From ethnography to the EAST method: A tractable approach for representing distributed cognition in Air Traffic Control

Guy H. Walker, Neville A. Stanton, Chris Baber, Linda Wells, Huw Gibson, Paul Salmon & Daniel Jenkins

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Command and control is a generic activity involving the exercise of authority over assigned resources, combined with planning, coordinating and controlling how those resources are used. The challenge for understanding this type of activity is that it is not often amenable to the conventional experimental/methodological approach. Command and control tends to be multi-faceted (so requires more than one method), is made up of interacting socio and technical elements (so requires a systemic approach) and exhibits aggregate behaviours that emerge from these interactions (so requires methods that go beyond reductionism). In these circumstances a distributed cognition approach is highly appropriate but the existing ethnographic methods make it difficult to apply and, for non-specialist audiences, sometimes difficult to meaningfully interpret. The Event Analysis for Systemic Teamwork method is put forward as a means of working from a distributed cognition perspective but in a way that goes beyond ethnography. A worked example from Air Traffic Control is used to illustrate how the language of social science can be translated into the language of systems analysis.

Statement of Relevance: Distributed cognition provides a highly appropriate conceptual response to complex work settings such as Air Traffic Control. This paper deals with how to realise those benefits in practice without recourse to problematic ethnographic techniques.

Keywords: distributed cognition; air traffic control; command and control; situational awareness

Introduction

Command and control

In command and control scenarios there is a common goal (comprising interacting sub-goals), there are multiple individuals who need to communicate and coordinate with each other in order to attain these goals and, increasingly, there are ever more complex ways of facilitating this process with technology. Command and control, at the most generic level, can be viewed as a form of management infrastructure for planning and organisation (Harris and White 1987). It involves the exercise of authority and direction by properly designated individual(s) over assigned resources, as well as planning, directing, coordinating and controlling how those resources are deployed (Builder et al. 1999).

‘Command’ can be viewed as the definition of overall system objectives or goals, whereas ‘control’ is the management of process and activities that lead to the achievement of these objectives (or to compensate for changes in the environment that hinder their achievement). Many contemporary socio-technical systems involve authority, planning, directing and coordinating and can be considered as forms of command and control. Air Traffic Control (ATC) is one example.

Distributed cognition

From a distributed cognition perspective (e.g. Hutchins 1995a), the task of ATC can be viewed as a form of ‘computation’ to maintain separation between aircraft in a region of airspace’ (Fields, et al. 1998, p. 86). It is further argued that the computations do not reside solely in the heads of individual controllers, instead they are distributed across the entire ATC system, comprising numerous controllers, teams and technical artefacts. The essence of distributed cognition is on ‘how [these computations] transcend the boundaries of the individual actor’ (Rogers 1997, p. 1, Hutchins 1995a, Hollan et al. 2000).

The language of representational states is used to describe the visible and external manifestations of
various ‘environmental contributions’ to the total system (Rogers and Ellis 1994, Fields et al. 1998). Representational states subsume the full range of observable interactions between people and artefacts, as well as the resulting states (and state changes) that arise from the various ‘computations to maintain separation between aircraft’. For example, an observable interaction might be a controller issuing an instruction to an aircraft. The resulting state might be a corresponding change in the aircraft’s representation on the radar display.

In command and control situations these computations and representational states interact. A change in representational state leads to further computations, further representational states and further computations. But whilst these simple low level mechanisms can be multiplied in simple ways to form the total ATC system, the high level function, the system’s aggregate behaviour, can be highly complex and adaptive (Chalmers 1990). Phenomenon ‘wherein complex, interesting high-level function is produced as a result of combining simple low-level mechanisms in simple ways’ is referred to as ‘emergence’ (Chalmers 1990, p. 2). A key emergent property of ATC is the so-called ‘picture’ or, in ergonomics parlance, situational awareness (SA).

**Distributed situation awareness**

The ability to sense changes in representational states, understand them, then perform some kind of computation based on them, not only describes the essence of distributed cognition but also that of situation awareness. At an individual level SA is about the psychological processes for, and information in working memory required, in order to develop ‘the picture’ (e.g. Endsley 1995, Bell and Lyon 2000). The controller’s picture is not the same as the radar display, it does not arise solely from any one physical or human component, it arises out of the interaction of many such components. It arises both from the parts of the ATC task that have been overtly designed (i.e. radar displays and other prescribed forms of communication) and those parts of the task that have not been overtly designed (i.e. the clicking of new flight data strips informs controllers that a new aircraft is about to enter their sector). Because the picture, or SA, arises from these myriad individual components yet its totality cannot be predicted solely from any one of them individually, it can be referred to as emergent.

