Cognitive Control Dynamics for Reaching a Satisficing Performance in Complex Dynamic Situations

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Abstract: The study of dynamic situations, in which the human operator can exert only partial control (such as in industrial process control, aircraft piloting, or air traffic control), has offered rare opportunities to examine the dynamics of cognitive control. Unlike most of the laboratory approaches to the study of cognition, this kind of study has stressed that several cognitive modes can act in parallel and that the distribution of control among the modes can evolve over time in relation to task requirements and human operator states. This article is a review of the arguments, developed in the literature on dynamic situations and by the authors themselves, in favor of a dynamic adjustment of cognitive control to situational features (integrating both the environment and the human) as a major component of adaptation. The main criterion used by the human operator to adjust cognitive control is *situation mastery*, as a guarantee that a satisficing performance will be reached with an acceptable quantity of resources. Two main dimensions are proposed to characterize cognitive control modes: the level of abstraction (symbolic/subsymbolic) and the origin (internal-anticipative, external-reactive) of the data used for control. Metacognition is considered as a means to distribute the cognitive control within these dimensions in order to ensure situation mastery. Theoretical, methodological, and practical implications of this perspective on cognitive control dynamics are drawn. From a theoretical viewpoint, the approach stresses the need to consider the cognitive system degrees of freedom to adapt to situations, and that therefore several solutions are possible in order to perform the same task. On the methodological side, the access to the diverse cognitive control modes, to their parallelism, and to the cognitive control dynamics requires new methodological approaches. The practical implications consist in developing support systems that keep the degrees of freedom open for adaptation and in trying to manage consistency.

Introduction

Dynamic situations such as industrial, medical, or traffic process control in uncertain environments have long been one of the major study targets for cognitive

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ergonomics and cognitive engineering (Bainbridge, 1978; Hollnagel, Mancini, & Woods, 1986; Woods & Hollnagel, 1987). In these situations, the human operator only partially controls the technical process or the environment. For example, the actions of a ship's helmsman do not fully determine the route taken by that ship. The combined effects of the steering of the ship, the current, the wind, and the inertia of the ship must also be taken into account.

The operator is subject to time constants and time constraints. The thermal state of a blast furnace, which produces cast iron from iron ore and coke, is notably determined by the proportion of coke in the load, which takes effect only several hours after its loading (time constant). A fighter aircraft must penetrate enemy territory, fire, and exit, respecting a variation of barely a few seconds from the planned schedule (time constraints). Finally, the operators are confronted with uncertainties, in particular because of their partial control of the situation. For example, a blast furnace could have been filled with low-grade ore, something that the operator may have become aware of only afterwards. Similarly, the pilot of a fighter aircraft may be surprised and attacked in a supposedly safe area without any anticipation from the intelligence service.

These uncertainties add significant risks to the basic (yet complex) nature of the task. Therefore, risk management is a central part of adaptive mechanisms, as well as for managing the risk to the operators themselves (e.g., fighter pilots), and for managing risks associated with the process (e.g., environmental risks, pollution, explosions).

These features imply a continuous adaptation of cognitive strategies and control modes. Reaching a maximum level of performance is not always possible – or indeed desirable – if one wants to preserve longevity at work. This is one of the most significant differences between work and laboratory situations. In the laboratory, the participants are often asked to solve difficult and nonstandard situations in a limited amount of time. They are prompted to reach the highest levels of performance without error. However, failures have no serious consequences, even if they are serious.

In a professional situation, total loss of control of the process is unacceptable. Results must be ensured not just at that moment but also for the duration of the process and during the lifetime of the company. On the other hand, except in totally exceptional cases, the situations are standardized, even when they are abnormal. Unforeseen events, operator errors, and the failure of the materials themselves are the norm for all these systems. The design of the situation (operator training, requested performance, in-depth defenses) incorporates sufficient margins on the result to absorb these local imperfections by means of successful online adaptations.

This logic of tolerance and online adaptation is a priority at all levels of operation, from the workstation to top-level management. Cognitive control, as cognitive resources management, is the main tool for online adaptation at the operator level. It guarantees an adequate level of performance (for work requirements and the management of unforeseen events) for an acceptable cognitive cost in the short term (workload reduction), medium term (preservation of relations with the environment and the sphere of private and social activities), and long term (fatigue avoidance).

Thus, one can make the assumption that an optimal use of cognitive control paradoxically results in setting the performance at a suboptimal level (compared with a given individual's cognitive potential). Such a level is still satisficing to fulfill the perceived requirements of the situation and preserves a capacity of parallel activities (work concerns or private thoughts) and effective work in the long term (resource saving). This is precisely the role of the cognitive compromise (Amalberti, 2001) to which we will return in this article. Many so-called cognitive biases described in laboratory studies have been reinterpreted as useful – or at least nonhandicapping strategies – when in the field (see, for example, Fraser, Smith, & Smith, 1992; Klein, Orasanu, Calderwood, & Zsambok, 1993).

The assumption that such macro control exists is attractive because it proposes a positive vision of the apparent weaknesses of cognition. It raises the level of analysis of cognitive activity. It also introduces the necessary compromises to achieve contradictory or competing goals at a global and integrated level of cognition (including the sphere of private concerns). Macro control is related to the concept of macrocognition (Hollnagel, 1993), although the two concepts are distinct. They stress the role of macro mechanisms in cognition, which are as basic as micro mechanisms but salient only in complex situations, often in field studies.

In a previous work, we took into account two dimensions of cognitive control that will be reexamined here: the level of abstraction of the data used for control and the temporal horizon for the feedback (Hoc & Amalberti, 1995). In this previous work, we adhered to a conception, widely shared at the time, which assumed some confusion between the two dimensions in the human operator's actual functioning. Symbolic data, needing deep interpretation and used within problem-solving situations, were assumed to enter into slow and anticipative processes, with a major planning component getting its feedback very late. Conversely, subsymbolic data-like sensations were supposed to enter into fast and reactive processes, receiving their feedback quickly.

In this paper, we argue that these dimensions must be considered to be orthogonal and that their crossing can generate several cognitive control modes. Furthermore, we will demonstrate that there is a dynamics of cognitive control, which distributes the control among the various modes (cognitive compromise) in order to ensure situation mastery.

In the second section of the paper, we define the main concepts used in this conception of cognitive control – *situation mastery*, *cognitive control, cognitive compromise,* and *cognitive control dynamics* – and indicate their theoretical roots in cognitive psychology and ergonomics.

The third section is devoted to a precise presentation of the two orthogonal dimensions that are used in order to define cognitive control modes. The first one is related to the abstraction level of the data used for control: symbolic versus subsymbolic data. The second one refers to the origin of the data used for control (external to the human with a reactive control vs. internal with anticipative control). A macro level – metacognition – is introduced, which plays a prominent role in cognitive control dynamics, especially when a change in the distribution of control over the diverse modes is needed to improve situation mastery or adaptation.

In the fourth section, the two dimensions are crossed in order to generate four main cognitive control modes, and two important questions are addressed. First, the parallel functioning of the modes are demonstrated as well as the relations (supervision and emergence) between the modes in the control of task performance. Second, transitions from one mode to another are described under learning conditions, as well as under temporal and mental workload constraints. Finally, this multiprocessor model (partly introduced by Hoc & Amalberti, 1995) is shown to play a major role in error management. We end with a discussion of the theoretical, methodological, and practical implications of cognitive control dynamics.

Cognitive Control Dynamics

Cognitive control refers to the control of cognitive processes, which in turn controls the external situation. Thus, cognitive control does not directly control the external situation. *Cognitive control dynamics* is closely related to the concept of situation mastery and to the concept of cognitive control, which we will define before introducing the concept of cognitive compromise, which corresponds to a relatively stable state of the control.

Situation Mastery

There is an abundance of literature on optimal performance in human engineering (Moray, 1986; Sheridan, 1992; Stassen, van Lunteren, & Sheridan, 1997; Wickens, 1984a), which is largely inspired by control theorists trying to make the best use of resources. However, studies of the human operator in dynamic situations usually conclude that performance is not optimal within the context of a certain amount of resources. For example, this property has continuously been stressed in the contributions of the naturalistic decision-making community (see Klein et al., 1993, for the first account continued during the next NDM biannual meetings). Before engaging in deep reasoning, the human operator first tries fast heuristics with low cognitive costs (cf. Klein's recognition-prime model, in Klein et al., 1993). In other words, the human operator seldom invests all the cognitive resources available, as H. A. Simon (1969) stressed. If the performance is not optimal, it is nevertheless satisficing. *A satisficing performance satisfies the minimal requirements necessary to achieve a particular goal from the human operator's viewpoint.*

The crucial question is the definition of both the goal and the requirements. A particular performance can be considered as satisficing in some conditions and not satisficing in other conditions. The goal can be more or less accurately defined. In general, it includes several properties that must be prioritized. Some properties are related to the perception of the situation's requirement and others to the worker's representation of what deviation he/she can control and achieve. An experienced driver or expert physician can apparently be much less precise than a beginner because he/

she knows that there is ample room for recovery and control (Amalberti, Vincent, Auroy, & de Saint Maurice, in press). This is typically the result of metacognition.

Regarding the perception of environment, let's consider, for example, the situation of air traffic control. The human controller must ensure timeliness, safety, passenger comfort, and so on. Spérandio (1977) showed that the priorities differ based on the workload. In other words, a satisficing performance at a low workload level must ensure passenger comfort, but when the workload increases, the priority allocated to this variable may be very low.

Vicente, Mumaw, and Roth (2004) considered this kind of activity (workload regulation) in their nuclear power plant operator model. When the goal is well defined, the quality of its achievement may vary in accordance with external conditions. For example, in the presence of a supervisor, performance level will be higher than when working alone. In a certain sense, performance is always optimal in relation to the minimal requirements, but the latter are flexible. That is why the notion of satisficing performance is preferable for the human operator.

These ideas are also well illustrated by Woods and Hollnagel (2006), who introduced a series of laws and principles (e.g., law of fluency, law of requisite variety) that allow operators to adapt to unstable or surprising environments. The authors point out that many adaptations are seen by observers as poor behaviors or even deviations and remain difficult to understand, but ultimately these adaptations aim to increase the resilience of the joint cognitive system (see also Hollnagel, Woods, & Levison, 2006).

Adaptation to a situation is evaluated by the fact that the human operator reaches a satisficing performance. Adaptation to the *external* requirements of a situation is the visible and behavioral part of an "iceberg" of cognitive activities wherein cognitive control holds a central position. However, a situation also has *internal* requirements for cognitive control, such as resource saving, because it integrates the human operator. There is also growing consideration for the influence of internal states of motivation and emotions on resource management and the choice of cognitive modes adopted in response to perceived demands (Damasio, 1994; Houdé et al., 2001). Thus, the criteria for a satisficing performance include the cognitive investment accepted by the operator and the emotional and social context. A performance can be considered as satisficing with a certain investment of cognitive resources and not satisficing with more investment. The expected performance quality is higher for an expert operator than for a beginner.

