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Towards a cognitive approach to human–machine cooperation in dynamic situations

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Human-computer interaction research has produced consistent results bearing on a well-established body of knowledge in cognitive science. In contrast, the new research domains of computer- supported cooperative work (CSCW) or human–machine cooperation are harder to develop because the problems to be solved are more complex and the theoretical frameworks more heterogeneous. However, dynamic situations with high temporal constraints create occasions where small teams (including humans and machines) can cooperate on an almost cognitive basis, reducing social or emotional effects. This paper reviews the state of the art on cognitive cooperation to extend an individual cognitive architecture and deal with these situations, combining private and cooperative activities that are highly task-oriented. Cooperation is taken as the management of interference between individual activities to facilitate the team members' sub-tasks and the team's common task when there is one. This review of the literature is a step towards a theoretical approach that could be relevant to evaluate cooperation and to design assistance in diverse domains such as air traffic control or aircraft piloting.

KEYWORDS: human–machine cooperation; human–human cooperation; cognitive cooperation; communication; cooperation assessment; cooperation support; cooperative machine.

1. Introduction

As computers dominate the modern workplace, conceptions of the human–machine relation have evolved considerably. Within human-computer interaction (HCI) research there has been a shift in focus from a physical conception of this relation (through the surface structure of the interface) to a cognitive one (implying signs and concepts). The physical aspects must be considered especially during the development of new interfaces, such as multimedia or virtual reality (Helander, Landaur & Prabhu, 1997), but the increasing intelligence of computers leads to problems such as comprehension between humans and computers. Thus, the solution cannot be found solely through the improvement of the interface. The design of "human-like" machines, that reason and represent things in the way humans do, has been explored (especially in aviation: Amalberti & Deblon, 1992; Boy, 1995). Another attempt at such design was the development of explanation capabilities in computers (Karsenty & Brézillon, 1995). The strict notion of

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interaction has been progressively replaced by the metaphoric concept of communication, so that HCI research resulted in a new research community, working on human–machine communication (Ogden, 1988; Blanford, 1993; Jones & Mitchell, 1994). The aim has been to increase not only the computers' linguistic capability, but also their communicational performance, on the basis of pragmatics (Austin, 1962; Searle, 1969; Grice, 1975; Sperber & Wilson, 1986). However, if agents communicate, their goals must be understood. Cooperation is absolutely necessary to understanding (Clark, 1996). Consequently, the metaphor must be enlarged to achieve human–machine cooperation† and to integrate action within a cooperative framework. In work situations, the human agents try to understand each other to act together. Now, agents are not only humans but also machines.

This new conception of the human–machine relation is very salient in the study of dynamic situations where the agents partly control the environment (industrial process control, air traffic control, highly automated aircraft piloting, etc.). In addition, there are high temporal constraints and risks within this type of situation. Automation has rapidly increased to solve technical problems arising from the management of high complexity. Machines are now able to make decisions and to implement them autonomously, being more than "assistants" to humans. The emergence of the cooperation approach to the human–machine relation within dynamic situations may be identified by the publication of a paper that considered human–machine systems as "joint cognitive systems" (Hollnagel & Woods, 1983). This approach clearly applied to the relation between humans and expert systems when it was shown that the human–machine performance was better when the user reasoned in parallel with the system (Roth, Bennett & Woods, 1988). In aviation, the notion of adaptive assistance appeared, stressing the mutual comprehension of the agents' actions and intentions (Billings, 1991). Many accidents have revealed difficulties in the human–machine relation [e.g. mode error in the cockpit (Sarter & Woods, 1995); and more generally (Funk *et al*., 1999)]. From a strict HCI point of view, suggestions have been made to increase the salience of such and such a piece of information. But this can result in interfaces with more flashing lights than a Christmas tree. More often than not, if the machine had been a human, the relational problem would have been identified as a cooperation problem. In addition, human behaviour interacting with machines often reveals a cooperative attitude on the human side (Nass, Fogg & Moon, 1996).

Four main types of difficulties between humans and automation are currently stressed (Parasuraman, 1997) and their translations in terms of cooperation are straightforward (mutual control, common frame of reference, models of oneself and of other agents, etc.).

(1) *Loss of expertise*. Whatever the task level is (diagnosis or action), when a certain type of task is allocated to the machine the humans do not maintain their skills (Sheridan, 1988). Mutual control of the humans and the machine is a possible remedy. In addition, automation puts the humans "out of the loop" and when they must take control again in case of an incident, their situation awareness is too poor (Ephrath & Young, 1981). If one considers that humans and machines are redundant systems, necessary to increase the overall human–machine system reliability, a common frame of reference must be maintained between them (Sheridan, 1996).

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† In the rest of this paper, instead of "computer" we will use the term "machine" that is more widely used in the supervisory control community, which deals with dynamic situations.

(2) *Complacency*. Some studies have shown that even expert operators, aware of the machines' limits, can adopt the machines' proposals although they know that their solutions are not optimal in relation to the actual situation (for example, pilots: Layton, Smith & McCoy, 1994; Smith, McCoy & Layton, 1997; Mosier, Skitka, Heers & Burdick, 1998; or air traffic controllers: Hoc & Lemoine, 1998). Some authors have recommended that machines propose several solutions instead of a single one to encourage mutual control (Clark & Smyth, 1993; Layton *et al*., 1994; Smith *et al*., 1997).

(3) *Trust*. In dynamic situations, the major risk felt by operators is the loss of control of the situation (Amalberti, 1996; Hoc, 1996). When the operators have the feeling that the machine is leading them towards a situation they think they cannot manage, they may override the machine [for example in training situations for pilots: Amalberti (1992); and more generally: Parasuraman (1997)]. Their behaviour may be related to a lack of self-confidence. More often it is due to a low level of trust in the machine. Self-confidence and trust are clearly linked to the availability of models of oneself and of other agents (as we will see further when discussing the work of Lee and Moray, 1994).

(4) *Loss of adaptivity*. In line with Bainbridge's criticisms (1987) expressed in her famous chapter "The ironies of automation", Reason (1988) has described this phenomenon in a powerful way: "System designers have unwittingly created a work situation in which many of the normally adaptive characteristics of human cognition are transformed into dangerous liabilities." (p. 7) Adaptation needs anticipation and feedback. Designers neglect the two when they conceive human cognition as a pure reactive system. The humans are the best to insure the human–machine system adaptivity. A cooperative conception of the human–machine relation is required to design machines providing humans with the data they need to play such a role within the system.

Cooperation is a broad research topic, including several disciplines in human sciences (sociology, linguistics, psychology, etc.) and engineering sciences (e.g. distributed artificial intelligence). This paper will not propose such a wide review but will focus on the literature that adopts a cognitive approach, which seems suitable to study small teams managing dynamic situations, highly task-oriented and composed of a small number of human and artificial agents. Although we think that Hutchins' approach of the team as a basic unit can be useful at a certain stage of analysis (1995), individual agents are our basic units. This work was initiated by a multidisciplinary investigation of the theoretical tools needed to design human–machine cooperation, combining the psychology and supervisory control points of view (Millot & Hoc, 1997). Our main thesis is that most of the problems encountered when trying to identify, assess, support, and design cooperative activities between humans and machines or between humans in this kind of situation can be addressed by enlarging the cognitive approaches currently used to study individual activities. Our secondary thesis is that this cognitive approach can (and should) be combined with other approaches, especially when social aspects must be considered [see e.g. Mantovani (1996), for such an attempt].

In the second section of this paper we will delineate the cognitive conception of cooperation in relation to other related concepts and approaches (collective activity, coordination, communication). The third and fourth sections will be devoted to two points of view on cooperation, from the knowledge and representation side (What is shared between agents?) and from the processing side (What are the cooperative activities?). Throughout this review, we will argue about how we can characterize the human–machine relation difficulties in terms of cooperation, how we can evaluate cognitive cooperation, and how we can define and design cooperative machines. The fifth section will sum up the main implications of this approach for evaluation and design.

2. Cooperation and related concepts

Two dimensions can be used to classify the studies of cooperation: the prescriptive/descriptive dimension and the structural/functional dimension. The first one distinguishes studies that try to prescribe what is cooperation [e.g. in aviation, to train teams within the framework of cockpit resource management (Wiener, Kanki & Helmreich, 1993; Rogalski, 1996)] from others that want to understand cooperation empirically (e.g. to derive design principles for support or for multiagents systems: Castelfranchi, 1998). There is a dialectic between the two, but our approach to the present review is more descriptive than prescriptive. Through the literature, we have tried to understand how human teams actually cooperate and, in order to identify the defects in the human–machine relation, to derive crucial aspects of cooperation that need to be improved in human–machine cooperation. The second dimension (structural/functional) separates studies stressing the nature of the relationships between agents [e.g. hierarchical, democratic, etc. (Koopman & Pool, 1991), between humans; (Millot & Mandiau, 1995), between humans and machines] from others describing the cooperative activities performed by the agents. Although there is a cross-determination between the two aspects, we are mainly interested here in the functional approach.