Individualistic approaches to SA dominate ergonomics but whilst they may be appropriate for tasks that are performed by individuals in isolation, few complex tasks are performed entirely independently of others (Perry 2003). In systems terms, SA is what helps entire socio-technical systems such as ATC to be orientated towards and ‘tightly coupled to the dynamics of the environment’ (Moray 2004, p. 4). A distributed cognition perspective applied to command and control scenarios requires a shift from traditional notions of SA that focus on the individual (e.g. Endsley 1995) to those that focus on the system (e.g. Sandom 2001, Gorman et al. 2006, Salmon et al. 2008). At face value the response to this might be the concept of team SA (e.g. Salas et al. 1995, Perla et al. 2000) but even here there are problems. ‘The degree to which every team member possesses the SA required for his or her responsibilities’ (Endsley 1995, p. 39) runs into difficulties when confronted with the twin concepts of ‘overlapping SA’ (i.e. portions of SA that are identically shared between people, normally represented as a Venn diagram) and ‘compatible SA’ (i.e. that which is ‘not’ overlapping between two or more people, but which fits together like a jigsaw; Salmon et al. 2008). The fundamental problem stems from a tacit assumption that the ‘situation’ can be defined as a single, objective, external reality and that the goal of the people operating within the situation is to respond to all features appropriately. This is problematic on three counts:

1. There are many aspects of command and control scenarios that require the individual to make judgements and interpretations (so the assumption of the ‘objective reality’ of a situation is not always valid).
2. There are multiple sub-goals and multiple views of the situation (so the idea of a single reality is also not valid).
3. Different agents within the system use different representational states to inform and support their work, so the notion that there can be a single view of the situation (as opposed to several interlocking views) is also not easily supported.

One way to resolve the mismatch between mainstream thinking in SA and distributed cognition of the sort encountered in complex systems, such as ATC, is to consider one of the relatively invariant properties of it: information. According to Bell and Lyon (2000): ‘all aspects of momentary SA are eventually reducible to some form of […] information in working memory’ (p. 42). Information, in the SA sense, refers to what, in distributed cognition language, are called representational states. The question to ask is whether ‘working memory’ is the only place where such states can be represented. Distributed cognition would suggest not. It suggests that non-human artefacts can create, manage and share such states (to
some extent at least), meaning that the technical aspects of a socio-technical system will be contributing to the exchange of representational states too. The totality of this will be a form of systems-level awareness that is not traceable to any one individual and consistent with a distributed cognition view of the world, nor does it reside exclusively in the minds of humans. Thus, not only is the individual-level ATC ‘picture’ emergent, so to is the systems-level ‘picture’.

Another consideration is that representational states can be promulgated around the system with very little in the way of overt communication. One of the great strengths of expert operators is their ability to chunk information, to abstract and pattern match, to develop a high level of awareness from relatively little information in the world (e.g. Chase and Simon 1973). The update of a representational state for one agent might lead to partial updating of that used by another. For example, as an aeroplane moves across a sector its route is plotted on the ATC displays and its position updated dynamically; if there is no definable risk, then the updating happens automatically and without the need for intervention.

Beyond ethnography

Whilst there is much to say in favour of blending some of the ideas connected with SA and distributed cognition, there are several problematic issues for actually applying either approach. It should be clear by now that purely individualistic approaches to analysis may not capture all the required information about complex command and control scenarios. It is also the case that the traditional experimental approach may lack predictive efficiency in the face of significant numbers of emergent behaviours. Distributed cognition, focusing as it does ‘on the material and social means of the construction of action and meaning’ (Hollan et al. 2000, p. 178) employs ethnography to understand how information is used to support decision making, how it is represented and how it is manifest in the physical and social world (e.g. Rogers and Ellis 1994, Hutchins and Klausen 1996, Hutchins and Holder 2000, Hutchins and Holder 2001). Ethnography is a form of naturalistic, qualitative description based on observation. True ethnography places a requirement to live as a member of the ‘tribe’ for an extended period (possibly weeks or months) and to undertake the tasks and rituals of the tribe. The understanding gained from this participatory observation normally forms the basis of a report written from a first person perspective as a participant observer. In the field of distributed cognition, ethnographic methods are deployed. The problems with ethnography in terms of applying it in practice are as follows:

1. The outputs of ethnographic approaches (as they are used currently) remain couched at a qualitative, often highly discursive level of analysis (e.g. Hutchins 1995b, Hutchins and Klausen 1996, Hutchins and Palen 1997). Such outputs may not be easily reconciled with a predominantly engineering, or at least non-social science audience (McMaster and Baber 2005).

