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Decision support in fighter aircraft: from expert systems to cognitive modelling

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Abstract. This paper reviews two major programmes for support of pilot decision making in a fighter aircraft: the US Pilot's Associate and the French Copilote Electronique. In addressing the problem of decision support in a highly complex and time-pressurised environment, both programmes migrated from a traditional expert systems approach to one based on cognitive modelling. This, however, is where most commonality ends. The paper shows how the differences between the programmes can be explained in terms of their assumptions of what constitutes pilot expertise. These views explain the method for analysis of pilot activities, the model of the pilot, what phase of the pilot's problem solving the programmes attempt to support, and the support philosophy. The paper concludes with a discussion on computer-based decision support in complex, dynamic domains, and how cognitive modelling may contribute.

1. Introduction

There is a relatively rich, if recent, history of developing computer-based decision support (see e.g. Guerlain *et al.* 1999). One domain where operators depend critically on decision support is fighter aircraft (Rouse *et al.* 1990). The modern air environment features a proliferation of sensors, weapons, and information technology. Sensors with long range, integrated communication networks to combat centre and air defence systems, and data links to other aircraft in the group continuously transmit data about current threats and tactical opportunities. Typically, the transmitted data is uncertain and often contradictory—mostly due to sensor properties and interference through electronic warfare. From this large amount of ambiguous data, pilots must assemble evidence from several partly automated sources (e.g. radar, countermeasures); assess situations and evaluate the significance with respect to mission goal and capabilities of own and opponents' aircraft and defence systems. The cognitive demands are severe; the consequences of failure grave (e.g. Snook 2000).

Opportunities for reflective activity are limited when flying a high-speed fighter aircraft under time pressure, stress, and risk. For example, when there are deviations from the original plan in a low level attack mission, only 10% of the time is invested in planning for a longer time horizon, and the majority of these periods are shorter than 20 s (Amalberti and Deblon 1992). Similarly, interpretation of even a moderate complexity of tactical information forces the pilot to increase altitude in low-level and high-speed missions (Svensson *et al.* 1997). Ambiguities in target identification are common, and fratricide is an ever-present risk (Snook 2000). Not surprisingly, a support system that aids the pilot with a more efficient use of his/her cognitive resources has long been considered critical for progress in military aviation. Since the mid 1980s, there have been considerable efforts to develop decision support systems for presentation of information and relevant task knowledge which adapt to the situation and the pilot's current goals. Most of these systems address specific applications, such as air-to-air combat, air-to-ground attack, or landing (see Emerson *et al.* 1992) and rely on approaches ranging from mathematical game theory and heuristic methods (Herbst 1992), to algorithmic assessments of important threats (Mitchell 1992).

Two systems are discussed in this paper—both the outcome of major research programmes for knowledge-based decision support in fighter aircraft: the US Pilot's Associate (Rouse *et al.* 1987) and the French Copilote Electronique (Amalberti and Deblon 1992). The reasons why these systems qualify as state of the art is that (1) both support the pilot during the whole mission from starting, flying to the assigned combat area, attacking

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targets, flying back to the base, and landing, (2) their purpose was to achieve better performance and adaptation in both air-to-air and air-to-ground missions, and more accurate responses to changes in the environment and failures of onboard systems; (3) both view the pilot's task as complex problem solving in a dynamic and uncertain environment where factors such as time pressure, uncertainties, dynamics, and cognitive resources must be balanced and managed to achieve the goal of the mission, and (4) they were both inspired by the powerful representation and inference mechanisms used in artificial intelligence. The advantage with these representations is their flexible semantics in comparison with traditional presentation and automation techniques. The pilot's intentions, the situation in the environment, and the status of the aircraft can all be represented in an integrated framework. A system with this information can in some sense intelligently adapt to the pilot's task in the current situation and provide appropriate support.

