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# Human communication, mutual awareness and system dependability. Lessons learnt from air-traffic control field studies

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**Abstract**

The dependability of many complex and critical systems strongly relies on human operators, both through human reliability and human ability to handle adequately the unexpected events. This paper focuses on ergonomics field studies of air traffic control activities, and more specifically on the analyses of communication within teams of controllers. We show how operators use spontaneously the natural redundancy and diversity of human communication (multimodality, addressing features,…), so as to successfully maintain mutual awareness. This is the key for reliable cooperation, for the sake of global system dependability that rests on mechanisms such as error detection, recovery, and prevention (by anticipation and regulation). This study helps in providing specifications for the design of systems efficiently supporting both human cooperation and human ability to contribute to dependability. 

*Keywords*: Human reliability; Human communication; Cooperation; Mutual awareness; Fault prevention; Fault tolerance; System dependability; Air-traffic control

## 1. Introduction

Modern technology allows more and more complex systems to ensure more and more critical functions. However, in most critical systems a significant role is still ensured by human operators, and especially teams of operators. In many work settings, humans have to maintain continuously a precise knowledge, related to the state of the technical system and of the environment on the one hand, and to the actions, intentions and knowledge of their colleagues on the other hand. This is the key for their ability to handle appropriately the unexpected events: detection of errors (due to human or technical components), diagnosis and selection of an appropriate sequence of actions. Up to a large extent, the global dependability of many socio-technical systems thus depends on the efficiency of teamwork.

Cognitive ergonomics, as a discipline, provides methods and tools aimed at understanding how humans actually behave, act and interact in work situations, and at identifying how given work settings constrain or improve human capabilities. Therefore, it can contribute significantly to the overall design and exploitation process of critical socio-technical systems.

This paper reports on our approach and the results gathered for several years on various domains (nuclear, space, air-traffic control, etc.). These are illustrated here on our most recent ergonomics field studies, conducted in an Irish Air-traffic control centre. Air-traffic controllers work in cooperation with colleagues (other controllers in the same or in other centres, pilots) and use the support of a computerised system, so as to provide a critical service, ensuring both the traffic handling (availability concerns) and the collision avoidance (safety concerns).

The paper focuses on the influence of the work settings on the cooperation, especially through the supports providing an efficient and reliable communication. It is advocated that multimodal communication within a shared workspace is an efficient support to reliable cooperation through the elaboration and updating of shared knowledge and mutual awareness, which in turn contribute to the global system dependability.

This paper is composed of seven sections. Sections 2 and 3 present the theoretical framework (cognitive ergonomics) and the methods guiding our study. Section 4 outlines the main characteristics of air-traffic control activities in Ireland. Section 5 describes the collaborative dimension of these activities and points out the importance of the shared workspace on communication. Section 6 shows how communication impacts on the system reliability, in enabling controllers to implement loops of controls. The last section discusses in more general terms the causal

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relationship between human communication and dependability, and tries to give some clues both on the ergonomics and the technical system sides, for the design and organisation of complex critical socio-technical systems.

## 2. Theoretical framework: cognitive ergonomics

Even though it is difficult to characterise it as a theory, cognitive ergonomics rests on a specific set of assumptions and views of the world.

Initially interested in the analysis of people at work, it is now defined more widely as the analysis of people interacting with their environment. The primary focus of ergonomics is the understanding of working conditions, in order to improve them (and originally reduce human pain and injuries). Close to the Anglo-Saxon "human factor" approach, cognitive ergonomics is still more than anthropometrics, as it does not focus on the physical aspect of work only. Last of all, ergonomics analyses are design-oriented in the sense that analysts aim to understand working situations in order to improve them (through design, modifications, or training).

The main assumption in cognitive ergonomics is the difference between the *task* defined by the organisation (what people are expected to do) and the *activity* observed in real work environments (what people really do).

This distinction is based on the observation that whatever the rules and procedures are, they cannot be guaranteed complete, efficient and correct in any circumstances. So, usually in real-time situation, operators have to adapt these rules and procedures to the constraints of the situation [1]. These constraints can be as diverse as technical failure, weather problem, human error, strike, etc.

One quality of the ergonomics approach is the emphasis put on the role of people in adapting their task to the specific requirements of the situation. Indeed, observations in the workplace highlight the limits of tasks description, and the modifications required in real situations. Taking into account the differences between task and activity enables the analysts to identify the limits of the procedure, and provides a better understanding of human capabilities and adaptive competencies [2].