2. Depending on the level of analysis, having the necessary requirement for an observer to be ‘imbued’ in the culture of the scenario can, in some cases, be incompatible with objectivity and validity in measurement (e.g. Hutchins 1995b).

3. Ethnographic analyses are not always easily amenable to generalisation, concerned as they are with specific and localised scenarios and phenomena. It is certainly difficult to imagine some analyses being amenable to repetition.

These issues limit the practical value of distributed cognition in command and control settings and serve as a barrier to employing what is potentially a useful and enlightened approach to the analysis of complex systems. A response to this problem, however, appears to lie in the fundamentals of the distributed cognition approach itself. By characterising complex systems using the language and metaphors of cognitive science, many of the phenomena of interest, such as communications, shared awareness and other determinates of decision superiority, are rendered physically and observably manifest. That is to say, they no longer reside just in the heads of individual actors, they become manifest in the way that information is represented, modified, communicated and shared. The purpose of this paper is to deploy the Event Analysis for Systemic Teamwork (EAST) method as a way of capturing these phenomena, to show that there are ways to leverage the favourable theoretical perspective of distributed cognition but in ways that are appropriate and relevant to systems designers.

The Air Traffic Control work setting

A case study from the ATC work domain is used to illustrate the complementary approach to ‘doing’ distributed cognition. The primary strategic objective of ATC is safety. This is achieved by providing instructions on height, speed and route to aircraft pilots so that individual aircraft maintain legally mandated physical separation criteria (typically 3 or 5 miles horizontally and 1000 feet vertically; Civil
A secondary tactical objective is to optimise the routing of aircraft so that they take off and land at prescribed times and follow the most expeditious routes to destinations. These strategic goals translate into the following operational level activities:

- Keeping in radio and/or radar contact with aircraft.
- Instructing aircraft in relation to speed, altitude and direction.
- Providing information to aircraft about weather conditions.
- Ensuring that minimum distances are maintained between aircraft.
- Handling unexpected events, emergencies and unscheduled traffic.

Underlying these activities are several key non-human artefacts. Like their human counterparts they contain, represent and modify information and are part of a system that a distributed cognition perspective is able to model. Fields et al. (1998) provide a cogent summary of the key informational artefacts contained within the ATC work domain. These are as listed below.

**Charts and standard routes**

These can be seen as a prescription of how certain manoeuvres should be made. The information is shared between controllers and pilots as well as being stored on aircraft flight management systems (Fields et al. 1998).

**Flight data strip**

These can be seen as a representation of the projected state of aircraft. It takes the form of a paper strip that contains information on aircraft height, speed, heading and call sign. This information is modified by the controller by hand when instructions are issued and confirmation of receipt is received (Fields et al. 1998).

**Flight data strip bay**

Whereas the individual flight data strip is a projected state of an individual aircraft, the totality of data strips that refer to a region of airspace provides a ‘schematic model’ of air traffic progress. (Fields et al. 1998, p. 87).

**Radar display**

‘The radar screen provides controller’s with a snapshot of the current horizontal […] locations of aircraft’ annotated with individual aircraft call signs and height (Fields et al. 1998, p. 88).

**Aircraft call signs**

These are the unique alpha-numeric codes given to individual aircraft. Aircraft call signs serve ‘as an important (indeed the only) means of coordinating the information represented in […] various media’, such as the flight strip and radar display (Fields et al. 1998).

**Communications**

These represent, in a practical sense, the ‘mediation of control’. Fields et al. (1998) argue that communications can also be seen as a ‘system of representations’ (p. 4). Of critical importance is that communications ‘are also situated in the network of artefacts and information, and are [only] made comprehensible by reference to a larger context of shared representations’ (p. 88).