In a dynamic situation, adaptive mechanisms are often activated by various unforeseen events. All these mechanisms contribute to the maintenance of global control of the situation – situation mastery remaining the operator's primary objective. It is worth noting that the concept of situation (Hoc, 1988), as used in this paper, deviates from the concept of task (as the external determinant of the activity).

> A situation is an interaction between a subject and a task. An individual masters a situation, when the individual maintains it within a field in which a satisficing performance can be attained with a tolerable quantity

of resources (declarative and procedural knowledge as well as energy; see also Roth & Woods, 1988).

The gap between requirements and resources is a source of stress (Lazarus, 1966), and this level of stress needs to be continuously managed within the classic inverted U-shaped curve of the effects of stress.

The concept of the successful mastery of complex situations has changed considerably in recent years. Before the 1980s, it was often restricted to the ability to solve contextual complex problems and to implement solutions, the framework being primarily the psychology of problem solving. Such an ability was considered the development of smart and fast resolution, with the operator relying as much as possible on productive thinking (in the spirit of the Gestalt theory; see for example, Wertheimer, 1959), followed or accompanied by symbolic, conscious, error-free supervision of the implementation of the selected solution. Literature on problem solving has paid little attention to routine activities, except for criticizing the poor results associated with reproductive routine problem-solving strategies.

The increase in field studies and observations of hands-on operators in the 1990s significantly changed the concept of the successful mastery of complex situations. The main shift came with the change in emphasis from rare and severe crisis conditions to the much more frequent usual situations: the little incidents and deviations that make up workers' days – which primarily demand a response in terms of routinized procedure-driven activities. Consequently, researchers also acknowledged the increasing importance of routine activities in the successful mastery of complex situations. They came to question the prevailing mutual exclusion between a conscious, controlled mode of activity, which should be an essential part of training if success is to be achieved, and an unconscious, uncontrolled set of routines, which should be reduced to a minimum in risky environments. Research on field studies during this period revealed that the findings demanded a continuum in the control of cognitive activities, including the potential for parallel supervision and the coordination of conscious and routine activities in order to achieve a safe and efficient control of so-called normal situations.

Situation mastery and adaptation only marginally relate to a closed-loop reactive model. Rather, they are based on an open-loop anticipative model. Anticipation directs the activity to achieve the goal while remaining in a controllable field of knowledge and know-how. The incidents are also processed using a logic that does not necessarily seek an immediate and radical solution but, rather, provides an opportunity to cancel or absorb the consequences of problems simply by waiting for the natural effect of time and process evolution. In other words, situation mastery is not limited to a particular moment but pertains to a certain period of time. If the human operator burns all his/her cognitive resources at a particular moment, situation mastery may not be available for a difficult situation in the near future.

Cognitive Control

The origin of the concept of cognitive control is related to work on attention and the distinction between controlled versus automatic processes. At the beginning of the 1970s, work in psychology focused on the explanation of the limitation of attention and presented routines such as "what does not consume resources" (Kahneman, 1973; Laberge, 1973; Norman & Bobrow, 1975). *Automatic processes* (irrepressible, fast, unconscious, and autonomous processes) were contrasted with *controlled processes* (slow, serial, and consciously controlled by individuals). The dichotomous models that contrasted routine with controlled activities were a particular case (Laberge, 1973; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Because they postulated that a process that does not require attention cannot be controlled, these models prohibited any concept of cognitive control of routines. Within this framework, cognitive control was compared with attention, and these mechanisms became relatively confused; the existence of a control of routines has long been refuted.

In the 1980s, many empirical results invalidated this position (Hirst, Spelke, Reaves, Caharack, & Neisser, 1980; Navon, 1979), and the idea of an indirect control or of a supervisory control of routine activities by controlled processes was gradually adopted (Norman, 1981; Rasmussen, 1986; Reason, 1984). Consequently, the models of control (of routine activities) became more sophisticated in the literature. Norman and Shallice (1986) proposed a model that makes the assumption that two systems are implied in the control of routines. *Competitive planning* functions by default as long as the context allows it. This control acts through the activation and inhibition of the routines in competition so that only one routine is started at a time. Each routine has an activation value and is selected and started when this value exceeds a certain threshold. The *supervisory attentional system* (SAS) uses part of the attentional resources to modulate the result of competitive planning by providing a source of additional activation or inhibition. Therefore, it skews the process of selection of the routines by raising the probability of releasing a given routine. SAS operates at key points in the action sequence or when the routine control mode of the activity is no longer adapted. It then requires a modification of the level of attention and a temporary return to the so-called controlled processes.

An automated process is controlled at a certain level and, consequently, has some adaptive capacity. We can walk without conscious control, but our step is continuously adapted to a variety of pedestrian conditions. Supervision, situated at a superordinate level, can set a point (e.g., direction) for the control of the walking routine. Cognitive control is strongly structured by the implementation of this "supervision/control" pairing at various levels. What is supervision at a lower level becomes control at a higher level. This conception was implemented in a computer model (CAP2), including some relationships between automated and controlled processes; the latter are able to modify the degree of activation of the former (Schneider & Chein, 2003).

> Cognitive control can be understood as the authority that makes it possible to bring into play, in the correct order and with the appropriate intensity, the cognitive representations and operations required for

adaptation, according to external and internal requirements. It includes direct control and supervisory control from one control level to another.

In addition, work carried out in the 1970s on awareness and metaknowledge in children (Piaget, 1974a; Flavell & Wellman, 1977) inspired rapid developments in artificial intelligence and its application to operator cognitive modeling (Pitrat, 1996; Valot & Amalberti, 1992). These studies showed that the situated use of competence requires a control authority to give the cognitive priorities according to the progression of the task. This awareness of one's own activity serves both the immediate adaptation toward the goal and adaptation in the long term through the memorizing of successes and failures. It is an essential tool for operational knowledge formation.

Pitrat (1996) supported the idea that any information-processing system designed to apply to very complex problems in which solutions are not unique (the typical case of field problems) cannot work without reflecting on itself. That is why it is necessary to consider a third level beyond direct control and supervisory control: the metacognitive control that aims to distribute control over its diverse modes in order to fully satisfy situation mastery.

Cognitive Compromise

The idea of *ecological* or *natural* adaptation and the control of complex situations have grown along with three new ideas: the importance of time, the importance of satisficing performance, and the importance of the dynamic combination between control modes. The level of performance required at work (in industry) is not likely to solicit the maximum performance level of cognition. Studies on natural decision making, similar to control errors that will be described later, show that a reasonable approximation, managed in time by successive corrections, allows sufficient situation mastery. The key phrase is *cognitive compromise*; that is, an effort of cognitive mobilization adapted to the required objective (satisficing performance). This effort frees margins with two objectives in mind: first, to avoid exhaustion, notably guaranteeing a relatively stable performance for the entire duty period; and second, to invest the conscious field in useful parallel activities. The latter can be in conjunction with work (e.g., anticipation or resolution of misunderstood points; see Falzon, 1994) or purely private activities.

The adjustment of the cognitive compromise passes through the simultaneous mobilization of diverse control modes (e.g., automated and controlled processes) in order to reach situation mastery or adaptation.

Adaptation, as described by Piaget (1974b), can be translated very directly into terms of situation mastery, but from a dynamic viewpoint. It consists in balancing two complementary mechanisms: the assimilation of the current situation to a mastered (known) situation and the accommodation of a mastered situation to the current (unknown) situation. Assimilation accounts for those aspects of activity driven by the resources and results in simplifying the situation so that it is manageable given the available knowledge and energy. Accommodation accounts for those aspects of activity driven by the requirements and results in an increase in the efficiency of assimilation in the long term: Knowledge can be increased, as can the performance of the strategies in terms of energy spent.

Cognitive compromise is the result of adaptation (i.e., the balance between assimilation and accommodation) and can be evaluated by the ratio between the investment in terms of cognitive costs and the result obtained in terms of performance. This ratio corresponds to effectiveness in Long's (1996) terminology. Thus, at first glance, the notion is mainly subjective. The human operators set their cognitive compromise at such levels that they feel they master the situations. If they feel that they have invested too much of their cognitive resources with a risk of overload or that they cannot reach acceptable performance levels, they will try to change their cognitive compromises.

The acceptability of the human operator's cognitive compromise depends on the situation. Assimilation can result in efficient heuristics if they lead to a satisficing performance. However, we previously noted that the criteria for evaluating a satisficing performance can vary in terms of its social acceptability, of invested resources, of temporal horizon, and so on. Thus, despite its cognitive cost, accommodation is triggered when assimilation does not lead to satisficing performance or when time, resources, and motivation are available.

Falzon (1994) has shown that human operators reflect on their own activities outside the work situation in order to improve performance on the job. The activity theory has long stressed that activity cannot be closed into automated (operations without conscious goals) and controlled processes (actions with conscious goals). Following this theoretical approach, a third level must be introduced that bears on motives (for a recent account, see Bedny, 2004). In other words, human operators can choose to go beyond a satisficing performance in order to satisfy their motivation at work.

Cognitive Control Dimensions

Several dimensions have been proposed in order to classify diverse cognitive control modes. We will focus on two of them and discuss their relations to the others.

- The level of abstraction of the data required for control (symbolic vs. subsymbolic data, mainly inspired by Rasmussen, 1986) in relation to controlled/automated processes (Schneider & Chein, 2003; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977), to conscious/unconscious processes (Richard, 1999), to attentional/preattentional processes (e.g., Fernandez-Duque & Johnson, 1999; Schneider & Shiffrin, 1977), and to explicit/implicit processes (Kirsner et al., 1998).
- The origin of the data used for control (internal vs. external data) in relation to anticipative versus reactive processes (Hoc & Amalberti, 1995; Hollnagel, 1993, 2002, 2005), but distinct from endogenous versus exogenous processes, stressing the genesis of the process (Trick, Enns, Mills, & Vavrik, 2004).

Crossing the two dimensions generates roughly four control modes among which cognitive control is distributed. A major mechanism – metacognitive control – is implied in this distribution in order to ensure situation mastery (Flavell & Wellman, 1977).

Levels of Abstraction of the Data Used for Control

Rasmussen (1986) introduced three levels of abstraction for control, which are presented in the order (adopted by the author) of the development of expertise (more precisely, of activity routinization) from the most expensive to the least expensive in terms of symbolic attentional resources (Anderson, 1985). The first two levels concern *symbolic* data processing (concepts and signs, always discontinuous and referring to meaning); the last concerns *subsymbolic* data processing (signals, often continuous and processed for their physical properties without reference to meaning).

Knowledge-based behavior (KBB). This level of control is founded on concepts, or declarative knowledge. Concepts are complex representational structures that imply semantic relations and associated procedures. This level of control is observed in problem-solving situations, especially with novices or with experts facing unknown situations. It is very demanding in terms of knowledge and symbolic attentional resources.

