Distributed Cognition in Flight Operations

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Abstract. Human Factors is no longer simply concerned with the design of equipment and work stations. This old view is being superseded by a systems-based approach which examines all aspects of the working environment and makes little or no attempt to separate the human, machine and task environment. This socio-technical systems approach complements the latest thinking from cognitive science which regards the human use of technological artifacts as a joint cognitive system. People work in teams, who all have a slightly different perspective of the system; the tools that they use serve as 'cognitive amplifiers' to enhance human abilities. This brief overview begins by examining the operation of commercial aircraft as a joint cognitive system and examines the role of CRM in promoting distributed cognition on the flight deck.

Keywords: Distributed cognition, Joint Cognitive Systems, Crew Resource Management, Distributes Situation Awareness.

1 The Operation of Commercial Aircraft as a Joint Cognitive System

Any aircraft is a small socio-technical system operating within a larger socio-technical system. The air transport system as a whole is a very large, complex system of socio-technical systems [1]. Socio-technical systems contain people, equipment and organizational structures linked by functional processes (which are essential for transforming inputs into outputs) and social processes, which are informal but which may serve to either facilitate or hinder the functional processes [2]. Hollnagel [3] illustrated this issue in terms of the layers relating to the aviation Joint Cognitive System (JCS). Hollnagel suggested that the JCS relating to an airliner could be characterized in a similar manner to the skins of an onion (see Figure 1). It was merely a question concerning the desired unit of analysis the determined the bounds of the system under examination, not the ultimate bounds of the system *per se*.

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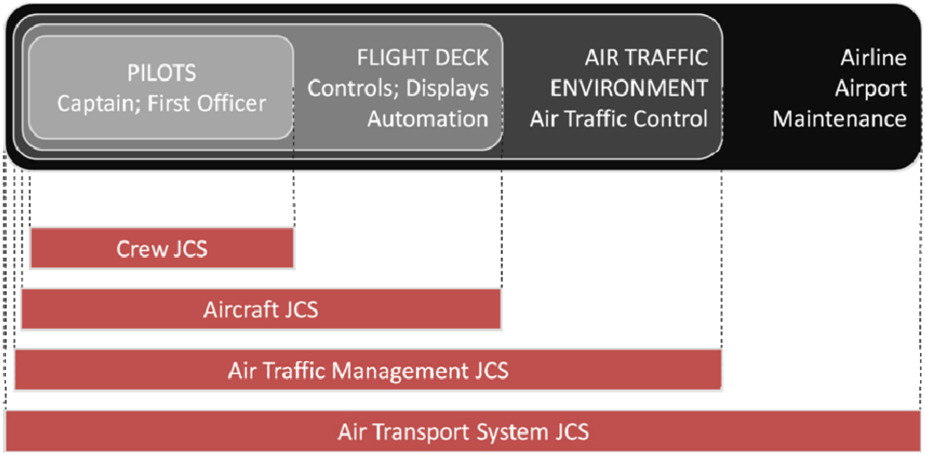

Fig. 1. The many bounds of a JCS for the air transport system (adapted from Hollnagel, E. (2007). Flight Decks and Free Flight: Where are the System Boundaries? *Applied Ergonomics, 38,* 409-416).

2 Distributed Cognition

Distributed cognition proposes that knowledge and cognition are not confined to the individual but are distributed across a number of interacting people and/or tools and objects. This approach takes a system-wide based view of people interacting with non-human (often technological) artifacts within an environment, where the emphasis in analysis is placed upon understanding how data, information and/or knowledge is represented and used. Cognition is a dynamic and emergent construct taking place in context. Key to this is the interchange of information between human and machine agents in a system and its representation. Hence it is necessary to describe how cognition is distributed and coordinated.

Salomon [4] proposed two general categories of distributive cognition: shared cognition and off-loading. The former category describes interactions between people engaged in a common activity; cognition across a group (the individual and shared representation of the situation) changes as their interactions progress. The latter category, off-loading, describes cognitive tool use.