**Distributed cognition methodology**

**The importance of methods**

Explicit methods lie at the heart of ergonomics as a discipline, enabling the practitioner to vary their approach between scientist (i.e. testing and developing theories of human performance using rigorous data collection and analysis techniques) and practitioner (evaluating the effects of change, developing best-practice and, fundamentally, addressing real-world problems). Ergonomics methods are useful in the scientist–practitioner model because of the structure and potential for repeatability that they offer over and above ethnography alone.

**Descriptive vs. formative methods**

This study uses the EAST method in an attempt to reconcile distributed cognition with the methodological traditions of ergonomics. EAST is based on the integration of seven individual methods, which in turn is a reflection of the multifaceted nature of the command and control. In other words, no one method can adequately describe all of the degrees of freedom inherent in such a complex socio-technical system. That said, no such claim is made for the EAST method, but it can be argued that at least some of the major human dimensions of the problem space can be explored by taking a multi-method approach.

EAST is a descriptive method. It does not specify a formal architecture and what ‘should’ happen. Even
though it uses normative methods such as task analysis and process modelling, these are populated with data on what is actually observed. Neither does EAST focus on constraints, boundaries and a problem space defined formatively by the scope of what ‘could happen’, such as cognitive work analysis. EAST focuses on what ‘did’ happen. CWA admits the possibility of non-linear and emergent behaviour, whereas EAST is designed to identify specific instances of it.

Despite their descriptive vs. formative differences, EAST and CWA are both representative of a shift in methodological thinking. They share two key aspects: both acknowledge that complex socio-technical systems require more than one approach (EAST comprises seven individual methodologies, CWA comprises five ‘phases’) and both acknowledge that these perspectives are as interlinked as the complex socio-technical phenomenon under analysis (i.e. they are both systemic in nature). This is a core principle of socio-technical design (Clegg 2000).

**Method integration**

The following formal methodologies combine to form EAST: hierarchical task analysis (HTA; Annett); coordination demand analysis; communications usage diagram; social network analysis (SNA; Driskell and Mullen 2005); propositional networks; an enhanced form of operation sequence diagram. A multiple method approach has a number of compelling advantages. Not only does the integration of existing methods bring reassurance in terms of a validation history but it also enables the same data to be analysed from multiple perspectives. Also, with over 200 existing methodologies to choose from (Stanton et al. 2005) there seemed little pragmatic need to develop yet more. Of course, multiple interconnected methods require greater effort to analyse but a companion to EAST, called workload, error, situation awareness, tasks and time, is designed to help. This is a software tool that greatly streamlines and simplifies the application of the method and it was used in the current analysis (Houghton et al. 2006).

EAST is structured as follows. The HTA provides input into the analysis of team working (CDA), communications usage (CUD) and the linkage (via communications) between agents (SNA). Data for the HTA are gathered from live observation of the scenario. The output of all these methods (HTA, CDA, CUD and SNA) is given a summary visual form by using an enhanced OSD. Interview data, in the form of the critical decision method (CDM; Klein and Armstrong 2005), are used to create a network of linked ‘information objects’ or representational states. This representation is called a propositional network and is rather similar in concept to semantic networks. It is important to note at this point that the purpose of this paper is not to introduce the methodological intricacies of the EAST method (the reader is referred to Stanton et al. 2005 for further detail) but to show the effect of method integration in terms of enabling a distributed cognition perspective upon ATC.

**Air Traffic Control scenarios**

Data were collected from the ATC work domain between 28 and 30 June 2004 at a major UK terminal and area control centre. Separate analyses were performed on four discrete scenarios that were observed to take place repeatedly. By dividing up the controller’s task in this way it was possible to capture something of the dynamics of the system. In practice, multiple aircraft are presenting themselves to the controller(s), prompting them to engage interchangeably in one of the following four behaviours:

Scenario 1: To bring aircraft inbound from a major air route into a holding stack and then pass them onto an aerodrome controller (the holding scenario).

Scenario 2: To deal with aircraft that have left the holding stack and are en route to airfield(s), but prior to the final approach phase (the approach scenario).

Scenario 3: To deal with over-flying aircraft in such a way as to avoid conflict with the holding stack and other en-route aircraft (the overflight scenario).

Scenario 4: To deal with departing aircraft in such a way as to avoid conflict with the holding stack (the departure scenario).

