) used in dealing with protocol data from the field, and the concepts developed to represent mental activities identified, particularly those involved in anticipation and preparation.

For any field study on a non-trivial scale, such as the current one, the raw data are rarely published. The reasons for this can be many (Cf. Roth *et al.*, 1987), but the consequence is straightforward: the reader has access only to the final, summary findings, but not to the intermediate process of how such final findings are drawn. This thesis attempts to break away from that pattern by including some of the raw data of the field study: the protocols. The protocols in the Appendices provide not only isolated references for the findings, but, in their totality, the *context* for understanding these references. Thus the reader can form his or her own judgment about the interpretations made in this thesis, and may in fact analyse these data in different ways and obtain potentially different results for comparison.

Apart from their reference value, the protocols included should also show the intermediate process of inferring cognitive activities and, in particular, how the proposed mental operations (Section 5.4) were applied to the protocol data. The process of analysing these protocol data, and the challenge encountered therein, were the driving force behind the conceptual work in this thesis. By examining the protocols, the reader will have a good understanding of why the planning model was proposed and the role of this conceptual work in an empirical study.

11.1.3 Phase 3: The peer review protocol study

The study of peer review protocols (PRPs) moved the field study from one type of naturalistic settings (mainly ORs) to another: case round discussions involving experienced anaesthesiologists and residents under training. The key issue to be addressed in the PRP study was the role of anticipation and preparation. This was an issue because, in the direct observation study and the protocol study, the performance of the anaesthesiologists was basically analysed by a single observer who was not by training an "insider" to the domain. Thus the PRP study acted as a means of verification of the assumption that anaesthesiologists emphasise preparation, behave with anticipation, and that they consider the skills in anticipation and preparation essential. Not only did the analysis of the recorded discussions provide some support to that assumption, it also revealed, among other things, that anaesthesiologists could quickly identify obstacles and precautions in executing selected action plans. This finding indicated that, in examining an action plan, experienced practitioners could identify likely trouble spots in the plan effectively and probably without detailed mental simulations.

* * *

In the management of complex systems, unexpected crises do occur that require on-site "inspiration." However, "deliberation" precedes most crisis situations. How well one anticipates and prepares for problematic situations has significant impact not only on the frequency and the nature of crisis situations, but also on the ways of dealing with them.

In general, the field study showed that, when behaving in a naturalistic environment and when the consequences of performance failure are costly, practitioners *can* and *do* anticipate future situations and prepare for them.

11.2 Summary of the modelling of preparatory activities

The preparatory nature in the observed activities posed special difficulties in understanding behavioural phenomena: How does mental preparation influence the subsequent behaviour or interactions with the environment, given that mental preparation observed in the field study was fragmentary, and occurred in various formats, ranging from general decisions, concerns and overall action plans to specific procedures and actions. Thus the role of anticipation and preparation became the focus of the attention.

A planning model was devised, based on an action control framework, the "decision ladder" (Rasmussen, 1976). The decision ladder framework captures a central characteristic of human information processing: an experienced practitioner can utilise the experience to short-cut information processing paths. High level goals, for example, are not always involved in making decisions. This flexibility in the process of decisionmaking also reveals that, when a solution is not readily available, high level goals have to be consulted and options have to be evaluated in some way. The components in the decision ladder, for example short-cuts, options, goals, branching rules, procedures, etc., are thus all important or potentially important in making decisions and controlling actions, and they are *action resources* for the practitioner to interact with the environment. The decision ladder can therefore be used as a way to represent action resources. The proposed planning model is a conceptual model, which specifies the process of planning as the preparation of action resources (as opposed to that of generating a sequence of actions), and the role of planning is to reduce response complexity when subsequently interacting with the task environment (as opposed to control action seqeunce).

The planning model was used to reanalyse the findings from the field study. A number of preparatory activities were represented as preparing nodes and links in the decision ladder. Preparation thus does not have to deal with all aspects of interaction with the task environment, but only those that, according to the practitioner's own evaluation, signify deficiency of action resources. The preparatory activities observed was accounted for by the planning model, and a generic strategy (*i.e.*, reducing response complexity) was identified out of a number of detailed, specific strategies in preparatory activities.

11.3 Implications

The implications of the field study and the conceptual work are discussed under three categories: *methodological*, *theoretical*, and *practical*.

First of all, the methodology used to analyse behavioural streams does not fit into the mould of traditional laboratory methods and sequential protocol analyses. Instead, the method of analysis emphasises the discovery of underlying structures in the observed behaviour—*i.e.*, how one activity is related to another activity; how a group of activities is related to another group. It is the author's belief that such methods are necessary for those studies that aim at behaviour in complex work settings over a span of time. In this type of behavioural conditions, one is likely to find that the subject actively organises his or her activities, instead of being a passive reactor to environmental stimuli.