2.1 Shared Cognition

Rogers [5] described four generic properties of distributed cognition in people working as a team, an instance of shared cognition:

- Cognitive systems comprising more than one person have properties over and above those individuals making up the system (e.g. an aircraft and its crew).

- The knowledge possessed by members of such a system is variable and redundant: teams working together on a task possess different kinds of knowledge and so engage in interactions that allow them to pool their cognitive resources.
- Knowledge is shared through via formal and implicit communication with prior knowledge of each other, enabling them to engage in heedful interrelating.
- Distribution of access to information and sharing access and knowledge promotes coordinated action.

Distributed cognition is predicated upon a degree of common understanding of a situation; about the aims and objectives of the task and the required method of achieving the goal. However, not every member of crew needs to know everything (indeed this would be very inefficient). For instance, when undertaking an ILS approach with one pilot flying and the other pilot monitoring both pilots should have a common understanding of the situation which overlaps completely. However, during the normal conduct of the flight the crew will not have such a close (shared) appreciation of their situation. There will be some common elements to their Situation Awareness (SA) for example, where they are and what their immediate and longer term intent is; many elements 'overlap'. However, each crew member will also be concentrating on the individual responsibilities associated with their role as Pilot Flying (flying the aircraft; dealing with navigation and general aircraft operation) or Pilot Not Flying (monitoring the flying pilot; monitoring aircraft performance; handling the radios; being responsible for monitoring the weather and for running the checklists). Thus, each pilot will be solely aware of several different things. They require SA for those factors relevant to undertake their duties for a specific task in a particular mission phase. These knowledge components are role specific but inter-dependent. The major challenge to achieve wider crew SA is in the co-ordination of these crew resources. To this end Endsley and Jones [6] developed a model of team SA comprised of four components:

- *Requirements* – What information and goals need to be shared between crew members?
- *Devices* – What devices are available for sharing this information (communication devices; visual and/or auditory displays, etc).
- *Mechanisms* – What mechanisms do crew members possess which support their ability to interpret information in the same way (such as shared mental models to facilitate communication and coordination)?
- *Processes* – What formal processes are used for sharing information; verifying understanding; prioritizing tasks and establishing contingencies, etc?

The '*requirements*' aspect is often a product of analyses which become instantiated via formal standard operating procedures (SOPs). '*Devices*' refers to the design of the physical equipment to support shared/team SA (and hence distributed cognition, more specifically cognitive off-loading). '*Mechanisms*' are a product of training, ensuring a degree of common understanding of processes and procedures in the crew; effective distributed cognition is predicated upon such an underlying basis. However, over the last three decades a great deal of effort has been directed at the '*processes'* component: specifically CRM (Crew Resource Management).

CRM was developed to promote pilots acting in a well co-ordinated manner. This was a direct result of several accidents where aircraft had crashed as a result of poor team working rather than technical failures, the root of which was often inadequate communication and/or cross-checking of crew actions (i.e. a failure to utilise all the human resources available on the flight deck in an appropriate manner). In several accidents these was also a failure to use the automation in an appropriate manner, thereby freeing up the crew's cognitive resources o undertake better management of the developing incident.

As early as 1998 the European Joint Airworthiness Authorities (JAA) inadvertently defined CRM in the terms of the processes in a JCS promoting distributed cognition: CRM was '*the effective utilization of all resources (e.g. crewmembers, aeroplane systems and supporting facilities) to achieve safe and efficient operation*'. UK CAA Civil Aviation Publication 737 [7] suggested that a CRM syllabus for flight crew should comprise:

- Human error and reliability, error chain, error prevention and detection.
- Company safety culture, SOPs, organizational factors.
- Stress, stress management, fatigue and vigilance.
- Information acquisition and processing, Situation Awareness and workload management.
- Decision making.
- Communication and co-ordination inside and outside the cockpit.
- Leadership and team behavior synergy.
- Automation, philosophy of the use of automation.

