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The issue of ground/cockpit integration: results from field studies

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A pilot activity analysis has been performed to study the relation between the cognitive behaviour of an expert aircraft pilot and the worksystem. The cognitive demand of the pilot's task is related to the level of automation (or mode) of the supporting tools. The mode choice stems both from a personal "flying style" and worksystem constraints. One of the most relevant constraints is the air traffic control operator's requests. A study on air traffic control operator stress shows that this demand actually comes from flow management and is propagated from the ground to the cockpit. Thus, our research, based on natural setting observations, confirms that operators, and designers, from both ground and cockpit sides, should better cooperate and consider that there is one and only one worksystem.

Keywords: pilot task, air traffic control, activity analysis, worksystem, cognitive demand, stress, use of automation.

Introduction

An increasing number of accidents caused by human factors has reinforced the demand for research in the field of cognitive behaviour in complex systems. In the aviation domain, a kind of human factors-related accident which is particularly disastrous— 68% of 1995 fatalities (Learmont, 1996)— is controlled flight into terrain, where a perfectly operating aircraft, under the control of the crew, is flown into terrain (or water) with no prior awareness on the part of the crew of the impending disaster (Wiener, 1977). In these cases, the crew has lost the awareness of what is going on and realises it too late or not at all. In other words, the problem stems from the fact that a situation, judged as safe or not judged at all, should actually not have been tolerated. Thus, human error and accident issues have to be tackled not only by studying human behaviour in emergency but also by analysing normal activity. Our contribution can be placed within this last perspective: it describes pilot cognitive activity in a normal flight context, in cases both of good and poor performance.

The flight context can be seen as the worksystem status. The worksystem gathers the components that help the pilots in their task but also the elements that might raise problems. The mission of the commercial pilot is to fly from point A to point B respecting safety, economy, schedule, and comfort criteria. During their task performance, pilots are supported by paper documentation— maps, procedures, check lists. They listen to radio bulletins, giving weather and airport information, and communicate with other human agents of the worksystem: crew members, cabin crew, passengers, ground people and air traffic control operators (ATCOs). They can also use highly automated instruments such as the flight management system (FMS) that provides them elaborated displays describing past, present and future situations and can perform "for them" navigation, performance calculations and systems control subtasks. Thus, pilots can choose between worksystem sources of information and control modes in order to counteract difficulties stemming from variations in meteorological conditions, route or profile modifications or even system failure. In modern "glass" cockpits, most of the worksystem-pilot relations can be apprehended by looking at the interaction with the FMS.

In the first part of this paper, we will present the main results of the pilot activity analysis, describing the variation in the cognitive activity in relation with the worksystem status. We will show how air traffic control (ATC) requests are demanding for the pilot since they increase cognitive demand and require great flexibility in the use of flight instruments. In the second part of this paper, we will present the ATC point of view that actually enlarges the perception of the same problem: we will show, using results from a field study at an

Italian airport, how certain types of ATC clearances that increase the pilot's workload, actually stem from strategies aiming at reducing the ATCOs workload.

Pilot's cognitive behaviour

As previously mentioned, cognitive activity is closely related to worksystem status. Moreover, the description of behaviour combines both a representation of the competence used by the pilot and a specification of the general cognitive mechanisms supporting task performance. Thus, we considered as a prerequisite for our study that a complete description of pilot cognitive activity must fulfil, at least, three requirements:

1. it must be related to a *cognitive architecture* supporting the general mechanisms governing human cognition that are relevant in the case of an expert pilot. So it must cope with situation awareness and decision making success and failure.

2. it must provide a list of the worksystem events (or *scenarios*) that affect the pilot's cognitive activity, i.e. that modify the cognitive demand of the situation.

3. it must comprehend the *competencies* used by the pilot during his activity (knowledge on instrument use, rules of thumb, procedures...) and express them in a format meaningful for the cognitive architecture.

A knowledge engineering methodology (Guida and Tasso, 1994) has been followed in order to comply with this prerequisite on cognitive activity description. It consists of two main steps: sampling and extensive knowledge elicitation.

