COGNITIVE FACTORS ISSUES ON DATA-LINK

Guy A. Boy

European Institute of Cognitive Sciences and Engineering (EURISCO)
4, avenue Edouard Belin, 31400 Toulouse, France
Tel. +33-62 17 38 38 - FAX +33-62 17 38 39
Email: Guy.Boy@onecert.fr

Abstract
This paper presents some research issues relevant to the datalink problem in aviation. It focuses on agents and cognitive functions as cognitive tools to represent and investigate communication issues in aviation. Cooperative work within the aviation system is analyzed using an agent-oriented methodology. Consequently, a method for human-centered automation is proposed. The main issue developed in this paper is the necessity for coordination rules in a multi-agent environment where human agents become more autonomous. In addition, new datalink systems should provide virtual peripheral information to replace and enhance party line information loss.

Keywords
Theory, methods, datalink.

Introduction
The main objective of this paper is to describe the work in progress on human factors issues related to the integration of data link (D/L) within the aviation system. D/L is a new technology that is still vaguely defined. D/L will enable the transfer of large quantities of data between the ground and the aircraft. What is not clear is the way these data will be transferred, and the philosophy that support the use of D/L.

Data link is currently a technological solution to replace existing air-ground communication systems such as Very High Frequency (VHF). All the involved participants need to be aware of what is going on in the airspace they are working in. Controllers need to know airplanes' locations, directions, as well as pilots' intentions and relevant problems. Pilots need to be correctly informed of the various possibilities for doing their job with the maximum of safety and comfort.

The work presented here has the following objectives: provide a cognitive engineering viewpoint on a possible evolution of air-ground communication issues; provide models and conceptual tools that would enable the analysis of such an evolution; provide a methodology that could be used in the ergonomic design of new D/L systems. This work is based on four basic attempts: a literature review of human factors issues on air-ground communications; a feasibility test of a specific knowledge elicitation method (the feasibility of the group elicitation method (GEM) has been demonstrated within the FANSTIC project); the implementation of the cognitive function analysis method for ergonomic design of new aeronautical human-machine systems. This method has been tested on the redesign of the Multifunction Control and Display Unit of the Flight Management System (MCDU). A synthesis of the results of the above attempts and a proposal for a longer research program.
Several assumptions have been made: this research is long-term but we focus on real-world data and experience; information technology is an integrating part of the evolution of our occidental societies; automation must be human-centered; pilots will continue to have an active role in the cockpit (aircraft will be flown and not remotely guided from the ground).

The agent representation (cognitive function analysis: CFA) can be used to analyze new air traffic management (ATM) scenarios. The CFA is both an analysis method and a synthesis method. It enables to incrementally specify an operator interface. It can be used from two different perspectives: by analysis and modeling interaction of an existing interface, or by progressively refining an operator interface "from scratch". Operational knowledge can be acquired using various techniques such as interviews, the GEM, and direct interaction with simulations created by the CFA. This method is usable both during design to help taking into account various anticipated human factors problems, or during validation to assess cognitive aspects of human-machine interaction. The ability to easily trace decisions within a CFA knowledge base enables to identify and define evaluation criteria. Simulations are easily created by adding real-world interface elements (metaphors) to cognitive functions (knowledge blocks).

In this paper, we first provide some air-ground communication (AGC) problems in order to show what is at stake in current AGC. We define the notion of agents and cognitive functions (CFs) in order to analyze cooperation aspects in the ATM domain (Karsenty & Boy, 1994). Even if we believe that ATM is technology-driven, D/L integration is not only a matter of replacing a communication medium by another. It is a matter of level of automation that enables new ways of communication and flight management. This paper provides an analysis demonstrating that an appropriate introduction of D/L would increase the autonomy of pilots. Data link should be designed and used to keep and extend situation awareness. This organizational transformation of the nature of the air traffic management stresses the need for the definition of coordination rules. Roles should be better refined between aircraft themselves as well as between aircraft and air traffic control (ATC).

**Air-ground communication problems**

Communication in the cockpit and between crews and ATC has become a major issue in the aviation community. An important data source on real-world information transfer problems is the Aviation Safety Reporting System (ASRS) which has been in operation at NASA Ames Research Center since 1976 (Billings, 1981). We here mention the results presented in 1981 and based on 28,000 reports from flights occurring during the period 1976–1981. These confidential reports were submitted by pilots and air traffic controllers. Nearly 70% of the reports mention information transfer problems, primarily problems in verbal communication, but there are also many examples of poor transfer of visual information. Most of the information on which the safety and efficiency of aviation operations depend is highly dynamic. Neither pilots nor controllers can make adequate decisions without clear and sufficient information. Deficiencies in information transfer therefore have direct safety implications.

**Information existence and availability**

These deficiencies can be attributed to the poor quality of communication media, human errors, and sometimes to inappropriate training of personnel. It should be noted
that analyses of subsequent data reinforce these results. Table 1 illustrates typical information transfer problems encountered in aviation operations. Information transfer problems are generally initiated by one or several faults. Information has two necessary conditions: existence and availability. The first condition involves the emitter of the information and perhaps an on-board receiving instrument in the cockpit. The second condition involves the human receiver of the information. Information must be available at the right time for the person who needs it. Many information transfer problems are attributable to the lack of adequacy and opportunity (i.e. its appearance at an inappropriate moment) of the message transmitted.