This justifies the importance put by ergonomics on field work. The work rests on the analyst's integration within the workplace [3]. What motivates this is the idea that only in the workplace analysts will grab what work is really about. Interviews with workers about their real work provide important information related to their vision and their perception of the way *they think* they perform their work. It is then obvious that certain aspects cannot emerge through interview as a result of two main reasons: first, actions are not always conscious, and second, complex sequences of actions are not perceived as a set of simple actions.

What ergonomics proposes is an external, objective description of what is taking place in the working environment. Using techniques as diverse as note-taking, sketches, photographs, interviews and video-recordings, ergonomics bases the analysis of the work practices on the description of the real performance of work, within its real context.[1]

In the next section, the method used in the context of the Air-traffic control (ATC) analysis is presented.

## 3. Field work

In Air-traffic control, people deal with a highly complex and safety-critical system. As described in the previous section, cognitive ergonomics insists on the necessity to perform field studies. In such a safety-critical context, where temporal constraints are important, the methodology used to approach the working situation and to collect data has to be very carefully prepared and implemented.

The observation and analysis of Air-traffic control activities performed in the Irish control centre aimed to describe and understand the work practices of controllers. We expected this study to reflect not only the performance of formal tasks, but also the contribution of controllers to system dependability through adapting their actions to the requirements of the situation. Thus, it aimed to analyse the collective activities, highlighting the use of environmental resources (people, tools and documents) and the role of communication in systems dependability.

As stated above, the ergonomics approach emphasises the importance of field studies. In Air-traffic control, we clarified that we planned to be in the control room, observing people, taking notes and from time to time even video recording activities. Our second request was in terms of controllers' availability, as we needed their explanations, comments and feedback, in order to validate our understanding of their work.

It was performed with respect to basic ergonomics "principles".[2] Thus, it followed two distinct steps, the first one focusing on the specified tasks (through reading documents and observing the work settings), the second one focusing on the real performance of work, usually called the activity (through observation of, and interviews with, controllers).

Our analysis of people's work practices focused on the verbal and non-verbal communication, cooperative mechanisms (help, mutual adjustment, awareness, regulation), use of tools, documents and procedures.

From these observations, we identified features that we considered relevant in the context of our study. Before discussing them in the next sections, let us first present the activity of ATC in Ireland.

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[1] This latter point refers to the fact that some could suggest a simulation of the activity in a laboratory. However, this would unfortunately eliminate external (and often unexpected) factors.

[2] Actually, in accordance with our ethic, we did clarify with controllers various points, such as their anonymity, the use of video-recording and the objectives and constraints of the study.

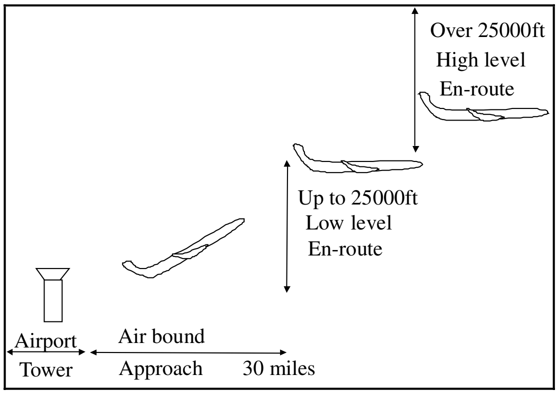


Fig. 1. From tower to en-route control. Case of departing aircraft.

## 4. Air-traffic control in Ireland

Air-traffic control is the service provided to airlines, ensuring that aircraft fly safely from one place (departure) to another one (arrival). Closely related to the temporal organisation of flights (air-traffic management), ATC is restricted to actions on aircraft from their taking off to their parking on airport areas. It aims at avoiding collisions between planes and managing the daily traffic.

ATC is usually divided into three main activities, called tower, approach and en-route control (see Fig. 1).

*Tower control* deals with the landing and take-off, as well as the parking of planes. This means that in addition to the control of aircraft, the controllers are in charge of the safety of the ground area (runway and parking). Theoretically, the aircraft is handed over from tower to approach control once it is air-bound, or conversely when it is positioned over the runway (usually between 3 and 5 miles away from the airport, depending on the speed of the aircraft).

*Approach control* refers to the movements of planes approaching or leaving the airports (up to 30 miles distance). Approach control does not only ensure the separation of aircraft, but could rather be described as the integration of aircraft within existing flow, with high constraints, especially in the case of landing.

*En-route* refers to the control of traffic within the airspace, at a minimal distance of 30 miles from the airport. In Ireland, en-route is split between low level (up to 25000 ft) and high level (above 25000 ft).