**Applying the method**

The first stage of the EAST method involves a two-step process of observation and interview (Annett 2005). This is similar in some respects to the ethnographically based approaches currently used in distributed cognition research but here there is not a particular requirement for the observer to be directly ‘imbued’ in the scenario. The focus instead is on unobtrusive observation. The bulk of the analysis derives from live audio feeds, which detail who is communicating to whom and about what. These data are supplemented by the observers’ notes and by in-depth technical critique and insight provided by subject matter experts.
Whilst observational techniques provide information on the observable artefacts of interaction, they produce limited data on the representational states internal to individuals. It is to the CDM (Klein and Armstrong 2005) that relevant insights can be provided. The CDM is a semi-structured interview technique that uses cognitive probes in order to elicit information on expert decision making. This was administered to each participant in relation to each scenario.

Representing distributed cognition
The data collection methods provide information on the activities performed within ATC, how those activities are facilitated and how non-human artefacts participate in the joint cognitive system by containing, representing and transforming information. Using more conventional ethnographic techniques, these facets of a scenario would be described, exhaustively, in a first person written account. While this can capture the nuances of the situation as it was observed, and is often illustrated with diagrams and photographs of the work setting, it is not easy to summarise the account in a manner that brings out common features. In this paper the EAST method is used to present multiple views of the situation in such a way as to complement an ethnographic account, if such an analysis were to be performed (which in a lot of ergonomics studies would be unlikely). The EAST method maps the tasks being performed (in a task network), the communications between agents (in a social network) and the representational states being sensed (in a propositional network). Figure 1 illustrates the relationships between these three views.

Task networks
HTA is a means of describing a system in terms of a structured hierarchy of goals and sub-goals with feedback loops (Annett 2005). Its appropriateness in this instance can be put down to two key points. First, it is inherently flexible and the approach can be used to describe any system. Second, it can be used for many ends, from person specification to training requirements, to error prediction, to team performance assessment and system design. Key to its present application is its ability to model the temporal relations between tasks and the external conditions upon which task activity is cued. The task network, specifically, is a way of representing the detailed task analysis in terms of the interaction of higher level goals. This technique allows complex task analyses to be easily compared according to differences in overall task structure and type. The task

![Diagram](image_url)

Figure 1. The three network-based approaches provide a detailed characterisation of a complex socio-technical system. SA = situational awareness.
analysis/network forms the foundation for developing insightful social and propositional networks.

**Social networks**

SNA is particularly compatible with the distributed cognition perspective because it ‘[… ] focuses on the relationships among actors embedded in their social context’ (Driskell and Mullen 2005, p. 58–1). Furthermore, it can represent the technological mediation of communication and networks in which some of the nodes are non-human. A social network is a way to represent individuals or teams who are linked by communications to each other and to subject that network to mathematical analysis using Graph Theory (Driskell and Mullen 2005). Two mathematical indices are used in the present analysis, namely ‘centrality’ (i.e. a numeric ranking allowing key agents in the network to be identified) and ‘density’ (the interconnectivity of the network as a whole). The metrics reveal certain important characteristics of the networks to be revealed, in turn allowing comparisons between them.

**Propositional networks**

Propositional networks offer a novel and effective means of visualising representational states as held/
Table 1. Results of social network centrality for individual agents (in descending order).

<table>
<thead>
<tr>
<th>Agent</th>
<th>Centrality</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATC System</td>
<td>16.8</td>
</tr>
<tr>
<td>Controller</td>
<td>14.0</td>
</tr>
<tr>
<td>Heathrow Director</td>
<td>12.3</td>
</tr>
<tr>
<td>Desk Coordinator</td>
<td>12.3</td>
</tr>
<tr>
<td>Welin Controller</td>
<td>11.6</td>
</tr>
<tr>
<td>Adjacent Controller</td>
<td>11.3</td>
</tr>
<tr>
<td>Flight Strip Computer (Heathrow)</td>
<td>10.5</td>
</tr>
<tr>
<td>Senior Watch Assistant</td>
<td>10.2</td>
</tr>
<tr>
<td>FMS 1</td>
<td>10.0</td>
</tr>
<tr>
<td>FMS 2</td>
<td>10.0</td>
</tr>
<tr>
<td>FMS 3</td>
<td>10.0</td>
</tr>
<tr>
<td>FMS 4</td>
<td>10.0</td>
</tr>
<tr>
<td>Flight Strip Computer (West Drayton)</td>
<td>10.0</td>
</tr>
<tr>
<td>Group Supervisor</td>
<td>10.0</td>
</tr>
<tr>
<td>Deputy Watch Manager</td>
<td>10.0</td>
</tr>
<tr>
<td>Watch Manager</td>
<td>10.0</td>
</tr>
<tr>
<td>Flight Strip Assistant</td>
<td>9.5</td>
</tr>
<tr>
<td>Pilot 2</td>
<td>9.3</td>
</tr>
<tr>
<td>Pilot 3</td>
<td>9.3</td>
</tr>
<tr>
<td>Pilot 4</td>
<td>9.3</td>
</tr>
<tr>
<td>Pilot 1</td>
<td>9.1</td>
</tr>
</tbody>
</table>