**Information expectation**

The ASRS shows that in many of the reports analyzed, a message either was not heard or, if it was heard, was misunderstood or misinterpreted. These reports also show that the expectation of a message plays an important role in the problem of information transfer. In other words, the active situation patterns, i.e. those which are present in the short-term memory and learned through experience, influence the behavior of pilots directly. The interface also plays a critical role here, if it is envisaged as an extension of the short-term memory of the operator.

**Table 1. Information Transfer Problems, ASRS–NASA Inquiry.**

<table>
<thead>
<tr>
<th>Nature of the problem</th>
<th># citations</th>
<th>% citations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Messages of indeterminate origin</td>
<td>4,039</td>
<td>37.4</td>
</tr>
<tr>
<td>Inadequate, incomplete, ambiguous or incoherent messages</td>
<td>3,959</td>
<td>36.6</td>
</tr>
<tr>
<td>Correct but inopportune messages</td>
<td>1,356</td>
<td>12.5</td>
</tr>
<tr>
<td>Messages not received, or misunderstood</td>
<td>1,165</td>
<td>10.8</td>
</tr>
<tr>
<td>Messages not transferred due to equipment failure</td>
<td>296</td>
<td>2.7</td>
</tr>
<tr>
<td>Total</td>
<td>10,815</td>
<td>100.0</td>
</tr>
</tbody>
</table>

**Information understanding**

Misunderstandings often happen because the receiver of the message hears what he expects to hear according to his usual know-how. This error is generally corrected when the message comes from a controller. If a message it is not received correctly, it is not confirmed correctly and will be retransmitted. In contrast, if a message which has been misunderstood is confirmed as correct, the subsequent evolution of the crew–aircraft–ground system will be based on false references.

**Table 2. Problems posed by information transfer supports.**

<table>
<thead>
<tr>
<th>Message support</th>
<th># citations</th>
<th>% citations</th>
</tr>
</thead>
</table>
Information media

The ASRS data (Table 2) suggest that information transfer by visual channels poses fewer problems (15% citations) than auditory information (85% citations). It should be noted that information transfer through manuals or cards is subject to very few problems. Usually, the problems associated with printed data concern difficulties in finding, reading or interpreting the data, particularly in conditions of poor visibility, turbulence, or during periods of high stress or heavy workload. For example, if during the final approach, the pilot has to change the landing runway and finds himself in an unexpected situation which engenders a very heavy workload, he has to identify and memorize the new data very rapidly. Currently, pilots and controllers can only use the VHF channel for air-ground information exchanges. This voice channel has advantages (flexibility, speed, friendliness, etc.) and disadvantages (unreliability, non rigorous, incompatibility with other tasks, saturation, etc.).

The frequency range is saturated (118 MHz to 138.975 MHz with a step of 25 kHz). Today each control sector uses one frequency. The increase of the number of aircraft will cause a decrease of sectors sizes, and then an increase in the number of frequencies causing a decrease of the frequency step from 25 kHz to 8.33 kHz. This evolution will introduce a risk of human errors (Preux & Chatty, 1993). This is confirmed by a more recent analysis of ASRS submissions received in 1985 and 1986, one fourth of the 14,000 reports involved problems in air-ground information transfer (Lee & Lozito, 1989).

Repercussion on datalink

Up to now, the ACARS (ARINC Communication Addressing and Reporting System) developed and in use by several major airlines is considered as D/L by pilots using it. Pilots can downlink arrival estimate, requests for weather reports, aircraft departure time and engine performance data. With the advance of satellite voice and digital communications, several other additions to these datalink communications are being proposed and tested, such as the ADS (Automatic Dependent Surveillance system). Pritchett and Hansman have found that some specific party line information (PLI) elements were perceived as important but not reliable, indicating information for which

<table>
<thead>
<tr>
<th>Information media</th>
<th>ns</th>
<th>ns</th>
</tr>
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<tbody>
<tr>
<td>Auditory information transfer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio</td>
<td>6,834</td>
<td></td>
</tr>
<tr>
<td>Intercom</td>
<td>855</td>
<td></td>
</tr>
<tr>
<td>Voice</td>
<td>450</td>
<td></td>
</tr>
<tr>
<td>Telephone</td>
<td>438</td>
<td></td>
</tr>
<tr>
<td>Tape recorder</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8,596</td>
<td>85.0</td>
</tr>
<tr>
<td>Visual information transfer</td>
<td>1,356</td>
<td>12.5</td>
</tr>
<tr>
<td>Video/CRT</td>
<td>587</td>
<td></td>
</tr>
<tr>
<td>Instruments, lights, etc.</td>
<td>416</td>
<td></td>
</tr>
<tr>
<td>Publications</td>
<td>309</td>
<td></td>
</tr>
<tr>
<td>Cards</td>
<td>203</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1,515</td>
<td>15.0</td>
</tr>
<tr>
<td>Grand Total</td>
<td>10,111</td>
<td>100.0</td>
</tr>
</tbody>
</table>
the "Party Line" is not the best modality of communication... and pilots indicated they were more receptive to the implementation of datalink if compensation is included for any PLI loss (Pritchett & Hansman, 1994).