The controlled airspace is divided into volumes called sectors. Each sector is managed by two controllers (radar and planning controllers), accountable for all the traffic crossing their sector. Besides the control of aircraft already in a given sector, their task consists also of anticipating forthcoming aircraft as well as informing other sectors, which will later accept the aircraft leaving their sector.

ATC is strongly based on co-ordination between sectors. Co-ordination occurs not only between similar sectors (en-route), but also between different types of sectors (en-route and approach or approach and tower control).

The activity of controlling the air-traffic differs according to the geographic area (near an ocean versus in the middle of a continent) as well as the location of planes in the air space (low level, high level, close to the border with another sector, close to an airport).

In Ireland, approach and tower control centres are located all over the country, in every airport. Shannon is the only Irish en-route control centre, combining the three types of control described above.

In spite of a quite small air space (i.e. quickly flown over), Shannon indeed plays a very important role among the European ATC centres due to its location at the Western European Point. This leads it to deal with all the "oceanic" traffic, composed of flights both arriving from and going to the American continent. The controllers have to deal successively with two different types of activities: (a) welcoming flights after their oceanic journey, making sure their separations are correct and integrating them safely into the European traffic; and (b) organising the succession of planes, so that they all fly safely over the ocean (where no control is ensured). In addition, the Shannon controllers are also in charge of the European traffic flying to, from, and within Ireland.

## 5. Collaborative activities involved in ATC

The tasks of controllers are described extensively in official documents. The objectives of ATC are to "ensure the separation standards between aircraft". Despite an explicit description of each function, the air-traffic control is considered as a joint task, in the sense that close cooperation between the two controllers is required. The planning controller is described as the "radar's assistant". The control of aircraft is considered as a "combined team effort between a radar and a planning controller". The planning (or procedural) controller's task is described as "to assist the radar controller to the fullest extent in the control of aircraft operating within the area of responsibility of the sector".

These descriptions focus on the responsibility of the controllers, but without explicitly mentioning how these responsibilities (or missions) have to be honoured. Moreover, even in the official documents, the organisation anticipates the need for real-time adaptation, and specifies clearly that "nothing in these duties precludes a qualified controller from using his own discretion and initiative in any particular circumstance".

Working together closely, the controllers have to integrate various sources of information in order to co-ordinate their actions in the global mission consisting in transporting efficiently and safely human beings and goods from one point to another. For example, when an airport is facing unexpected problems (strike, weather conditions, accident), the controllers have to integrate the information in their strategy, in order to choose an appropriate solution.

In the remaining parts of this paper, we exclusively focus

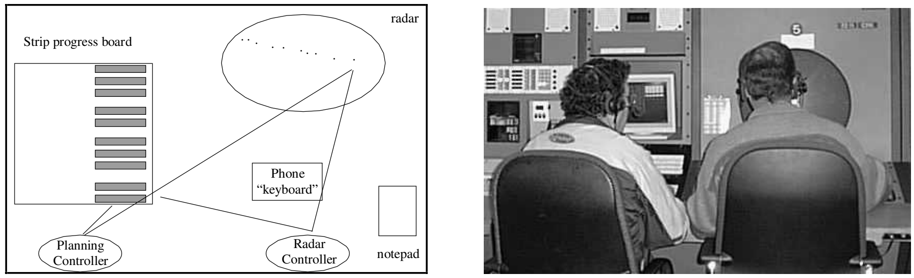


Fig. 2. Visibility of information in the shared workspace. Each controller has visual access to his/her colleague supports of information (sketch left, picture right).

on the activities of controllers in charge of en-route, and more specifically, high level sector.

In the next section we consider the pair of controllers as an entity, and describe how it cooperates with external actors (inter-cooperation with pilots, other sectors, etc.). Then we describe the intra-cooperation within this entity.

### *5.1. Inter-cooperation: co-ordinating activities*

In accordance with Suchman's descriptions [4], each working position can be identified as a co-ordination centre, which continuously co-ordinates its activity with other people's activity. Each sector appears as a node within a complex network, in charge of co-ordinating various actions and decisions.

The network is composed of people involved in the control of planes, while they are in a specific sector. These people are pilots, controllers from adjacent sectors, co-ordinator and data assistants.

The different agents in interaction with en-route controllers may either:

- be mutually dependent without sharing operative goals (e.g. cooperation between high level and approach, which are not directly related, but might affect one another);
- cooperate directly in order to achieve shared goals (e.g. cooperation between two adjacent sectors about a same plane, still in one sector, but soon to enter the next one).