Empirical inquiries in naturalistic settings deal with complex phenomena, which are often little known to the researcher. The current field study employed a three-phased method, containing the exploration of a domain, the generation of patterns in the observed behaviour, and the empirical testing of findings. With the increasing need for naturalistic studies of complex behavioural phenomena, the method used here should provide other researchers with both conceptual tools for capturing cognitive activities and techniques for collecting and analysing behavioural data from various sources under actual working conditions.

Secondly, as an empirical inquiry, the primary goals for the field study are not only to identify a set of behavioural patterns at the phenomenological level, but also to provide a necessary account for the phenomena observed. When tackling the issue of the role of anticipation, the field study deals with a fundamental question: How to resolve the apparent paradox that we as human beings do anticipate and plan, whereas our plans never control action in deterministic ways. The field study devised a conceptual model of planning and action control for that purpose. The model opens up a number of ways in which we can investigate interactions between a proficient worker with the complex task environment. For example, the model directs the attention of human planning research to the examination of action resources and the preparation of action resources of various types, such as options, goals, *ad hoc* rules, and foci of attention. In contrast, the research of planning is currently largely on action scheduling—*i.e.*, the ordering of actions.

Being an influential framework, the decision ladder has not been used widely in analysing human performance. The proposed planning model provides an opportunity to expand its usage, and consequently a chance to explore potentials embodied in the framework.

Thirdly, as the ultimate goal of the field study, training and aiding has been the underlying driving force behind both the empirical work (the collection of phenomenal data) and the conceptual, theoretical endeavour. The field study highlights the role of anticipation and the so-called pro-active approach. It shows that a key component in expertise is to anticipate and to prepare. It provides a list of specific areas of activities where problem solving situations arise. To the people who design interfaces and training programmes, these findings should provide both general and specific guidelines on how to support and train practitioners.

Previously, training research has not concerned itself with the preparatory activities that were revealed in the field study. For example, the comprehensive review of training theory and technique done by Cannon-bowers *et al.* (1991, in particular Fig. 1) shows that training-related theories and techniques address mainly knowledge in procedures and diagnosis. The current field study witnessed, in the case round discussions, that practitioners (in the domain of anaesthesiology at least) have realised the importance of the skills in anticipating and preparing. Such form of training deserves further studies from the viewpoints of what types of skills and knowledge are transferred, and what constitutes critical skills in anticipating and preparing.

Similarly, the research on the design of aids also shows the lack of attention paid to the preparatory activities (*e.g.*, Wiener & Curry, 1980; Carrera *et al.*, 1991). The current field study indicated that identifying concerns is often more valuable to practitioners than providing solutions. What practitioners need is probably more towards the identification of potential problems than towards the solution of problems. In fact the former could be achieved in relatively simple ways by providing the practitioners with effective checklists of concerns that should be considered. Such lists can be obtained by arranging peer reviews (as in the PRP study in the current field study) on performance in prototypical cases, and can be made context-sensitive so that only a small number of concerns are presented to practitioners.

11.4 Future work

As an empirical enquiry into a phenomenon as complex as human behaviour, the field study is essentially an exploration of possibilities and a search for tools that can assist in such an exploration. The framework developed to summarise field findings, and the planning model devised to understand these findings, are largely conceptual, and thus not compatible with the more "conventional" concept of generating specific hypotheses and testing them quantitatively. The findings collected, with the help of the practitioners and prolonged experience in the domain, are basically the interpretation of data by one person.

The field study has already pointed to a promising direction in studying the anticipatory and preparatory behaviour. That is the PRP analysis. The natural discussions among peers have been shown to address some of the key problem solving activities, among which are those involved in anticipation. More protocols collected in such settings and analysis can potentially lead to the parameterisation of preparatory activity, which can lay the ground work for quantitative analysis and modelling.

11.5 Epilogue

The present field study represents a journey, from a position of being overwhelmed by the magnitude of variation of observed activities to that of being attracted to a few, repeatedly occurring patterns. It has been both a search for invariant features and a search for tools that can reveal invariant structures within the transient, changing phenomenon known as *behaviour*.

Bibliography

Aitkenhead, A. R., and Smith, G. (Eds.). (1990). *Textbook of Anaesthesia* (2nd ed.). Edinburgh: Chrchill Livingstone.

Allport, D. A. (1980). Patterns and actions: Cognitive mechansism are content-specific. In: Claxton, G. (Ed.), *Cognitive Psychology: New Directions.* London: Routledge & Kegan Paul.