D/L may have various goals such as improving situation awareness both on-board and on the ground. It should allow the improvement of negotiation and task sharing. D/L should enable to decrease workload due to the use of current technology in air-ground communications by removing the part of workload due to the interaction and leave a larger room to the actual communication acts. In particular according to Pritchett's and Hansman's results, new D/L systems should provide timely and accurate peripheral information on aircraft on landing runway, windshear, collision avoidance, visibility and ceiling, and thunderstorms (Pritchett & Hansman, 1994).

About agents and cognitive functions

Agents
Agents have been described by various researchers in artificial intelligence (Minsky, 1985; Ferber, 1989; Dieng, 1995). Wangermann and Stengel (1994) talk about agents evolving in the aircraft/airspace (AAS). These agents can be aircraft, airlines, or traffic control units. It is based on the concept of cognitive functions that are used by AAS agents. An agent can be represented by an information processor, a knowledge-base, and interaction channels (Figure 1). The Larousse Dictionary qualifies as agent anything that acts, e.g., light and heat are natural agents. It can be someone who acts for someone else or for an organization. An agent has its own information requirements in order to act. These information requirements are acquired through receiving channels. These channels have specific properties such as: sequentiality of information chunks; persistence of the acquired information in the sensory memory (e.g., 250 milliseconds for the visual channel); situation awareness power; precision; etc. These properties can be improved or modified by the introduction of adapted devices. The main problem here is to design tools (machine agents) that extend human capabilities, and sometimes enable people to do things that were not possible before, e.g., design machines that enable people to fly. In this sense, an aircraft is an agent that enables a human being to fly. The crucial human factors problem in the use of such an agent is to find out what is the information required to safely and comfortably fly the aircraft.

The definition of new agents involves new kinds of behavior and processing. Human beings need to adapt to new situations created by the introduction of these new agents. In order to better characterize these shifts, let us list a series of properties of agents:

- delegation: we delegate a task to an agent;
- cognitive value: results from interaction with the agent;
- context: an artificial agent is designed in a specific context that defines the limitation of the agent;
- adaptation: human agents can adapt to almost anything, whether artificial agents may be adaptive (if they are programmed this way) in very limited contexts;
- predictability: whenever we can predict the behavior of an agent, we can trust him/her/it;
- user expertise: artificial agents are designed for either experts or general public;
- type: artificial agents can be reactive (simplest form) or cognitive; we say that an
agent is cognitive either when it has a cognitive architecture (design viewpoint) or when it has a cognitive behavior (use viewpoint);
- complexity: artificial agents can be more or less complex according to the complexity of the task they need to perform.

Society of agents: hierarchy vs. orchestra
In Minsky's sense, basic agents are very simple entities (Minsky, 1985). Cognitive behavior comes from groups of agents working together in an "cognitive way", i.e., processing problems together. The notion of agent is mutually inclusive, i.e., a consistent group of agents working toward the same goal(s) can be called an agent (Figure 2). Minsky talks about society of agents. A society of agents is an agent itself. The way this society is structured is often crucial.

![Figure 2. An agent as a society of agents.](image)

Various organizations can be proposed for a society of agents. The hierarchical organization often comes to mind because it reflects the way conventional organizations work in our social world (Figure 3). Each agent has a specific task to perform. Usually this task is assigned by an agent in the hierarchy. At the bottom of the hierarchical structure, basic agents perform elementary tasks. The more an agent is nearing the top of the organization, the more its job is cognitive. We say that a job is more cognitive than another when it involve more cognitive tasks and activities, i.e., more information processing (thinking).

An alternative to hierarchy is the orchestra organization. It is represented in Figure 4. In an orchestra, each agent performs an equally complex task. However, in contrast with the hierarchical organization where agents either control other agents and/or report to another agent, each orchestra agent acts according to a common set of rules (that can be transposed). These are coordination rules. These rules are defined by a syntax and a semantics. For instance, music theory provides a set of such rules for music players in an orchestra. These rules are defined at the highest level. In addition, there are transversal communication channels, and an overall coordination is managed by a single conductor.
In the ATM domain, the more aircraft become autonomous, the more they should become knowledgeable and informed agents. By autonomous, we mean that they know where they are located and what their environment (situation assessment) is, and where they need to go according to the current and future situation (goal-orientation). In the past, the hierarchical organization of the airspace was necessary and sufficient because aircraft were not autonomous from a navigational point of view. Today (and tomorrow), this state is changing. For instance, most aircraft are now equipped with global positioning systems (GPSs) that provide more autonomy (Stix, 1994). The GPS provides the pilots with a more precise location of the aircraft, thus pilots situation awareness is improved in theory, and then they are in a better position to decide by themselves (autonomy). This statement is valid if they trust the GPS. The hierarchical concept is no longer compatible with this evolution. However, the orchestra concept is more appropriate. Each aircraft is an agent. Control centers are other agents that work as conductors. The difficulty with several possible conductors is guidance coordination and consistency.