ATC = Air Traffic Control; FMS = Flight Management System.
Note: The most central node is the assemblage of displays, equipment and ground aids.

Table 2. Number of communications links that exist between geographically disperse locations.

<table>
<thead>
<tr>
<th>From/To</th>
<th>Number of Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft to Airfield</td>
<td>3</td>
</tr>
<tr>
<td>Aircraft to TCC</td>
<td>6</td>
</tr>
<tr>
<td>TCC to Airfield</td>
<td>3</td>
</tr>
</tbody>
</table>

TCC = Terminal Control Centre.

experienced by the individuals at work within the system. The data used to construct them are based on the outputs of the CDM, in which a content analysis of the interview transcripts permits representational states to be extracted and causal links between them defined. Representational states take the form of specific knowledge objects within these networks, which, in turn, are analogous to propositions, i.e. entity or phenomena about which an individual requires information in order to act effectively. The propositional network offers four perspectives.

(1) They do not differentiate between different types of representational state (e.g. information related to states, people or ideas); therefore, from a design perspective they do not constrain assessments to consideration of existing configurations of people and states, rather to the required representational states associated with a scenario (Stanton et al. 2005, Walker et al. 2006).

(2) The network shows the totality of information used in the scenario (within the constraints of the data collection techniques used) regardless of whether agents in the scenario are human or technical.

(3) Shared SA can be accessed from the CDM, in which multiple agents can be attributed to common knowledge objects/states within the network.

(4) The dynamic aspects of SA can also be captured by animating the propositional network. This is achieved by highlighting active and non-active knowledge objects/states occurring in different task scenarios.

These individual network-based outputs not only meet the need to go beyond reductionism (and focus on interconnections as well as parts) but they can also be linked to provide several different perspectives on the scenario.

Application to Air Traffic Control

Analysis of agents in the distributed cognition system

The social network representation provides a particularly powerful example of distributed cognition; in particular, the idea of a joint cognitive system of collaborating human and non-human agents. The SNA of all the actors participating in the ATC task shows that there are 21 agents in the network, 14 human and seven non-human (shown as shaded in Figure 2) joined by 22 communication links. Note that this network has been simplified somewhat. The number of aircraft that an individual controller would be expected to handle could be significantly larger than the four shown for illustration in Figure 2.

The metrics ‘status’ and ‘centrality’ are used to identify key agents in the scenario and these are shown in Table 1. Between them they indicate the degree of connectedness an individual agent has and, consequently, the amount of influence that agent has on the performance of the network as a whole. Key agents can be defined as having high status and high connectedness. The analysis indicates that the controller (as one might expect) has high status and centrality in the network, but the metric also reveals that the most significant agent is in fact non-human; the ATC technical system (which is the technical infrastructure and assemblage of ground aids, communications systems, radar displays, etc). A great deal of information is received, stored, displayed or otherwise transformed by this (non-human) agent. This is a similar finding to that of Houghton et al.’s...
In addition to the distribution between collaborating human and non-human agents, cognition is also distributed in a geographical sense, between, for example, aircraft in flight within the sector, controller(s) based at the control centre and controllers based at airfield(s). Table 2 presents the number of times communication links cross these geographical boundaries. Geographical dispersion is further illustrated in geographical regions. The type of communications media is physically constrained in cases where links between nodes cross from one shaded region to the other. For example, verbal communications are not physically possible between controllers on the ground and pilots in flight without some sort of facilitation by technical means (such as radio). There remain a host of other local conditions that may also require some form of technological mediation. For example, individual controllers have to remain at their workstation during their shift in order to communicate with controllers who are not immediately adjacent, the telephone is used and/or the agent acting in the role of desk coordinator may have to facilitate.