The above list it is not just about the human flight crew members in the aircraft; coordination and communication outside the aircraft is also considered and the use of the automation is also specifically included. The trend in flight deck design has been one of progressive 'de-crewing' coupled with increasing levels of computerisation and system integration [8]. Now just two pilots, with much increased levels of on-board automated assistance and surveillance from the ground, undertake the same job once accomplished by twice this number. However the introduction of automation did not just replace members of flight crew; it changed the nature of the piloting task. The emphasis is now upon being a flight deck manager rather than a 'flyer'. The aircraft and its systems are now more usually under supervisory control rather than manual control. The key skills required are crew and automation management rather than minute-to-minute navigation, communication and flight path control.

Kanki and Palmer [9] listed five methods by which communication facilitates CRM performance. They could equally have described its function as five means by which it promotes distributed cognition. Communication:

- Provides information.
- Establishes relationships.
- Establishes predictable behavior patterns.

- Maintains attention to task and monitoring.
- Is a management tool.

2.2 Cognitive Off-Loading

At the simplest level possible, a pencil and paper improves human memory, either in the long-term (e.g. as in a diary) or in the short term (e.g. when noting intermediate steps when doing long division). However, by doing long division using a pencil and paper, the main information processing limitations are now not the storage capacity and characteristics of Working Memory but the accuracy of recalling and executing the required arithmetical procedures (from Long Term Memory) for doing such a calculation, and the symbolic representation of the digits. The long-division process is now distributed between a human and a non-human component. The artifacts being used serve as a 'cognitive amplifier' [10] enhancing human abilities by distributing the tasks between the artifacts and the user. However, the use of such external aids simultaneously changes the nature of cognition. A different skill set is now required to develop the skills and knowledge allowing exploitation of the artifact(s) enhancing the user's cognitive system. In this instance a new skill set is required to fly the current fourth and fifth generation, highly automated airliners compared to earlier second and third generation commercial jet aircraft from only three decades years ago.

Modern technology can also transform data on behalf of the human, a process that would previously be done either in Working Memory directly or via a series of processes and calculations using rudimentary technology. To help characterize these transformational processes Ackoff [11] suggested the following categorization:

- *Data* – Basic building blocks/symbols.
- *Information* – Data that have been combined and processed concerning questions such as 'who', 'what', 'where' and 'when'.
- *Knowledge* – This applies information to questions concerning 'how'?

As an example, certification requirements mandate the display of fuel flow and quantity (*data*), however, these parameters are of limited utility: what is required is *information* concerning what the remaining amount of fuel represents in terms of range or endurance and *knowledge* about how the subsequent management of the flight. Modern flight deck automation can transform raw *data* from sensors to supply *information* (and even *knowledge*) via the displays to the pilots. The production of *information* for the pilots to use is now off-loaded to the machine. First and second generation jet airliners supplied only *data* requiring a mental manipulations on the part of the pilots to convert it to the required *information/knowledge* and thereby also increasing the mental workload and error potential.

Hutchins [12] illustrated the manner in which the cognitive representation of speed and the processes for calculating target speeds were distributed across human and machine agents on a flight deck. The agents used included pilots' LTM (Long Term Memory); speed bugs on altimeters; speed reference cards and flight deck/ATM (Air Traffic Management) procedures. Speed calculation and speed awareness was not simply a problem in Working Memory. It was regarded as a problem in distributed cognition across the flight deck which ultimately resulted in a more resilient system: air speed representation and calculation was best understood from a system-wide perspective.

3 Shared Cognition and Cognitive Off Loading in the wider Joint Cognitive System

The operation of complex systems by a team has cognitive properties over and above those accounted for by individual cognition. The example in table 1 describes a situation where the aircraft's weather radar detects a cloud formation ahead (heavy precipitation and electrical activity) and effectively warns that that it may pose a risk to flight. Noticing the information on the display the First Officer commences in-flight re-planning activities but even before the First Officer communicates his concerns to the Captain, the latter notices the First Officer's activities and becomes aware that a change of course will be required. In this case, output from the weather radar is input for the First Officer. The First Officer's unexpected activity is the Captain's input. However, it needs to be noted that (a) information is dispersed across human and non-human components in the system and (b) there is implicit communication rather than a detailed exchange of mental models.