Coordination, safety and consistency requires the definition of cooperation rules that need to be applied by all agents in the society. For instance, this is the case with cars. There is a road rule system that guides the behavior of car drivers. There are also policemen who make sure that these rules are well applied to insure the safety of the road system. By analogy with an orchestra, the conductor makes sure that each player plays the right music at the right time with the right mood to contribute to the harmony of the symphony. Note that these rules can be explicit or implicit. In this view, data link needs to be thought in a very different way since the current air-ground communication system is purely hierarchical. Our claim is that new technology brings more autonomy to aircraft if it provides appropriate peripheral information to the pilots. This means that new cooperation rules need to be defined and incrementally refined.

Cognitive functions
According to the French tradition in ergonomics, a distinction is made between task (prescribed task) and activity (effective task). When a job needs to be performed, it can be decomposed into tasks. Thus, tasks (at any level) are the requirements of the job. When someone performs a task, he/she produces an activity. This activity may differ from the original requirements, i.e., the effective task differs from the prescribed task. This is due to the fact that all situations are very difficult to anticipate when tasks are designed. A human operator facing a situation produces a specific activity according to
the requirements, but may need to adapt the task to this situation.

When a new device is being designed, it is extremely difficult to anticipate how it will be used. The designer has a use in mind, but cannot imagine all the possible uses of this device. Cognitive functions are the representation of the mechanisms that produce activities (Figure 5).

![Cognitive Function Diagram](image)

**Figure 5.** A cognitive function transforms a task (what is prescribed) into an activity (what is effectively done).

In the sense described above, cognitive functions are agents. From a pure pragmatic viewpoint, the term cognitive function is better suited to describe human cognitive agents (processes). The term agent denotes humans or machines, cognitive functions denote the processes that they use to perform the task that are assigned to them. At design time, these cognitive functions can only be speculated according to past experience, accumulated knowledge and know-how. At evaluation time, they can be inferred from the observation of real activities. In both cases, they enable to simulate cognitive processes. We call cognitive simulation the simulation of the appropriate cognitive functions. Examples of cognitive functions are: clearance transmission; frequency change; rolling authorization; parking space allocation; flight level allocation; etc.

A cognitive function (CF) can be decomposed into smaller grain cognitive functions. In particular, a CF invoked for performing a specific task can be decomposed into two main CFs (Figure 6): the CF devoted to the interaction: it is related to the syntax used to perform the task; the CF devoted to the content of the task itself: it is related to the semantics of the task. The more the interface is easy to use, the less the interaction component of the cognitive function is complicated. For instance, if the task is to select a new frequency, the pilot needs to push and turn buttons (e.g., first interaction sub-CF is devoted to locate the right button and check numbers on a display), get and check appropriate ATC frequencies, etc. The interaction component of the overall CF can be complicated.

![Interaction and Task Content Diagram](image)

**Figure 6.** Interaction and task content components of a cognitive function.

**Redefining automation**

D/L can facilitate the execution of such CFs by taking over part of the job currently performed by people. If the sharing of the communication subtasks (and consequently their underlying cognitive processes that we have called CFs) is well balanced between
the humans and the machines, human agents should better communicate between each other. This means that the cognitive functions that are purely devoted to interaction itself could be directed towards the machine (Figure 7), and the CFs that are purely devoted to the content of the task are directed towards the humans. *Transferring cognitive functions from humans to machines is also called automation.* In this sense, integrating D/L in the cockpit is a matter of cognitive functions transfer, and then automation.

![Figure 7. Transfer of part of an interaction cognitive function (I-CF) to the machine.](image)

Note that task-content CF can be transferred to the machine also. I-CF transfer defines an automation that transforms a demanding interaction into a more natural interaction. Such transfer defines purposeful artifacts of a virtual environment. In particular, *party line information* (PLI) requires that the pilot filters the necessary information, captures additional information that provides trends and potential anticipatory information, and eliminates unnecessary information. We propose that new D/L systems should provide the necessary and additional information in the periphery (Midkiff & Hansman, 1992). It requires a careful analysis of pilot's I-CF, such as capture and interpretation of useful information from raw information available from PLI.

TC-CF transfer defines an automation that distribute the responsibility of the task amongst the human and the machine. The way TC-CF are understood by the designers is crucial because a transferred TC-CF has necessarily a limited autonomy. The way this autonomy is perceived by end-users is an important issue. Sometimes it may happen that users do not anticipate this limited autonomy because the system (using the transferred TC-CF) works fine most of the time.

**Human-centered automation**

Billings proposes several goals that motivate automation: *safety*: to conduct all flights, from pushback to docking, without harm to persons or property; *reliability*: to provide reliable transportation without interference from weather or other variables; *economy*: to conduct all flights as economically as possible; *comfort*: to conduct all flights in a manner that maximizes passenger and crew health and comfort (Billings, 1991, page 68). *Simplicity* should be added to this list of goals.