The first step, sampling knowledge engineering, led to a general view of pilot activity, matching the first requirement. It has been performed by synthesising the background supplied by existing models such as COSIMO (Cacciabue et al., 1992) and COCOM (Hollnagel, 1993) and the work carried out to develop of a Crew Resource Management Course (Amat et al., 1995; Kjaer-Hansen, 1995). This view or theory about pilot activity has led to the first version of a cognitive architecture (1st requirement) and to the definition of an initial format for describing the competencies used by the pilot.

The second step, extensive knowledge elicitation, is being performed through pilot interviews and observations in the cockpit. We could thus identify the elements modifying cognitive demand (2nd requirement) and grasp the competence used for performing the task (3rd requirement). A flight can be seen as a sequence of flight phases. During this second step, we focused on the descent phase, where the cognitive activity is very relevant in terms of both planning and monitoring and where the complexity of the situation is still manageable for an external observant. Starting by following the hierarchical and goal/means task analysis philosophy (Sébillote, 1991), the activity has been described as a "task units" graph, each task unit associating the strategies performed and the goals aimed at by the pilot.

Our study on pilot cognitive activity provides three kinds of information, complying with the three requirements previously developed. It also encompasses the relationship between those aspects of the activity. We have focused, here, on the relation between pilot activity (requirements 1 and 3) and the worksystem context. Since the loss of situation awareness often seems to be connected to an inadequate cognitive demand or workload (Tenney et al., 1992; Sarter, 1991), we have chosen to examine the relation in light of cognitive demand variations. This approach has some links with the one described in Woods and Hollnagel (1987); however, our objective is not to provide a domain independent cognitive description but to stick to the case of pilots in normal conditions.

According to the theory of our cognitive architecture, pilot task performance can be analysed in terms of four main cognitive activities: (1) strategic planning, (2) tactical planning, (3) control and (4) monitoring. We have presented hereafter some results of our pilot study, giving examples of these four activities and specifying the related cognitive demand.

(1) Strategic planning

Strategic planning copes with goal management. Indeed, it regards both the elaboration of a plan— i.e. building or, more often, retrieving a goal breakdown— and the capability of adapting this plan in case of disturbance, i.e. of questioning the current goal, dealing with competing goals.

As regards the descent phase, most of the strategic planning is made during descent preparation. This "sub-phase" aims at preparing aircraft systems and pilot for the "ideal" descent. The ideal profile and its related performance calculations are done by the flight management computer, on the basis of data given by the pilot and stemming from the choice of approach procedure. Thus, the choice of approach procedure and the identification of control points— points indicating a change in the aircraft system or target and summarising the constraints of descent— are fundamental for the descent execution. They also provide elements for performing the briefing, a kind of mental simulation of the approach phase. The approach procedure is chosen by considering aircraft and airport facilities, meteorological conditions and by following some personal safety trade-offs. So the cognitive demand of this task comes from the variety of parameters and their interdependency. In reality, experience and synchronisation constraints among subtasks give structure to this task: the choice, in routine cases, can be made by following a sequence of tests. Furthermore, the choice is also facilitated by the information available that allows the reduction of the number of alternatives.

Thus, the cognitive demand basically depends on the availability and reliability of information and on the familiarity with airport approaches procedures.

The descent plan might have to be modified during the execution of the descent: a descent path or profile could be modified to avoid turbulence for instance, or to comply with ATC requirements. The case of ATC interventions might simply correspond to the introduction of a new goal in the previous plan. But sometimes, the requests can be such that the current plan has to be replaced by another: see the case presented in the ATCO section, where the pilot of the A2 aircraft heard the ATCO telling him "A2 climb to Flight Level 110 (FL110)" while he was descending and approaching the airport.

The descent planned during the preparatory phase corresponds to the theoretical one (ideal descent). Sometimes, the experienced pilot who knows the habits of the ATCOs, and can predict the modifications that could be made later on in the descent path, can elaborate another descent plan, a back-up plan, not directly supported by cockpit tools. This is done to avoid the cognitive demand related to the unexpected change of plans and might allow choosing a tactic facilitating a switch from one plan to another: for instance, when arriving at the northern Italian airport we focused on, a pilot will more easily accept being late with regard to the planned path if he knows that the chance of cutting a planned curve is great (cutting a curve might allow him to get back on schedule). This double planning has thus some advantages in the sense that it allows better anticipation of changes; however, the drawback is related to the overconfidence bias: a very experienced captain with a moderate attraction for highly automated system could neglect the preparatory phase of the descent, saying "anyway, they never let us follow the standard procedure, so we just have to wait to be taken in charge and directed by radar vectoring".