Each aircraft requires co-ordination between sectors, at least when the aircraft is handed over. This co-ordination is usually implicit, as controllers use shared resources (as described in the next section) in order to anticipate the entrance of an aircraft in their sector. There is also explicit and indirect co-ordination, mediated by pilots, who are first told to change their radio frequency (by the sector they leave), and then are in charge of contacting the new sector.

Co-ordination between sectors is direct, explicit and verbal when a specific aircraft might cause problems. In this case the sector foreseeing a problem contacts the adjacent sector in order to agree jointly on a decision.

Controllers have the possibility to access multiple sources of information and knowledge such as observations, heuristics, diagram of the installation, indicators, and evolution of parameters. This gives them the opportunity to confront their observations and then combine the various sources of information. As stressed in Ref. [5], multiple points of view on a similar aspect are essential, especially in situations such as problem solving (conflict resolution in the case of ATC).

In this context, as discussed below in this paper, the two controllers in charge of a given sector need to share an updated representation of the situation.

### *5.2. Intra-cooperation: working in a shared space*

In addition to co-ordination between sectors, and with pilots, ATC is a highly collaborative activity that requires two controllers to work jointly on a same airspace for the efficiency and safety of the traffic control.

In order to make decisions, controllers need to be aware of the current situation, in terms of the features of each aircraft (destination, speed, altitude) as well as the features of the traffic in the sector. It is interesting to observe that in this situation, the system is aimed to provide information, not to one controller only, but to both of them.

The physical workspace functions as a common information space [6] in which agents cooperate, communicate and exchange information in order to control the technical system. This shared workspace (called a suite) is not only an open space within which information is exchanged, but also a medium in the sense that each component of the environment functions as a resource in providing itself information [7].

The suite is composed of a radar screen, a strip progress board (full of strips[3]), an electronic data display (EDD), a printer, various keyboards and track balls (connected to the radar, the EDD and the radio), and notepads. Headphones enable controllers to communicate with pilots (radio) and other control centres (telephone).

If we focus on a specific suite, we notice that its design

[3] The strips are paper documents presenting various features of flights (departure, destination, expected times, level, speed). Planning controllers organise them accordingly to these features in order to represent a dynamic image of the air-space.

takes into account the collective dimension. Most of the information supports, even if individual, are accessible to both controllers. The controllers share visual as well as audio resources. Lastly, thanks to their proximal location, they can monitor one another's position and movements (Fig. 2).

The co-located agents have the opportunity to observe each other, distributing and acquiring explicitly as well as implicitly information, through verbal messages, visual observation of other agents and of informational supports such as the radar screen, the strip progress board, the radio or the notepad. Thus, the working position provides some cues and informs about the current and the planned actions and usually enables co-operators to infer their colleague's current intentions and strategies.

Yet, the availability of information is not sufficient to ensure dependability, it has to be validated. The system is designed in order to provide both controllers with information related to the same events, but presented under different formats. Actually, if you consider the radar screen and the strip, they both inform about aircraft, but some information are given to one controller, and inferred by the other. For example, the planning controller reads on the strips the direction of the aircraft, while the radar controller infers it from the image. Similarly, the expected times are written on the strips, but only inferred from watching the radar: here, the radar controller infers from the current location and speed where an aircraft will be in the next few minutes.

These redundant data contribute to the quality and diversity of the available information, allowing the team members to elaborate a rich and shared representation of the situation, to know the current actions and potentially to detect errors, thus contributing to the system dependability.

### *5.3. Multimodal/artefactual cooperation*

Cooperation in shared workspaces is mediated both by human and technical supports. We do consider "communication" as every attempt made by one person to distribute or/and acquire information. This involves both the production and the reception of messages. Once we define communication as an exchange taking place between people, then most of cooperative acts (talking to someone, pointing at a device) work as communication [8]. Therefore, in this section we illustrate various modalities of communication observed in the case of ATC.

As stressed in Ref. [9], communication supports the confrontation of experiences, the creation and updating of knowledge, the elaboration and circulation of norms and the negotiation of working domains.

The communication observed within and without the control room is constituted of either verbal messages (spoken communication), written ones (paper documents, information on screen, location of strip), or "gesture-based" (other's position or actions within the space and/or on the environment).

Physical behaviour (movements, deictic), para-verbal signs (pitch, rhythm of verbal messages) and environmental resources are used to give information or to acquire others' attention).