What is human-centered automation (HCA) from a cognitive function viewpoint? As it is said earlier, eliciting and constructing cognitive functions that are involved in a specific task facilitate understanding of what should be automated according to a set of principles and guidelines that are given in this section. HCA can be defined in terms of attributes that will help decide the transfer of cognitive functions between the human operator and the machine. A first list of attributes of human-centered aircraft automation discussed by Billings (1991) such as:
- accountable/subordinate;  
- predictable/adaptive;  
- comprehensible/flexible;  
- dependable/informative;  
- error-resistant/error-tolerant.

**Cooperative work in the aviation system**

**Specificity of the aviation system**

First, pilots and controllers are *physically remote*. They do not have direct personal contact. They do not know each other. A good cooperation is grounded on the fact that people try to understand the mental and operational model\(^1\) of the other. This is difficult when people are face to face. The difficulty is even greater when the people do not see each other (in particular several interaction modalities are lost such as gestures and facial expressions), communicate with a language that is not their usual language, do not know very well the cultural specificity of the interlocutor (in the ATM for instance, the usual cultural specificity is based on procedure following, it may happen that some actors of the ATM do not comply to procedure following just for cultural reasons—cultural differences must be diluted by the application of common protocols that are understandable by the various parties interacting), etc. (Degani & Wiener, 1991)

Second, pilots and controllers need to *cooperate under time pressure*. Time pressure is often a major constraint that handicaps the communication. This implies that precode messages should be available to speed up communication exchanges. In any case, when the pressure is very high, people tend to use their mother tongue. For instance, in the 1976 Zagreb accident, a collision between a Trident and a DC9 BE of Adria Airlines (September 1976), when the controller understood that both airplanes were facing each other on the same trajectory, he switched from English to Serbo-Croatian to inform the crew, and made an error in his message (wrong flight level). This is a typical case where a systematic transmission of the flight level of the other airplane should have avoided the accident.

Third, messages should be shared by other agents than their original expected destination. The *party line* is a crucial factor that places pilots in a continuous feedback mode. The party line induces a mental comfort to pilots. It does not provide precise information, but is essential for keeping the pilots in an appropriate state of vigilance. In particular, the human short term memory (STM) is limited (7+/2 chunks) and extremely volatile. Thus, this STM should be frequently refreshed. This refreshment depends upon the vigilance (activity) of the people. In other words, people's minds should be available at any time to receive a critical piece of information.

Finally, to summarize, *situation awareness* is always a problem in aviation. In particular, pilots need to know where their aircraft is located, and where other aircraft are located in their environment. They need to be able to anticipate at any time because flying is a closed-loop activity. *Anticipation* is then a key issue in ATM. Thus, a major question is: how can data link facilitate and improve pilots' situation awareness and anticipation?

\(^1\)This can be a task model (what another human agent is expected to do), a performance model (what another human agent usually does), a system model (how a machine agent works), etc.
Various types of agent communication

A multi-agent model of the aviation system is needed to better understand the communications problems and, in particular, the data link issue. Such a model could be further used to help design data link systems. We have done this exercise in the MESSAGE system (Boy, 1983; Tessier, 1984; Boy & Tessier, 1985). An agent is an information processing system that is able to communicate with other agents.

When designing integrated systems the designer needs to consider the nature of communication among the agents, human and machine. The type of interaction depends, in part, of the knowledge each agent has of the others. An agent interacting with another agent, called a partner, can belong to two classes: (class 1) the agent does not know its partner; (class 2) the agent knows its partner. The second class can be decomposed into two sub-classes: (subclass 2a) the agent knows its partner indirectly (using shared data for instance), (subclass 2b) the agent knows its partner explicitly (using communication primitives clearly understood by the partner). This classification leads to three relations between two agents communicating:

(A) competition (class 1);
(B) cooperation by sharing common data (subclass 2a);
(C) cooperation by direct communication (subclass 2b).

In the competition case, the agent is totally ignorant of the existence of other agents. This can lead to conflicts for available resources. Thus, it is necessary to define a set of synchronization rules for avoiding any problems of resource allocation between agents. Typically, these synchronization rules have to be handled by a supervisor (Figure 8). The supervisor can be one of the partners or an external agent. Obviously, if available resources exceed the requirements of all the agents, conflicts are automatically avoided.

In the case of cooperation by sharing common data, the agent knows that its partner exists because he/she is aware of the results of (at least) some of the partner actions. Both of them use a shared data base (Figure 9). Such a shared data base can be an agent itself if it actively informs he various agents involved in the environment, or requests these agents for new information (self updating). Agents use and update the state of this data base. An example would be both agents noting all their actions on a blackboard to which the other agent refers before acting. Agents have to cooperate to manage the shared data base.
This is no longer a problem of resource allocation, but a problem of sharing data which each agent can use as it is entitled to. This paradigm is called a data-oriented system. Such a system has to control the consistency of the shared data. Cooperative relations between agents do not exclude competitive relations, i.e., shared data are generally supported by resources for which the corresponding agents may be competing. In this case, synchronization rules have to deal with resource allocation conflicts and corresponding data consistency checking.