Although both Pilot's Associate and Copilote Electronique admittedly are rather old relative the developments in computer science, they both ended in the early 1990s, their assumptions about decision support are still valid for current research programmes. The associate concept has been used for the US Army's Rotorcraft Pilot's Associate (Miller and Hannen 1999), the future main battle tank in Crewman's Associate (Pechacek and Webb 1996), and UAVs (Geddes and Hoffman 1990, Miller and Goldman 1999). The associate concept is also an example of approaches that exploits and represents procedural task characteristics to capture time varying task demands (see Miller and Vicente 2001). Other examples of the approach can be found in driver support systems (Michon 1993, Remboski *et al.* 2000, Bellet *et al.* 2002). In principle, the associate and similar systems maintain all necessary knowledge to perform individual tasks at an acceptable level. The knowledge is adapted to the situation and presented as recommendations to the operator or transformed into actions. However, in complex and dynamic domains, such as a fighter aircraft, there are often ill-defined situations where solution oriented approaches may show brittleness, poor consideration of individual differences, and is difficult to understand and challenge due to a form of reasoning that is far from the heuristics pilots use to cope with the time pressure (Amalbert and Deblon 1992). Instead Copilote Electronique proposes a support directed at operators' situation assessment, a form of support that has received increasing interest (see Cohen *et al.* 1996, Freeman and Cohen 1998). Since both programmes illustrate contrasting approaches for decision support, a review may form a window on the different assumptions that govern the development of computer-based decision support systems—even in other domains (e.g. Dekker and Hollnagel 1999). Specifically, the review considers how the programmes confronted the common challenges on:

- How to model, and subsequently support, the human's understanding of the situation;
- How to analyse and decompose work for allocation between human and the support system;
- How to determine human authority relative to the system.

Next Pilot's Associate is reviewed followed by Copilote Electronique and a discussion of the contrasting approaches for support. The review concludes with how assumptions on pilots' expertise guided the development of the decision support systems and directions for future work.

2. Pilot's Associate (PA)

In 1986, the Defense Advanced Research Projects Agency (DARPA) initiated the Pilot's Associate programme with the purpose to develop a fully integrated decision support system for fighter aircraft pilots (Banks and Lizza 1991). The associate concept provides one of the most extensive forms of support in the full action cycle for assessment of the situation, planning actions, and execution of actions (Geddes and Shalin 1997). Commonly, several tasks must be processed at the same time and system competence can support the pilot when s/he is preoccupied or incapable of performing suitable actions. This means presenting information and advice relevant to the situation, and assuming control of some portion of the task when suitable (Rouse *et al.* 1987).

Such support is useful for the pilot in several ways: automatic presentation of task relevant information improves the pilot's awareness of the situation, appropriate advice complement the pilot's knowledge, and a task allocation that is sensitive to the pilot's workload improves efficiency (Rouse *et al.* 1990).

The adaptation of information and advice to the situation required a detailed understanding of pilot competence. The modelling of pilot competence in Pilot's Associate has many similarities with a traditional hierarchical task analysis where the system preserves online the knowledge needed for performing all tasks at an acceptable level. The operational knowledge was based on interviews with experienced pilots and experts on mission planning, air combat, sensor management, and diagnostics. The elicited knowledge was implemented as expert systems that combine specialized algorithms and declarative rules for how to integrate information and apply the algorithms. Although rooted in the oft-criticised expert systems approach for supporting the pilot, many problems are addressed through the Pilot-Vehicle Interface (PVI) that manages all communication between the expert systems and the pilot. Before discussing the interaction with the system through the PVI in more detail it is important to know a little bit about the types of recommendations the pilot receives for support of acceptable performance. Therefore, the PA modules are reviewed shortly.

2.1. *Mission Planner (MP)*

Before take-off in an air-to-ground mission the pilot spends considerable time planning how to achieve the goal of the mission, such as the best route that avoids known and possible threats. The route is partitioned into a series of navigational points that the pilot attempts to pass at speeds and times calculated during the mission planning. These points provide a structure to the mission that allows the pilot to compensate for deviations locally and still achieve the overall goal of the mission. The purpose of the Mission Planner is to reduce the need for mental compensation in case of deviations by adapting the plan to the current situation (Key 1987). When the margins of error are exceeded, a new route is generated that minimize threat exposure and conserve fuel.