So, the co-location enables controllers to use both audio and visual channel to transmit and acquire information. For example, the planning controller can take into account the direction of the look (part of the screen, strip board, other sector in the same room), the reactions to instructions (stress, humour, concentration), the gestures (actions) and the artefacts acted upon.

The arrangement of the work space influences the communication pathways, which can be either:

- Explicit and face-to-face within the shared space: the radar controller informs the planning controller of a request just received from the previous sector (an aircraft is already put on its clearance level).
- Explicit and mediated between the shared space and other areas: due to the situation, any communication between controllers and pilots, or between sectors is mediated either by radio or by telephone. Thus, all instructions given to pilots, or information transmitted to other sectors are mediated, but direct and explicit. For example, "climb to level 370".
- Implicit within the shared space: the planning controller can hear the direct communication addressed by a radar controller to a pilot or to another sector. In this case, we talk of implicit communication, in the sense that it is not addressed, but available due to the public nature of information in the shared workplace. Similarly, when a planning controller updates a flight strip, he/she makes it public that he/she knows that a modification occurred.

In terms of the intention of the emitter, the communication may be *addressed* (as in the former two cases) or *non-addressed* (as in the latter one).

*Addressed* messages are sent intentionally to one or several receivers, who may be designated more or less explicitly according to the context and to the communication media. A message may explicitly mention the intended receivers, by their name or the identification of their role. In a shared workspace, an oral message is generally associated to visual information (moving head, looking at someone, etc.) identifying the intended receivers and indicating to the emitter that the receivers identify themselves as such. In case of mediated communication, on a dedicated telephone line or frequency radio, the intended receivers are identified by the support itself (however, the name or the role is generally also included in the message, at least at the beginning of an exchange, for verification purpose). On communication media allowing information broadcast, the intended receivers may also be identified by the contents of the message. The classical use of information broadcast is for instance when air-traffic controllers broadcast weather information to all pilots in a given sector, using a dedicated radio frequency (the broadcast communication support improves then the communication efficiency and dependability, avoiding repeating a message or forgetting a potential receiver). The controllers may also use the broadcast facility to send a message to an intended receiver though they are not able to identify this receiver (e.g. a controller asking on a shared radio frequency if someone recently spoke with a given aircraft).

*Non-addressed* communication corresponds to messages that are, due to the communication support, available to receivers without the explicit intention of the emitter to send them these messages. This does not mean that the emitter is not conscious that messages are available to these non-intended receivers, nor that the emitter actually wants that they do not receive these messages. In the situations we study, non-addressed communication is a complementary feature, induced by the communication media (or naturally in a shared workspace), in association to explicitly addressed messages. The emitters are generally aware that their messages are publicly available to a wider audience than the explicitly addressed one, and this facility is used by all the operators to send and acquire additional information and improve the understanding of the situation. This happens naturally in shared workspace, where we also frequently observe for instance that operators using a telephone may repeat what the interlocutor says, not only for "collation" purpose (acknowledgement for the interlocutor) but also for transmitting the information to other operators present in the room. Another example is what is called the "party-line" making available to other pilots the one-to-one radio exchanges between one pilot and the ATC centre.

The various modes and addressing characteristics of communication are complementary and enrich one another, usually enabling the success of communication through taking away ambiguity and supporting error detection.

## 6. From communication to dependability

We saw in the previous section that the controllers, seated side by side, are able to access, use and act on shared resources. Their proximal location enables them to see what the other is doing (or watching), to hear what is said or done, to modify the other's environment, to perform the other's task, or to emphasise what should be done. Multimodal and direct communication is extensively used.

In this section, we draw a line between communication and dependability in showing that: (i) communication is basically used to inform people; (ii) this information enables people to develop a mutual awareness; and (iii) this awareness is the main support for human reliability and finally global system dependability.

### *6.1. Communication informs*

The basic and most obvious function of communication in the workplace is information. Controllers communicate in order to exchange information, both verbally and non verbally. The latter refers to the fact that sometimes actions on artefacts provide information about what the actor is doing and inferences about what he/she is up to. When a radar controller is pointing at the radar screen, even without a word, he/she is then not only attracting the other's attention, but also giving information about a specific aircraft, which has to be monitored.

The information can be direct or indirect. For example, when a radar controller informs a pilot about turbulence or weather conditions in a specific area, we can consider the information as given explicitly and directly. From the planning controller's point of view, the heard communication provides information about what the pilot knows, or what he/she is supposed to do. So, in this case, we consider that the communication, even though non-addressed to the planning controller, still contains information relevant to his/her own activity.