Since we focused on cases of normal activity where information is available, modifications of the plans are seen as the main source of cognitive demand. The cognitive demand stemming from strategic planning could be evaluated by considering the number of interrupted goals and the frequency of the goals triggered.

(2) Tactical planning

Tactical planning deals with strategy management. It consists of choosing a strategy for current goal achievement.

During descent preparation, the cognitive demand related to this level of planning is quite low since only a few strategies could reach the same goal, or since there is a perfect match between the current context and conditions related to the first strategy that comes into mind. During descent execution, the effort related to tactical planning should also be quite low, if it is be performed by following the plan. But, very often in European countries, ATC intervenes during the flight, and modifies the descent profile. We saw that this could induce strategic re-planning, but it also provokes a reconsideration of the current strategy. Indeed, typically, it might question the current navigation mode. Vertical navigation can be performed using three main modes, corresponding to different levels or style of automation, with different time responses, and allowing regulating different parameters. In case of a request such as "descend to FL140 at a rate of

1500ft/min", the pilot would disengage the highest automated function "vertical navigation" and engage the vertical speed mode, since it allows to maintain the vertical speed by regulating the thrust. These transitions from one mode to another, or mode "usage" (Degani et al., 1995) are the manifestation of the pilot's flying style. In our study, we considered one style and, based on it, we studied the cognitive demand. We did not consider that tactical planning was, in itself, cognitively demanding since the effort made for choosing the mode is very context driven. However, the consequences of this switching of modes (or strategies) might be demanding since control of the system and monitoring activities depend on the mode. In our example, after having switched to vertical speed mode, the pilot has to monitor that the aircraft is not close to overspeed and perform a control action if that is the case.

Thus, we did not consider that strategic planning was, in itself, cognitively demanding; however frequent strategic changes might be significant since they induce changes in controlling and monitoring activities.

(3) Control

We call "control of the system" actions to be performed when the need of intervening on the system process has been identified, mostly during monitoring activity. Since we deal with a highly automated cockpit, we have not considered manual control; we have coped with actions such as entering a value in the FMS, setting an instrument, modifying a target value on the autopilot and the cognitive activity related to this.

The cognitive demand related to these control actions varies according to the effort needed for determining the value of the parameter to set. During the execution of the descent, most of the target values are directly given by the ATC ("descend to FL180", then the target flight level becomes 18000ft) or established by simple calculations ("descend to FL100 in 4min": when at FL180, this means loosing 8000ft in 4 min or flying at a vertical speed of 2000ft/min for 4 min— FL100 =10000ft and FL180=18000ft with a standard pressure setting on the altimeter.) The control actions that allow sticking to the programmed profile or staying in the current mode (in other words, remaining in the same strategy) are not very demanding either, since, most of the time, control is made by a trial and error process based on the experience and knowledge of the dynamics of aircraft systems: for instance, in vertical navigation mode— the highest level of automation— a control action could be to add "a little" speedbrakes or spoilers when the message "DRAG REQUIRED" appears on the screen or, in flight level change mode, a medium level of automation, it could be to increase the speed "a bit" because, during the monitoring activity, the need has been identified. It is important to note that these subjective values are closely related to the result of the monitoring activity that gives an idea of how much the speed, for instance, has to be increased. Furthermore, monitoring is also important in the trial and error process to check that the modification of the parameter was right. During planning of the descent, a control action might require more demanding calculations: for instance, the evaluation of the reference speed is made by considering current speed, time before landing, and wind.

Thus the cognitive demand stemming from the control activity is related to the number of parameters taken into account in the rule determining the value to set, and to the number of actions to perform.

(4) Monitoring

Monitoring activity aims at maintaining situation awareness. This ranges from perception, through identification, to the interpretation of a parameter status. Monitoring activity is directed by the current goal, or, more precisely, by the strategy that specifies relevant parameters, provides some expectations with regard to system evolution and defines the current safety envelope.