Rule-based behavior (RBB). This level of control is founded on rules connecting conditions to activities. The conditions are represented as signs; that is, units with two sides ("form-content"), the use of which requires minimal interpretation. This level of control applies to procedures that still require strong symbolic attentional control. It is relatively expensive in terms of symbolic attentional resources.

Skill-based behavior (SBB). This level of control is founded on routines. These include not only sensorimotor skills but also cognitive skills in a wider sense (e.g., mental calculation), in which control relies on internal or external signals. They are low-cost procedures, although they may require subsymbolic attentional controls (e.g., visual attention). The recognition-primed decision process described by Klein et al. (1993) belongs to this class.

Symbolic data processing is sequential, attention-demanding, and thus sensitive to overload. Through a form of coding, it "discretizes" information and proceeds step by step, without allowing the "smoothing" imposed by certain activities (e.g., playing tennis). On the other hand, it gives access to meanings and allows generalizations. Subsymbolic control relies on signals without soliciting major interpretations. It is parallel and does not require symbolic attention. It allows the continuity of the processing of feedback and opens up the possibility of smoothing the action. However, some symbolic supervisory control may be needed to reach a satisficing performance with routines, especially for error management (Noizet & Amalberti, 2000; Rizzo, Ferrante, & Bagnara, 1995).

This dimension is very close to the controlled/automated processes discussed previously (Schneider & Chein, 2003; Schneider & Shiffrin, 1977; Shiffrin &

Schneider, 1977). The main difference is the stress on the nature of the data used for control – symbols, signs, and concepts, in Rasmussen's terms, or symbolic versus subsymbolic data in our terms (needing interpretation or not). Thus, the diverse properties discovered for controlled and automatic processes can be transferred here (Schneider & Chein, 2003).

The dimension is related to but not confounded with the three other dimensions evoked previously in relation to it. The *conscious/unconscious* processes refer to the recourse to consciousness (Richard, 1999). Usually, in cognitive psychology, consciousness is situated at the metacognitive level. It implies some representation of the psychological activity itself, which is accessible to verbal report. Subsymbolic processes are seldom conscious. However, symbolic processes can be only partly conscious. The human operator can have a representation of the data being processed without being able to say how the data are processed. Several experiments on possible dissociations between the performance and the knowledge of the procedure executed to reach the performance have addressed this question (Berry & Broadbent, 1984, 1995). In other words, performance can be good, whereas the conscious knowledge of the procedure is false or poor.

Some conditions likely to reduce the dissociations and improve consciousness have been tested (Sanderson, 1989). The *attentional/preattentional* dimension is often confused with the symbolic/subsymbolic dimension (Fernandez-Duque & Johnson, 1999; Schneider & Shiffrin, 1977). Symbolic data processing requires attention because it needs the development of interpretative processes. However, in light of Wickens's multiple resources model (1984b), some varieties of attention must be defined. Thus, subsymbolic processes may require some form of attention (e.g., visual attention). A distinction between symbolic attention, related to symbolic information, and subsymbolic attention, related to signals, should be considered.

Finally, opposition between *explicit and implicit* processes has been used for a long time (Kirsner et al., 1998) in order to separate deliberate and conscious processes from nondeliberate and unconscious processes, especially in the domain of learning. This dimension introduces another viewpoint on the symbolic/subsymbolic dimension – that of task requirements (Milleville-Pennel, Hoc, & Jolly, in press). An explicit process is triggered by an instruction from outside or from the human operator her/himself in order to adopt a deliberate and conscious way of processing. Thus, the symbolic control mode is triggered. Without specific instruction, the subsymbolic mode is more likely to be triggered if it is sufficient to reach a satisficing performance.

One of the most visible features of expertise is the richness of what Raufaste, Eyrolle and Mariné (1998) called a *lattice of routines*. These authors showed that even complex expertise, such as radiological diagnosis, relies mainly on this lattice. However, routines are often supervised by symbolic processes, as shown by many studies on human error. For example, Reason (1990) defined skill-based errors in relation to supervision malfunctions (e.g., mistimed or omitted supervision).

The supervision of routines was well illustrated by Noizet and Amalberti (2000), who looked at maintenance activities in a nuclear power plant in order to improve the understanding of confusion errors between components. A computer simulation was designed to create step-by-step pictures representing all corridors and pathways of the plant's electrical facility. A navigation function was operated by clicking on the screen (e.g., to open a door, close an electrical circuit). All slides were formally analyzed to index the associated potential for error. The index took into account two categories of risks. One was the risk of confusion, when a slide showed a choice between similar pathways or materials. Another risk was that of missing an action on the artifact (mouse), which could result in activating an irrelevant action pattern for task completion at hand, thus imposing an undo or redo maneuver. Field operators (subjects) were free to choose the way they navigated through the building to carry out the job. The simulation automatically recorded the path selected by each subject and the time spent per view (TSV). A basic assumption was that TSV reflects the intensity of cognitive processes, especially the symbolic supervision of routines.

The authors observed two results. First, risks associated with pictures had a significant effect. TSVs were significantly longer for pictures presenting a higher risk of missing an action or a higher risk of confusion. Second, another significant result related to decelerations in the progression toward the goal at places where there was no risk indexed on the slide. The results showed that these specific decelerations were unstable from one subject to another and from one repetition to another. Given that these slow passages remained constant in volume, and even increased when instructions of temporal pressure were given, we regarded these periods of deceleration as necessary. We interpreted them as the time invested in reflexive control aimed at facilitating the supervision of the subject's own activity. We interpreted the result as a logical consequence of self-protection against error. The increase in pressure increases the risk of error and requires a more intense supervision of one's own cognition.

Origin of the Data Used for Control

Hoc and Amalberti (1995) and Hollnagel (2002) stressed two drawbacks of the current cognitive ergonomic models when one tries to apply them to dynamic situation management. First, they considered the internal determinants of performance too exclusively, neglecting the role of the external determinants. Following Zhang and Norman (1994), cognition relies not only on internal representations but also on external representations, which both alleviate the mental workload and structure the cognitive activity. One of the aims of ergonomics is to precisely design environments that are capable of improving the human operator activity.

In a recent study of several process control situations, Vicente, Mumaw, and Roth (2004) identified facilitating activities and externalized data for the control. This observation confirmed another observation by Xiao, Milgram, and Doyle (1997) in the preparation of the anesthesia process. In this case, during the planning phase, the anesthetist was shown to put Post-Its™ on the technical devices each time the operator anticipated a difference between the usual practice and the need for an adjustment to the specific patient during the operation. Second, the current ergonomic models neglect the role of time in dynamic situation management, especially the need for making decisions before getting the necessary feedback.

This dimension relates to the opposition between internal or anticipative control and external or reactive control. As expertise improves, some external data are required less and less often for control. For example, the learning of a series of basic sensorimotor skills results in very few external data requirements (e.g., walking with eyes closed or when reading a newspaper) while being primarily based on internal coordination. Expertise may also allow the operator to distance himself from written external symbolic instructions, relying on routines based on internal data (Anderson, 1985). The internal character of control does not necessarily assume recourse to abstract data.

On the contrary – but in parallel with the changes described previously – the acquisition of expertise may result in cognitive control relying more and more on data that are located in the environment and that have affording properties for the guidance of routine activities. In line with Norman (1988), we broaden the restricted definition of *affordance* proposed by Gibson (1979) (perceptual native affordances common to all humans, so-called *basic* affordances) and generalize the concept to include every element of the environment with the potential to suggest a spontaneous direction for action/reaction when perceived, and with lengthy experience (so-called *expert* affordances). In this last case, the connection between perception and action is not natural but results from a long period of training and routinization.

Once launched, control of the routines is largely based on the affordant characteristics of the environment. Affordances occur at the time of repeated interaction with the objects in the environment and return to a perceptive phenomenon of resonance through which the perceptive system adapts to the invariant structures of the visual space. In line with the concepts of Gibson, two other authors (Zhang & Norman, 1994) showed that problem solving in a natural situation is founded on a double system of representation: an internal representation of the problem space and an external representation entangled in the environment and the perceived world. O'Hara and Payne (1999) added to this viewpoint by explaining why subjects sometimes voluntarily prefer to follow the affordances of the environment on an automatic basis instead of investing resources in planning. However, these positions of confusing routines (low abstraction control level) and external control must be qualified. Some routines, also elaborated through experience, are mainly controlled internally (e.g., a musical performance), although some external determinants are also considered (e.g., audience reaction or fellow musician interaction) and some supervision is necessary. No activity can be completely closed into a particular control mode but can rely much more on one mode than on the others.

It is worth noting that the origin of the data used by cognitive control in order to master the situation is independent from the mobilization of the various levels of abstraction. Symbolic data may be either in the head (e.g., symbolic representations) or in the environment (e.g., written instructions). Subsymbolic data may also be either in the head (e.g., internal coordination of actions) or in the environment (affordances). Therefore, the two dimensions must be considered as orthogonal.

The COCOM model of Hollnagel (1993), as well as the first formulation of Hoc and Amalberti's model (1995), stresses the temporal span of control; that is, the time for effective feedback after implementation of the decision. Hollnagel defined four temporal spans of control. According to our own interpretation, the first two temporal spans can be related to control that is based on affordances. Control is reactive and relates to external data in the sense that it is shaped in a major way by events in the environment. The last two temporal spans correspond to an anticipative control that relates to internal data because they shape behavior on the basis of internal representations.

- *Scrambled control*: The operator's behavior looks scrambled because it is based on basic affordances. These invite action in a way that is not easily repressible. Behavior becomes erratic any time the environment is badly structured with respect to the tasks to be achieved.
- *Opportunistic control*: The subject's behavior appears to be better structured because it is based on so-called expert affordances, inviting more sophisticated procedures of action acquired in training.
- *Tactical and strategic control*: These two control modes ensure adaptation in the medium and long term.

More recently, Hollnagel (2005) reformulated his model in terms that are related more to control theory.

- *Tracking*: Closed-loop behavior nullifying external disturbances.
- *Regulating*: Introduction of short- to medium-term goals for the previous level.
- *Monitoring*: Introduction of plans.
- *Targeting*: Introduction of high-level goals.

Within the context of driving a vehicle, Trick et al. (2004) made use of our first dimension (abstraction) and also introduced a second one in order to classify several cognitive control modes: the distinction between endogenous and exogenous processes. However, their second dimension is very different from ours. In fact, the dimension is related to the genesis of the control mode and not its result in terms of mechanism in operation. An endogenous process is the result of a learning process by experience. It comes from the human operator's knowledge and goals. On the other hand, an exogenous process is the result of the meeting between properties related to a species and particular stimulus pattern (e.g., the consequences of visual illusions). An endogenous process may result in a process controlled on the basis of external data with little anticipation (by the externalization of expert affordances). An exogenous process may lead to a process governed by internal data if a basic affordance triggers a complex response without needing guidance on the basis of external data.