Amalberti, R., and Deblon, F. (1992). Cognitive modeling of fighter aircraft process control: A step towards an intelligent onboard assistance system. *International Journal of Man-Machine Studies*, **36**, 637–671.

Ashby, W. R. (1958). General systems theory as a new discipline. *General Systems*, **3**, 1–6.

Baerends, G. P. (1941). Fortpflanzungsverhalten und Orientierung der Grafwespe *ammophila campestris* jur. *Tijdschrift voor Entomologie*, **84**, 68–275.

Bainbridge, L. (1974). Analysis of verbal protocols from a process control task. In: Edwards, E., and Lees, F. P. (Eds.), *The Human Operator in Process Control.* London: Taylor & Francis.

Bainbridge, L. (1979). Verbal reports as evidence of process operator's knowledge. *International Journal of Man-Machine Studies*, **11**, 411–436.

Bainbridge, L. (1983). Ironies of automation. *Automatica*, **19**, 775–779.

Baron, S., Kruser, D. S., and Huey, B. M. (Eds.). (1990). *Quantitative modeling of human performance in complex, dynamic systems.* Washington, DC: National Academy Press.

Bateson, G. (1979). *Mind and nature: A necessary unity.* New York: E. P. Dutton.

Beishon, R. J. (1967). Problems of task description in process control. *Ergonomics*, **10**, 177–186.

Beishon, R. J. (1974). An analysis and simulation of an operator's behaviour in controlling continuous baking ovens. In: Edwards, E., and Lees, F. P. (Eds.), *The Human Operator in Process Control.* London: Taylor & Francis.

Bernard, H. (1988). *Research mothods in cultural anthropology.* Newbury Park, CA: Sage Publications.

Bisantz, A. M., and Vicente, K. J. (in press). Making the abstraction hierarchy concrete. *International Journal of Man-Machine Studies.*

Bratman, M. E. (1987). *Intention, Plans, and Practical Reason.* Cambridge, MA: Harvard University Press.

Broadbent, D. E. (1977). Levels, hierarchies, and the locus of control. *Quarterly Journal of Experimental Psychology*, **29**, 181–201.

Bruner, J. S. (1970). The growth and strcuture of skill. In: Connolly, K. (Ed.), *Mechanisms of motor skill development.* New York: Academic Press.

Cannon-Bowers, J. A., Tannenbaum, S. I., Salas, E., and Converse, S. A. (1991). Toward an integration of trainign theory and technique. *Human Factors*, **33**, 281–292.

Caplan, R. A., Posner, K. L., and Cheney, F. W. (1991). Effect of outcome in physician judgments of appropriateness of care. *Journal of the Amerian Medical Association*, **265**, 1957–1960.

Card, S. K., Moran, T. P., and Newell, A. (1986). The model human processor: An engineering model of human performance. In: Boff, K. R., Kaufman, L., and Thomas, J. P. (Eds.), *Handbook of perception and human performance.* New York: Wiley.

Carey, S. (1983). Are children fundamentally different thinkers and learners than adults? In: Chipman, S., Segal, J., and Glaser, R. (Eds.), *Thinking and learning skills.* Hillsdale, NJ: Erlbaum.

Carrera, J. P., Easter, J. R., and Watson, C. D. (1991). Providing decision suppport in Westinghouse nuclear power plant man-machine interface systems. In: *Proceedings of Human Factors Society 35th Annual Meeting*, 629–633.

Carrie, L. E. S. (1982). *Understanding anaesthesia.* London, UK: William Heinemann Medical Books.

Carroll, J. S., and Johnson, E. J. (1990). *Decision research: A field guide.* Newbury Park, CA: Sage.

Chi, M. T. H., Glaser, R., and Farr, M. J. (Eds.). (1988). *The nature of expertise.* Hillsdale, NJ: Erlbaum.

Chung, D. C., and Lam, A. M. (1990). *Essentials of Anesthesiology* (2nd ed.). Philadelphia: W. B. Saunders.

Cohill, A. M. (1992). Architects at work: The structure of design information. In: *Proceedings of Human Factors Society 36th Annual Meeting*, 389–393.

Cole, M., and Scribner, S. (1974). *Culture and Thought.* New York: Wiley.

Conant, R. C., and Ashby, W. R. (1970). Every good regulator of a system must be a model of that system. *International Journal of Systems Science*, **1**, 89–97.

Cook, R. I., Woods, D. D., and McDonald, J. S. (1991). *Human Performance in Anesthesia: A Corpus of Cases,* CSEL Report CSEL 91.003. Columbus, OH: Ohio State University.