The effort for monitoring the situation depends on the flight context (approach to control point, unexpected event...) and on the mode used. At the highest level of automation (selected for instance during the planning of the descent), the demand is mostly at the level of attention since FMS interfaces allow a quick check of the profile. At medium level of automation, such as flight level change, the anticipation of future status is not obtained directly by looking at instruments. It needs a more elaborated treatment of the information that might require the consideration of parameters not relevant in other modes. For instance, when checking if the actual altitude is acceptable while descending, pilots might monitor the difference between the current altitude and the one obtained by using a rule-of-thumb which transforms the distance to the airport into a prescribed altitude.

Thus, indicators of monitoring demand could be the "distribution of the relevance" among the parameters (our idea of relevance is close to the notion of cognitive and physical salience presented in Cacciabue et al.,

(1992) and the "complexity" of the calculations to do to realise the implications of the values of the parameters.

We have presented a view of pilot cognitive behaviour, focusing on four types of complementary activities. To complete this description, the dynamic dimension of the task has to be stressed. Indeed, it plays a determining role in the evaluation of the cognitive demand, even if it is difficult to underpin with indicators. Furthermore, we noted that the temporal horizon is divided into segments that are actually defined by a backward chaining scheduling of the operation which is also at the basis of goal subdivision. The temporal pressure is thus relative within these segments and can be evaluated by looking at the execution conditions inherent to the strategy used.

The description of the nature of the cognitive demands encountered by the pilot provides a qualitative view of cognitive demand. For switching from this qualitative view to a more quantitative one, the notion of cognitive profile has to be introduced. Indeed, the evaluation of cognitive demand is subjective: each individual has his/her own rating scale and gives a different weight to each of these indicators. By writing some functions of these indicators, some rules indicating the personal priorities, one can trace the variation of the cognitive demand. However, we have chosen here to use common sense assumptions regarding the respective weight and measurement of the indicators in order to be able to generalise our findings and affirm that some scenarios are more demanding than others.

In routine cases, the highest cognitive demand is encountered during the execution of the descent when the pilot has to change his plan several times. Indeed, common policy is to use the highest level of automation, checking that the programmed profile is followed. When the profile has to be changed, switches to lower levels have to be made and a strategy set up to return to the most automated, or to intercept the planned trajectory, hence an increase in cognitive demand. Furthermore, medium levels of automation are more flexible to use, have a quicker time response but are also more demanding cognitively, mainly because of the monitoring and control activities that have to be continuously done. A variation in the meteorological conditions might induce such a transition towards a lower level of automation. More frequently, changes are caused by ATC intervention. Moreover, in case of step-let-down descent, these changes are not only unexpected but also repeated: the ATCO first gives a clearance for a flight level, the pilot responds to this "order" by adapting his original plan, then other clearances are given, while the pilot does not know what the next clearance will be. Thus, in these cases, often found in Europe, the pilot has at his disposal a set of highly automated functions, programs them and prepares himself/herself for their use, but is constrained to use a medium level of automation because of unforeseeable profile changes provoked by the ATCOs.

So, from this point of view, it seems that the improvements made to pilot worksystem instruments are, in operational context, limited by the ATCO problem to cope with the situation. In order to analyse more precisely the causes of pilot’s cognitive demand variation, we will now give a description of the ATCO worksystem and activities.

Features of ATCO activity

One important category of perturbation that has considerable impact on the reliability of the predicted flight profile is related to the human actions of the ATCO. At any instant, the ATCO may change the route, cruise level and airspeed as a function of the perceived overall traffic situation.

In this part of the paper we will focus on the discrepancy between the structure of the pilot’s task, guided by the automatic tools provided in the cockpit, and the constraints stemming from ATC interventions. These "annoying changes" from the pilot’s point of view are actually only the visible part of the larger problem of flow management.

The objective of ATC is flow management according to three criteria: (1) optimisation of flight safety in order to avoid possible conflicts between aircraft and transgression of minimal separation rules; (2) flight economy to minimise fuel consumption; (3) fluidity of traffic flow in order to maintain scheduled flights.

The air traffic control task is a continuous task since the controller regularly verifies that each aircraft follows the right trajectory. It is composed of sub-tasks: radar screen monitoring; management of communication between pilots, tower controllers, controllers of adjacent sectors through different means— radio, telephone, intercom; strip management; monitoring of weather conditions at controlled airports.