2.2. *Tactics Planner (TP)*

When approaching a target or threat the pilot must select heading and speed considering the type of threat, constraints on fuel and time, and use of sensors and suitable weapons. The purpose of the Tactical Planner is to support the pilot in choosing a response by representing possible alternatives in a flexible framework. This framework specifies the conditions when the alternative is appropriate, and how to adapt the alternative to the current situation (Edwards 1986). Within this framework parts of plans may be modified or replaced without losing the overall structure of the plan. The TP does not generate new alternatives since this would take too long and probably not be comprehensible for the pilot. For comparison of alternatives, a measure of effectiveness is calculated that depends on the exposure to threats, vulnerability and risk, and probability of success.

2.3. *Situation Assessment (SA)*

Improvements in sensors and information technology have significantly increased available information about the combat environment. A variety of sensors with different characteristics cover longer ranges, and data may be transmitted through integrated communication networks and data links. The purpose of the Situation Assessment module is to support the pilot and planners for tactics and mission with an integrated interpretation of the combat environment. This way the system conveys meanings that map more directly onto plausible pilot actions (cf. Klein 1993, Flach 2000). The SA module correlates sensor data by identifying and resolving conflicts, derives information at a higher level of abstraction, interprets data from intelligence and combat centre in the current situation, and plans how to use sensors for threats currently not covered (Sweet *et al.* 1986). The focus of the SA activity is guided by the continuous changes in the pilot's information requirements for the goals currently pursued, the threat situation, status of own aircraft, and other planners' information needs (Whiffen *et al.* 1989).

2.4. *System Status (SS)*

Several warnings are typically available to alert the pilot when measured internal sensor, such as engine temperature and oil pressure, are not within specified boundaries, and thus probably indicate a malfunction. The difficulty is that while warnings are useful for single component faults, the complexity often causes faults to propagate to other systems resulting in additional warnings (Singer and Dekker 2000). Quick reconfiguration of the aircraft is then necessary to avoid further damages. The purpose of the System Status is to support the pilot and PA planners with a more efficient diagnosis and responses to malfunctions (Dietz and Pomeroy 1986, Pomeroy 1989, Pomeroy *et al.* 1990; see also Billings and Dekker 1997). When a fault is detected, the failed component causing the fault is searched with generation and test of fault hypothesis at successively lower levels in the system hierarchy. The cause of the fault and suitable corrective actions are presented to the pilot.

2.5. *Pilot-Vehicle Interface (PVI)*

The purpose of the Pilot-Vehicle Interface is to manage the communication between the pilot and Pilot's Associate modules, monitor for critical errors, and take control of portions of the task when suitable

(Rouse *et al.* 1987). Central to these efforts is the recognition of the pilot's intentions since this gives a common system-level view of what the pilot is doing (Geddes 1986, Hoshstrasser and Skidmore 1991, Hammer and Small 1995). When the pilot's intentions are known, relevant information can be presented using on-line display design and the system's expertise focused on relevant areas. The relation between pilot's actions and intentions is represented with a normative analysis of the task in a hierarchical plan-goal graph. The graph describes possible goals, the set of plans that may achieve the goals, conditions for when plans are valid and invalid, possible side effects, and rules for what actions are associated with the plans used in achieving the goals (Geddes 1985). Intentions are inferred from the plan-goal graph in a bottom-up search, starting with the observed action (Hoshstrasser and Geddes 1989). While this procedure allows only a coarse inference of the intention, it is still sufficient for the system to interpret at a higher level of abstraction what the pilot wants to do. An implicit communication of intentions is functional as long as incorrect inferences are not catastrophic or long lasting (Hammer and Small 1995).

Three support functions are handled specifically by the Pilot-Vehicle Interface:

- The information manager automatically presents information judged to be useful for the pilot.
- The adaptive aiding automatically performs tasks when the pilot's workload increases, provided the pilot has authorized the task transfer.
- The error monitor informs the pilot when the aircraft approaches a critical situation with a saliency depending on the urgency. If the situation is not stabilized in the available time, control is transferred to the adaptive aiding.

2.6. *Evaluation of Pilot's Associate*

An extensive evaluation of Pilot's Associate was conducted when the programme ended (Geddes 1991). To pilots, the most visible feature of the Pilot's Associate was the automatic management of presented information. Generally, pilots appreciated the automatic integration and presentation of information. In the first PA version the information manager made the same selection of presentations as the pilots in 70% of the cases (Howard *et al.* 1988). Further, pilots rated the information manager highest of the support functions discussed above, in terms of viability, acceptability, validity, and desirability (Sewell *et al.* 1987). During most of the time in a simulated mission the pilot did not need to manipulate the displays, and no one criticized the choice or timing of displays (Banks and Lizza 1991, Hammer and Small 1995). In an initial evaluation of the information requirements by a pilot observing a precomputed mission, only one fault was found among five hundred requirements (Rouse and Hammer 1991).