Cox, D. R., and Miller, H. D. (1965). *The theory of stockastic processes.* New York, NY: Wiley.

Crossman, E. R. F. W., and Cooke, J. E. (1962). Manual control of slow-response systems. In: *International Conference on Human Factors in Electronics.*

Crossman, E. R. F. W., and Cooke, J. E. (1974). Manual control of slow-response systems. In: Edwards, E., and Lees, F. P. (Eds.), *The Human Operator in Process Control.* London: Taylor & Francis.

de Groot, A. D. (1965). *Thought and choice in chess.* Netherlands: The Hague Mouton Publishers.

de Groot, A. D. (1992). An European perspective in psychology. *Heymans Bulletins Psychologisch Instituut R. U. Groningen*, **HB-93-1095-EX**.

Degani, A., and Wiener, E. L. (1993). Cockpit checklists: Concepts, design, and use. *Human Factors*, **35**, 345–359.

Doherty, M. E. (1993). A laboratory scientist's view of naturalistic decision making. In: Klein, G. A., Orasanu, J., Calderwood, R., and Zsambok, C. E. (Eds.), *Decision making in action: Models and methods*. Norwood, NJ: Ablex.

Dreyfus, H. L., and Dreyfus, S. E. (1986). *Mind over Machine*. New York: Free Press.

Edwards, E., and Lees, F. P. (Eds.). (1974). *The Human Operator in Process Control*. London: Taylor & Francis.

Ericsson, K. A., and Simon, H. A. (1984). *Protocol Analysis: Verbal reports as data*. Cambridge, MA: MIT.

Fink, B. R. (1993). Letter to the editors. *Scientific American*, **268**(1), 12.

Firby, R. J. (1989). *Adaptive execution in complex dynamic worlds*. Yale University: Unpublished dissertation.

Flanagan, J. C. (1954). The critical incident technique. *Psychological bulletin*, **51**, 327–358.

Friedman, L., Howell, W. C., and Jensen, C. R. (1985). Diagnostic judgment as a function of the preprocessing of evidence. *Human Factors*, **27**, 665–673.

Gaba, D. M. (Ed.). (1991). *Proceedings of Conference on Human Error in Anesthesia*. Pacific Grove, Calif.: Anesthesia Patient Safety Foundation.

Gaba, D. M. (in press). Dynamic decision-making in anesthesiology: Cognitive models and training approaches. In: Evans, D. A., and Patel, V. L. (Eds.), *Advanced Models of Cognition for Medical Training and Practice*. Berlin: Springer-Verlag.

Gaba, D. M., and DeAnda, A. (1989). The response of anesthesia trainees to simulated critical incidents. *Anesthesia and Analgesia*, **68**, 444–451.

Gaba, D. M., and Lee, T. (1990). Measuring the workload of the anesthesiologist. *Anesthesia and Analgesia*, **71**, 354–361.

Gallistel, C. R. (1980). *The organization of action: a new synthesis*. Hillsdale, NJ: Erlbaum.

Gillis, J., and Schneider, C. (1966). The historical preconditions of representative design. In: Hammond, K. (Ed.), *The psychology of Egon Brunswik*. New York: Holt, Rinehart, & Winston.

Gladwin, T. (1970). *East is a big bird*. Cambridge, MA: Belknap Press.

Gravenstein, J. S. (1982). As for pilots, instruments are important. *Engineering in Medicine & Biology*, **1**, 23–25.

Hammond, K. R. (1993). Naturalistic decision making from a Brunswikian viewpoint: Its past, present, future. In: Klein, G. A., Orasanu, J., Calderwood, R., and Zsambok, C. E. (Eds.), *Decision making in action: Models and methods*. Norwood, NJ: Ablex.

Hansen, J. P., Lϕvborg, L., and Rasmussen, J. (1990). Simulation of cognitive behaviour in computer games. In: *Second MOHAWC workshop on cognitive modelling*.

Hart, S. G., and Wickens, C. D. (1990). Workload assessment and prediction. In: Booher, H. R. (Ed.), *MANPRINT: An emerging technology, advanced concepts for integrating people, machine, and organizations*. New York: Van Norstrand Reinhold.

Hayes-Roth, B., and Hayes-Roth, F. (1979). A cognitive model of planning. *Cognitive Science*, **3**, 275–310.

Hiscock, W. G. (1938). Selection tests for chemical process workers. *Occupational Psychology*, **12**.

Hoc, J.-M. (1988). *Cognitive Psychology of Planning* (translated into English by C. Greenbaum. Originally published in French by Presses Universitaires de Grenoble as *Psychologie Cognitive de la Planification* in 1987). London: Academic Press.