Anticipation has often been related to expertise, especially in dynamic environments (Cellier, Eyrolle, & Mariné, 1997). Anticipation makes it possible to reasonably bet on the world to come, and then accordingly select a repertoire of plausible actions. Waiting until the last minute to build the repertoire can lead to restrictions that allow the constraints to grow uncontrolled and prevent the operator from adopting the appropriate action. However, the benefit follows a reversed curve. On the one hand, it is beneficial to proceed to a minimal anticipation on the basis of an internal model of the future situation. On the other hand, the mental model of sustaining anticipation is never fully correct; therefore, too much anticipation can lead to costly errors by exceeding the threshold of utility and relevance.

In the blast furnace control, interviews conducted in view of various pieces of information that are available in the control room (Hoc, 1989) have shown that the rules of information use were mainly verbalized in the form of rules of diagnosis (largely integrating the forecast and thus anticipation), as opposed to rules of (reactive) intervention. Observations carried out on operation reproductions (Hoc, 1996; Samurçay & Hoc, 1996) have also shown that the operators spent considerable time in developing least-commitment strategies for generating and testing hypotheses on the evolution of a series of internal and unobservable physicochemical phenomena. Conversely, when it was a question of making decisions, verbalizations were based primarily in the short term on surface factual variables without a direct bond with these internal phenomena. Behind this apparent paradox, one can see the need for long-term anticipative strategies that make it possible to define contexts so that the validity of short-term rules of action, which are based on available data, could be evaluated and to ensure correct interpretation of these data.

The importance of anticipation has also been stressed in aircraft piloting (Amalberti, 2001; Amalberti & Deblon, 1992). Combat pilots spend considerable time developing tests of hypothesis on the nature of potential threats during preparation of the flight rather than during flight because of the high speed of the process. However, while becoming experts, the pilots pass from a broad analysis (considering many hypotheses with relatively generic levels of response) to an in-depth analysis (considering few hypotheses for which the responses are very precisely prepared, in particular in their capacity for adaptation). At the same time, these strategies provide strong guidance for the flight by establishing an imposed field of validity beyond which the mission becomes impossible (the art of piloting is to adapt the environment to the flight plan rather than the reverse) and the degrees of freedom around this field of validity to account for unanticipated surprises and constraints. They also make it possible to bring into play the heuristics of guiding cognitive activity toward well-controlled solutions with available and effective routines. This situation is a good example of an internal and anticipative cognitive control in the service of situation mastery.

The same strategy has been found in air traffic control (Morineau, Hoc, & Denecker, 2003). Operators anticipate conflicts by the mental simulation of future positions in order to elaborate a problem space within which commitments to particular problems and solutions will be carried out at the last second. Solutions are apparently triggered by affordances but are prepared by schematic anticipation of the traffic evolution. This situation illustrates the importance of an adequate balance between internal (anticipative) and external (reactive) cognitive control. The balance enables controllers both to avoid commitments too early when it is not yet possible to anticipate all the relevant properties of the traffic, and to act in time.

However, a number of recent results also show that too much time available for anticipation can be counterproductive. Two experiments were carried out on the microworld called NEWFIRE – the "story" was forest firefighting from a headquarters location (Løvborg & Brehmer, 1991) – by changing the speed of the process (Hoc & Moulin, 1994; Hoc, Amalberti, & Plee, 2000). Task quality and actions on the interface (orders to virtual firefighting units) were recorded and analyzed, as were verbal reports. When the process was fast, the strategy was very reactive, although under the control of a schematic plan that was seldom questioned. When the process slowed, the strategy appeared more anticipative. There were possibilities for planning and replanning in real time, which improved performance. However, continuing to slow the process resulted in a deterioration of performance to the point that it was the same as that achieved under the control of the fastest process. Anticipative strategies, then, are seen as useful for dealing with many tactical details until the point is reached that the really strategic aspects of the situation are neglected. These strategies are, moreover, well beyond the participants' competences in the microworld, as demonstrated by the increase in the rate of knowledge errors (KBB) as opposed to skill errors (SBB) (see Reason, 1990, for this distinction).

Metacognitive Control

Metacognition is a central cognitive element of the processes of adaptation and control. This element is embedded in the operator's own history, in the construction of his/her knowledge, and as such does not appear in the observable activity. However, past failures and successes are powerful markers of the controllable field of adaptation. Metacognition primarily intervenes in risk management and adaptation by means of two dominant modalities in the service of situation mastery. The first one avoids, as much as possible, all situations that have the potential to exceed the operators' coping strategies and know-how. The second one is the forecasting and shaping of future conditions of interactions, which thus creates room to tailor the future situation to fit the action repertories that the operators think they are able to successfully exhibit.

Several examples from the study of fighter pilots illustrate these two methods. One such study compared the strategies used by young pilots and expert pilots to complete a reconnaissance mission (Amalberti & Deblon, 1992). The results showed that the young pilots were chronically overwhelmed by the complexity of mission preparation work and therefore were likely to be late for takeoff. In order to avoid this potential risk, and aware of their own inability to authorize a takeoff in time, the young pilots elaborated flight plans that were different from those created by the expert pilots. In their plans, they integrated a long detour in the first leg of the flight when flying over friendly territory and before crossing the line (something like a half loop). This enabled them to cross in the half loop if they were late at takeoff and recover up to 5 minutes before entry into enemy territory.

In another study on fighter pilots, Valot (2002) showed that the margins of adjustment that were accepted and used by pilots varied in direct correlation with the control of the repertoire of responses. He showed that the fighter pilots made numerous online micro-replannings to avoid situations in which they were likely to be confronted with uncertain know-how. Pilots are accustomed to accepting some apparently complex situations without reluctance (from an outside viewpoint) when they have made a satisfactory anticipation and have set up a prepared response that is compatible with their knowledge.

Metacognition is an important variable in successful situation mastery. The criteria imposed by an operator on an objective (i.e., the original contract between the operator and the company) influence all the supervision procedures and represent the first input used to fine-tune the accepted risk level for execution. Fine-tuning the performance contract is highly dependent on metacognition (Valot & Amalberti, 1992).

Given these very dynamic characteristics, situation mastery can be expressed through some practical paradoxes, well known since Dörner (1980) and revalidated by recent research.

The feeling that the situation is mastered is often linked to imperfect performance at that moment in time but is associated with the awareness that there is at least one solution available (and, if possible, an alternative) to reach the objective through either personal or collective know-how. However, there is awareness of what "remains to be done" that helps the operator to allocate cognitive priorities. This awareness often explains any drifting away from the pattern, whose sole purpose is often only to provide more time to catch up on actions that have been postponed. The anticipation can be false, however, if the mental model of the situation is inaccurate. In this case the feeling of situation mastery is fallacious, as shown previously in a firefighting microworld (Hoc et al., 2000).

Paradoxically, when operators lose the feeling that the situation is mastered, they quickly experience cognitive overload, which results in a reduction of so-called behavioral waste. Operators make fewer errors; the solution thought nominally to be the most effective is sought; parallel activities are reduced (especially private activities); and operators make a concerted effort to look for an alternative solution.

When mastery is totally lost, operators often escape into a better-known subset of the problem at hand, where no errors can be made. The rest of the situation and its final outcome are then left to collective action or to automation.

We have already pointed out the prominent role of metacognition in the adjustment of the cognitive compromise. Cognitive control (*stricto sensu*) and metacognitive control have different purposes. Cognitive control manages the execution of cognitive activity. Metacognitive control manages the choice of this activity. If one accepts the distinction made by Piaget (1974a) between simple abstraction and reflective abstraction, which is largely used in the modeling of dynamic situation management (Hoc, 1996), then the level of metacognitive control is partially correlated with the level of abstraction. It casts into relief the metacognitive data concerned with knowledge of one's own operation. However, the question of knowing whether the metaknowledge is exclusively symbolic or if it can also be subsymbolic remains open (Valot & Amalberti, 1992). Norros' concept (2005) of "habit of action," which denotes a generic property of a personal behavior exemplified by two types of high-level strategies in anesthesia, may remain unconscious or, conversely, may intervene in a reflective way in order to control the activity explicitly.

Thus, we will consider three dimensions for cognitive control (in a broad sense): abstraction level, origin of data, and cognitive or metacognitive control. Crossing these dimensions will generate several cognitive control modes with specific properties, which can be developed in parallel in order to ensure adaptation. Transition between the modes can reflect the development of expertise or the improvement/deterioration of adaptation.

Cognitive Control Modes

Crossing the Dimensions

There are a variety of models of cognitive control, most of which are unidimensional. Their dimensions can be diverse. The question is not to find the only dimension that is relevant and discard the others. As we have mentioned previously, each dimension stresses a particular aspect of cognitive control that is obviously relevant with a certain objective in mind. For example, Trick et al. (2004) proposed the dimension *exogenous/endogenous,* which is very relevant when studying learning because this dimension concerns the genesis of cognitive control. We prefer the dimension *internal/external* (origin of the data needed for the control) because we are mainly interested in the mechanisms of cognitive control at a particular moment. If some dimensions present some partial correlations, as previously mentioned, then the two dimensions we have selected appear to be orthogonal. For this reason, it is justifiable to cross them in order to generate several cognitive control modes.

Trick et al. (2004) implemented the same idea, but with a different dimension. Within the context of vehicle driving, they crossed the two-dimension automated/controlled and exogenous/endogenous processes and generated four control modes:

- Automated exogenous: reflex (basic affordances)
- Automated endogenous: habit (expert affordances)
- Controlled exogenous: exploration (unfamiliar task)
- Controlled endogenous: deliberation (familiar task)

However, within this classification, the actual mechanism of cognitive control can be similar from one class to another. For example, the mechanism can be the same for the two first classes, although the robustness of the first one can be higher than that of the second.

Our vision of the diverse control mechanisms model (Figure 1) led us to cross the level of abstraction of the data implied in the control (symbolic or subsymbolic) with the origin of these data (internal or external) and to integrate metacognitive control. Four control modalities are considered, crossing the first two dimensions with the intervention of metacognition as a third dimension.

- The *symbolic* control level can rely on *external* data; for example, following written instructions in problem-solving situations such as the first use of a new device. It is very costly in terms of symbolic attention.