2.1. COLLECTIVE ACTIVITY

Collective activity (or tasks), as implying operations performed by several agents, is a superordinate concept in relation to cooperation, which we will define as interference management in real time. Several authors consider that cooperation implies a common goal shared by the cooperative agents (e.g. Grice, 1975; Marwell & Schmitt, 1975; Bagnara, Rizzo & Failla, 1994). Some authors admit a distributed form of cooperation where the role of the common goal can be weaker compared with those of private goals (Schmidt, 1991, 1994; Rogalski, 1994). However, the requirement of a common goal leads the observer to consider that agents, only sharing common resources (without a common goal), do not cooperate. In addition, it could be difficult to accept that agents could cooperate in problem solving since the (common) goal is not defined at the beginning. Finally, in many work situations, agents are actually doing tasks related to each other without clear consideration of a common task, except if one adopts a very abstract level of analysis, which is not very action-oriented. For example, in air traffic control, we have studied a dynamic task allocation paradigm (Hoc & Lemoine, 1998). Conflicts between aircraft could be allocated either to the human controllers or to a machine as a function of the human workload. Clearly, the machine had no representation of the overall management of the traffic and we adopted the cooperation point of view to analyse this kind of collective activity.

We propose a further extension of the concept of cooperation to counter the strong requirement of a common goal and to define a more flexible conception of cooperation. In other words, there is cooperation when at least some agents performed more than their private activities, that is cooperative activities (defined in Section 2.4 and in the rest of this paper). There is no cooperation when the agents act together but with perfectly autonomous actions [in the sense of Clark (1996) without public goals and without coordination in real time] from their point of view. More often than not a designer or a coordinator has managed the relationships between the individual tasks beforehand. Hence, the more autonomous the agents are, the less they can cooperate in terms of interference management. This kind of situation is very rare in dynamic situations where the environment and the agents' behaviours are difficult to predict. In this case, the agents themselves must solve coordination problems in real time. Hence, cooperative activities play a major role in adapting the multiagent system to its environment.

Consequently, cooperation will be considered as a sub-class of collective activity (acting together) where there is interference management in real time without necessarily a common goal playing a regulation role.

2.2. COORDINATION

Coordination is performed by meta-operations that apply to operations to organize them so that they fulfil certain criteria. Coordination is clearly situated at a planning (and abstract) level [as stressed by Piaget (1965), in his definition of cooperation; see Section 2.4)]. Thus, theories of planning can be of great value in approaching this aspect of cooperation (Sacerdoti, 1977; Suchman, 1987; Hoc, 1988). Operations can be organized in a single and coherent subgoal network to reach the main goal, as is the case in private activity. Another form of coordination, more specific to cooperation, could be to find a decomposition of the goal into independent subgoals and corresponding networks without mutual impediments. The presence of several agents leads to a higher complexity than in individual planning. Following Castelfranchi (1998), considering two artificial agents, coordination can be unilateral (only one agent changes its plan), bilateral (two), or mutual (with the conscious coordination intention and agreement). It depends on the agents' ability (in human–machine cooperation the humans are more likely to change their plans than the machines) or on the task priority (in air traffic control the planning controllers, in charge of the medium term, are more likely to adapt their plans to the radar controllers constraints, in the very short term). In addition, this author considers that coordination by one agent can serve its own interest (ego-centred coordination) or those of both (collaborative coordination). Such criteria can be relevant to assess the depth of cooperation, because coordination is an important component of cooperative activities. However, cooperation cannot be reduced to coordination and other types of activity must be defined.

2.3. COMMUNICATION

Many studies of communication are relevant to cooperation because communicating aims at being understood by the partner and cooperation between the two is necessary to reach this goal (Clark, 1996). However, here we will take communication as a means to cooperate. Very often, observers study natural language communication to evaluate cooperation. However, in dynamic situations where temporal constraints are strong, non-verbal communication is as important as verbal communication. Expert operators rely on informal codes reflected by their own individual behaviour (Cuny, 1967; Schmidt, 1994). For example, in one of our studies on cooperation between a pilot (P) and a navigator (N) in a fighter aircraft, N can infer from the effects of P's behaviour that P is overloaded and decides to perform a task initially allocated to P (Loiselet & Hoc, 1999). In air traffic control, the planning controller can anticipate the type of conflict resolution that will be adopted by the radar controller and decides to perform an action that is a precondition for that (Hoc & Lemoine, 1998). In these two examples, no oral communication is performed before the decision, but just after, in order to be sure that the other operator is aware of what is done by the agent. If one can consider these activities as cooperative, on the basis of the definitions that will be given later, their identification needs a good knowledge of the work domain since communications are not explicit for the observer.

2.4. COOPERATION

A cognitive approach to cooperation can be mainly based on cognitive psychology, more especially on the definition of cooperation proposed by Piaget in 1965. We will not enter here into the false debate, during this period, between interpretations of Piaget's work as an entirely internal conception of cognitive development and interpretations of Vygotski's (1978) work stressing the major role of social interactions, which is mainly due to translation problems. Piaget's (1965) paper confirmed his interactionist conception of cognition, describing the close relationships between cognitive development (access to formal operations) and generation of what we will call "know-how-to-cooperate" (as opposed to "know-how"), after Millot and Lemoine (1998). Authors working on training pilots to cooperate in the cockpit have shown that know-how in the domain is a prerequisite to the development of know-how-to-cooperate. In their studies on cooperation in the cockpit, Orasanu and Salas (1993), and Stout, Salas and Carson (1994) have shown a correlation between domain expertise and cooperation. In a pilot training situation, Rogalski (1996) has demonstrated that know-how is acquired before know-how-to-cooperate can develop.

Piaget (1965) wrote (our translation): "Cooperating in action is operating in common, that is adjusting the operations performed by each partner by the means of new operations. It is coordinating each partner's operation into a single operation system, the collaboration acts themselves constituting the integrative operations." (p. 91) An interpretation of this conception is that cooperation implies meta-operations, defined at a higher abstraction level (to be added to "private" operations) and assumed to introduce a decentering from one's own activity. However, several abstraction levels will be defined among cooperative activities.

More precisely, the following definition for cooperation (between two human or artificial agents, but generalizable to more agents) is consistent with most of the literature in the domain (Hoc, 1996; Millot & Hoc, 1997). We will make its different aspects more precise in the subsequent paragraphs.

Two agents are in a cooperative situation if they meet two minimal conditions.

1. *Each one strives towards goals and can* interfere *with the other on goals, resources, procedures, etc.*
2. *Each one tries to manage the interference to* facilitate *the individual activities and/or the common task when it exists.*

The symmetric nature of this definition can be only partly satisfied.

This definition is minimal in that it does not impose the implementation of all possible cooperative activities in a particular situation. For example, it does not suppose the generation of a common goal or a common plan. However, as opposed to private situations, cooperation situations are created by the fact that individual activities are not independent (interference). In addition, cooperation differs from competition on the sole basis of facilitation. This minimal definition can prove to be heuristic in approaching the human–machine and the human–human relations in dynamic situation supervision by small teams of agents, when cognitive aspects are prominent.

2.5. INTERFERENCE AND FACILITATION

The notion of interference is borrowed from the literature on planning and is opposed to the notion of independence between goals or procedures (including resources). Its negative connotation is taken away, as is the case of physics from where it is imported in a metaphoric way. Interferent signals can indeed reinforce each other if they are in phase or, on the contrary, hamper each other if they are not. At the same time as Hoc (1996), Millot and Hoc (1997), Castelfranchi (1998) stressed the crucial role of interference in cooperation. Following this author, interference relies on the fact that "the effects of the action of one agent are relevant for the goals of another: i.e. they either favour the achievement or maintenance of some goals of the other's (positive interference), or threaten some of them (negative interference)". (p. 162)

More precisely, several types of interference between individual activities can be defined. The following list is not exhaustive but covers most of what is often observed, especially in studies of highly dynamic situations. The first two types (precondition and interaction) can be found in private activities and solved at the individual level. When activities are distributed among several agents, interference processing belongs to cooperation. The last two types (mutual control and redundancy) are peculiar to cooperation situations.