The communication can be described at various levels: information about the current situation (weather conditions), about the sharing of knowledge (pilots are aware of these conditions) and last of all about the impact these shared information have on the pilots' actions and preferences. Of course, this last level is based on the combination of the real-time information and controllers past experiences. Indeed, from past experiences, controllers expect certain information to have specific impact on pilots or on other controllers' decisions and actions (for an example, see Ref. [10]).

### *6.2. Information provides awareness*

Cooperation between controllers requires them, first to share an understanding of the current situation, and second, to know that they do share this understanding. In other words, they need to be mutually aware of the situation (including both the process and their respective knowledge). Mutual awareness is a large concept, referring to individual knowledge of a shared situation. We talk of mutual awareness when people are not only aware of each other's activities, but also aware of their reciprocal awareness. The supports for awareness in ATC are audio (radio, telephone, paraverbal signs) and visual (observing gestures, actions, as well as data on the radar and strips).

Awareness can be related to the actors, the system, the availability and location of people and resources, the current objectives, actions, tasks, the context (normal vs. incidental), the situation and the current state of the process (e.g. in Shannon, West bound vs. East bound). It is enhanced by many means, from a shared training and experience to the access to real-time data. Let us illustrate this with a few examples, associating means with the awareness they enhance:

- *Awareness about who is talking:* supported by watching the communication keyboard (as a specific button lights up according to the caller, and indicates the sector), by listening to a conversation and identifying its topics, by observing what the speaker is watching, or where he/she is oriented to.
- *Awareness about the availability of the other:* supported by observing the physical posture, by listening if they are engaged in communication, by observing their actions.
- *Awareness about current actions:* supported by watching which planes are acted upon, by listening to comments from actors while they work, by listening to the instructions they give, by observing their physical behaviour.
- *Awareness about current situation:* supported by observing the position of strips, the sequences of aircraft on the radar screen, by listening to the pitch and tone of discussions.

In ATC, controllers have to monitor others' performance and provide information related to their on-going activity. It thus appears that the task prescribed for each member of the team (i.e. controlling the traffic) necessarily involves a specific activity, not explicitly prescribed, consisting in acquiring information about related actions and functions and making one's task visible.

Let us now point out how this part of the activities contributes directly to the reliability of human operations and cooperation, and therefore contributes to system dependability.

### *6.3. Awareness supports human reliability*

As defined in Ref. [11], the dependability of a system is the trustworthiness of the service it provides to its users. Dependability must be addressed considering the threats, which could prevent the system from providing its service, and the means allowing to cope with these threats.

In ATC, we identified as safety-critical both technical components (radar, radio, data links) and human processes (perception, communication, information processing, actions). The main dependability attributes in the situation are the availability (both have to be ready to intervene efficiently) and the safety (collision avoidance).

In relation with the object of this paper (human factors), we now focus on the controllers' dimensions (dependability attributes and means, as defined above).

The organisation ensures the availability of controllers in planning roasters, enabling peripheral listening and the sharing of resources (both enabling people to quickly notice when their help is required). People enhance this in accepting this informal extension of their task (as described in Ref. [1]).

The main means used by the controllers are the *prevention* and the *tolerance* of faults. Part of these means are introduced by the organisation, while others are implemented spontaneously by the controllers.

*Prevention* refers to the anticipation and avoidance of faults (or of errors caused by humans). In Air-traffic control, the organisation provides multiple sources of information, requires regular interactions (inter-sectors, and with pilots), and allows the real-time reorganisation of teams (opening new sectors, providing an extra controller at a specific position). Controllers at work regularly infer and assess other's intentions, observe their actions (both verbal and non-verbal), anticipate their needs (contacting pilots, modifying plans) and regulate each other's activity (taking in charge each other's tasks). All these mechanisms are made possible by the availability of information (shared and accessible resources) and by the existence of an updated mutual awareness.

*Tolerance* refers to the fact that a service can be provided, a mission ensured despite the presence of faults in the system. This can be described in terms of error detection and recovery (or compensation) and is enabled by the existence of redundancies and loops of control in the system. In ATC, the organisation provides redundant and overlapping information (radar and strips). Controllers detect errors because they are sharing information, they continuously monitor each other's actions (peripheral vision and listening) and they are mutually aware of what is going on (this enables them to detect unexpected and doubtful decisions or instructions). Recovery is supported by the fact that both controllers can talk with pilots, and each controller can take charge of the other's activity, as well as modify the other's actions. This last point is facilitated by the organisational documents.[4]

## 7. Discussion and perspectives

It finally appears that cooperation in a shared workspace between operators with closely related tasks and skills, naturally exhibits powerful dependability features, where redundancy and diversification are exploited within the team as means for preventing or even tolerating potential errors from team members. These capacities are mainly based on mutual awareness, which in turn is mainly and efficiently supported by human communication within the team, including underlying mechanisms spontaneously associated to human communication to improve its efficiency and dependability. In this concluding section we discuss from a more general perspective this relationship, and try to give some clues both on the technical system and the ergonomics approach sides for the design and organisation of complex critical socio-technical systems.