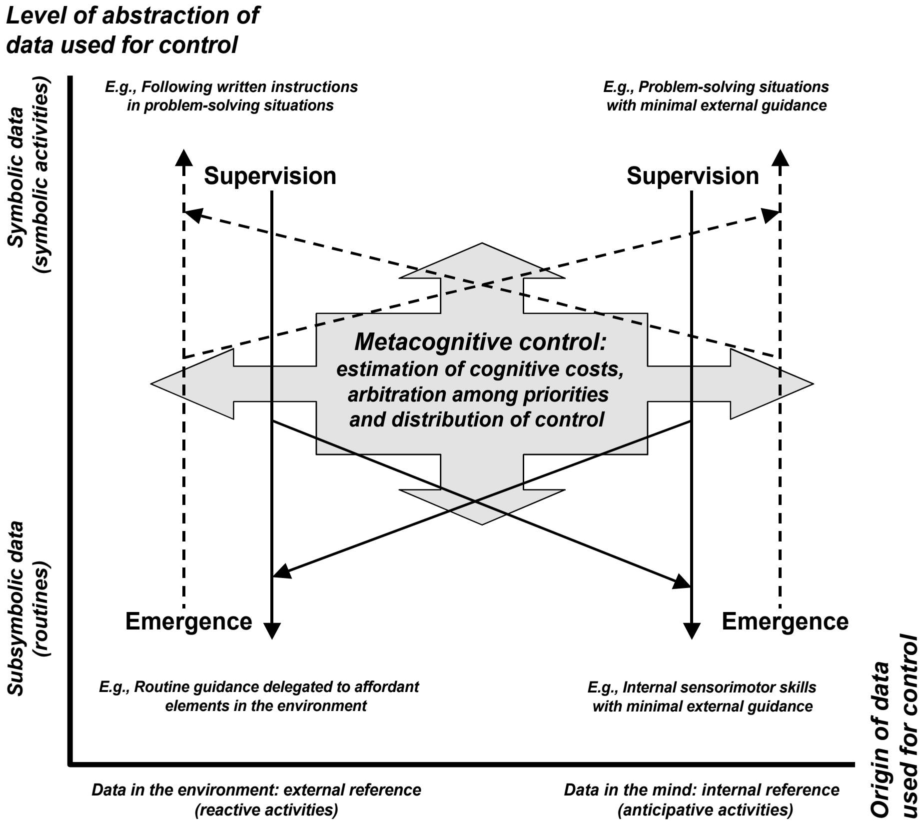

Figure 1. Cognitive face of the model of dynamic situation control. This face of the model emphasizes the roles and interrelations of the four main control modes (crossing the two dimensions, symbolic vs. subsymbolic control, and external vs. internal control). Metacognitive control distributes the cognitive control of a particular activity among the control modes in order to optimize cognitive compromise.

- The *symbolic* control can also rely on *internal* data – mental representations and intentions. Again, it is costly, although avoiding a search through external data can result in resource saving. However, when the needed search is limited, external guidance can cost less than internal guidance. An example could be the routinized demonstration of a theorem when the method is well known.
- The *subsymbolic* control level can rely on *external* data when it is mainly guided by (basic or expert) affordances situated in the environment. If the environment is badly structured, this type of control can appear scrambled (using Hollnagel's term, 1993). In vehicle driving, the risk of an accident is greatly reduced by an improvement in the perceptive "readability" of the road; for example, by means of white strips on the sides of the road.
- *Subsymbolic* control can also rely on *internal* data; for example, sensorimotor

skills with minimal external guidance, such as serving in tennis. This control mode is the least expensive.

Metacognitive control arbitrates between the four preceding modes, managing the costs (of cognitive activities) at an acceptable level for a satisficing performance, especially in relation to the management of parallel activities and tasks. Some symbolic activities are temporarily inhibited (the ones needing complex and lengthy cognitive reasoning, or regarding unrelated task problems) depending on the evaluation of cognitive costs and ongoing priorities. This arbitration may or may not be symbolic and can require either more or fewer resources.

For example, in traffic, most drivers usually spend their symbolic resources on private activities or anticipations based on subsymbolic control that is anchored in external data (signals, visual flow, etc.). However, drivers can reverse priorities any time the situation brings the control into question. For example, a driver who is surprised by a hard turn (a) will immediately discontinue any private activities (e.g., a discussion inside the car, which is typical of subsymbolic control of driving based on external data), (b) quickly reverse to an internal representation on the feasibility of the maneuver while (c) mobilizing sensorimotor skills to remain on the road (subsymbolic control that is based on internal data). The level of personal trust afforded by rapid access to the adequate repertoire of knowledge (symbolic control on internal data) and the feedback on the adequacy of the intended maneuver will rapidly feed a global level of confidence of the controllability and good result of this maneuver. This will feed a positive metaknowledge assessment well before the end of the maneuver and then permit immediate reversion to the discussion.

In other circumstances, the problem is the reverse. The driver will spontaneously concentrate on the erratic traffic and difficult road, adopting symbolic control on internal data (respecting low speed and careful driving on the right lane), but the cognitive urgency may appear to be using a mobile phone to call someone about for a job problem. In that typically conflicting case, as fighter pilots are likely to do (Amalberti & Deblon, 1992), most drivers will probably choose to timeshare the type of controls for a limited period. They reverse from one type of control to another on the basis of successive estimates of acceptable level of trust. These acceptable levels of trust may sometimes be perceived as unachievable, leading the operator to make strong decisions like stopping the car in order to make a phone call.

Parallelism between the Modes

Originally limited to automated processes, research on attention and dissociation, the conception of a parallelism between several cognitive activities, was recently introduced into the core of one of the best-known cognitive models: ACT-R (Anderson, Bothell, & Byrne, 2004). Researchers frequently underestimate the number of tasks that are performed by the human operator at any one time, including work-related tasks and private tasks (or thoughts). The term *parallelism* will be used here in its weak form to include strict parallelism (e.g., between sensorimotor tasks performed under separate nervous control centers) and time-sharing (e.g., between tasks that cannot be performed in strict parallelism), which is similar to parallelism at a certain level of granularity. Such a parallelism implies the management of priorities and interruptions so that the workload is maintained at an appropriate level in order to obtain responses at the appropriate time and to preserve a real priority for immediate control. A significant part of the know-how needed for this control consists in managing a number of parallel activities. Often, one's fight against time limits the opening of new activities or closes them before they are completed.

It is worth noting that this parallelism between tasks is nevertheless desirable, depending on the operator's decision and motivation. Conversely, it is regarded as a potential risk when it is imposed by the situation. In the results presented next, we show two ways of remaining in control when there is too great a parallelism.

The observations previously reported on blast furnace control (Samurçay & Hoc, 1996) were in agreement with the parallel operation of two of the levels of control defined by Rasmussen: the control level based on declarative knowledge (KBB: elaboration of a representation of internal phenomena) and the control level based on rules (RBB: triggered by the observable parameters within the context of this representation). They are consistent with the results obtained by Roth (1997) in a nuclear power plant. Roth found that operators who were considered to be spending their time applying procedures actually carried out only a limited number of diagnoses in parallel to make sure that the current situation was always that which was the justification for starting that particular procedure. In the same way, parallelism between a planned activity and the resolution of unexpected problems was underlined in anesthesia (Gaba, 1994).

The pilot manages several objectives simultaneously, but the completion of those objectives is carried out through time-sharing. When workload increases, the number of managed tasks falls and the fractionation of these tasks also decreases (the time spent on each task before reverting to another lengthens in this condition). Conversely, when workload decreases, fractionation increases. A detailed analysis of flights (Amalberti, 2001) indicated that those tasks with a short execution time (less than 30 s) were carried out in one attempt in almost all cases. On the other hand, tasks lasting several minutes were stopped and restarted on at least one occasion.

Postmission debriefings make it possible to gain a better understanding of the strategy of risk management. This strategy relies on the knowledge and use of the latencies of events in the most essential tasks. This heuristic of less risk was observed by analyzing the nature of the inserted tasks and confirmed by questioning the pilots. It consists in carrying out short but complete tasks during these waiting times. These tasks are defined to fit into the supposed waiting time. The pilot can hope to finish them as a block during this time. This heuristic makes it possible to minimize the number of tasks that remain unfinished.

The parallelism between distinct control modes is also illustrated by a previously cited study on air traffic control (Morineau et al., 2003). The experimenters asked controllers to manage a session of simulated traffic. The simulation was frozen every 2 min and the operators were invited to report their main concerns as they would during a work shift. The controllers were told to draw on a chart the position of the aircraft about which they were speaking. During the rest of the time, the controllers worked as usual, spontaneously dialoguing with their colleagues. When the simulation was frozen, strong marks of anticipation were evident. The aircraft were drawn in advance of their positions, and the conflicts were represented as being more serious and urgent than was actually the case. Contrary to the type of results described previously and those obtained during a work shift, the activity during online control appeared to be highly synchronized with events. Although minimal data for the identification of a problem were present on the interface more than 2 min before the presence of the conflicting aircraft on the radarscope, this identification (verbal report of the problem) was contemporaneous with the presence of the two aircraft on the radarscope. Also, although the partial availability of the control (at least one of the aircraft in radio contact) was satisfied more than 3 min before radio contact with all other aircraft concerned by the conflict, the first resolution decision occurred approximately 30 s after the full availability. The affordances of the environment (significant traffic events) probably played a major role in this synchronization. It is likely that the late implementation of routines for conflict resolution corresponded to a minimal commitment strategy within the framework of an anticipated analysis of the problem space structure.

Note that the various control modes can supply one another by providing alternative data. For example, when a routine cannot feed data into the field (because of poor access or readability), the symbolic level can supply them for a limited time with data originating from mental models. Although they can act in parallel, the control modes do not operate independently. Two complementary processes are brought into play so that the modes can derive benefit from each other.

- Supervision is a means of calibrating the routine operations to fulfill superordinate goals. It plays an important role in error management, given that passing control entirely to routines can result in large deviations from the original intentions (Reason, 1990).
- Emergence enables routines to return feedback to symbolic activities. In this way, symbolic control can be active when necessary. It can send new set points to be satisfied by routines or can replace routines in the control of the activity when the situation requires it.

Transitions from One Mode to Another

When expertise increases by learning and activity routinization in order to respond to temporal constraints and an increase in the number of parallel tasks, the distribution of control is facilitated by two complementary mechanisms (Figure 2):

- Routinization enables the expert to perform more and more activities without symbolic control, although symbolic supervision is always necessary (Anderson, 1985; Anderson et al., 2004). This alleviates the workload of the symbolic control mode and enables more sophisticated supervision and the processing of more tasks at the same time.