2.5.1. Precondition interference. One agent's activity can be a precondition for the other's activity or can be transformed to satisfy this property. For example, in air traffic control (ATC), the planning controller (PC), in charge of inter-sector coordination, will decrease the exit level of an aircraft to enable the radar controller (RC) to solve a conflict close to the boundary of the sector by making this aircraft descend. Without PC's action, this type of solution would be impossible to implement. This can be done without any explicit communication if PC anticipates the RC's goal on the basis of the conflict type and its context. Within the precondition interference class, Castelfranchi (1998) stresses the particular case of dependence when an agent cannot strive towards a goal without the other agent. In fact, a precondition may be optional when the same agent (indeed with the risk of increasing the workload) can produce the precondition. Many examples of dependence can be found between PC and RC (e.g. strip transfer to RC) and between a navigator and a pilot (e.g. preparation of the weapon system to fire).

This kind of interference has a direct impact on coordination and, in dynamic situations, on synchronization. It may correspond to serial sub-task sharing in performing a common task or to successive tasks without any common task (e.g. resource sharing). In the first case, precondition interference management can be insured by a common plan or by sub-task fulfilment as a triggering condition for the following sub-task. In the second case, there may be a problem when reaching the main goal of the preceding task is not sufficient to create the precondition for the performance of the following task. Sometimes, after reaching one's own goal, there remains something to do (postcondition) to enable another agent to act. For example, an agent can have a high workload and may not notice the realization of a precondition on the interface, so that the other agent must communicate verbally (postcondition) that the precondition is met. In individual problem solving, it has been shown that postcondition is very often forgotten (Richard, 1990) because the main goal is reached. This fact can be a source of ineffectiveness in cooperation when there is no explicit timing, no common plan, or at least no ability to infer the partner's goals and precondition. In terms of design, this kind of difficulty suggests the implementation of a graph of tasks showing this type of relation in real time (Pacaux & Loiselet, 1999). ISAM, an intelligent support for activity management, was developed by Jones and Jasek (1997) to play this role. In our studies on fighter aircraft piloting, such a graph of tasks, evolving in real time, proved successful.

2.5.2. Interaction interference. The two agents' activities may mutually jeopardize their respective goals and must be designed in such a way as to avoid this negative issue. In fighter aircraft piloting, the navigator (N) would like to optimize the flight plan changing the next destination goal on the route. To do that, N must change the pilot's (P) displays, that is P's resources and current activity conditions; consequently, P will have to change the current activity (as N does). Castelfranchi (1998) distinguishes two types of interaction. Mutual dependence stands for agents who depend on each other to reach a common goal (in the previous example) and reciprocal dependence when they depend on each other to reach their individual goal. An example of reciprocal dependence can be found in an experiment in air traffic control (Carlier & Hoc, 1999), where we have distributed the aircraft over two human controllers to study this kind of interference, and to derive recommendations for the design of human–machine cooperation. We have created occasions where two different aircraft conflicts are distributed over the two controllers who must find solutions that do not interfere with each other.

Interaction interference is much more difficult to manage than precondition interference without a common plan, elaborated before task performance or in real time. It is one of the main criteria used by Dearden, Harrison and Wright (2000) when deciding task allocation between humans and machines. They discuss the example of engine shutdown in aviation when there is an engine fire. The shutdown can be easily automated (simple procedure and low cost) but there is a close interaction interference with the pilot's task to manage the engine power to keep the aircraft in the flying envelope. The authors consider that this task should not be automated in order to let the pilot control the shutdown procedure timing, so that interaction interference is minimal. The solution is obviously based on the fact that the automation is not as adaptive as it should be to cooperate with the human.

2.5.3. Mutual control interference. For safety and reliability reasons, aviation authorities encourage mutual control in many domains, for example the pilot who is not flying controls the actions performed by the pilot who is flying, and the planning controller checks the radar controller decisions in air traffic control. Mutual control implies that the task actually performed by one agent, by reason of responsibility, is also performed, but mentally, by another for checking purposes. When there is disagreement between the agents a search for a consensus is initiated. Three types of criteria may be used in mutual control: one's own task (ego-centred control), the other agent's task (alter-centred control), or the common task (team-centred control).

Mutual control is very often suggested to avoid complacency effects (Smith & Crabtree, 1975; Clark & Smyth, 1993; Layton *et al*., 1994; Denecker & Hoc, 1997; Glover, Prawitt & Spilker, 1997; Roth, Malin & Schreckenghost, 1997; Smith *et al*., 1997; Dijkstra, 1999; Guerlain *et al*., 1999; Skitka, Mosier & Burdick, 1999). This research trend usually compares situations, where the machine does the job and the human uses the result, to situations where the machine "looks over the operator's shoulder" and detects discrepancies from the usual procedure, in a mutual control way. Task performance is shown to be better with such a "critiquing" machine, especially in design or diagnosis activities, than with a "prosthesis" machine. A long time ago, Roth *et al.* (1988) had shown a better human–machine system performance (diagnosis expert system and trouble-shooters) when the operators played an active role (performing the diagnosis in parallel) than when they restricted their role to data entry. With the active attitude, the operators filtered data so that the machine remained on the right track and was not influenced by irrelevant data. With the critiquing systems, the machine critics have not only a "behavioural" role, but also trigger deeper analysis of the situation.

Mutual control interference has a positive effect on performance. In his categorization of cooperative situations, Schmidt (1991) defines "debative" cooperation as grouping together several agents with the same kind of expertise to reach a better performance, having the agents "debugging" the individual activities. Dalal and Kasper (1994) have explored the possible complementarity between the human and the machine in terms of cognitive styles (analytic vs. heuristic). More generally, the design of human–machine cooperation is often confronted with the question of facilitating the cooperation between (human) reasoning and (machine) calculus. More often than not, this implies introducing an abstract level above the calculus to translate it into reasoning features, which are often implicit. However, there remains a problem of responsibility when there are decisional conflicts. Human–machine cooperation cannot be fully symmetric because responsibility cannot be shared, the human remaining the sole component of the human–machine system to be responsible for the overall performance (Jones & Mitchell, 1994). This is justified not only by legal reasons, but also because the main problem is adapting the human–machine system to circumstances unforeseen by the designers or which the machine is not able to deal with. Obviously, the human adaptation ability is much higher than the machine adaptation capability. Thus, the best risk management is to let the human operator make the final decision. Dearden *et al.* (2000) suggest avoiding a rigid task allocation to the machine when the task interferes too much with the human role (defined in terms of responsibility). They recommend a dynamic (or adaptive) allocation paradigm in this case, because in certain contexts the human may consider that the task can be allocated to the machine.

2.5.4. Redundancy interference. In dynamic situations where the performance conditions are not fully predictable, it may be the case that a particular task cannot be allocated to a particular agent beforehand. The best available agent when the task has to be done, in terms of location, workload, available resources, etc., will perform the task. In fighter aircraft piloting the search for the target can be done by the two operators (pilot or navigator), but with different means. The first operator able to identify the target will acquire it for the laser guidance.

An important feature of cooperation is the possible redundancy between agents (Sheridan, 1996; Militello, Kyme, Klein, Getchell & Thordsen, 1999). Such a redundancy insures the adaptive power of the team to deal with unexpected circumstances. Rigid task allocation between humans and machines has often been criticized in relation to adaptation (Mosier, 1997; Roth *et al*., 1997; Mouloua & Koonce, 1997; Endsley & Kaber, 1999). One of the main reasons for that is the unavoidable "brittleness" of the machine when the situation goes beyond the domain of validity of the technical system (Layton *et al*., 1994; Smith *et al*., 1997). In this case, the human must take control of the machine's task. Another reason is the large variation in a human's workload in certain situations like air traffic control when the temporary allocation of part of the task can alleviate the workload (this paradigm was tested by Debernard, Vanderhaegen and Millot, 1992, Millot and Mandiau, 1995 and Hoc and Lemoine, 1998). The acceptance of such a redundancy between humans and machines means that human–machine systems are designed in such a way that they can resolve redundancy interference easily. The main question to be solved is probably to find ways to facilitate the performance of a task by an agent who is not prepared by a predefined plan to perform it. Especially, the fulfilment of the preconditions must be precisely examined because it will play a major role in the evaluation of cooperation.

2.5.5. Facilitation. These diverse types of interference show that the negative or positive nature of interference is not related to its definition, but to assessment criteria that have something to do with facilitation. Any interference can be considered as an impediment to the smooth development of individual activity. In that sense, it would be always considered as negative. Precondition interference can result in delay, interaction interference in workload increase (change in procedure), mutual control interference in bad self-image, and redundancy interference in individual plan modification. However, ease of individual performance is not the only criterion used by the agents to assess their individual or collective activity. Interference can be positive if it enables the agents to improve their individual performance or the team performance. That is why a good representation of a common task is needed to help the individuals to go beyond the sole objective of having the others facilitate individual activities. Hence, facilitation is related to the way in which interference is processed by the cooperative activities that will be described in Section 4, after describing the representational structure on which these cooperative activities will act.