In modelling the pilot's task performance, the assumption was made that when some duties were assigned to the system the pilot would have more time for higher-level decision-making. However, when evaluating the system in air-to-air combat the shift in pilot assignments added more workload than was removed (USAF 1995). Managing allocation of task for rapidly changing goal priorities and needs were not sufficiently considered. While the PA's backup philosophy may complement the pilot in some areas, more benefits may be gained from supporting the pilot's situation awareness (Hammer and Small 1995). Recommendations should not be presented if more information could suffice (see Endsley 1995).

In summary these experiences of Pilot's Associate show that:

- In testing the system, pilots appreciated an adaptive system that presented advice and information depending on the situation and the mental workload.
- The derivation of intentions is very coarse and sometimes erroneous but is sufficient for the purpose of focusing expert systems and presenting relevant information.
- Pilot interaction with the system in air combat turned out to raise the mental workload—rather than lowering it.
- Instead of recommendations, pilots may benefit more from support of situation awareness; that is the interpretation and evaluation of complex information.

3. Copilote Electronique (CE)

Where Pilot's Associate emerged from research in human factors and artificial intelligence, Copilote Electronique followed a rather different route with a much stronger emphasis on the pilot's cognitive processes, and how the system could support these processes for an improved overall performance. Just as the cockpit is designed for the pilot's physical characteristics, the support system should be designed for his/her cognitive characteristics and aid in the decision making process (Woods 1986, Hollnagel 1997, Vicente 1999). Design of support systems that corresponds to the pilot's cognitive characteristics requires an understanding of how s/he utilizes important information, assesses the situation, and co-ordinates the dynamic demands on resources and cognitive activity. Co-ordination of the cognitive demands is an important consideration as the specific task knowledge is only one aspect of the competence for control in a dynamic environment. Equally important is how individual tasks are combined and prioritized into a coherent set of activities and how the pilot may regulate his/her activities considering the level of ambition for reaching the goals. Signals used in the control of the activity are for example the pilot's perception of mental workload and errors. An elaborated model of the cognitive process may give a better understanding for how the systems proposals should be coupled to the pilot's form of decisions making.

To develop a cognitive model of the pilot, the researchers combined the francophone tradition of field studies using activity analysis and contemporary research in cognitive science (cf. De Keyser 1992). Contrary to other approaches in human factors the activity analysis is basically performed bottom-up from observational protocols to a theory of activity (Amalberti 1992). The analysis relies on extensive field observations of operators in both real and simulated tasks, and semi-structured or open-ended interviews where operators explain how they view their task. Various theoretical frameworks in psychology, sociology, logic, and cognitive anthropology are then used for constructing a theory that describes the operators' behaviour. Central for this description is an understanding what the multiple goals and the external and internal constraints mean from the operators' point of view (De Keyser 1991). The result of the activity analysis is an ecologically valid model of operator activity in the natural work environment.

As a first step towards the complete system, the researchers made an in-depth analysis of the pilot's cognitive processing in low-level air-to-ground missions (Amalberti and Deblon 1992). In this type of missions the pilot must be at the specified location within a margin of only a few seconds. The time is critical both when crossing the front line and at the target location. Own air defence systems will refrain from firing during only a brief period and time over target is chosen to maximise the surprise of attack. To succeed with the mission the pilot must fly at high speed and utilise cover from the terrain. The flight path is chosen to avoid known threats within the constraints given by the objective of the mission. Often, however, the pilot may receive radar warning from unknown threats or fly into bad weather, which causes deviations from the planned trajectory. Thus, there must also be some margins in the overall plan.