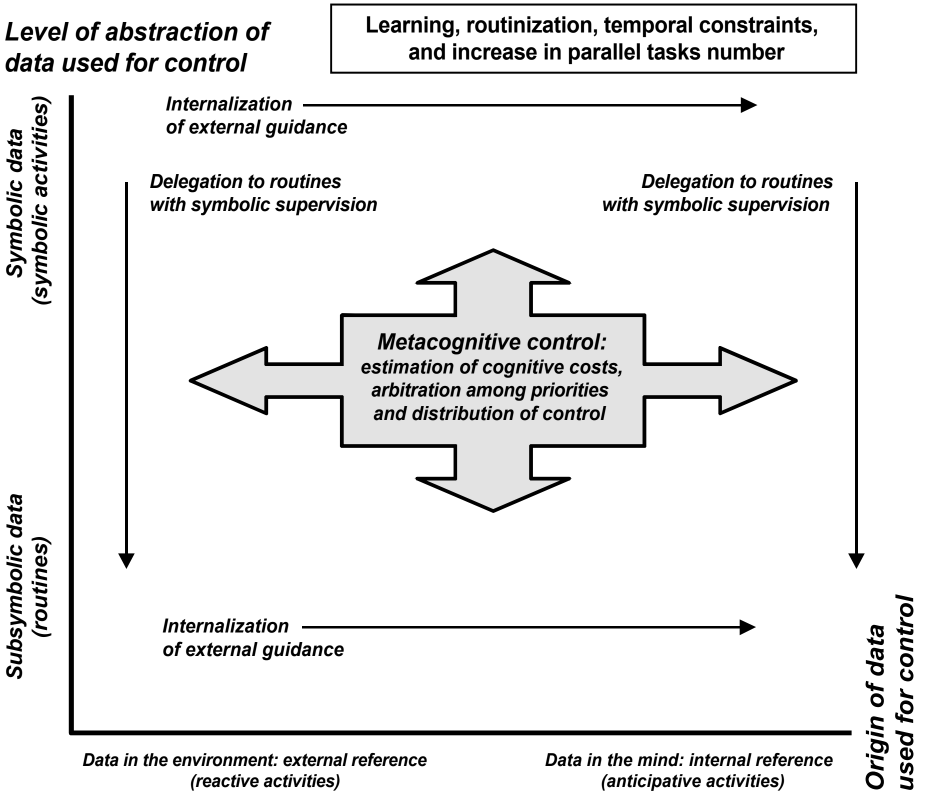

Figure 2. Effects of expertise on cognitive control.

- The availability of internal representations enables the cognitive system to operate with less external data gathered from the environment. This process can alleviate workload when a search for information is costly or can smooth its movements. However, when the search cost is very low and smoothing unnecessary, the use of external data by the control may be preferable. Expertise plays an important role in data filtering and affordance creation (Norman, 1988).

Work on routines has gradually been removed from the debate on controlled processes/automatic processes and the explanation related to a limited reserve of available resources. Some of the work on attention is gradually being reoriented toward the field of learning and expertise acquisition. The role of practice and repetition in sensorimotor skill acquisition is well known. Logan (1988) reconsidered the theories accounting for automatic processes by refuting them and proposing an alternative explanation of the current results by the properties of storage in and access to the memory of routine knowledge.

Since the 1980s, this idea was extended to the process of expertise acquisition (Anderson, 1985; Rasmussen, 1986). Expertise acquisition concerns the transformation of declarative knowledge into procedural knowledge. It starts from an execution that is completely under symbolic control and then goes step by step until an execution fully delegated to the routines, with possible supervision. At the beginning of skill acquisition or in a difficult situation (e.g., walking on a wire), symbolic control can precede or replace subsymbolic or routine control. Then, when this last kind of control is possible, symbolic control can remain in charge of supervision.

Error Management

A standard method of observation consists in comparing and then judging an operator's observed performance step by step with a zero error ideal reference procedure in mind. The validation of adaptation must relate rather to the global tactical and strategic management of errors and the final acceptability of the result compared with usual standards. The method employed to analyze the subject's activity must consequently change, in particular by controlling the granularity of analysis, and avoid falling into the trap of an overinterpretation of too many local situations. The operator's incomplete comprehension of the situation is a recurring result in field studies. Not all explanations place blame on the operators, despite the fact that these explanations are sometimes related to poor situation awareness. Some explanations are more ecological. For example, a series of studies converge to show that if operators have the choice, they prefer to act rather than to understand, because the action helps comprehension (for example, Piaget, 1974b; Reason, 1990; Rasmussen & Rouse, 1981). In other cases, cognition appears to be restrained (compared with the comprehension level that the subject could access and exhibit in a nondemanding situation) and the error rate may increase (excessive schematization of the world, excessive attraction by nonrelevant external affordances).

Several experiments in aeronautics have shown that pilots who are exposed to breakdowns seek neither the cause of the problem nor the very nature of the problem when the failure-support assistance system fails to provide a report. They give priority to the search for and maintenance of at least one valid procedural solution that is compatible with a tractable objective. The concept of valid solution relies on both the fact that, first, pilots can estimate the extent of what is still working in the system (trust condition) and, second, that the candidate solution remains compatible with their know-how and demands an acceptable workload level for the rest of the flight (metacognitive evaluation). It is only when there is no solution, or if the solution is too difficult for them, that the pilots invest in a more extensive problem-solving activity (Plat & Amalberti, 2000).

A study carried out with TRACON (an air traffic control microworld) involving professional controllers as well as experimental subjects trained on the game showed that the control of error is only one variable among the many used in the successful control of a situation (Wioland & Amalberti, 1996). With the exception of absolute beginners, the subjects produced a constant flow of error, whatever their level of expertise. Paradoxically, the error rate tended to drop in the most demanding situations (reinforced cognitive control), but in this last case, the rate of detection also tended to break down (lack of resources).

The risk of loss of control is much more closely correlated with the decrease in the error detection rate than with the increase in the error rate. The expert subjects let pass more and more errors that were inconsequential for the work in progress (72% of the controllers' unrecovered errors were without consequences, whereas only 13% of the beginners' unrecovered errors were of this kind). Similar figures can be found in the results presented in several recent studies. For example, Helmreich, Klinect, Wilhelm, and Sexton (2001) placed observers systematically aboard airliners to monitor crews' errors (as measured by LOSA, or Line-Oriented Safety Audits). They observed an average rate of two errors per flight over a series of 3,500 flights. An impressive 57% of errors that were inconsequential for the flight, and which, for the most part, remained unrecovered.

Metacognitive activities are at the core of adaptation in error management. The more the experience, the better the feeling that either the actions that are recognized as being carried out incorrectly or the noncompliance with protocols are acceptable. One reason is that the experts know the true effect of these errors. Many expected consequences of the action failure are unimportant in an absolute or relative sense. Another reason is that operators also know they have ample room for recovery (Amalberti et al., in press).

The role of metacognition in error management is not solely to accept the occurrence of repetitive minor errors and disobediences that are supposedly inconsequential for the task achievement, but also, during task completion, to optimize the recovery of these "accepted" errors and disobediences. In this way, the global strategy of control is maintained at a lower cost for best efficiency.

This is typically what we do when writing a first draft of a paper on a computer. It is not a good strategy to avoid all spelling mistakes and look for the perfect syntax while the principal problem is to select or organize ideas. Such an error-free strategy could considerably slow the writing process and, even more seriously, suppress the capture of ideas by moving the cognitive control to the wrong targets. It may not even be efficient to take the time to correct all grammatical problems at the end of the first draft if the ideas to be communicated have yet to be stabilized. Again, the best cognitive compromise may suggest postponing error correction until much later in the process of writing the paper.

In a study carried out under the emergency medical telephone regulations of Paris's Central Hospitals, Marc and Amalberti (2002) showed the contribution of individuals to group safety. The regular team included telephone operators and physicians. Their goal was to provide assistance to patients who called regarding medical problems. The coding scheme (verbal protocols and context observation) described the safety-related events in relation to the context, the group activity, and the situation control mode. Results showed that most safety-related events were not dedicated to the detection and recovery of errors but merely to alerting and preventive actions in order to increase group awareness about the loss of control of situations.

This type of result is not unique and echoes a growing body of literature on teamwork (see, for example, Hoc, 2001; Salas, Prince, Baker, & Shrestha, 1995).

Implications and Conclusions

Theoretical Implications

The results in this paper show that many questions remain unanswered when one admits that adaptation is critically dependent upon the satisfactory adjustment of a cognitive compromise, thanks to a distribution of cognitive control among various modes. If one temporarily excludes the question of attention, two orthogonal dimensions must be crossed: the level of abstraction and the origin of the data used for control. The viewpoint presented in this paper points out more directly the theoretical and methodological research problems that remain to be resolved in order to understand and assist operators with the appropriate modes. Three research questions need to be considered. First, comprehension of the mechanisms of voluntary inhibition of cognition for reasons of control of the cognitive cost, and more generally, comprehension of the cognitive compromise adjustment is required. Although the influence of situation requirements and the subject's expertise are reasonably integrated into the present models of cognitive control, we must acknowledge that we do not sufficiently consider the emotional stage of the situation and the subject, and that we still have great difficulty in modeling the potential high speed of reversion or parallelism from one type of control to another. We continue to explain too much of the subject's behavior by external rational factors (work demand, goal changes, and supposed subject's knowledge), and we chronically fail to give enough consideration to the inner competitive and continuous cognitive focus on personal (private or emotional) affairs that so often explain bizarre arbitrations.

Second, if this mechanism of arbitration and inhibition is a prerequisite for keeping the feeling of control at the right level, it could then bring into question those theories that consider the limitation of analysis (bounded rationality) as a bias. This would lead to the design of assistance for better awareness and better comprehension and disregard the cost for cognition, with its associated risk of making the human operator just a follower of an artificial agent.

Third, the normative approaches (to permanently bringing back the operators on an ideal calculated model) leave room for more pragmatic approaches. The results presented in this paper encourage us to go one step further in the design of ecological assistance in order finally to give less support to symbolic activities and more to natural control mechanisms, not necessarily of a symbolic kind. In particular, they support the development and controllability of the routines on a level that is safe for the process and sufficient for performance.

The multiprocessor approach to human cognition – with parallelism and flexible distribution of control in relation to situation mastery, adaptation, and satisficing performance – is becoming accepted in the literature. It is questioning a rigid approach of cognitive control, which cannot be restricted to a particular mode beyond a certain period. In this paper, we tried to show that a multidimensional conception of cognitive control is also necessary. Although some dimensions that are currently found in the literature are correlated, others are orthogonal, such as those we selected. We think that the abstraction and the origin of the data necessary for control are two main dimensions to cross in order to generate several control modes. Beyond their theoretical importance, they can also be directly translated into terms of a human-machine (or human-work) interface.

This approach stresses the fact that there are many degrees of freedom in the cognitive system. Several solutions are possible in order to do the same task and to reach a satisficing performance. One of the main challenges for those studying cognitive control is to give more consideration to the processes that underlie the dynamic reconfiguration of the cognitive system, based on the degrees of freedom. This implies a need to avoid an approach that focuses strictly on the symbolic level. It is absolutely necessary to introduce metacognition in order to explain the adjustment of cognitive control.