In the previous cases, the interaction is always indirect. In the case of *cooperating by direct communication*, agents interact directly with the others (Figure 10). They share a common goal and a common language expressed by messages, e.g., experts in the same domain cooperating to solve a problem. Common goals and language can be described using the block representation.

### ATM communications

We consider the airspace as an environment of agents (Figure 11). An environment of agents is a set of agents interacting between each other. In the following, we analyze how the various agents interact along with the three types of communication already described. In the real-world, all three types of communication take place at various degrees according to the situation. The first type of communication is usually supervised by *procedures and checklists*. In aviation, procedures are usually learned and remembered by pilots. Checklists are implemented and used to extend the human STM. They are guides used to maintain people on the "right track". The second type advocates the use of a (party line) common database to improve situation awareness. The third type advocates appropriate mechanisms to facilitate the construction of the interlocutor mental model of his/her task. All three types have in common the fact that a *shared context* should be always constructed when two agents need to communicate.
There are *levels of authority* within the aviation system. Usually the control authority is left to the ground (ATC). Pilots need to comply to ATC orders. Controllers supervise semi-autonomous agents. One important question is: how much the introduction of data link will increase or decrease the *autonomy* of commercial airplanes? If airplanes have more accurate and complete information about where they are and where they can go, they are likely to become agents that have their own agendas. These agendas can be regulated by rules (company rules or universal rules).

The second type of communication involves a common database that can be physically-supported or mentally-supported. As the current *party line* is supported by oral communications, the correspondent database is mentally-supported. The use of the STM is essential. This forces the pilots to be always aware of what is going on in their environment. Vigilance is a key issue. This party line can be extended to a physically-supported database when using the datalink. Datalink will enable pilots to communicate synchronously with other airplanes. In addition, since the ATC will be able to send large amounts of information, it will be possible to recreate the airspace surrounding the airplane on a display. The STM of the pilot will then be extended. Beside the party line issue, there are other benefits that the datalink can create in the way of creating a common database shared by several agents. *Situation awareness* can be improved.

The third type of communication involves people in a face to face interaction mode. They either know each other or they learn more or less quickly to know the interlocutor. *Constructing the model of the other is a common human task*. This process is even recursive, since they also want to know the model that the interlocutor has of them (model of model). This task is complex and requires time to construct an appropriate model. Such models are often *incomplete* and may lead to human errors. People may be convinced that the interlocutor has such a background, such an intention, such a motivation, etc., based on a few interactions. People tend to infer very rapidly. They make a first impression that they revise afterwards. However, if the revision is not done correctly (which can be the case in real-time operations), related human errors are possible. Implicit knowledge is often dangerous, but it is inherent to human beings.

An important issue that needs to be addressed is *context continuity*. When an aircraft flies from one ATC sector to another, the context needs to be kept both by pilots and controllers even if they are not the same persons. D/L should clearly address this issue. One solution would be to use multimedia software agents that make it possible to transfer contexts from one ATC to another. Continuity will help cooperation.

**Defining artificial channels (intelligent interfaces between agents)**

*Minimal situation awareness* means that each agent does need to be aware of
everything happening in the world. He/she needs to be aware of the events and facts that are necessary for him/her to perform his/her job. When two agents are not face to face, their interaction is usually technology-mediated. Each agent is facing an interface that provides information from the interlocutor, and enables him/her to send some information to the interlocutor. This interface usually enhance the feeling of interaction between agents, but this is just an illusion that needs to be well thought and revised from experience. Even if human being tends to adapt to tools despite their design (Hollnagel, 1995), and not because of their design, we need to better understand what each agent needs to communicate "directly" with other agents when those are remote. This is one topic of research on data link. Another topic of research is the study of the influence of this new technology on intra-cockpit communication (cockpit resource management).

How to improve situation awareness?
- provide peripheral information: with the integration of computer technology, the central vision is more used than the peripheral vision for instance; the notion of periphery is not limited to the visual channel. Periphery is a component of contextual information and knowledge; processes are more analytical (cognitive) and less situational (proprioceptive and sensory-motor);
- provide precise information when necessary;
- provide incentives to make information available and noticeable (situation awareness facilitation);
- increase motivation;
- information consistency;
- information that can be trusted; etc.

There are two other artificial ways to improve situation awareness: train operators to scan the environment in an appropriate manner (cockpit resource management is a method for instance); provide appropriate artificial channels that extend natural channels. An artificial channel is an interface agent that enables and enhance interaction between a machine agent and a human agent. Both solutions can be taken and are complementary. The former is currently used by default. In this paper, we will focus on the latter. We will consider that each agent is equipped with a set of artificial channels that enable (remote) interaction with other agents (Figure 12). They extend human channels. Artificial channels are intelligent controls and displays. Up to now, the design of controls and displays implicitly took into account some cognitive factors.
For instance a bug on a speed indicator enables to reduce pilot's cognitive load because the pilot does need to control several digits up to a speed limit but the crossing of this speed limit. In general, the role of artificial channels is to improve and not reduce information exchanges between agents. Information exchanges can be improved by providing the right information at the right time in the right format. This can only be assessed experimentally at the moment.