Holding, D. H. (Ed.). (1989). *Human skills* (2nd ed.). Chichester: Wiley.

Hollnagel, E., and Woods, D. D. (1983). Cognitive systems engineering: New wine in new bottles. *International Journal of Man-Machine Studies*, **18**, 583–600.

Hollnagel, E., Pedersen, O. M., and Rasmussen, J. (1981). *Notes on Human Performance Analysis* (Riso-M-2285). Roskilde, Denmark: Riso National Laboratory.

Holton, G. J. (1986). *The advancement of science, and its burdens.* Cambridge: Cambridge University Press.

Hutchins, E. (1980). *Culture and inference: A Trobriand case study.* Cambridge, MA: Harvard University Press.

Hutchins, E. (1983). Understanding Micronesian navigation. In: Gentner, D., and Stevens, A. L. (Eds.), *Mental models.* Hillsdale, NJ: Erlbaum.

Johannsen, G., and Rouse, W. B. (1983). Studies of planning behavior of aircraft pilots in normal, abnormal, and emergency situations. *IEEE Transactions on Systems, Man, and Cybernetics*, **SMC-13**, 267–278.

Keele, S. W. (1986). Motor control. In: Boff, K. R., Kaufman, L., and Thomas, J. P. (Eds.), *Handbook of perception and human performance.* New York: Wiley.

Kirlik, A. (1993). Modeling strategic behavior in human-automation interaction: Why an "aid" can (and should) go unused. *Human Factors*, **35**, 221–242.

Kirlik, A. (in press). Requirements for psychological models to support design: Towards ecological task analysis. In: Flach, J. M., Hancock, P., Caird, J., and Vicente, K. J. (Eds.), *An Ecological Approach to Human-Machine Systems I: A Global Perspective.* Hillsdale, NJ: Erlbaum.

Klein, G. A. (1989). Recognition-primed decisions. In: Rouse, W. B. (Ed.), *Advances in Man-Machine Systems Research*, vol. 5. Greenwich, CT: JAI Press.

Klein, G. A. (1993a). A recognition-primed decision (RPD) model of rapid decision making. In: Klein, G. A., Orasanu, J., Calderwood, R., and Zsambok, C. E. (Eds.), *Decision making in action: Models and methods.* Norwood, NJ: Ablex.

Klein, G. A. (1993b). Twenty questions—Suggestions for research in naturalistic decision making. In: Klein, G. A., Orasanu, J., Calderwood, R., and Zsambok, C. E. (Eds.), *Decision making in action: Models and methods.* Norwood, NJ: Ablex.

Klein, G. A., and Calderwood, R. (1991). Decision models: Some lessons from the field. *IEEE Transactions on Systems, Man, and Cybernetics*, **SMC-21**, 1018–1026.

Klein, G. A., Calderwood, R., and Clinton-Cirocco, A. (1986). Rapid decision making on the fire ground. In: *Proceedings of Human Factors Society 30th Annual Meeting*, 576–580.

Koedinger, K. R., and Anderson, J. R. (1990). Abstract planning and perceptual chunks: Elements of expertise in geometry. *Cognitive Science*, **14**, 511–550.

Lave, J. (1977). Cognitive consequences of traditional apprenticeship training in West Africa. *Anthropology and Education Quarterly*, **8**, 177–180.

Lave, J. (1988). *Cognition in practice: Mind, mathematics and culture in everyday life.* Cambridge: Cambridge University Press.

Lees, F. P. (1974). Research on the process operator. In: Edwards, E., and Lees, F. P. (Eds.), *The Human Operator in Process Control.* London: Taylor & Francis.

MacKay, D. G. (1982). The problems of flexibility, fluency, and speed-accuracy trade-off in skilled behavior. *Psychological Review*, **89**, 483–506.

McDermott, D. (1978). Planning and acting. *Cognitive Science*, **2**, 71–109.

McDonald, J. S., and Dzwonczyk, R. (1988). A time and motion study of the anaesthetist's intraoperative time. *British Journal of Anaesthesiology*, **61**, 783–742.

McDonald, J. S., Dzwonczyk, R., Gupta, B., and Dahl, M. (1990). A second time-study of the anaesthetist's intraoperative period. *British Journal of Anaesthesiology*, **64**, 582–585.

Meijler, A. P. (1987). *Automation in anesthesia, a relief? A systematic approach to computers in patient monitoring.* Berlin: Springer-Verlag.

Miller, G. A., Galanter, E., and Pribram, K. H. (1960). *Plans and the Structure of Behavior.* London: Holt, Rinehard and Winston, Inc.