3. Knowledge and representation architecture

A cognitive approach to cooperation, as is the case for individual cognition, cannot avoid combining the dual points of view of knowledge and representation, on the one hand, and of processing on the other hand. One of the essential properties of an individual or collective cognitive system is its use of internal models of its environment in order to adapt to that environment. Hence cognitive activities cannot be understood without any idea of the knowledge or representational structures utilized and transformed by these activities. Within the limited framework of this paper we will not develop the usual distinctions between knowledge (considered as recognized) and belief (to be proved), or between knowledge (as a set of permanent structures stored in long-term memory) and representations (temporary structures instantiating knowledge to specific situations).

3.1. COMMON FRAME OF REFERENCE (COFOR)

In relation to the cooperation situation, several authors have stressed the importance of a shared knowledge, belief and representation structure between the agents (Grice, 1975; Marwell & Schmitt, 1975), which we will call COFOR (standing for Common Frame of Reference). In the French-speaking literature, the equivalent term (*référentiel commun*) has been widely used after De Terssac and Chabaud (1990) who defined it as (our translation): "The sharing of competencies to prepare and perform an action; this sharing of competencies at the same time complements each individual representation of the task to be done, and enables the adjustment of each individual decision considering the others' knowledge" (pp. 128 and 129). Piaget, in his essay of 1965, did not give a particular name to this structure, which he, however, defined from a logical point of view as a common scale of intellectual values: a language, a system of notions, of basic propositions to which one can refer in case of debate. That enables agents to agree on values used in evaluation and to keep propositions recognized earlier to be able to return to them at any time. This conception leads one to consider that COFOR is generated and regularly updated during the course of cooperation.

Clark (1996) reached the same type of notion when he introduced the concept of *common ground* in his study of cooperation in communication. He proposed this concept to refer to the common abstract meaning of several terms used in diverse disciplines in relation to different points of view: *common knowledge* in philosophy, *mutual knowledge* in linguistics, *joint knowledge* in artificial intelligence, and indeed *shared representation* in psychology. He complemented Piaget's definition by including the (logical or empirical) justifications of the shared propositions in the shared structure. He recognized the same function of this structure in cooperation as that stressed by De Terssac and Chabaud. However, he probably introduced too strong a constraint requiring each agent's awareness of the COFOR sharing.

In our experiment on air traffic control (Hoc & Lemoine, 1998), we have shown an improvement in the COFOR maintenance in a situation where machine assistance enlarged a shared information space between controllers. From very laconic communications, controllers reached the meaning of the messages more easily. Several studies have been devoted to the design of shared information spaces to support COFOR and have probably dealt with a determining factor to improve cooperation (Cannon-Bowers, Salas & Converse, 1993; Jones, 1995; Salas, Prince, Baker & Shrestha, 1995; Jones & Jasek, 1997). In fact, Orasanu and Salas (1993) have shown, in aviation, that the most efficient crews are those who develop the best shared situation models. Such a sharing creates a basis for decision-making that enables each agent to use the overall team cognitive resources. In a recent experiment studying cooperation between two radar controllers in the same sector, most of the communications were related to the elaboration and maintenance of the COFOR (Carlier & Hoc, 1999). This enabled them to anticipate interference occasions and to solve it implicitly, without need for verbal communication. Only half of the communications between the pilot and the navigator concerned the COFOR in fighter aircraft cockpit, probably because of a more unexpected environment (Loiselet & Hoc, 1999).

COFOR is at the core of cooperation and plays a role similar to that of the current representation of the situation at the individual level in dynamic situation management, as shown by Hoc and Amalberti (1995) in their extension of Rasmussen's decision ladder (1986). Diagnosis and decision-making cannot be fully understood by means of strictly procedural models. In certain situations, situation understanding is the key aspect. For example, in expert air traffic control, the main difficulty is not to find a solution to a conflict between aircraft, but to be sure that the relevant aircraft structure is identified (for example, to be sure that an aircraft constraining the solution of a conflict between two others has actually been considered) (Hoc, Morineau & Denecker, 2000).

Most of the psychological studies of shared representation in collective activity have considered it exclusively at the symbolic (and attentional) level. It would be beyond the scope of this paper to argue on the need for an extension of this approach to the subsymbolic level [see the opposition between controlled and automatic processes by Shiffrin and Schneider (1977), the distinction between symbolic and connectionist models by Rumelhart and McClelland (1986) and the application of these approaches to immediate inference in medical diagnosis for example by Raufaste, Eyrolle and Mariné (1998)]. Shared representations may be a critical precondition to successful cooperation, not only when the agents are aware of their sharing, but even when they are simply not aware of them.

COFOR is similar to the concept of *team* (shared) *situation awareness* (Salas *et al*., 1995) if one adopts a wider conception of the notion of situation than that which is described in this research trend. Endsley (1995*a*, *b*), who has done abundant studies on *situation awareness*, at the individual level, and proposed a precise and validated method for access to it, has described it as a three-levelled structure: (1) perception of raw information on the environment; (2) interpretation of information (diagnosis); and (3) projection towards future (prognosis). The three levels are highly important to consider, but this conception of situation as a purely external object, although in accordance with the usual understanding of the term, must be enlarged. Individuals very often integrate themselves as part of the situations, especially in dynamic environments evolving partly as a consequence of spontaneous phenomena (their own dynamics), partly reacting to human operators' actions (Amalberti & Deblon, 1992; Hoc & Amalberti, 1995). In these situations, operators integrate their plans, representations of their resources and of the risks they personally incur (workload increase, risk of losing the control of the situation, etc.). Salas *et al.* (1995), after Morgan, Glickman, Woodard, Blaiwes and Salas (1986) and Cannon-Bowers *et al.* (1993), clearly integrate the team activity as part of team situation awareness.

Hence, it is convenient to consider the notion of situation, not in the restrictive sense of the state and evolution of the external environment, but rather in the wider sense of the state and evolution of a human-task system (Hoc, 1988). Such an extension applies obviously to collective activity where COFOR may integrate not only shared representations of the environment, but also representations of one's own or others' plans, intentions, goals, resources, risks, etc. In this sense, the examination of the evolution of the COFOR components along time is very useful to evaluate cooperation. As is the case at the individual level, COFOR is composed of several abstraction levels (orthogonal to those introduced by Endsley). We will define three levels: the action level, the plan level, and the meta-level.

3.2. ACTION LEVEL

Cofor includes action specifications that can be symbolically represented, especially in novel or problem-solving situations where subsymbolic (automatic) control is not adequate. However, the greater part of these specifications is not processed at the symbolic (attentional) level. Cooperation can produce attentional activations of these specifications because of interference or communication.

The content of the messages exchanged by agents enables the observer to access the COFOR elements that are the focus of attention. In our study of air traffic control, the assistance tools have led controllers to focus on action specifications (Hoc & Lemoine, 1998). As these tools widened the shared information space, the need for adjusting representations on higher abstraction levels was reduced. In the study of fighter aircraft piloting, the initial plan and the high temporal constraints also led operators to focus on action specifications (Loiselet & Hoc, 1999).

Some studies on cooperation in process control have shown the same phenomenon. In a study on blast furnace supervision, Samurçay and Delsart (1994) have found that operators *duos* did not spontaneously cooperate on diagnosis (situation understanding). They reached cooperation at this level only when they disagreed on decision-making. Grusenmeyer (1995) has made the same observation in a study of handover between two operators in a paper-mill plant, where the operators communicated what they had done rather than the reasons for their actions (diagnoses).

When the machine's intelligence is limited, it may be difficult to have it communicate at a very abstract level, but feedback can be given to the operator. For example, in aviation, feedback of automatic control on the manual instruments (e.g. throttle hand lever) has been recommended. However, this kind of low-level communication at the action level is not sufficient. A good example is procedure following: (a) in aviation (Karsenty, 2000), where pilots show a need for explanation at a higher abstraction level to use them or (b) in process control (Roth, 1997), where nuclear power plant operators have been shown to develop two parallel activities: procedure following and diagnosis to check their validity in the current situation.

3.3. PLAN LEVEL

In fact, we put several abstraction levels together in a single level. In cooperation, this level is implied in situation understanding and action planning. Here we take the term planning in the wide sense of generating schematic representations organized into a hierarchy and utilized to guide activity (Hoc, 1988). In dynamic situation management, the notion of the action plan must be extended because the spontaneous dynamics of the process under supervision must be considered to give sense to the operators' actions (Hoc, 1995). In cooperation situations, this plan level of the COFOR integrates common goals, common plans, and function allocation. It is not necessary to assume that private plans are perfectly compatible with these common elements. Besides, the COFOR plan level may be very poor. The elaboration of the COFOR plan level and of private plans compatible with common plans is an integral part of cooperation activity.