Table 1. Distributed Situation Awareness on the flight deck as part of a response to potential bad weather ahead [13]

Agent	Perception	Comprehension	Projection
Weather Radar	Senses radar returns of storm clouds	Compiles picture of extent of cloud formation, distance and bearing	Displays information (along with projected tack) in appropriate color to alert pilots
First Officer	Sees storm cloud formation on weather radar/navigation display	Determines thunderstorm may present a risk to the aircraft	Needs to quickly determine new route to avoid the storm
Captain	Sees First Officer interrogate Navigation Display, Flight Management System and charts	Determines thunderheads present a risk to passengers and crew	Re-plans flight and initiates a diversion

Stanton, Baber, Walker, Salmon and Green [14] proposed a set of basic tenets that may form the basis for supporting distributed cognition in a JCS.

- Data, information and/or knowledge can be held by both human and non-human elements in a system.
- There are multiple views of any circumstance held by all the different agents, human or machine.
- Non-overlapping and overlapping knowledge depends on the human or machine agent's goals, which may be different but still compatible.
- One component in the system (human or machine) can compensate for degradation in another.
- Communication between agents in the system may take many forms including non-verbal behavior or ingrained customs and practices.

4 Promoting Distributed Cognition on the Flight Deck

Distributed cognition is not a product: it is also a process. Task goals (and hence the automation functions activated and the parameters within which they work) are set and managed by human operators. There is a reciprocal relationship between schemata (knowledge about the environment held by either person or machine) which directs exploration of that environment (by either person or machine) and which gathers information from the environment, which then in turn modifies the schemata held by the wider joint cognitive system (q.v. Neisser's perceptual cycle [15]). The wider human-machine system awareness determines what is attended to which subsequently dictates how data (or information) is perceived, interpreted and what further information is subsequently actively sought out. Hollnagel [3] described these components as an 'inner view' (knowledge in the head) comprised of issues such as workload, attention, SA, decision making, etc. and an 'outer view' comprising the job context, system boundaries, nature of the task, responsibility and control, etc.

Dekker [16] suggested that he question for successful automation should not be 'who has control' but 'how do we get along together' (p. 194). Automation needs to be transparent [17] if it is to be trusted and managed effectively. A 'good team player' makes their activities observable for their fellows and they are easy to direct. These are all issues in promoting distributed cognition, either from a shared cognition or a cognitive off-loading perspective. Machines have to be managed in a similar manner to that by which people are managed. Machines have certain levels of responsibility delegated to them: sometimes this is a 'boss/slave' relationship ('I say – you do'); other times it is a more collaborative relationship where responsibility is assigned to the computer within certain parameters. To exceed these parameters requires assent from the manager (choice of options or confirmation of proposed course of action). However, automation can also be 'strong and silent' apparently pursuing its own course of action with little oversight of, or communication to its manager (obviating distributed cognition).

To design for effective distributed cognition in a JCS is difficult. There is almost a fundamental contradiction in that distributed cognition adopts a more holistic analytical approach, however the design process requires reduction of larger components to smaller components and the formal specification of how they interact.

To start off with an overall representation of the system is required which includes (as a minimum, and in no particular order):

- Description of the system boundaries (which may not necessarily be fixed)
- System objectives
- Potential system states
- The relationships (required transformations) between data/information/knowledge
- Control requirements
- Display and communication requirements
- A philosophy for the role of the human(s) in the system.

The core information requirements that all components in the system (human and non-human) need to be aware of must be identified for each phase of operation (task). Peripheral items that may be allocated to an individual or machine artifact also need to be identified, as does that mechanism for promoting awareness of these issues when necessary (communication). Machines do not have to be 'transparent' in their operation concerning 'how' they are doing something but the human components in the system do need to be aware of 'what' they are doing. However, all the above is predicated on a shared mental model possessed by the humans in the system (the pilots). This is a product of training, and only the humans in the system can be trained. Furthermore, only humans can define the objectives of a system, either in terms of its design or its operation. A machine can only perform what a human can imagine.

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