The orchestra organization assumes that agents are smart, and are able to communicate with some of the other agents of the society. This communication should be improved (and not handicapped) by artificial channels. Artificial channels can be considered as agents themselves. If they are well designed, they usually give the illusion of a direct communication (Tognazzini, 1993). The main problem is to keep human agents who use them aware of their limitations. The orchestra organization (taken as a global requirement for the design of artificial channels) should improve situation awareness from two viewpoints:

- artificial channels (by design) should bring the right information at the right time in the right format—synchronous and asynchronous aspects of D/L should be exploited to satisfy this specific requirement; assuming that D/L will enable more direct communication (through an appropriate I-CF transfer);
- pilots should better focus on coordination rules (in addition, an ATC conductor will make sure that these coordination rules are applied)—by focusing on coordination rules, pilots should be inclined to better monitor required information².

**Cooperative dataspace**

According to the above rationale, a data link system should enable the pilots to maintain a high situation awareness. Pilots need to know at all times where they are, where they need to go, where other proximal agents (airplanes and ATCs) are. These objectives are currently satisfied using maps, calculations and essentially communications. Data link systems should improve the satisfaction of these objectives as well as the way these objectives are satisfied. We already mentioned that coordination is mandatory because D/L will bring more autonomy to aircraft. This coordination can be managed either by the individual application of coordination rules, or by an external control of the application of these rules. Thus, it is necessary to develop a corpus of coordination rules associated to the development of the artificial channels. It results from the above analysis that D/L integration can be reduced (at least in the first place) to the incremental design of artificial channels associated with the design of coordination rules.

**Cognitive function analysis for human-centered automation**

**Cognitive function analysis: Why?**

Glass cockpits have shown the necessity for the crew to better cooperate and coordinate their actions. This is a specific case of a more general trend caused by the integration of computers in work situation. Since computers process most workload-demanding tasks, they transform previously tiring tasks into highly cognitive activities. *Energy-based*
activities are replaced by information-based activities. This evolution has two different consequences: people trained according to the energy-based technology (e.g., "old" pilots flying conventional aircraft for a long time) need to adapt to new cognitive skills — it can be hard to re-construct new (human) automatisms (e.g., the use of the flight management computer); people trained according to the information-based technology (e.g., young people using computers) may lack physical appreciation of the world.

Situation awareness is again a crucial issue. When someone does not receive a critical information, he/she constructs a surrogate information to satisfy his/her information need. When an information is needed, people either get it from a reliable source (often predetermined in aviation), or from a prediction involving a cognitive effort. The main problem with the introduction of computers is that the world is deconstructed and reconstructed according to "rational" goals. The reconstruction often reduces the original world. For instance, some proprioceptive cues that were available in the past are now reduced for performance and comfort improvement. Pilots need to involve more cognitive processes to reconstruct physical parameters (that were directly available in the past). This does not means that introducing computers is not a good choice. This means that we should better analyze what we lose by automating some functions previously devoted to humans, and what we gain. In other words, we should analyze how the job is transformed. Each agent has responsibilities, requires access to resources, and has particular knowledge appropriate to tasks. Some tasks may be done in parallel, others may require results from other tasks performed by agents. D/L integration can be a good example of human centered automation. We see several goals that should be raised in this project: increasing communication links between ATC and A/C; reducing pilot’s workload due to pure human-machine interaction (e.g., frequency selection); focusing on navigation issues (awareness of the aircraft location and the locations of other aircraft around, as well as information about the environment such as weather information); etc. In order to better understand the issues involved in air-ground communications, we propose to perform a cognitive function analysis. The construction of cognitive functions that are involved in the ATM should enable to better master ergonomic design of D/L.

Cognitive function analysis: Elicitation methods

The first step is to elicit concepts that govern the field that we want to investigate. Eliciting concepts from experts is not a trivial task. Cognitive functions are constructed from these elicited concepts. Indeed, it is required to (re)construct them from discussions with ATM experts, from various analyses of ATM-related databases and reports, from various kinds of observations, and from simulations incrementally modified by assessing their results. We propose to implement four types of knowledge elicitation techniques to develop a list of cognitive functions:

- **Interviews** of commercial pilots and test pilots, as well as instructors. These interview should be based on structured questionnaires.

- **Group knowledge elicitation** (using the Group Elicitation Method). In order to refine and extend the above initial list of ATM-relevant concepts, we plan on doing three new knowledge elicitation experiments involving pilots, controllers, and a mixture of pilots and controllers. The main goal of this experiment is to elicit a larger set of **ATM-relevant concepts acknowledged by domain experts**. These experiments are planned for the second semester of 1995. From this list of concepts defining relevant
contexts for block decomposition, a set of cognitive functions could be derived either experimentally (scenarios must be defined) or analytically with ATM experts.

- Eliciting knowledge from incident and accident reports.
- **Analysis of the communication activity.** In all cases, it is difficult to avoid an analysis of the communication activity of the various operators. A research project is going on at EURISCO on the way pilots use checklists.