At this plan level, two types of representation can be identified—the focal and the contextual representations. A focal representation concerns the main function of the plan (its functional value in the sense of Duncker, 1945), its main objective. A contextual representation concerns a secondary implementation aspect. In his *context mediated behavior* theory, Turner (1998) has proposed a definition for context in problem solving, illustrating it by examples borrowed from robotics: "A context is an identifiable configuration of environmental, mission-related, and agent-related features that has predictive power for behavior." (p. 312). Such a definition is compatible with a large variety of "features". However, the examples given by the author show that the definition of context requires us to consider at least two abstraction spaces. One of the examples is the reaching of a safety state (focal representation), in the case of a problem for a small submarine robot. In an out-at-sea context, it is surfacing, whereas in a harbour context, it is putting the robot on the bottom (two contextual representations). In the operational space where the plan is specified, contextual elements lead to different instantiations. Brézillon, Pomerol and Saker (1998) who define contextual knowledge as that which indirectly constrains a solution (e.g. the consideration of the secondary effects of a drug when making a therapeutic decision) also share this conception.

Context sharing plays a major role in cooperation, especially when temporal constraints are high. Our study on air traffic control has shown that the more the assistance was developed (in terms of shared information space), the less contextual information was communicated (Hoc & Lemoine, 1998). In his overview of communication at work (e.g. between air traffic controllers and pilots or between medical secretaries and patients in making appointments by phone), Falzon (1991) has shown that communication on context is only required when the agents do not share the same schema. Besides, this kind of communication is very costly. When cooperation is fluent, the contextual representations are probably processed mostly at the subsymbolic level.

3.4. META-LEVEL

The more the operators are implicated in the proximal control of the process to be managed, the more they are led to take their own processing characteristics into consideration. Then, meta-knowledge (as knowledge on their own activity) may be evoked and can play a major role in planning (Amalberti & Deblon, 1992). Such meta-knowledge enables the operators to manage internal risks, resources and costs.

Among the major risks for the operators, the risk of losing control of the situation is prominent. The evaluation of the collective activity in real time can be anticipative when it relies on meta-knowledge. An anticipative evaluation can lead to task allocation, on the basis of anticipated workload, of easy access to necessary data, of expertise in the task domain, etc. (Rasmussen, Pejtersen & Goodstein, 1994). The availability of models of oneself, of other agents, and of the overall team in the COFOR is absolutely necessary to reach this meta-level of representation. We will see later that this level can account for self-confidence and trust.

4. Processing architecture

From the design point of view, the following account of the cooperative activity, derived from the literature, can provide the machine designer with functions to be implemented to reach the level of a cooperative machine.

4.1. ACTION LEVEL

The level of cooperation in action is achieved by a team working together to perform operational cooperative activities directly related to goal and procedure management in real time during task performance. These activities actually manage interference, even if they must be prepared by cooperative activities situated at higher abstraction levels, such as those that will be described later. They are also likely to feed and regularly update the COFOR. At this action level four types of activity can be defined, which have short-term implications for activity, as opposed to more abstract types that have medium- and long-term implications.

4.1.1. Local interference creation. Indeed, this class corresponds to the deliberate creation of interference with the aim of facilitating one's own task, the other's task, or the common task. Precondition interference creation can enable each agent to take advantage of the others' activities to fulfil the preconditions of the individual's activity, or the agent can create the preconditions for the others' activities (some examples have been described in fighter aircraft piloting and air traffic control above). Interaction interference creation is just more complex in that a symmetry is introduced. Mutual control creation supposes that one agent performs another agent's task mentally, in parallel, to express agreements or disagreements, in order to improve the individual or the common task (good examples are critiquing systems). Precondition and mutual control interference creation rely on some ability to infer the other agents' intentions (see below). Redundancy interference creation aims at facilitating the other agents' or the common task (an example has been given in fighter aircraft piloting above). It supposes an evaluation of the difficulties encountered by the agent to be replaced (workload, ease of access to data, etc.). Thus, it could be greatly facilitated by a model of the other agent (to infer these difficulties) and a model of oneself (to decide whether the agent will be able to perform the task).

4.1.2. Local interference detection. To be able to manage an interference, one must indeed be able to detect it. When the interference has been created deliberately, there is no problem of detection, because it is often accompanied by explicit communication. However, some interference occasions may be non-deliberate. In our study of cooperation between two radar controllers in ATC, interference detection was as frequent as interference creation (Carlier & Hoc, 1999). The detection concerns a possible facilitation or impediment for one's own or another agent's activity. Further, the type of interference must be identified in order to choose the best resolution method. For evaluation purpose, failure in interference detection can be classified, as usual, into two categories: (1) interference not detected (in time) and (2) false alarm.

4.1.3. Goal identification on the basis of domain knowledge. At this abstraction level, the other agent's goal or subgoal identification only bears on knowledge in the domain. In air traffic control, it is not necessary for the planning controller (PC) to have a sophisticated model of the radar controller (RC) to anticipate that the more probable resolution of a particular conflict between aircraft consists in making one of them descend, given the context. If there is a potential interference between this type of solution and the definition of the exit level of an aircraft, PC can anticipate this interference and immediately act on the exit level to facilitate RC's task. This cooperative activity is very important since it enables the agents to detect and resolve interference by anticipation (Castelfranchi, 1998). Besides, very often interference does not concern final goals but subgoals through which it is necessary to go in order to reach final goals. In other words, goals may not interfere, but subgoals may. Expertise in the domain plays a major role in identifying the subgoals. This is probably why know-how in the domain is a prerequisite to know-how-to-cooperate. In the study just cited in ATC, interference anticipation (on the basis of goal and subgoal identification) was as frequent as interference detection. For a long time a large research effort has been devoted to intention identification in many domains, but especially within advice-giving systems (Jackson & Lefrere, 1984; Giboin, 1988). As far as human–machine cooperation is concerned, intention identification is probably a key point to overcome many difficulties between humans and automation. This may rely on models of agents, but also on intention communication.

4.1.4. Local interference resolution. Local interference resolution refers to actual interference resolution. One of the crucial problems to solve in cooperation is determining the relevant abstraction level to adopt to find a solution to an interference. Sometimes it is sufficient to intervene locally at the concrete action level. It is this level which is considered here. However, sometimes it is worth questioning the plan to find a lasting solution. Sometimes one agent's plan is sufficient to consider, sometimes several agents must be considered. Interference resolution is not a topic specific to cooperation. It has been largely studied in the planning literature (Sacerdoti, 1977; Hoc, 1988).

4.2. PLAN LEVEL

The following cooperative activities occur at an abstraction level higher than that of action execution. Indeed they can facilitate cooperation in action. In most of the cases they arise in the medium term rather than the short term. In certain cases they may arise very rapidly and cannot be *a priori* excluded from the short term. All of them imply large modifications of COFOR that must be distinguished from the frequent local updating produced by cooperation in action or even some private activities. For example, interference resolution at the action level can feed COFOR with common representations without requiring an abstract elaboration like those considered at this planning level.

4.2.1. COFOR maintenance and elaboration. These cooperative activities at the planning level can go from the simple *maintenance* of COFOR to more or less difficult *elaboration.* In the first case, they can be identified by unitary communications followed by a simple agreement acknowledgement. The new information is compatible with the partner's representation and this person integrates it immediately. In the second case, a more or less developed series of speech turns, punctuated by disagreements or surprises, precedes a final agreement, which terminates the elaboration. In the experiments on ATC (Hoc & Lemoine, 1998; Carlier & Hoc, 1999) and on fighter aircraft (Loiselet & Hoc, 1999), COFOR maintenance activities appeared to be prominent. This could be related to this type of situation where the process is quite rapid and with a large expertise overlap between agents.

4.2.2. COFOR on the controlled process or on the control activity. COFOR maintenance or elaboration can concern two types of entities: the controlled process (the situation external to the team) or the control activity itself (the situation internal to the team). Indeed, the communications on the controlled process are not unconnected with its management. However, this distinction must be made because these communications can indicate either information on the controlled process that are not already well integrated to the plan, or pieces of information non-accessible to each agent that need to be grouped together.