Miller, G. A., Galanter, E., and Pribram, K. H. (1960/1986). *Plans and the Structure of Behavior.* New York: Adams, Bannister, Cox.

Miller, P. L. (1983). ATTENDING: Critiquing a physician's management plan. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **PAMI-15**, 449–461.

Miller, P. L. (1986). *Expert critiquing systems.* New York: Springer-Verlag.

Moray, N. (1986). Monitoring behavior and supervisory control. In: Boff, K. R., Kaufman, L., and Thomas, J. P. (Eds.), *Handbook of perception and human performance.* New York: Wiley.

Moray, N. (1992). Toward an agenda for error research. In: *Proceedings of Human Factors Society 36th Annual Meeting*, 640–643.

Moray, N., and Huey, B. M. (1988). *Human factors research and nuclear safety.* Washington, DC: National Academy Press.

Moray, N., Lootsteen, P., and Pajak, J. (1986). Acquisition of process control skills. *IEEE Transactions on Systems, Man, and Cybernetics*, **SMC-16**, 497–504.

Moray, N., Dessouky, M. I., Kijwoski, B. A., and Adapathya, R. (1991). Strategic behavior, workload, and performance in task scheduling. *Human Factors*, **33**, 607–629.

Neisser, U. (1976). *Cognition and reality—Principles and implications of cognitive psychology.* New York: W. H. Freeman.

Newell, A., and Simon, H. A. (1972). *Human problem solving.* Englewood Cliffs, NJ: Prentice-Hall.

Newtson, D. (1976). The process of behavior observation. *Journal of Human Movement Studeis*, **2**, 114–122.

Nisbett, R. E., and Wilson, T. D. (1977). Telling more than we can know: Verbal reports on mental processes. *Psychological Review*, **84**, 231–159.

Norman, D. A. (1988). *The psychology of everyday things.* New York: Basic Books.

Norman, D. A. (1991). Cognitive science in the cockpit. *CSERIAC Gateway*, **2**(2), 1–4.

Payne, J. W., Bettman, J. R., and Johnson, E. J. (1992). Behavioral decision research: A construcutive processing perspective. *Annual Review of Pschology*, **43**, 87–131.

Payne, S. J. (1991). Display-based action at the user interface. *International Journal of Man-Machine Studies*, **35**, 275–289.

Pew, R. W. (1974). Levels of analysis in mortor control. *Brain Research*, **71**, 393–400.

Pew, R. W., Miller, D. C., and Feehrer, C. E. (1981). *Evaluation of proposed control room improvements through analysis of critical operator decisions,* NP-1982. Palo Alto, CA: Electric Power Research Institute.

Poincaré, H. (1905/1952). *Science and method* (Originally published by Walter Scott in (1905)). New York: Dover Publications.

Polya, G. (1957). *How to solve it – A new aspect of mathematical method.* Carden City, New York: Doubleday Anchor Books.

Raby, M., and Wickens, C. D. (1990). Planning and scheduling in flight workload management. In: *Proceedings of Human Factors Society 34th Annual Meeting*, 71–74.

Rasmussen, J. (1976). Outlines of a hybrid model of the process plant operator. In: Sheridan, T. B., and Johannsen, G. (Eds.), *Monitoring behavior and supervisory control.* NY: Plenum.

Rasmussen, J. (1983). Skills, rules, and knowledge; Signals, signs, and symbols, and other distinctions in human performance models. *IEEE Transactions on Systems, Man, and Cybernetics*, **SMC-13**, 257–266.

Rasmussen, J. (1986). *Information Processing and Human-Machine Interaction.* New York: North-Holland.

Rasmussen, J. (1988). A cognitive engineering approach to the modeling of decision making and its organisation in: Process control, emergency management, CAD/CAM, office systems, and library systems. In: Rouse, W. B. (Ed.), *Advances in man-machine systems research*, vol. 4. Greenwich, CT: JAI Press.

Rasmussen, J. (1990). The role of error in organizing behaviour. *Ergonomics*, **33**, 1185–1199.

Rasmussen, J. (1993). Deciding and doing: decision making in natural context. In: Klein, G. A., Orasanu, J., Calderwood, R., and Zsambok, C. E. (Eds.), *Decision making in action: Models and methods.* Norwood, NJ: Ablex.

Rasmussen, J., and Jensen, A. (1973). *A study of mental procedures in electronic trouble shooting,* Riso-M-1582. Roskilde, Denmark: Riso national Laboratory, Electronics Department.

Rasmussen, J., and Jensen, A. (1974). Mental procedures in real-life tasks: A case study of electronic trouble shooting. *Ergonomics*, **17**, 293–307.