When ATCOs detect a possible conflict, they solve it by modifying level, heading and speed with respect to safety, economy and fluidity of traffic flow. They have to constantly verify the evolution of the density of the traffic they are in charge of, and to plan the distribution of the traffic over time.

Different conditions can challenge the task performance of ATCOs and increase their level of workload and stress. Stress for the ATCO seems to be a joint effect of high attention required and high level of responsibility as measured by the cost of an error (Warr, 1987).

As a result of a field study in an Italian airport, where the activities of the ATCOs were examined at the approach control working position, the following conditions affecting ATCO cognitive demand have been identified (Bellorini, 1996): geographical allocation of airways; traffic conditions in terms of complexity, volume (number of aircraft in charge) and number of holding aircraft; airport capacity and support; procedures and rules; communication density and possible overlapping; appearance of unexpected situations or conflicts.

In order to cope with the increase in cognitive demand related to these conditions, ATCOs apply safety-centred strategies based on task sharing and workload distribution.

They decompose the general problem into localised sub-problems, giving priority to safety rather than flight economy and fluidity of traffic flow and treating the problems sequentially, one by one. The number of parameters taken into account decreases and strategies become economical in terms of the cognitive effort of the ATCOs.

Another observed economical solution is the application of individual strategies and actions, successfully tested, to avoid the main conflict. These actions are generally directed to the aircraft which the ATCO knows the flight history (previous heading, speed ...).

The following example shows how ATCOs have managed a conflict between four aircraft (Bellorini and Vanderhaegen, 1995). This case involves two ATCOs of the approach control working position (C1 and C2), controlling two specific geographical sectors, and the pilots of four aircraft (A1 to A4), landing at the same airport. C2 is in charge of A1 and A4; C1 is in charge of A2 and A3. C1 receives A2 at only 10 NM before the "gate" from an ATCO of an adjacent sector. A2 is at the same level as A3, that is, in holding pattern on the gate. In order to maintain minimal separation, C1 decides, first of all, to increase the level of A2, in order to avoid a conflict of level with A3, and, secondly, to give an heading to A2 so that it avoids the gate.

We can see, in this case, how the solution applied by the ATCO, on one hand, reduces workload and stress by solving the salient problem: safety is ensured by minimal separation, even if the increase in level is not economical and does not help traffic fluidity. But, on the other hand, as explained in the section on pilot activity, this solution increases pilot cognitive demand. Thus, the increase of the pilot's mental load can be seen as an effect of the ATCOs workload transfer.

Conclusion

In normal conditions, the workload of the pilot and the ATCO varies and can reach high levels. Moreover, there is often a link between these increases of workload. Mostly during the descent and approach phases, the ATCO workload can be transmitted to the pilot. At this stage of the flight, an increase in cognitive demand is not the most welcome, since it can damage the pilot's situation awareness and might contribute to a controlled flight into terrain accident.

The current aviation worksystem allows this workload propagation. Nor does it guarantee an optimum co-operation. What happens, in practice, is that there is no integration between the pilot and ATCO worksystems, which have been considered as two separate entities. The existing mismatch between cockpit automation and ATCOs support tools shows this clearly (Gras et al., 1994).

Furthermore, an important way to cope with workload propagation in distributed systems is to share knowledge about the respective tasks (Hutchins and Klausen, 1992) and to efficiently support the agents of the system. A contribution towards better integration of the two worksystems could be made through training programs, which includes a presentation of the task, and the means available to the other agents within the system. But fundamental changes will come by modifying the approach taken while developing support tools and considering the air traffic management (ATM) problem as the common denominator.

To maintain safety as well as fluidity of traffic flow, integration between the two worksystems—ATC and cockpit—has to be supported. Thus, further research towards the development of automatic systems supporting the ATCOs and towards a better transfer of information to the cockpit has to be undertaken. The Communications, Navigation and Surveillance (CNS) and Air Traffic Management (ATM) concepts developed by the International Civil Aviation Administration (ICAO, 1994) point in that direction. NASA and FAA, along the same lines, have been field-testing a new generation of decision support software for ATCOs (Descent Advisor, (Erzberger, 1992)), that also reduces delays and increases fuel efficiency, thus complying with pilot criteria.

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