When cooperation activities at the planning level concern the external situation, they aim at generating shared contextual representations that improve communication and the choice among alternative implementations for plans. Karsenty (2000), in several studies on synchronous cooperation (between engineers and draughts(wo)men) or asynchronous cooperation (in re-use in design—between designers—or in procedure application in aviation—between pilots and designers), has assimilated these activities to explanation. In a study in progress (ATC) on the design of a computer support capable of calculating optimal deviations from schematic plans (e.g. "turn an aircraft to the right", without precision on the angle), much attention is devoted to the sharing of a common decomposition of the problem space into almost independent sub-problems between the human and the machine (Hoc *et al.*, 2000). When calculating a trajectory, the machine will be capable of identifying contextual aircraft that render the plan unfeasible and of prompting the controller to modify the problem representation.

Now, we will turn to three main categories of cooperative activities at the planning level, often cited in the literature, which concern the control activity.

4.2.3. Common goal maintenance or generation. The common goal is the design and evaluation criterion of the collective activity during a certain period of time. The goal is not already defined in terms of means by which it is to be reached. It guides the team's activity. For example, in fighter aircraft piloting, operators may have to agree on the modification of a destination goal, after an incident or the communication of a non-planned target. Such a goal is necessarily common since the operators are aboard the same aircraft. In certain situations it can remain implicit, as a simple consequence of changes in individual goals, and this can result in difficulties in anticipating interference and task achievement. For this kind of activity, as for the following one (common plan maintenance and generation), computer support by means of a graph of tasks could be of great help (Pacaux & Loiselet, 1999). This solution has been suggested in fighter aircraft piloting after our studies of cooperation in the cockpit. However, such a tool is, for the moment, restricted to plan following, without re-planning facilities (Jones & Jasek, 1997).

4.2.4. Common plan maintenance or generation. This type of activity concerns the means. When several agents are implied in task execution, a common plan may be needed to resolve coordination questions in advance. Such a plan integrates external resource allocation and may be useful although there is no common task. For example, after a train accident in the London suburbs, Dowell (1995) has shown the impact of a lack of common plan between the diverse actors in rescue operations. He has developed a simulator and a training method to improve the development of this aspect of the collective activity. Although many kinds of tools exist to assist common planning, common replanning is not as well assisted as planning. In civil aviation, Layton *et al.* (1994), and Smith *et al.* (1997) have shown that an autonomous re-planning facility leads to brittleness and complacency phenomena. They suggested that the pilot should be more active in the common plan elaboration, for example choosing among alternatives.

4.2.5. Role allocation maintenance or generation. We will not enter here into the distinction between role, task and function. We will adopt the notion of function as a generic term to cover all these entities, as is the case with most of the literature. However, the distinction is useful at a certain level of analysis. In the psychological literature, role is strongly related to accountability and does not clearly concern the machine side, but the human side of human–machine cooperation (Dearden *et al.*, 2000; Wright, Dearden & Fields, 2000). Task allocation presupposes that the human considers the entity to be allocated as a unitary task, associated with an intention to be protected (Amalberti, 1996).

Although function allocation can be considered in relation to a common plan, it may change without plan revision, in terms of actions to perform. For example, in fighter aircraft piloting, the navigator evaluates the pilot's workload and decides to perform the function of target acquisition instead of the pilot. The plan is not changed, but only the function allocation with the aim of a better adaptation of the team to the current situation.

Among the function allocation activities, Castelfranchi (1998) gives an important status to delegation, the relevance of which is obvious in human–machine cooperation. According to the author, delegation can be more or less explicit *vis-à-vis* the other agent: by taking advantage of the other's spontaneous action, by inducing an action in order to exploit it (without the other's awareness), or by negotiating this action. The delegated function can be purely executive, or more productive (giving some degrees of freedom to the other). It may concern a domain function or a purely cognitive activity (planning or control).

Dynamic function allocation between humans is often observed in human–human cooperation [see, e.g. a study of Navarro, Terrier & Courteix (1981) on this question between planning and radar controllers in ATC]. Function allocation between human and machine, performed *a priori* or in real time, has been studied by several authors (Rieger & Greenstein, 1982; Sheridan, 1988; Debernard *et al.*, 1992; Millot & Mandiau, 1995; Parasuraman, Mouloua & Molloy, 1996; Older, Waterson & Clegg, 1997). These studies stress the limitation of an *a priori* allocation in terms of adaptive power of the human–machine system. However, the allocation of a tactical function to an operator who already has a strategic role can lead to debatable results. In civil aviation, Jentsch, Barnett, Bowers and Salas (1999) have interpreted the possibility of the captain taking control in just those terms, noticing that a majority of serious incidents (especially in terms of loss of situation awareness) occur in these conditions. In ATC, it has been also shown that supervision of human–machine function allocation should be devoted to the planning controller rather than the radar controller (Debernard *et al.*, 1992; Hoc & Lemoine, 1998).

4.3. META-LEVEL

The prefix "meta" is taken here in a weaker sense than that which stands for meta-knowledge. There is no idea here of a cooperation on cooperation, but we refer to an abstraction level higher than the planning level. At this third level, more general data are produced that can be useful to the cooperative activities of the two lower levels: communication codes, compatible representation systems, and models of oneself and of the other agents. This activity level is related to the other ones by the same kind of relation as that which Falzon (1994) has defined between "meta-functional" and "functional" activity. The former is reflective on the development of the latter (directly linked to operational goals), and it enables the individual to make tools capable of facilitating the future functional activity. The former ones are often produced outside action (e.g. problem-solving outside action resulting in the discovery of a new procedure).

4.3.1. Communication code generation. Within technical domains, especially when time constraints are severe, team members use what Falzon (1991) called "operative" languages. These languages are restrictions of the natural language to reduce communication length and time while transmitting variable values of well-known schemas. Such codes are often formal or at least acquired beforehand, for example in surgical operating rooms, between pilots and air traffic controllers, etc. Sometimes, they are especially designed for a particular task when existing codes are not adequate.

In our experiment on air traffic control (Hoc & Lemoine, 1998), we have made use of electronic strips. (The strips were displayed on a computer screen and could be moved.) However, in order not to be too remote from their habit of writing on strips, controllers could use icons of different colours to mark the electronic strips. Such marks for example enabled the controllers to identify aircraft conflicts, aircraft landing at the same airport, etc. In the beginning of the experiment controllers came to an agreement on the meanings given to icons and colours.

4.3.2. Compatible representation generation. Typically, this kind of cooperative activity is observed in "integrative" cooperation (Schmidt, 1991) where agents have distinct, but complementary types of expertise. For example, an architecture project team combines several types of expertise, as in strength of materials, steel structure work, manufacturing (if the building is a factory), ergonomics, etc. To a certain extent, two-seater fighter aircraft piloting combines two types of expertise: pilot and weapon system officer correspond to two distinct occupations. However, there is a large overlap between the two domains of expertise and certain degrees of freedom remain possible for function allocation. In air traffic control, radar control and planning control do not correspond to distinct occupations since a controller is used when working on each position from one watch to another.

Regardless of the difference between the types of expertise, the type of representation of the situation is different if the function is different. Sometimes, there can be a certain redundancy between the agents (similar function), but the cognitive styles can be complementary, as shown by Dalal and Kasper (1994) in human–machine cooperation. If different persons must cooperate, it is easier when they are able to translate their representation into the terms used by the others in their representation system and vice versa. In our study on air traffic control, very often planning controllers transmitted information to radar controllers (RCs) in their own terms and RCs were able to translate this information, as an acknowledgement, into their own terms (e.g. from a state representation to an action-oriented representation).

When types of expertise are close to each other, such skills concern changing points of view. When they are very different these skills are related to translation or explanation, widely studied in artificial intelligence (Karsenty & Brézillon, 1995). Explaining consists in producing cues necessary to the other to integrate new information to a pre-existing known information network (Karsenty, 1996). It goes beyond a simple change in point of view.

4.3.3. Generation of models of oneself and of other agents. As we have already seen, domain knowledge may enable each agent to infer goals and subgoals pursued by each other from behavioural cues. However, it may happen that knowledge of the particular characteristics of an agent is necessary to produce such inference, which plays a major role in anticipative interference management and which is likely to produce optimal solutions. Castelfranchi (1998) calls this activity "mind reading". For that purpose, the agents must have at their disposal a model of the others, but also models of themselves, since it is the confrontation between the models that will enable them to manage interference. In a study of emergency operations after a train accident, Dowell (1995) has shown that one of the main sources of problems of coordination was the lack of models of the other agents.