Methodological Implications

The theoretical stakes developed in this paper have their corresponding methodological stakes. However seductive the theory, even if there is some sound empirical evidence to support it, without reliable methods it would be very difficult to make progress in this promising direction. Cognitive ergonomics has long been devoted to the study of symbolic processes. Verbal reports analysis methods have been very refined because they constitute direct access to symbolic information processing. However, when subsymbolic processes are considered, these methods are not suitable. Psychology is used to approach these processes by relying more on behavioral methods. The risk is the generation of models of observable behavior rather than of models of the underlying activities. In addition, it could be very difficult to access symbolic supervision and control processes.

A potential approach to accessing the multiple aspects of cognitive control is to adopt a two-tier strategy of analysis. The first tier consists in grasping behavioral markers that permit one to identify the network of parallel tasks to be achieved at each stage of progression. Two types of markers may be accessible.

A first family of markers, along the continuum between external and internal control, focuses on the temporal horizon for the control. The removal from the environment of information assumed to be necessary for control is a good way to identify the anticipation temporal horizon. This has been done, for example, in a vehicle-driving study that focused on identifying the role of certain areas of the visual field in anticipation and in online control of the trajectory (Land & Horwood, 1995). By specifically masking some of these areas, the effects on driving can be characterized at either the level of anticipation or the level of online control.

A second family of markers relates to the parallelism between symbolic and subsymbolic activities. As stated previously, this parallelism includes strategic or tactical task-sharing between goals at the conscious level (allocating time and priorities to each of these goals), as true massive parallelism of routinized tasks. But even these routinized tasks need recurrent emerging controls at the conscious level when the individual is facing problems of completion or when ending and asking for the next program or routine. These emergences are resource consuming. They slow the course of action, producing interruptions or disturbances in task-sharing at the strategic or tactical level and then becoming accessible to fine observation. Such access to emergences requires a combination of spontaneous traces of activity, including verbal reports and careful subject monitoring using videos and chronometric analysis (see Noizet & Amalberti, 2000). Eye movement analysis can be a source of complementary data for that purpose, although the mind does not always perceive what the eye sees.

Once this network is reasonably accessible to the observer, the second tier of the analysis must focus on the arbitrations and prioritizations the subject makes between these multiple tasks in order to remain under global control of the situation and attain her/his objectives. Such a reconstruction is based on a model of activity aided by video confrontations and interviews with the subject. However, the analyst must be reasonably knowledgeable in the work domain or ask for assistance from peers. Task decomposition is another useful means to help to access the model of activity. For example, this was done in an air traffic control study (Hoc & Debernard, 2002).

Another factor that limits progress in this direction is the lack of (and therefore the need for) multidisciplinary teams to address the question and set up ad hoc protocols. These would include a mix of cognitive, clinical, and psychosensory specialists in psychology as well as computer scientists. Neurosciences – especially imagery or electrical activity – could also be invaluable for grasping and typifying competitive cognitive activities. No such multidisciplinary teams exist. The inconvenience of a long time spent on these protocols for an uncertain publication result is only one of the many reasons why teams are unavailable.

In addition, we need to adopt a longitudinal approach to gain access to cognitive control dynamics and the intervention of metacognition. The important role of the criteria used by the human operator to determine what a satisficing performance is implies the continuous evaluation of these criteria.

Practical Implications

Our approach may orient the design of assistance, easing the cognitive control of situations. Until now, we have exploited two main principles, derived from this theoretical approach, while contributing to the development of operator assistance.

First, this approach can aid in the design of assistants that prevent the human operator from having to systematically return to symbolic control while engaged in routine control. An example is a so-called natural decision support system for fighter pilots (pilot's assistant or electronic copilot; see Amalberti & Deblon, 1992). In-service experience has shown that in numerous cases, use of sophisticated assistants has not produced the expected result, confusing instead of aiding the pilot in critical situations. The electronic copilot was therefore primarily designed to reduce the cost of dramatically changing and raising the level of abstraction during the occurrence of unexpected events. The basic strategy was to support and optimize the strategy of the pilot, instead of proposing alternatives that required a deep reevaluation of the representation. Moreover, when the situation was time critical, the assistant was supportive of pilots' reactive strategies, focusing on survival rather than explaining, and thus postponing the making of suggestions. Despite the apparent suboptimality of the advice, evaluation of the mockup of the aid provided by the electronic copilot has been proven to be as efficient as the most advanced decision support system and planners (Amalberti & Champigneux, 1990). What was lost in the accuracy of the decision, plan, and reaction was saved in the absence of hesitation, in the speed of reaction time, and in the increased feeling of control and associated trust.

Within the context of driving a vehicle, we have known for years that the average speed of drivers varies with the sophistication level of the car. The better the chassis and engine, the greater is the speed. Technology drives the metacognitive control to accept higher performance for the same value of risk. In doing so, all the systems, specifically the routines, move to higher spontaneous performance. One way to limit the performance of these new high-tech cars is perhaps to induce a transitory artificial feeling of unstable control before maximum speed is reached and then produce a metacognitive signal that limits the engagement of routines. This is exactly what is being tested; signals that are aimed at evoking in the driver a sense of unease, based either on a haptic modality (on the steering wheel) or a moving seat that amplifies the feeling of acceleration in turns.

Within the same context of in-vehicle driving assistance, devices are being designed that promote subsymbolic communication between the human and the machine in order to improve routine operations (Hoc & Blosseville, 2003).

Second, the approach we describe in this paper could contribute to the design of human-machine cooperation so that the machine operation is integrated into the human cognitive control architecture.

In a research program aimed at designing and evaluating an automatic device for aircraft conflict resolution to alleviate air traffic controller's workload during peak periods, we validated a principle of function delegation from the human controller to the machine against a principle of task allocation between the human controller and the machine (Hoc & Debernard, 2002). The first principle assumes that the human controller defines the task and uses the machine as a device to perform functions within the framework of the task. The second principle assumes that the machine defines several tasks that an agent (machine or human) allocates to the human controller or the machine. In the second case, cognitive control is more difficult because the task decomposition performed by the agent is not necessarily the same as that performed by the human controller. This produces negative interference and is likely to lead to the well-known complacency phenomenon, which results in a lack of supervision of the machine by the human and in a rigid separation between the human's and the machine's fields of operation.

In summary, the main practical implication of this approach is to open the degrees of freedom, in terms of cognitive control distribution among the modes, in order to improve adaptation. However, operator assistance should be designed to maintain coherence, especially by intervening at the level of the criteria used by the human operator for evaluating a satisficing performance. This implication is especially well satisfied by the design method precisely formulated by Vicente (1999).

References

Amalberti, R. (2001). *La conduite de systèmes à risques* [Controlling risky systems]. Paris: Presses Universitaires de France. (First published 1996)

Amalberti, R., & Champigneux, G. (1990). *Man-machine coupling: The key for electronic copilot architecture.* Paper presented at the *NATO Conference: The human electronic crew: Is the team maturing?* Ingolstadt, Germany.

Amalberti, R., & Deblon, F. (1992). Cognitive modelling of fighter aircraft's control process: A step towards intelligent onboard assistance system. *International Journal of Man-Machine Studies, 36,* 639–671.

Amalberti, R., Vincent, C., Auroy, Y., & de Saint Maurice, G. (in press). Framework models of migrations and violations: A consumer guide. *Quality and Safety in Healthcare*.

Anderson, J. (1985). *Cognitive psychology and its implications*. New York: Freeman.

Anderson, J. R., Bothell, D., & Byrne, M. D. (2004). An integrated theory of the mind. *Psychological Review, 111*, 1036–1060.

Bainbridge, L. (1978). The process controller. In W. T. Singleton (Ed.), *The study of real skills, Vol. 1: The analysis of practical skills* (pp. 236–263). St. Leonardgate, UK: MTP.

Bedny, G. (2004). Activity theory [Special issue]. *Theoretical Issues in Ergonomics Science, 5*(4).

Berry, D. C., & Broadbent, D. E. (1984). On the relationship between task performance and associated verbalizable knowledge. *Quarterly Journal of Experimental Psychology*, *36A,* 209–231.

Berry, D. C., & Broadbent, D. E. (1995). Implicit learning in the control of complex systems. In P. Frensch & J. Funke (Eds.), *Complex problem-solving: The European perspective* (pp. 131–150). Hillsdale, NJ: Erlbaum.

Cellier, J. M., Eyrolle, H., & Mariné, C. (1997). Expertise in dynamic environments. *Ergonomics, 40*, 28–50.

Damasio, D. (1994). *Descartes' error.* New York: Avon Books.

Dörner, D. (1980). On the difficulties people have in dealing with difficulty. *Simulation & Games, 11*, 87–106.

Falzon, P. (1994). Les activités méta-fonctionnelles et leur assistance [Metafunctional activities and their assistance]. *Le Travail Humain, 57,* 1–23.

Fernandez-Duque, D., & Johnson, M. L. (1999). Attention metaphors: How metaphors guide the cognitive psychology of attention. *Cognitive Science, 23,* 83–116.

Flavell, J., & Wellman, H. (1977). Metamemory. In J. Kail & C. Hagen (Eds.), *Perpectives on the development of memory and cognition* (pp. 3–34). New York: Wiley.

Fraser, J. M., Smith, P. J., & Smith, Jr., J. W. (1992). A catalog of errors. *International Journal of Man-Machine Studies, 37,* 265–307.

Gaba, D. M. (1994). Human error in dynamic medical domains. In M. S. Bogner (Ed.), *Human error in medicine* (pp. 197–224). Hillsdale, NJ: Erlbaum.

Gibson, J. (1979). *The ecological approach to visual perception*. Boston: Houghton-Mifflin.

Helmreich, R., Klinect, J. R., Wilhelm, J. A., & Sexton, J. B. (2001, March). *The Line Operations Safety Audit (LOSA)*. Paper presented at the first LOSA week. Cathay Pacific, Hong Kong.

Hirst, W., Spelke, E., Reaves, C., Caharack, G., & Neisser, U. (1980). Dividing attention without alternation or automaticity. *Journal of Experimental Psychology: General, 109*, 98–117.

Hoc, J. M. (1988). *Cognitive psychology of planning*. London: Academic Press.

Hoc, J. M. (1989). Strategies in controlling a continuous process with long response latencies: Needs for computer support to diagnosis. *International Journal of Man-Machine Studies, 30,* 47–67.

Hoc, J. M. (1996). *Supervision et contrôle de processus: la cognition en situation dynamique* [Process supervision and control: Cognition in dynamic situation]. Grenoble, France: Presses Universitaires de Grenoble.

Hoc, J. M. (2001). Towards a cognitive approach to human-machine cooperation in dynamic situations. *International Journal of Human-Computer Studies, 54,* 509–540.

Hoc, J. M., & Amalberti, R. (1995). Diagnosis and decision making, some theoretical questions raised by applied researches. *Current Psychology of Cognition, 14*, 73–101.

Hoc, J. M., Amalberti, R., & Plee, G. (2000). Vitesse du processus et temps partagé, planification et concurrence attentionnelle [Process speed and time sharing, planning, and attentional concurrence]. *L'Année Psychologique, 100*, 629–660.