These elicitation techniques can be used either sequentially or in parallel. Note that they are listed by order of increasing complexity and task demand. A first set of cognitive functions will be developed with respect to three classes of criteria: **operations:** users' information requirements, context and information continuity, information consistency, expected human adaptation to D/L; **theory:** cooperation between agents, agent coordination, information processing, decision making, D/L multimodality, agent models to explain and anticipate; **limitations:** incidents, accidents, human errors, risks, design flaws.

**Cognitive function analysis: Representation and simulation**

Cognitive functions are difficult to capture. The main idea of the method is to **incrementally refine elicited cognitive functions** in order to simulated cognitive interactions, in new air-ground communication setups for instance. Cognitive simulations make it possible to test design alternatives.

A cognitive function analysis (CFA) (Figure 12) uses the block representation (Boy, 1991; Mathé, 1990). When physical metaphors of cockpit or ATC scenes are attached to each knowledge blocks, a cognitive simulation can be generated (Figure 13). A cognitive simulation using the block representation is started by specifying a starting context and satisfying one (or several) triggering conditions. There is a direct correspondence between the formal knowledge block and its external "face", i.e., an appropriate metaphor of its meaning. For instance, if a block represents the various actions to take in the "before V1" context, its external "face" will be all the relevant instruments and procedures to follow in this context. This external face can be static or dynamic according to the level of detail that we would like to investigate. Standard hypermedia tools can be used to develop such external faces (Figure 13). We claim that this method (cognitive simulation) enables to study both human-machine and human-human interactions. This is due to the fact that it has been intrinsically based on the concept of agent. The main difficulty is to determine the level of granularity that we would like to study. There are tradeoffs and compromises to make. This simulation enables domain experts to assess the relevance and correctness of the CFA. In particular, the level of granularity of the representation is essential in order to capture relevant and necessary CFs useful in air-ground communications.
The CFA method consists of the following steps:

- define a first sub optimal set of contexts using the elicitation methods previously described;
- develop the knowledge blocks that describe processes responsible for both pilots’ and controllers’ activities within these contexts;
- run a cognitive simulation and assess the relevance and correctness of it;
- refine current contexts and knowledge blocks;
- run a new cognitive simulation and assess the relevance and correctness of it.

The user interface issue

The user interface should be designed according to the results of the previous analyses. However, we can already anticipate possible recommendations and (tentatively) solutions such as:

- transferred information should be kept simple—measurements of simplicity have to be defined in terms of quantity to quality of the information that needs to be transferred;
- information data bases should be easily consulted on-board (asynchronous interaction with the ground)—in particular direct interaction should be preferred to menu-driven or command driven interaction; a case-by-case study is however required in most cases;
- the D/L user interface should facilitate intra-cockpit interaction and cooperation (cockpit resource management)—experimental tests are necessary here;
- speech recognition and voice synthesis tools should be experimented (an assumption is that multimodal interaction—when appropriate and natural—is much better than monomodal interaction (such as the use of visual screens);
- finally, a virtual periphery should be designed, complementing the too busy central vision channel, and providing appropriate situational awareness including useful information that is currently provided through party line...

Discussion and perspectives

The main objective of this paper was to trigger discussions on data link (D/L). D/L is a new technology that is still vaguely defined. We know that D/L will enable the transfer
of large quantities of data between the ground and the aircraft. What is not clear is the way these data will be transferred. The following D/L integration issues need to be addressed: information content and support that define the multimedia aspects of the transferred information between human agents; artificial agents (channels) that will help human agents in information transfer, understanding and processing; information infrastructure that is related to the organization defined by this new way of agent interaction.

More fundamental issues need also to be addressed such as shared context, continuity of context, and situation awareness that deal with time and belief. Since D/L will introduce the new concept of information infrastructure, pilots will need to trust information more than before. It seems that the major shift is in the nature of cues that pilots usually rely on to form their beliefs. In the past, these cues were almost exclusively physical. In the future with D/L, they will be almost exclusively informational. Another major concern in the multi-agent perspective is the delegation of activities from agent to agent. Resource assignment needs to be addressed since there are individual resources (process control) and collective resources (cooperation). Each agent needs to control and manage resources that he/she needs. This is not trivial since it involves attention, concentration, training, etc.

Various cognitive simulation scenarios should be developed such as: reconstructed party-line, context continuity and free flight; trajectory negotiation; interactions within a mixed airspace, i.e., where some aircraft are equipped with D/L and other are not; scenarios of failure. A three year effort is planned to develop these various aspects of datalink integration. It should be articulated around the following research agenda:

- investigation of the relevant ATM concepts using the elicitation methods that are described in this paper;
- development of a preliminary cognitive function analysis on a restricted domain of the ATM—in particular develop a set of external "faces" that will enable cognitive simulations; this preliminary construction of cognitive functions will suggest a number of experimental scenarios to be developed and implemented; these tests could be performed by instructors on Line Oriented Flight Training (LOFT) sessions (in a full-flight simulator), for instance, other real-world tests could be implemented on-board with airline pilots, and controllers;
- assess the results of the related cognitive simulation—a document including the results and recommendations will be produced;
- iterate on the current cognitive function database by incrementally assessing it through cognitive simulation and testing of various technological options—a synthesis document including the results and recommendations will be produced at the end of the project.

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