This question is close to the trust and self-confidence problem addressed by Muir (1994) and then pursued by Lee and Moray (1994). Muir has distinguished three steps in the development of trust of the human towards a machine: (1) faith (or doubt) when there is no experience of cooperating with the machine, (2) predictability when the human can predict the machine's behaviour in some well-known situations, bearing on some experience of the machine and (3) dependability when predictability can be extended to a wide set of situations. Some difficulties encountered by humans with machines can be understood by such an approach, especially when operators bypass automation due to a lack of trust. However, in their empirical studies, Lee and Moray (1994) have convincingly shown that mere trust in the machine is not sufficient to explain shifts from manual

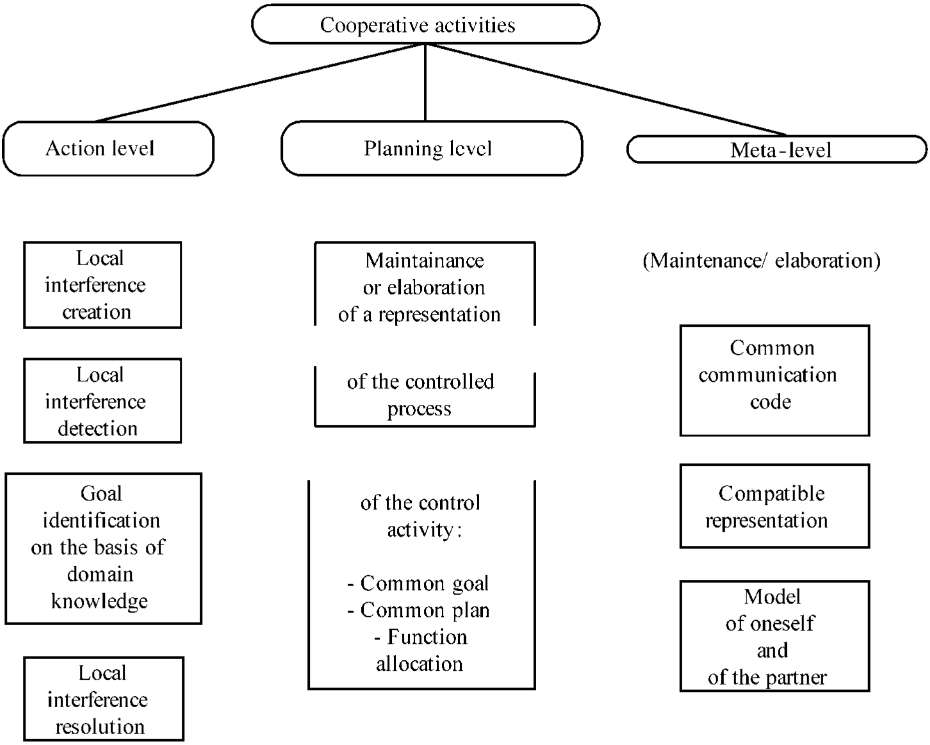

FIGURE 1. Cooperative activities.

to automatic mode (in a pasteurizer plant supervision where the two modes were available). The best model to fit the data was the trade-off between trust and self-confidence. The automatic mode may be adopted when the operators do not really trust the machine, but have much less confidence in their own abilities to manage the situation. Ultimately, the trade-off is regulated by the degree of elaboration of a model of oneself (the human operator) and of a model of the partner (the machine).

Such elaboration can take long periods of time. For example, even among pilots who have long experience with *glass cockpits*, the proportion of pilots who say they are sometimes surprised by what machines do is not negligible (Sarter & Woods, 1992; this result was confirmed by Funk *et al.*, 1999). The abstraction level needed by these kinds of elaboration was well identified by Piaget (1965) when he compared it to the abstraction level needed by the development of formal operation at the individual level. That is why he thought that intellectual development goes hand in hand with the development of what can be called "know-how-to-cooperate".

Figure 1 sums up the overall set of cooperative activities described above.

5. Prospects

Now, we will sum up the main implications of this theoretical approach, stemming from the literature, in terms of method of analysis and for design. These implications are three-fold. Firstly, this approach can guide reflection on modelling and evaluating cooperation. This question of evaluation is crucial for guiding design, training, and support for cooperation, and to provide choice criteria between alternatives. Secondly, this approach can orient research to design support for cooperation in small teams, especially in human–computer cooperation. On this topic, our work is only beginning, in air traffic control, in fighter aircraft piloting, and in drone supervision. Thirdly, going much further, this approach can lead to a re-definition of the concept of "cooperative machine" and to highlight the salience of new research perspectives in artificial intelligence and supervisory control theory in this domain.

5.1. MODELLING AND EVALUATING COOPERATION

5.1.1. Modelling cooperation. A method of coding elementary activities in protocols involving two humans or a human and a machine has been designed in ATC (Hoc & Lemoine, 1998; Carlier & Hoc, 1999) and two-seater fighter aircraft piloting (Loiselet & Hoc, 1999). It relies on the decomposition of cooperation into the elementary cooperative activities defined in this paper. It is implemented by the use of the predicate (activity)/argument (representation and activity specification) structure of the MacSHAPA software (Sanderson, Scott, Johnson, Mainzer, Watanabe & James, 1994), as a coding scheme.

The examination of the differences in distributions of predicates or of arguments among different types of simulated situations (e.g. process speed, type of assistance or type of dynamic function allocation between the human and the machine) was a way to evaluate the quality of cooperation and the effects of the experimental conditions on cooperation. Some results of these experiments have been reported above, for example the importance of COFOR maintenance activities or the complacency effects. This has led to some design solutions of general value, such as the development of external support for COFOR or the increase of human supervision on machine operation (mutual control).

However, this kind of analysis remains static and does not throw light on the dynamic course of cooperation. A dynamic analysis is in progress in fighter aircraft piloting to describe the diverse ways of resolving each kind of interference: precondition, interaction, mutual control, and redundancy. Such a more dynamic approach to cooperation could result in more accurate recommendations in terms of facilitation of interference management.

5.1.2. Evaluating cooperation. The evaluation problem has been examined on a general basis in Hoc (1998), in relation to the coding scheme. As with any other cognitive activity, cooperation can be evaluated from two points of view (Brannick, Salas & Prince, 1997). On the one hand, one can be interested in the effects produced by cooperation on task achievement. Thus, cooperation is evaluated in terms of external performance and evaluation criteria are borrowed from the task domain in relation to an optimal performance. For example, in air traffic control, one can be interested in aircraft expedition, fuel consumption, economy in deviation due to conflict resolution, or frequency of *near misses*. This type of evaluation is external. On the other hand, cooperation activities can be evaluated in comparison with what could have been an optimal development of cooperative activities (e.g. in terms of costs). Thus, cooperation is evaluated from the internal performance point of view and the evaluation criteria are psychological. For example, one could be interested in the mental workload implied by cooperation development. It is an internal evaluation.

5.1.2.1. The external point of view. For a long time, researchers have been interested in external evaluation of cooperation, by comparing performance reached either by single individuals (*solos*) or by teams (especially *duos*). The results obtained by this kind of study are diverse.

Comparisons between *solos* and *duos* in problem-solving situations very often conclude that *duos* are better than *solos* [in blast furnace supervision (Delsart, 1995); in commercial aviation (Krems & Severin, 1995); in microworld scientific discovery (Okada & Simon, 1997)]. Nevertheless, this type of study does not use a theoretical framework for cooperative activities to relate them to problem-solving activities. At least for the type of situation under investigation, it is to the credit of Okada and Simon that their study tried to identify the reasons for the *duos*' better performance. From the external performance point of view, *duos* produced more crucial experiments in terms of information received. From the internal point of view of problem-solving activities, they considered more hypotheses, which led to more explanations and debates between alternative ideas. They also produced more justifications. This type of approach, which tries to produce an explanatory model of the increase in performance, at first by the role of cooperation on problem solving, then of problem solving on external performance, seems to be the right orientation for research. The theoretical approach that we have proposed was relevant to that purpose.

Other works have tried to relate cooperation quality with performance quality [in aviation (Orasanu & Salas, 1993; Rogalski, 1996); in blast furnace control and firemen headquarters: (Samurçay and Rogalski, 1993; Samurçay & Delsart, 1994)]. The major conclusion of these studies is that it is very difficult to distinguish between the effect of cooperation and the effect of expertise in the domain. For example, Rogalski (1996), studying a training situation to cooperate in the cockpit, showed that the acquisition of expertise in the domain preceded the acquisition of know-how-to-cooperate. Thus, it is convenient to perform comparisons between teams at comparable levels of expertise to reach a better distinction between the two factors. For that purpose too, the present theoretical approach could be useful. Foushee (1984) has produced data that show that cooperation quality (in terms of communication frequencies) is related to a better performance (in terms of error rate) in aircraft crew activity. In the same domain, Stout *et al.* (1994) have found a positive correlation between cooperation ability and performance, maintaining the know-how level constant.