**Facilitating technology**

Figure 4 shows how ATC operations are facilitated by seven types of communication media. Face-to-face communication comprises verbal communications. Face-to-face communication also contains a visual component. Controllers will point and demonstrate visually to aid in understanding
instructions. Telephone and radio technology facilitates voice communication. Radio also facilitates the dissemination of data, as do data network facilities. Written communication is dominated by the flight data-strip aspect of the task, although machine interfaces (e.g. the radar display) also contain written information as well as visual representations. Table 3 provides a summary by crossing communications modality with communications media to provide a technology/modality matrix.

Table 3. Communications modality/technology matrix.

<table>
<thead>
<tr>
<th>Modality</th>
<th>Phone</th>
<th>Radio</th>
<th>Network</th>
<th>Strips</th>
<th>MMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Written</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visual/Other</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ATC is a highly evolved and proceduralised work domain and the prominent role of implicit communications is also noted. The CDM interview gives access to some of these unobservable artefacts of interaction, one of which is a system of passing aircraft between sectors that does not rely on explicit verbal exchanges. The system works by putting aircraft into a particular position in the new sector at a pre-agreed height, speed and heading. As soon as the controller sees an aircraft in this position, he/she knows it is being passed onto them and they can take control of it. A wider awareness is gained via open channel radio communications and instructions to aircraft overheard from other controllers. Several contextual factors, such as the high tempo of operations and the proceduralised nature of the task, enable this level of shared understanding and this form of communication to take place. From a distributed cognition perspective it can be seen how a comparatively lengthy verbal exchange is often replaced with a far simpler visio-spatial task (facilitated by external technological artefacts such as
Figure 5. Knowledge network representing the entire knowledge base for the air traffic control work domain. Knowledge that is active during task enactment represents situational awareness at the systems level.

Table 4. Summary table of key knowledge objects (KO) that are active during different phases of air traffic control process.

<table>
<thead>
<tr>
<th>Knowledge Object</th>
<th>Departure</th>
<th>Over-Flight</th>
<th>Holding</th>
<th>Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressures</td>
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<td>Stack</td>
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<tr>
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<td>Flight Level</td>
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<tr>
<td>Strip</td>
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<tr>
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<tr>
<td>Read-back</td>
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<tr>
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<td>Flight Plan</td>
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<tr>
<td>Sector</td>
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<tr>
<td>TOTAL KO (16)</td>
<td>10</td>
<td>10</td>
<td>7</td>
<td>8</td>
</tr>
</tbody>
</table>

Note: The table demonstrates changes in systems level state of situational awareness.

the radar display and flight data strips; Hutchins and Klausen 1996). These are captured in the social networks. In other words, the presence of a link does not necessarily have to connote an overt form of communication but also implicit ones.

Control architecture

Although Figures 2, 3 and 4 are visually complex, it is possible to discern certain features of the social network. It can be noted that there is a diverging hierarchy from the Watch Manager level downwards. This hierarchy splits into the Group Supervisor level (and downwards towards individual controllers) and the Senior Watch Assistant level (and downwards towards Flight Strip Assistants). According to Dekker (2002) this so-called ‘split architecture’ provides some of the benefits of centralised planning with tactical adjustments to new information from subordinate units’ (p. 5). At this level of ‘air traffic management’, the inherent complexity appears to justify a degree of hierarchical sub-division so that aspects of complexity can be spread across agents. The possible
trade-off in situations where the state of the world is changing rapidly (a fast tempo), and where decisions need to be enacted quickly, is that any delay in the dissemination of information through a hierarchy becomes critical (Dekker 2002).

At the tactical or ‘air traffic control’ level, in cases where one agent requires some form of assistance, or to avoid the degradation of aircraft separation, the controller can interact sideways through the structure to an adjacent controller so that issues can be resolved and task load shared or re-distributed quickly. This pattern of communications is known as ‘peer to peer’ or a ‘negotiation architecture’. In these instances, each agent is more or less independently responsible for a defined area (Dekker 2002) and is able to react promptly to rapid changes in the environment.