Rasmussen, J., and Lind, M. (1981). *Coping with complexity,* Riso-M-2293. Roskilde, Denmark: Riso national Laboratory, Electronics Department.

Rasmussen, J., Pejtersen, A. M., and Goodstein, L. (1989). *Cognitive engineering: Concepts and applications.* Working paper.

Ravin, M. B. (1981). *Problems in Anesthesia: A case study approach.* Boston: Little, Brown and company.

Reason, J. (1987). Cognitive aids in process environments: prostheses or tools? *International Journal of Man-Machine Studies*, **27**, 463–470.

Redding, R. E., and Cannon, J. R. (1992). Expertise in air traffic control (ATC): What is it, and how can we train for it? In: *Proceedings of Human Factors Society 36th Annual Meeting*, 1326–1330.

Rigney, J. W., Towne, D. M., and Mason, A. K. (1968). *An analysis of the structure and errors in corrective maintenance work.* LA: University of Sourthern California, Electronics Personnel Group.

Rogoff, B., and Lave, J. (Eds.). (1984). *Everyday cognition: Its development in social context.* Cambridge, MA: Harvard University Press.

Rosenbaum, D. A. (1983). The movement precuing techinque: Assumptions, applications, and extensions. In: Magill, R. A. (Ed.), *Memory and control of action.* Amsterdam: North-Holland.

Roth, E. M., Bennett, K. B., and Woods, D. D. (1987). Human interaction with an "intelligent" machine. *International Journal of Man-Machine Studies*, **27**, 247–525.

Rouse, W. B., Rouse, S. H., and Pellegrino, S. J. (1980). A rule-based model of human problem solving performance in fault diagnosis tasks. *IEEE Transactions on Systems, Man, and Cybernetics*, **SMC-10**, 366–376.

Runeson, S. (1977). On the possibility of "smart" perceptual mechanisms. *Scandinavian Journal of Psycholology*, **18**, 172–179.

Sacerdoti, E. D. (1974). Planning in a hierarchy of abstraction spaces. *Artificial Intelligence*, **5**, 115–135.

Sanderson, P. M. (1989). The human planning and scheduling role in advanced manufacturing systems: An emerging human factors domain. *Human Factors*, **31**, 635–666.

Sanderson, P. M. (1990). Verbal protocol analysis in three experimental domains using SHAPA. In: *Proceedings of Human Factors Society 34th Annual Meeting*, 1280–1284.

Sanderson, P. M. (1991). *ESDA: Exploratory sequential data analysis,* EPRL-91-04. Urbana, IL: Engineering Psychology Research Laboratory, University of Illinois at Urbana-Chapaign.

Sanderson, P. M., James, J. M., and Seidler, K. S. (1989). SHAPA: An interactiive software environment for protocoal analysis. *Ergonomics*, **32**, 1271–1302.

Scheflen, A. E. (1966). Natural history method in psychotherapy: Communicational research. In: Gottschalk, L. A., and Auerbach, A. H. (Eds.), *Methods of research in psychotherapy.* New York: Appleton-Century-Crofts.

Scherer, K. R., and Ekman, P. (1982). Methodological issues in studying nonverbal behavior. In: Scherer, K. R., and Ekman, P. (Eds.), *Handbook of methods in nonverbal behavior research.* Cambridge, UK: Cambridge University Press.

Schmidt, R. A. (1988). *Motor control and learning: A behavioral emphasis* (2nd ed.). Champaign, IL: Human kinetics publishers.

Scribner, S. (1984). Studying working intelligence. In: Rogoff, B., and Lave, J. (Eds.), *Everyday cognition: Its development in social context.* Cambridge, MA: Harvard University Press.

Scribner, S., and Cole, M. (1973). Cognitive consequences of formal and informal education. *Science*, **182**, 553–559.

Sheridan, T. B. (1967). Three models of preview control. *IEEE Transactions on Human Factors in Electronics*, **HFE-7**, 91–102.

Sheridan, T. B., and Hennessy, R. T. (Eds.). (1984). *Research and modeling of supervisory control behavior: Report of a workshop.* Washington, DC: National Academy Press.

Sheridan, T. B., and Johannsen, G. (Eds.). (1976). *Monitoring behavior and supervisory control.* NY: Plenum.

Simon, H. (1969). *Science Of the Artificial.* Cambridge: MIT Press.

Singleton, W. T. (Ed.). (1978a). *The analysis of practical skills.* Bolton: MTP.

Singleton, W. T. (1978b). Introduction. In: Singleton, W. T. (Ed.), *The analysis of practical skills.* Bolton: MTP.