[4] These documents, as we mentioned earlier say that "nothing […] precludes a qualified controller from using his own discretion and initiative in any particular circumstance".

### *7.1. Situation awareness and dependability*

The notion of mutual awareness discussed in Section 6 is related to the notion of situation awareness. The situation awareness designates the knowledge and the understanding of a human operator, about the current situation (state and current evolution of the system and of its environment in so far as it affects the system state and evolution). Situation awareness is clearly necessary for the operator to select an appropriate action (or sequence of actions), whether this selection is based on the application of a predetermined set of rules, or on a problem-solving approach (combining a mental behavioural model of the system, a set of objectives, and the current context).

There is strong and well-established evidence that situation awareness conditions the operator's ability to react appropriately, especially in front of unexpected situations. It thus contributes positively to the system dependability, first through avoiding operator's errors, and second through recovering from abnormal conditions in the system (technical faults) or its environment (both physical and human, e.g. wrong interactions with other operators). This justifies the many efforts towards the elaboration of work settings facilitating the elaboration and continuous updating of the operator's situation awareness (through the overall system design, task allocation and definition, procedures, training, and also of course the human-machine interfaces).

### *7.2. Mutual awareness and dependability*

The notion of situation awareness is easily extendable to collaborative situations. In this case, each operator may act on the system and affect its state and current evolution and especially a part that may be significant with respect to the potential effects of the actions of another operator (including the absence of action). This means that the second operator's situation awareness includes information (or at least beliefs) about what the first one is doing or intending to do.

Speaking of mutual awareness is still another step forward. As stated in Section 6.2, the term "mutual" refers not only to the awareness of each operator about what the other ones can be expected to do, but more importantly to a common, a shared awareness, including the awareness about the fact that it is shared. The viewpoint is thus not that of an operator interacting with other ones, but an emergent entity resulting from the cooperation among operators, with emergent properties that cannot be analysed only from the viewpoint of the individual activities of each operator within the team.

Focusing on dependability issues in the work setting described in this paper, it appears that each controller has his/her own role whose combination with the other one leads to the global service from the control position. In addition to this first characteristic, *complementarity*, there is a second one, *redundancy*: each controller is also able to provide additional support to the other controller's activity. The control position can thus be seen as an internally redundant entity, able to deliver the service despite dependability threats either through prevention means (e.g. anticipating and preventing controller's errors through workload regulation) or even tolerance means (detecting and signalling, or even correcting, the other controller's errors before they could lead to unrecoverable effects).

With respect to the complementarity characteristic, in the same way as in Section 7.1, the situation awareness is the key factor for the efficiency and correctness of each controller's activities. But with respect to the redundancy characteristic, the key factor is the mutual awareness, allowing efficient mutual monitoring and error recovery to be performed.

### *7.3. Rules, efficiency and dependability*

We observed that operators build and update mutual awareness through a combination of mechanisms supporting human communication, including implicit mechanisms. The term "implicit" raises an important issue since it is more often associated to dependability threats, rather than to dependability means. Indeed, "implicit" is often associated to informal or ambiguous contexts. In most cases, designers of critical systems and of their organisational aspects base the procurement and validation of dependability on the precise definition of explicit mechanisms (be they technical or human, e.g. task definition, communication and cooperation rules, etc.). However, as observed in the field study reported here and in many other ones, implicit mechanisms indeed play an important and positive role both for the efficiency and the dependability of systems.

Their positive impact on dependability should neither be underestimated nor overestimated. It is based on the classical notions of redundancy and diversification, especially when associated to explicit central communication acts. It happens in some situations, that rules related to such explicit mechanisms are not always observed rigorously. Relying only on implicit mechanisms to maintain the mutual awareness is generally feasible in nominal situations, and it may even be necessary to achieve the required level of efficiency (it may also be due to an underestimation of the risks, not so rare in highly dependable systems). It is generally observed that in degraded situations operators immediately switch back to a more explicit cooperation mode. However the problem is that implicit information may remain unnoticed, as well as its correct reception and understanding. This may lead to a situation where awareness is no longer mutual, while operators still think it is.