Before discussing the details of the cognitive model it is important to know how it was used in the system for support of the pilot. Amalberti and Deblon (1992) describe how the system, in low-level air-to-ground mission, can support the pilot by supplying additional information from another point of view. This form of coupling with the operator, a 'critic', has been suggested as one of the most promising approaches (Woods 1986). The support is directed at the pilot's conceptualisation of the situation rather than the full action cycle (as in Pilot's Associate). Thus, the system will use the same information as the pilot, but contribute with it is own interpretation and assessment of the situation. There are several advantages with this approach:

- A system that uses heuristics familiar to the pilot will be easy to understand.
- A homogenous style improves coherence of the generated advice and fits into the framework of the pilot's expectations. This increases his/her confidence and trust in the system.
- The use of heuristics limits the problem of generating advice in real-time from underlying theoretical knowledge.

3.1. *The cognitive model in Copilote Electronique*

Amalberti and Deblon (1992) describe two in-depth studies of pilot activities in low-level air-to-ground missions. The purpose of the first study was to identify the main characteristics of the cognitive processes and used a single pilot. The study included a job analysis of manuals and instruction books, goal analysis, eight operational flights by the pilot that were recorded on video, and 30 interview sessions where the pilot viewed the videotapes and explained his activity. The second study complemented the first using a full-mission simulator where eight pilots of varying expertise performed low-level air-to-ground mission. The result of the studies show that due to the time pressure and high demands on attention the pilot tries to reduce uncertainties both before take-off and during the mission. Before take-off the pilot spends considerable time planning how to achieve the goal of the mission (see the Mission Planner above). This detailed preplanning solves many problems in advance, such as the best route to avoid known and potential threats, use of cover from the terrain, effects of weather, the tactical approach, and possible events and how to respond. The generated plan, however, varies considerably depending on the pilot's experiences and capabilities. First, since the expert pilots are more skilled in navigation and control of the aircraft, they can use small and precise navigational points, such as isolated houses or road intersections. Inexperienced pilots, on the other hand, prefer large objects and fewer navigational points than the experts do. Thus, the inexperienced pilots are more constrained in selecting the route and may have to fly a longer distance. Second, inexperienced pilots build in more degrees of freedom and margins in the plan than the experts do. Finally, the pilot's experiences are important for the events s/he expects during the mission.

With more experience the experts can reduce the decision tree by readily selecting events that require immediate responses and delaying other decisions to the following legs. During the flight the pilot attempts to pass the navigational points at predetermined speeds and times. This allows him to compensate for deviations locally and still achieve the overall goal of the mission. Compensation for deviations with preplanned responses gives him more time for anticipation of future situations. The short-term control of the aircraft always has the highest priority and the pilot can only direct his/her attention towards long-term planning during periods when the flight is sufficiently stabilized. In fact, the pilot actively tries to remain within situations where s/he can resort to preplanned responses. A rapid solution to the problem may be more important than a correct diagnosis. Three categories of activity stand out from the analysis of flying a low-level air-to-ground mission.

- Short-term handling with systematic checks of desired speed and time at the start of each leg. Simplified rules are used for compensation of deviations.
- Coherence and confidence assessment of the situation and status of the aircraft before directing the attention towards long-term planning. Often simple heuristics are used based on the redundancies of aircraft data.
- Navigational and tactical anticipation of future events and the effects of responses to these events.

The cognitive model has been implemented as computer simulation for validation and demonstration of the support philosophy. The cognitive simulator is organised in two levels for short-term navigation and long-term anticipation and adjustment of the situation. Both levels use a similar architecture for co-ordination of actions, timing actions, performing actions, and adapting to the situation. The activities are performed in parallel within the constraints of the resource management. This involves priority to short-term activities and restrictions on the number of simultaneous activities. Preplanned responses are activated to manage the disturbance when incidents arise. Severe disturbances may require compensation and adaptation on several legs or even a change in strategy.

3.2. *Evaluation of Copilote Electronique*

The thorough approach for development of the cognitive model in Copilote Electronique resulted in a valid description of how the pilot uses mental resources when flying low-level air-to-ground missions (Amalberti and Valot 1993). The model reveals how management of resources influences planning of the mission, the confidence assessment that the situation is stable enough for switching of focus to long-term planning, and adaptation towards known situations where preplanned responses can be applied. All these activities are often based on the pilot's meta-knowledge of his/her own capabilities and experience (see also Valot and Amalberti 1992). In planning a mission, meta-knowledge influences the degrees of freedom in the plan for dealing with disturbances, the route chosen, and the anticipation of critical events. Similarly, during the flight the pilot adapts in advance to possible future events using the degrees of freedom that are built into the plan for each mission. This is necessary to utilise the pilot's capabilities and preplanned responses. Finally, incidents are handled in two steps. The situation is first stabilized using a preplanned response. This gives the pilot time for the second step of handling the long-term consequences.