Sinnott, J. D. (Ed.). (1989). *Everyday problem solving.* New York: Praeger.

Slovic, P. (1976). Towards understanding and improving decisions. In: Salkovitz, E. I. (Ed.), *Science, Technology, and the Modern Navy: Thirtieth Anniversary 1946-1976.* Arlington, VA: Dept of the Navy, office of Naval Research.

Slovic, P. (1982). Towards understanding and improving decisions. In: Howell, W. C., and Fleishman, E. A. (Eds.), *Human performance and productivity, Vol.2: Information processing and decision making.* Hillsdale, NJ: Erbaum.

Sperandio, J. C. (1971). Variation of operator's strategies and regulating effects on workload. *Ergonomics*, **14**, 571–577.

Suchman, L. A. (1987). *Plans and Situated Actions.* Cambridge: Cambridge University Press.

Sundström, G. A. (1991). Process tracing of decision making: An approach for analysis of human-machine interactions in dynamic environments. *International Journal of Man-Machine Studies*, **35**, 843–858.

Toda, M. (1962). The design of a fungus-eater: A model of human behavior in an unsophisticated environment. *Behavioral Science*, **7**, 164–183.

Tolman, E. C. (1932/1968). Behavior, a molar phenomenon. In: Care, N. S., and Landesman, C. (Eds.), *Readings in the Theory of Action* (from Chapter I of *Purposive Behavior in Animals and Men* by E. C. Toman, Century Company, 1932). Bloomington: Indiana University Press.

Vallacher, R. R., and Wegner, D. M. (1987). What do people think they're doing? Action identification and human behavior. *Psychological Review*, **94**, 3–15.

van Hooff, J. A. R. A. M. (1982). Categories and sequences of behavior: Methods of description and analysis. In: Scherer, K. R., and Ekman, P. (Eds.), *Handbook of methods in nonverbal behavior research.* Cambridge, UK: Cambridge University Press.

Vicente, K. J. (1991). *Supporting knowledge-based behavior through ecological interface design.* University of Illiois at Urbana-Champaign: unpublished dissertation.

von Bertalanffy, L. (1968). *General System Theory: Foundations, Development, Applications.* NY: George Braziller.

Weinstein, C. J., and Schmidt, R. A. (1989). Sensorimotor feedback. In: Holding, D. H. (Ed.), *Human Skills* (2nd ed.). Chichester: Wiley.

Wickens, C. D. (1992). *Engineering Psychology and Human Performance* (2nd ed.). New York: Harper Collins.

Wiener, E. L., and Curry, R. E. (1980). Flight deck automation: Promises and problems. *Ergonomics*, **23**, 995–1012.

Woods, D. D. (1982). Operator decision making behavior during the steam geneartor tube rupture at the Ginna nuclear power station. In: Brown, W., and Wyrick, R. (Eds.), *Analysis of steam generator tube rupture events at Oconee and Ginna.* Institute of Nuclear Power Operations.

Woods, D. D. (1984). Some results on operator performance in emergency events. In: *Ergonomics problems in process operations—Proceedings of Institution of Chemical Enigeers Symposium Series No. 90.*

Woods, D. D. (1988). Coping with complexity: The psychology of human behavior in complex systems. In: Goodstein, L. P., Andersen, H. B., and Olsen, S. E. (Eds.), *Tasks, Errors, and Mental Models.* New York: Taylor & Francis.

Woods, D. D. (1993). Process tracing methods for the study of cognition outside of the experimental psychology laboratory. In: Klein, G. A., Orasanu, J., Calderwood, R., and Zsambok, C. E. (Eds.), *Decision making in action: Models and methods.* Norwood, NJ: Ablex.

Woods, D. D., O'Brien, J. F., and Hanes, L. F. (1987). Human factors challenges in process control: The case of nuclear power plants. In: Salvendy, G. (Ed.), *Handbook of human factors.* New York: Wiley.

Woods, D. D., Roth, E. M., and Pople, Jr., H. E. (1990). Modeling operator performance in emergencies. In: *Proceedings of Human Factors Society 34th Annual Meeting*, 1132–1135.

Xiao, Y., Zhang, S. W., and Zhang, Y. (1988). An internal model approach in the modelling of human preview control. In: *Proceedings of IEEE Conference on Systems, Man, and Cybernetics*, 839–844.

Xiao, Y., Milgram, P., and Doyle, D. J. (1992). Incident evolution and task demands: An analysis and a field study of 'going sour' incidents. In: *Proceedings of Human Factors Society 36th Annual Meeting*, 1279–1283.