Hoc, J. M., & Blosseville, J. M. (2003). Cooperation between drivers and in-car automatic driving assistance. In G. C. van der Veer & J. F. Hoorn (Eds.), *Proceedings of CSAPC'03* (pp. 17–22). Rocquencourt, France: EACE.

Hoc, J. M., & Debernard, S. (2002). Respective demands of task and function allocation on human-machine co-operation design: A psychological approach. *Connection Science, 14,* 283–295.

Hoc, J. M., & Moulin, L. (1994). Rapidité du processus contrôlé et planification dans un micromonde dynamique [Controlled-process speed and planning in a dynamic micro-world]. *L'Année Psychologique, 94*, 521–551.

Hollnagel, E. (1993). *Human reliability analysis: Context and control.* London: Academic Press.

Hollnagel, E. (2002). Time and time again. *Theoretical Issues in Ergonomics Science, 3*, 143–158.

Hollnagel, E. (2005). Extended control model (ECOM). *http://www.ida.liu.se/~eriho/ECOM_M.htm*. Accessed March 16, 2007.

Hollnagel, E., Mancini, G., & Woods, D. D. (Eds.). (1986). *Intelligent decision support in process environments.* Heidelberg, Germany: Springer-Verlag.

Hollnagel, E., Woods, W., & Levison, N. (2006). *Resilience engineering: Concepts and precepts*. Aldershot, UK: Ashgate.

Houdé, O., Zago, L., Crivello, F., Moutier, S., Pineau, A., Mazoyer, B., & Tzourio-Mazoyer, N. (2001). Access to deductive logic depends on a right ventromedial prefrontal area devoted to emotion and feeling: Evidence from a training paradigm. *NeuroImage, 14*, 1486–1492.

Kahneman, D. (1973). *Attention and effort*. Hillsdale, NJ: Prentice Hall.

Kirsner, K., Speelman, C., Maybery, M., O'Brien-Malone, A., Anderson, M., & MacLeod, C. (Eds.). (1998). *Implicit and explicit mental processes.* Mahwah, NJ: Erlbaum.

Klein, G. A., Orasanu, J., Calderwood, R., & Zsambok, C. E. (1993). *Decision making in action: Models and methods.* Norwood, NJ: Ablex.

Laberge, D. (1973). Attention and the measurement of perceptual learning. *Memory and Cognition, 1*, 268–276.

Land, M. F., & Horwood, J. (1995). Which parts of the road guide steering? *Nature, 377*, 339–340.

Lazarus, R. S. (1966). *Psychological stress and the coping process.* New York: McGraw-Hill.

Logan, G. (1988). Toward an instance theory of automatization. *Psychological Review, 95*, 492–527.

Long, J. (1996). Specifying relations between research and the design of human-computer interaction. *International Journal of Human-Computer Studies, 44,* 875–920.

Løvborg, L., & Brehmer, B. (1991). *NEWFIRE – A flexible system for running simulated fire-fighting experiments* (Report No. RISØ-M-2953). Roskilde, Denmark: RISØ National Laboratory.

Marc, J., & Amalberti, R. (2002). Contribution de l'individu au fonctionnement sûr du collectif: L'exemple de la régulation du SAMU [Contribution of the individual to team safe operation]. *Le Travail Humain, 64*, 201–220.

Milleville-Pennel, I., Hoc, J. M., & Jolly, E. (in press). The use of hazard road signs to improve the perception of severe bends. *Accident Analysis & Prevention.*

Moray, N. (1986). Monitoring behavior and supervisory control. In *Handbook of perception and human performance, Vol 2* (pp. 40.1–40.51). New York: Wiley.

Morineau, T., Hoc, J. M., & Denecker, P. (2003). Cognitive control levels in air traffic radar controller activity. *International Journal of Aviation Psychology, 13,* 107–130.

Navon, D. G. (1979). On the economy of the human processing system. *Psychological Review, 86*, 214–255.

Noizet, A., & Amalberti, R. (2000). Le contrôle cognitif des activités routinières des agents de terrain en centrale nucléaire: Un double système de contrôle [Cognitive control of nuclear power plant field operators' routines]. *Revue d'Intelligence Artificielle, 14*, 107–129.

Norman, D. (1981). Categorization of action slips. *Psychological Review, 88,* 1–15.

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

Norman, D., & Bobrow, G. (1975). On data-limited and resource-limited processes. *Cognitive Psychology, 7*, 44–64.

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In G. S. R. Davidson & D. Shapiro (Eds.), *Consciousness and self-regulation* (Vol. 4, pp. 1–18). New York: Plenum Press.

Norros, L. (2005). The concept of habit in the analysis of situated actions. *Theoretical Issues in Ergonomics Science, 6*, 385–407.

O'Hara, K., & Payne, S. (1999). Planning and the user interface: The effect of lockout time and error recovery cost. *International Journal of Man-Machine Studies, 50*, 41–59.

Piaget, J. (1974a). *La prise de conscience* [Becoming aware]. Paris: Presses Universitaires de France.

Piaget, J. (1974b). *Adaptation vitale et psychologie de l'intelligence* [Vital adaptation and psychology of intelligence]. Paris: Hermann.

Pitrat, J. (Ed.). (1996). Reflection and meta-level AI architectures [Special issues]. *Future Generation Computer Systems, 12* (2–3).

Plat, M., & Amalberti, R. (2000). Experimental crew training to deal with automation surprises. In N. Sarter & R. Amalberti (Eds.), *Cognitive engineering in the aviation domain* (pp. 287–308). Hillsdale: NJ: Erlbaum.

Rasmussen, J. (1986). *Information processing and human-machine interaction*. Amsterdam: Elsevier.

Rasmussen, J., & Rouse, W. B. (Eds.). (1981). *Human detection and diagnosis of system failures.* New York: Plenum.

Raufaste, E., Eyrolle, H., & Mariné, C. (1998). Pertinence generation in radiological diagnosis: Spreading activation and the nature of expertise. *Cognitive Science, 22*, 517–546.

Reason, J. (1984). Absent-mindedness and cognitive control. In J. Harris & P. Morris (Eds.), *Everyday memory actions & absent-mindedness* (pp. 113–132). London: Academic Press.

Reason, J. (1990). *Human error*. Cambridge, UK: Cambridge University Press.

Richard, J. F. (1999). Object, limits and function of consciousness. *Journal of Consciousness Studies, 6*, 276–280.

Rizzo, A., Ferrante, D., & Bagnara, S. (1995). Handling human error. In J. M. Hoc, P. C. Cacciabue, & E. Hollnagel (Eds.), *Expertise and technology: Cognition & human-computer cooperation* (pp. 195–212). Hillsdale, NJ: Erlbaum.

Roth, E. M. (1997). Analysis of decision-making in nuclear power plant emergencies: An investigation of aided decision-making. In C. E. Zsambok & G. Klein (Eds.), *Naturalistic decision-making* (pp. 175–182). Mahwah, NJ: Erlbaum.

Roth, E. M., & Woods, D. D. (1988). Aiding human performance. I: Cognitive analysis. *Le Travail Humain, 51*, 39–64.

Salas, E., Prince, C., Baker, D. P., & Shrestha, L. (1995). Situation awareness in team performance: Implications for measurement and training. *Human Factors, 37,* 123–136.

Samurçay, R., & Hoc, J. M. (1996). Causal versus topographical support for diagnosis in a dynamic situation. *Le Travail Humain, 59,* 45–68.

Sanderson, P. M. (1989). Verbalizable knowledge and skilled task performance: Association, dissociation, and mental models. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15,* 729–747.

Schneider, W., & Chein, J. M. (2003). Controlled & automatic processing: Behavior, theory, and biological mechanisms. *Cognitive Science, 27*, 525–559.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: Detection, search, and attention. *Psychological Review, 84,* 1–66.

Sheridan, T. B. (1992). *Telerobotics, automation, and human supervisory control.* Cambridge, MA: MIT Press.

Shiffrin, R., & Schneider, W. (1977). Controlled and automatic human information processing: Perceptual learning, automatic attending and a general theory. *Psychological Review, 84*, 127–190.

Simon, H. A. (1969). *The science of the artificial.* Cambridge, MA: MIT Press.

Spérandio, J. C. (1977). La régulation des modes opératoires en fonction de la charge de travail chez les contrôleurs de trafic aérien [Adaptation of the modes of operating to mental workload by air traffic controllers]. *Le Travail Humain, 40,* 249–256.

Stassen, H. G., van Lunteren, T., & Sheridan, T. B. (Eds.). (1997). *Perspectives on the human controller: Essays in honor of Henk G. Stassen.* Mahwah, NJ: Erlbaum.

Trick, L. M., Enns, J. T., Mills, J., & Vavrik, J. (2004). Paying attention behind the wheel: A framework for studying the role of attention in driving. *Theoretical Issues in Ergonomics Science, 5*, 385–424.

Valot, C. (2002). An ecological approach to metacognitive regulation in the adult. In M. I. P. Chambres & P. J. Marescaux (Eds.), *Metacognition: Process, function and use* (pp. 201–221). Dordrecht, Netherlands: Kluwer.

Valot, C., & Amalberti, R. (1992). Metaknowledge for time and reliability. *Reliability Engineering and Systems Safety, 36*, 199–206.

Vicente, K. J. (1999). *Cognitive work analysis.* Mahwah, NJ: Erlbaum.

Vicente, K .J., Mumaw, R. J., & Roth, E. (2004). Operator monitoring in a complex dynamic work environment: A qualitative model based on field observations. *Theoretical Issues in Ergonomics Science, 5*, 359–384.

Wertheimer, M. (1959). *Productive thinking: A gestalt view of problem solving and how to teach it.* New York: Harper & Row.

Wickens, C. D. (1984a). *Engineering psychology and human performance.* Columbus, GA: Merrill.

Wickens, C. D. (1984b). Processing resources in attention. In R. Parasuraman & R. Davies (Eds.), *Varieties of attention* (pp. 63–101). New York: Academic Press.

Wioland, L., & Amalberti, R. (1996, November). *When errors serve safety: Towards a model of ecological safety.* Paper presented at the First Asian conference on Cognitive Systems Engineering in Process Control (CSEP 96), Kyoto, Japan.

Woods, D., & Hollnagel, E. (1987). Mapping cognitive demands in complex problem solving worlds. *International Journal of Man-Machine Studies, 26*, 257–275.

Woods, D, & Hollnagel, E. (2006). *Joint cognitive systems: Patterns in cognitive systems engineering*. Boca Raton, FL: Taylor & Francis.

Xiao, Y., Milgram, P., & Doyle, D. J. (1997). Planning behavior and its functional role in interactions with complex systems. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans, 27*, 313–324.

Zhang, J., & Norman, D. (1994). Representation in distributed cognitive tasks. *Cognitive Science, 18*, 87–122.

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