The computer simulation of the cognitive model turns out to be a valid description of pilot activities and a support system based on this simulation enhances the pilot's understanding (Amalberti and Valot 1993). Consistent with the evaluation of the Pilots' Associate, the cognitive modelling effort for the Copilote Electronique confirmed how the system should support a pilot's anticipation and understanding rather than generate optimal reactive solutions.

In summary this review of Copilote Electronique shows that:

- The time pressure during the mission force the pilot to reduce uncertainties as much as possible by anticipating possible events, and how they should be handled.
- The planned route serves as a flexible framework with degrees of freedom to accommodate disturbances.
- Meta-knowledge is used to maintain the situation within areas where know solutions can be applied.
- Incidents are managed in a two-step process where the situation is stabilized with preplanned responses and then the long-term consequences are controlled.
- A support system using a homogenous style and similar heuristics as the pilot may enhance the pilot's understanding of the situation.

4. Pilot's Associate and Copilote Electronique: contrasting approaches for support

There are many similarities between the Pilot's Associate and Copilote Electronique for support of pilot decision making. In terms of scope they intended to cover all aspects of the pilot's missions in all phases of the flight during both air-to-air and air-to-ground missions. Both used contemporary research in cognitive science and artificial intelligence as tools for modelling of the expertise that was implemented in the system. However, as the reviews show, there are also many differences between the programmes. The most important of these differences is the view of pilot expertise that was consequently modelled in the systems and relied on for the kind of support offered. Pilot's Associate views the pilot's expertise as consisting of individual tasks. The system's competence contributes in the interpretation of the situation, planning of actions, and automatic presentation of relevant information, and implementation of actions. Copilote Electronique, on the other hand, views the pilot's task from a cognitive perspective where the competence for performing individual tasks is only one aspect of pilot expertise. Equally important is the pilot's awareness of his/her own expertise and resources that form the basis for how individual tasks are combined into a coherent activity (see Amalberti and Hoc, 1998).

These divergent views of the expertise determined the method of analysis for describing the competence and the cognitive model represented in the system. Pilot's Associate used a task analysis approach for competence description which was represented in the plan-goal graph; a general form of knowledge representation. Copilote Electronique, on the other hand, included additional aspects of the pilot's competence and used activity analysis for deriving a valid model of how pilots cope with the situation in a fighter aircraft. A common experience when analysing expertise at this level is that the strategies and representations operators use tend to be closely related to the actual constraints and dynamics encountered in the environment. Thus, a specialized model and form of representation would be needed for the task at hand (cf. Sternberg and Frensch 1991). This was the case in Copilote Electronique where the specialized model of the pilot could not be understood outside the context of fighter aircraft operations (Amalberti and Deblon 1992).

The view of the expertise also influences the type of support the pilot receives. Both the phase of the pilot's problem solving where the system supports the pilot, and the philosophy of the support, are affected. With the strict organization of the competence in Pilot's Associate, the system can support the pilot in all phases of the action cycle: information assimilation, planning of actions, and execution. Since the system is assumed to have a sufficient competence for performing these tasks at an acceptable level, they are simply allocated to the system when the pilot is preoccupied. Copilote Electronique, on the other hand, is more concerned with the support of the pilot's assessment of the situation rather than the actual solution of the problem. Specifically, the system focuses on the pilot's conceptualization of the situation or problem identification by stimulating self-reflection. The assimilation of information together with a more complete understanding of the situation may improve the pilot's choice of approach for handling the situation.