A further characteristic of the scenario (from a structural perspective) is the amount of information sharing. This relates back to the ATC system and its displays (which subsume the entire radar, aircraft identification, warning, communication and ground systems in general) being the highest ranking agent in terms of ‘centrality’. Overlain across these two interleaved command architectures (split and negotiated) is the provision of high quality information to facilitate decision making within them. This overall configuration, known variously as a ‘negotiation architecture with information sharing’ is an emerging paradigm in several alternate domains, where it is referred to as ‘network centric’. The benefits of this architecture are agility, fast response and the ability to quickly organise and re-organise. In the theoretical work by Dekker (2002), the negotiation architecture with information sharing proved to be the most effective in high tempo tasks.

**Systemic situational awareness**

Systemic SA is modelled using propositional networks (Figure 5). From these networks it is possible to divine certain structural characteristics of the knowledge base that underpins effective SA for the total ATC task.

Central nodes in the network are identified using a centrality metric based simply on divining nodes with five or greater links. Table 5 presents an analysis of core knowledge objects for each individual scenario based on this criterion. By representing and simplifying SA in this manner, the table shows that depending on the task (which occurs at different points in time) not only does the type of information change, but by implication, so does the structure of it. This information can be used to explore and understand the information needs of controllers and, moreover, how one might go about supporting them.

**Temporal aspects of command and control in Air Traffic Control**

The controller will typically switch backwards and forwards among the four scenarios detailed above. As they do so, not only does the type and structure of information change (as shown in Table 4) but so do the characteristics of the task and social networks. To visualise the temporal aspects of the interrelations between the networks requires an alternate form of representation. Some form of animation seems a likely candidate for bringing this facet to life but this, and further refinements to the method, though eminently feasible, are within the purview of future work.

**Conclusions**

The purpose of this paper has been to show how the EAST method puts ergonomic analyses in touch with the distributed cognition perspective, rendering the output much more tractable than comparable ethnographic techniques. Although this paper is necessarily couched at a summary level of analysis, the following key characteristics of the ATC work domain are identified in Table 5. Within the table is a checklist used to sign-post where the system designer will find detailed insights into the type, nature and structure of these distributed cognition artefacts.

This paper has focused on a systems level description of the ATC scenario and serves to illustrate that this description can be achieved with the EAST method in live settings. The strength of this descriptive level of analysis can be summarised as follows:

- The methods avoid bias by focusing on objective and manifest phenomena.
- The methods are applicable to any domain and the results gained are comparable across and within domains.
- The results are graphical and easily interpreted, yet amenable to further summarisation using tables and numerical indices.
- The summary level is underpinned by considerable detail that can be explored further in the context of system design.
- It is consistent with existing narrative approaches to distributed cognition analysis.

As well as providing a descriptive level of analysis, the real potential of the method lies in its ability to offer predictive insights, that is to ‘model’ complex socio-technical systems. In theory, it should be possible to subject the networks to known changes (in task, social or information structure) and to derive outputs as to the effect of these under various performance contexts. For example, an
alteration in the command structure may influence the type of communications available to an agent, therefore affecting the type of information that is able to be communicated to other agents, leading to a deleterious affect on SA (or indeed vice versa). The modelling aspect of this work is at a nascent stage but shows promise for further development. What can be communicated about the current application of the method to live data is that the highly relevant theoretical perspective of distributed cognition is within the reach of systems designers and ergonomists.

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References


Table 5. Key characteristics of the air traffic control work domain and the network approach in which detailed systems level insights reside.

<table>
<thead>
<tr>
<th>Key Characteristic</th>
<th>Task Network</th>
<th>Social Network</th>
<th>Knowledge Network</th>
</tr>
</thead>
<tbody>
<tr>
<td>The coordination of individuals and teams to achieve a common goal (comprising separate though interacting sub-goals, knowledge and situational awareness (SA))</td>
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<tr>
<td>The technologically mediated geographical dispersion of &quot;agents&quot; (from controllers located in area control centres, or actual airfields, to specific aircraft in controlled airspace). A substantial technology infrastructure (providing high quality, accurate, real-time information via seven different communications modalities), which supports the dispersion and representation of knowledge and a systems level state of SA. A high degree of information sharing (where most agents have access to parts of the technology infrastructure) A highly evolved and proceduralised mode of operation, (involving implicit communication between and among separate actors in the scenario)</td>
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</tbody>
</table>


Hutchins, E. and Holder, B., 2001. What pilots learn about autoflight while flying on the line. 11th international symposium on aviation psychology, 6 March.