However, these evaluations of cooperation quality and of performance remain too coarse (relying on final performance) to lead to causal explanations. In line with Okada and Simon (1997), the application of our fine-grain coding scheme could result in a better description of why cooperation can improve or degrade performance.

5.1.2.2. The internal point of view. The cognitive architecture, which we have proposed to describe cooperative activities, shows many relationships between these activities. All these activities are likely to support each other. The main internal criterion to evaluate cooperation is thus the exhaustiveness and cost of the developed activities. At the lowest abstraction level (action level), it can be understood that the inability to infer goals and subgoals of the other agents leads to reactive cooperative strategies, because interference cannot be managed by anticipation. In dynamic situation management, time constraints can thus be a major impediment to these reactive strategies producing their results in time. If this goal identification mechanism needs more than domain knowledge, that is, the availability of a common plan or a model of the other agents, there is a lack of abstraction level. It is the same case when interference resolution cannot reach a good result at the local level. If a common plan is needed and if this level of abstraction is missing (plan level), performance will be poor and/or the workload excessive. For the most part, the criteria reviewed recently by Militello *et al.* (1999) to evaluate human–human cooperation are consistent with our framework.

However, we think that this structured framework could enrich these criteria and more accurately identify the precise sources of ineffectiveness in a particular cooperation situation. The best way to proceed is probably to evaluate interference management and facilitation of individual or common tasks. Nevertheless, a more difficult problem to solve is the evaluation of the trade-off between cost and performance. At a certain point, it is highly probable that further increase in cooperation quality may result in a poor gain in performance and possibly in a decrease, but in a considerable increase in cost. This is also true for human–machine cooperation when the cost of an improvement in the machine's cooperative power may overtake the gain in performance.

5.2. SUPPORTING COOPERATION

The architecture that has been proposed for cooperation can also be utilized to define support for cooperation between humans and between the human and the machine. The agents of a team can potentially implement all the cooperative activities we have presented, but may be unable to perform them without support. Sometimes, especially in human–machine cooperation, only one agent (the human) is really able to develop cooperative activities, but needs some help from the other (the machine). Several studies have stressed the importance of COFOR maintenance (Jones, 1995; Lemoine, Debernard, Crevits & Millot, 1996; Jones & Jasek, 1997; Carlier & Hoc, 1999; Garbis & Wærn, 1999; Loiselet & Hoc, 1999). Indeed, this entity plays a crucial role in anticipative interference management and it is not surprising that it receives a great deal of attention.

Within the multidisciplinary research team on dynamic task allocation in ATC, grouping together control theorists and psychologists, the first design principle proposed by control theorists was to develop a system capable of implementing abstract plans on individual aircraft and rerouting, integrating negotiation with the controller during the process. This principle was a possible solution to avoid the complacency phenomenon by encouraging mutual control (by the human over the machine). However, our studies have shown the importance of a COFOR between the agents in terms of a common structured problem space. Obviously, the anticipated limits of the projected "machine" imply that the human controller would elaborate this COFOR. So, the design will integrate some graphical support to the human elaboration and utilization of this problem space, which will be systematically utilized to structure the communication between the human and the machine. In addition, the machine will be able to enrich the representation of a particular problem, suggesting the addition of new aircraft discovered as interfering when trying to implement a plan. In that way, the machine will not only say that a plan is difficult to implement, but also the reason for this difficulty in terms of problem definition. Without deep cooperative capability, the machine could support a COFOR.

The study on fighter aircraft piloting suggested that COFOR support be developed between the pilot and the navigator, support which could also be utilized between a human navigator and a machine pilot (e.g. drone). Two graphical supports are currently being tested. The first one is very close to the ISAM principle (Jones & Jasek, 1997). It consists of a graph of tasks, representing the earliest and the latest due time to perform a task (as is the case for production management) and an indication of task allocation status (not allocated, allocated to the pilot or the navigator). The main limitation of this principle is the restriction of the elaboration to pre-planning (during mission preparation), excepting possible changes in task allocation. For the moment, re-planning is not integrated in the support. The second support is a map of the mission, representing the series of goals. The two agents can write information (with icons and short texts) nearby each goal. This can be utilized to communicate important events, preconditions, coordination needs, etc.

More generally, this theoretical approach can contribute to identifying the more crucial cooperative activities implied in a specific situation and to providing specific and precise assistance to these activities. If it is impossible to expect that a particular machine has a minimal know-how-to-cooperate at its disposal, it is, nevertheless, unreasonable to abandon the cooperation framework as a means for analysing and designing the human–machine relation. Even if the machine is not able to perform any cooperative activity, it can be designed to support its users, who have a know-how-to-cooperate at their disposal and can perform human–machine cooperation activities. As far as interference management is concerned, a number of solutions are available, for example designing machines capable of returning appropriate feedback, including anticipated feedback. Informing the user of what the machine is doing and of what it will do in the near future is a significant support to interference detection and anticipation. The identification of the minimal knowledge of the machine operation required to enable the user to adequately manage trust in the machine is also a key point. All these features lead us to consider that human–machine cooperation can be considered as a cooperation between the designer and the user (Karsenty, 2000). It is clear for example that, if the designer denies the brittleness of the machine, mutual control will not be encouraged and necessary information to transfer to the human when manual control is needed will not be anticipated.

5.3. DESIGNING COOPERATIVE MACHINES

The approach we have highlighted can be a basis for defining what could be considered as a "cooperative machine". However, the cooperation capability must be evaluated in relation to performance, and of time constraints for the development of communication. (This problem is similar between humans.) Following this approach (interference management and facilitation), Millot and Lemoine (1998) have developed some interesting ideas within the typology of cooperation situations introduced by Schmidt (1991). This typology considers three types of cooperative situations. Augmentative and debative cooperation concern several agents of similar expertise, the former to solve workload problems, the latter to encourage mutual control and performance quality. Integrative cooperation implies several agents with distinct expertise to cover all the aspects of the task. Millot and Lemoine consider that these three types of situations can be considered as a sufficient set of primitives to generate (by combination) all the possible cooperation situations. For each one, they have defined the know-how-to-cooperate, in terms of interference management and facilitation.

However, some difficulties remain in the implementation of the know-how-to-cooperate. As is the case for the study of human–human cooperation, the role of implicit knowledge (e.g. implicit expectations) in the COFOR is difficult to address. It can play a major role in reducing the need for communication. The same is true for implicit communication, by a common access to information from which COFOR elements can be inferred without formal communication. Cooperative goal or plan elaboration remains a difficult topic, without the role of a coordinator, which can be played by one of the agents (with implication on workload) or by an extra agent, specifically designed for that purpose. Above all, replanning in real time under time constraints is not often implemented.

6. Conclusion

Without neglecting the relevance of social approaches to cooperation, the cognitive approach suggested here appears necessary to guide cooperation evaluation and support, and to orient the design of cooperative machines. Although it is restricted, this approach enables us to extend individual cognitive models to cover the cognitive study of team work, at least in situations where the cognitive dimension is major, certainly in those where temporal constraints and risks are high. To a certain extent, this approach stresses the main characteristics of cooperation in such dynamic situations.

This approach can be considered to be productive in the medium term in designing a human–machine relation as close as possible to human–human cooperation, given the machine intelligence constraint. With this aim, the human model plays a critical role, since one of the components of the cooperative system is human. However, we think that it is not reasonable, at any price, to transfer all the complexity of human–human cooperation to human–machine cooperation. The human–machine couple is indeed a chimera and the current limits of the machine do not enable us to make such a transfer. Nevertheless, we think it is possible to design cooperative machines, on the basis of the current state of the art, without waiting for long-term research developments. It would be a great pity to acknowledge such inaccessible complexity and to be content with a poor human–machine relation when it can be improved.

However, the necessary development of research on this question of human–machine cooperation can only produce exploratory solutions *vis-à-vis* the difficult questions of their implementation in real settings. Any increase in the machine's intelligence, even in terms of know-how-to-cooperate, may create boundary effects, which are not anticipated. Further, the development of machines capable of cooperating could enable us to study such effects and to reflect on possible answers.

Pursuing multidisciplinary work between human and engineering sciences is crucial to define the research to be developed correctly. As far as psychology is concerned, without neglecting the complexity of human cognition, this discipline should give productive data for designers. The reinforcement of formal approaches and conceptual elaboration remains necessary, as well as the increase of observational and experimental data of more general value than simply producing illustrations. In artificial intelligence, without forgetting the feasibility constraints, researchers should go beyond the strict framework of human–machine interaction or communication. Above all, designers should more firmly adopt the point of view of a human–machine system than the strict point of view of the machine. Many keys to human–machine cooperation rely on the availability of a model of the human during the design process. Rather than speaking of human–machine cooperation, it would be preferable to speak of designer–operator cooperation.

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