5. Conclusions

The evaluations of Pilot's Associate and Copilote Electronique show that both programmes succeeded at least partly in their goal of developing a decision support system for fighter aircraft pilots. In the Pilot's Associate programme a complete system was developed for support of the pilot in the whole action cycle with assessment of the situation, planning of actions, and execution. The support is based on an operator centred backup support philosophy with automatic management and presentation of relevant information, adaptive aiding depending on the pilot's workload, and error monitor for enhanced information and safety barrier. Generally, the pilot's appreciated the support. However, there were also disappointing results in terms of increased mental workload when using the system, and a preference for support of the situation awareness rather than the planning of action. This indicates that the theoretical assumptions of pilot activities and how to support them may have been too static, or fixed too prematurely, or both. In fact, as Guerlain *et al.* (1999) argue, the whole point of getting away from expert system-based approaches is to invert the notion of decision support: instead of the machine generating solutions for the user to critique, the system should be put in a position to critique solutions proposed by the user (cf. Sillince 1994, Cohen *et al.* 1996). In its heavy reliance on supporting situation assessment more than anything else, Copilote Electronique moved much closer to that ideal than Pilot's Associate.

Indeed, the Copilote Electronique programme invested considerably more time in the development of a cognitive model for how the pilot manages his/her resources within the time pressure and constraints of flying a fighter aircraft mission. The cognitive model of pilot activities in low-level air-to-ground missions gives a valid description for how the pilot reduces uncertainties both before take-off and during flight. The model shows how the pilot's meta-knowledge of own capabilities is utilized for the planning of navigational points, and for how the situation is maintained within areas where preplanned responses can be applied. The first prototype of the support system used this cognitive model for enhancing the pilot's understanding of the situation. The development of the complete system started only after such painstaking theoretical analysis.

The programmes' diverging views of pilot expertise motivate how the support systems were developed. Pilot's Associate view the pilot's expertise as consisting of the competence in specific tasks. This motivated an analysis similar to a traditional task analysis where the competence was represented in a general hierarchical plan-goal graph. The system can then support the pilot with generation of situation assessments, planning of actions, and execution. Copilote Electronique, on the other hand, adopted a much broader view of pilot expertise as not only consisting of individual task knowledge, but also how tasks are combined into a coherent activity within the time pressure and constraints of the situation. Thus, an activity analysis was used for cognitive modelling and the results were implemented in a computer simulation that cannot be understood without reference to fighter aircraft operations. The support that relies on this cognitive model is directed at the pilot's conceptualization and understanding of the situation, and supports the situation assessment phase, rather than the full action cycle—echoing research results on the 'front-loaded' nature of naturalistic decision making (Orasanu and Connoly 1993).

Both Pilots' Associate and Copilote Electronique also show how difficult a problem pilot support really is—or decision support in general. A general problem when developing human-centred decision support systems is the difficulty of developing a model of operator activities at a sufficiently descriptive level for available technology to provide the necessary support. Any effort in this area must somehow address the transformation of results from the cognitive modelling into design recommendations. Pilot's Associate emphasized the technological development, which simplified the transformation. Copilote Electronique, on the other hand, emphasized the theoretical development which may have made the transformation more difficult.

The developments of support for the pilot's specific problems identified in Pilots Associate and Copilote Electronique have continued as separate efforts. Most aircraft have integrated presentation of system warnings and guidance for what the pilot is expected to do. Automation has been developed for configuration of weapon parameters, critical aircraft manoeuvres in beyond visual range combat, and low-level flight. There are also systems available for in-flight mission replanning. These efforts for addressing specific problems when technological solutions are available will continue in the future. A gradual evolution of support systems is likely, although the integrated approach in Pilot's Associate and Copilote Electronique for addressing the whole range of pilot activities has many advantages. The technology that presently may have the largest impact on support of the pilot and reduced mental workload is the development of statistical data fusion algorithms for automatic integration of multiple observations of the same object (see Waltz and Llinas 1990, Steinberg *et al.* 1999, Blackman and Popoli 1999). Currently, the information from sensors and data links is presented in overlays that the pilot integrates himself. The rapid development of many types of sensors with increased range and integrated communication networks will, however, make the displays difficult to interpret. Some form of automatic integration will be necessary in the next generation of displays for support of the pilot's situation awareness. The displays that are developed for the statistical algorithms must, however, conform to the pilot's expectations and form of reasoning. Cognitive modelling and principles of cognitive ergonomics may be a suitable approach for the development of such displays.

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