These mechanisms, as many other and especially human related ones, have both a positive and a negative side. They should not be prevented (or forbidden), but they certainly should not either be the only cooperation support in safety-critical systems. The organisation, rules, tasks, system support, etc. should establish appropriate conditions so as to take the maximum benefit from the various mechanisms and of their combination.

### 7.4. Perspectives on system design

The efficiency and reliability of human operations and cooperation clearly depend on the work setting resulting from the design of the system (in the broadest sense, including the definition of the technical system and its interfaces, the organisational aspects, the definition and allocation of tasks, etc.). This requires then a careful analysis of the support provided to communication and mutual awareness. This analysis should take into account the potentially negative impact on the underlying mechanisms spontaneously used by the operators to successfully communicate and maintain mutual awareness. These underlying mechanisms prove to be efficient and dependable. They are conducted as peripheral activities, with quite low cognitive load and disturbance, and bring on significant redundancy and diversification, allowing for an efficient detection of errors or inconsistencies (be they due to the emitter or to a wrong perception of the situation by the receiver).

Technical support to communication (between humans or between humans and the system) generally improves the efficiency and dependability of the communication according to some characteristics (distance, precision, feedback, etc.), but it sometimes drastically reduces the number of available modalities and the natural pluri-addressing capabilities, as observed in natural communication within a shared workspace. This results in improving the characteristics of the central communication acts, but reducing the ability to compensate their weaknesses through the associated peripheral activities. On the contrary we advocate that new technologies should be used, not only for avoiding restricting unnecessarily the useful characteristics of the human communication (multi-modality, natural pluri-addressing, etc.), but also to improve as much as possible all these characteristics, including the peripheral ones, and compensate their weaknesses. For instance, in addition to the (re)introduction of complementary communication modalities and of pluri-addressing capabilities, new technologies could help improving the information stability (compensating the lability of oral information), improving its perceptibility, and the feedback to the emitter, according to the concerned modalities and their combination (e.g. in natural environment audio information are more perceptible, though more disturbing, than visual information, but give less feedback about whether they are perceived).

Though it did not appear in the study reported in this paper (due to the close relationship between the operators' activities), another important point is that peripheral information about what other operators are doing may lead, in some situations, to a huge quantity of information, a very little part being actually of interest for current or future activities of a given operator. This suggests studying how a communication support could help in the selection of relevant information at the arrival, but also in memorising, sorting and presenting appropriately already received information according to the current needs.

Finally, it is important to insist on the interest of field studies, which give feedback on how operators actually use a given system in the real context, as compared to what was foreseen during the design stage, allowing the identification of both potential design weaknesses, and human capacities that might be better exploited.

### 7.5. Perspectives on ergonomics approach

It is worth noting that the field study reported here, which benefited from the support of the controllers and their management, has been conducted over a period of 3 months. It enabled the collection of rich and diverse data, thanks to the fact that the theoretical background and the methodology have been previously implemented in other complex and critical domains. We used the study as an opportunity to validate and generalise the existence of collaborative mechanisms previously observed in these other situations (described extensively in Ref. [12]).

The general ergonomics approach we developed is based on the combination of macroscopic and microscopic field studies. The former ones address a set of different working situations, which are compared at a relatively high abstract level, from available documentation and global observations from the field. The latter ones focus on in-depth field analysis of one or more situations. This is an iterative process where the macroscopic analyses provide a first selection of analogous or distinguishing characteristics and of generic mechanisms. This increases the efficiency of the microscopic analyses, and facilitates the generalisation or transposition of their results through their assessment within the macroscopic analyses, complemented if needed by some specific detailed observations on other situations.

Our first set of situations was constituted of work settings in various domains related to safety critical systems (nuclear control, satellite control, medical emergency service, computer and telecommunication network supervision, air traffic control, etc.). We now envisage to complete our methodology through the comparison of very similar situations, e.g. air-traffic control in different countries. An initial comparison between our observations and studies in other European countries [13,14] highlights differences at various levels (task distribution, conventions in work practices and available resources). Our objective is to investigate these differences and understand how, despite such diversity, controllers achieve similar objectives. Through this approach combining macroscopic and microscopic analyses on both various and very similar situations, we especially intend to understand how, in different environments, very similar basic cooperative mechanisms emerge. The underlying hypothesis is that the identification of the basic and natural cooperative mechanisms, along with their conditions of emergence and their global impact on the system behaviour, provides the necessary clues to design socio-technical systems benefiting as much as possible from their positive impact on dependability.

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